FALCULTY OF SOCIAL SCIENCES AND HUMANITIES

DEPARTMENT OF DESIGN AND TECHNOLOGY

INTEGRATION OF VIRTUAL REALITY TECHNIQUES INTO COMPUTER AIDED PRODUCT DESIGN

BY

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Contents

Figures and tables in the text

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ABSTRACT

FACULTY OF SOCIAL SCIENCES AND HUMANITIES

DEPARTMENT OF DESIGN AND TECHNOLOGY

Ph.D.

INTEGRATION OF VIRTUAL REALITY TECHNIQUES INTO COMPUTER AIDED PRODUCT DESIGN

Jilin Ye

This research is concerned with using virtual reality technologies to provide more natural and intuitive human computer interfaces (HCIs) for the product design process, especially at the stage of conceptual design.

The research background, research aim and research objectives which give the overall guide to this research are introduced first. A comprehensive literature review and a list of designers' requirements drawn from human factor analysis of CAD techniques through case studies are then presented. These are used to define the characteristics for a new conceptual design system – the Loughborough University Conceptual Interactive Design (LUCID) system – and translated into system components including interface hardware devices, application software components, design functions and model data formats. Four new HCIs (two-handed operation, haptic interaction, stereoscopic display and sound feedback) are investigated focusing on their interactive concepts, working modes, advantages in design applications and software processing procedures used for their integration and implementation into the LUCID system. The non-uniform rational B-splines modelling approach is used to represent 3D freeform curves and surfaces. A 3D freehand sketching design tool and four freeform feature-based design functions (sculpting feature, sweeping feature, lofting feature and blending feature) are presented along with demonstration examples. User evaluation tests are conducted and the results drawn from them are analysed. Finally, conclusions about the outcome of the research and suggestions for future work are provided.

The main contributions of this research include: i) a deeper understanding of both the limitations of current CAD systems and designers' expectations of the HCIs for the next generation of CAD systems has been obtained through case studies and user evaluation tests; ii) a new direct, more natural and more intuitive interaction paradigm has been introduced which enables designers to take fuller advantage of their visual, auditory and tactile sensorial channels to create, view, touch, manipulate and listen to CAD digital models easily and freely; iii) a new 3D freehand sketching design tool has been created to support a true 3D design capability and iv) freeform feature-based design functions have been developed for use with both direct haptic and sound feedback operations.

Keywords
Conceptual design; virtual reality; interface technologies; product design; HCI; CAD.

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Finally, I would like to dedicate this thesis to my son, Tianmeng Ye, to encourage him to pursue his life aim through hard working.

List of abbreviations

2D	Two Dimensional
3D	Three Dimensional
3DM	Three Dimensional Modeler
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
B-rep	Boundary Representation
BOOM	Binocular Omni-Orientation Monitor
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAVE	Cave Automatic Virtual Environment
CDS	Conceptual Design Space
CG	Computer Graphics
CNC	Computer Numerical Control
COVIRDS	COnceptual VIRtual Design System
CPU	Central Processing Unit
CRT	Cathode Ray Tube
CSG	Constructive Solid Geometry
CT	Computed Tomography
CUP	Conceptual Understanding and Prototyping
CVE	Collaborative Virtual Environment
DXF	Data eXchange Format
DOF	Degree of Freedom
FDM	Fused Deposition Modeling

FEA	Finite Element Analysis
FFD	Free Form Deformation
GHz	Giga Hertz
GHOST	General Haptic Open Software Toolkit
HCI	Human Computer Interface
HKU	the University of Hong Kong
HMD	Head Mounted Display
HP	Hewlett Packard
Hz	Hertz
IBM	International Business Machines
IGES	Initial Graphics Exchange Specification
IMACS	Interactive Manufacturability Analysis and Critiquing System
ISAAC	Immersive Simulation Animation And Construction
IVECS	Interactive Virtual Environment for the Correction of STL files
LCD	Liquid Crystal Display
LUCID	Loughborough University Conceptual Interactive Design
MFC	Microsoft Foundation Class
MRI	Magnetic Resonance Imaging
MVC	Manchester Visualisation Centre
NC	Numerical Control
ND	New Design
NURBS	Non-Uniform Rational B-Splines
OpenGL	Open source Graphics Language
PC	Personal Computer
PDM	Product Data Management
PLUS	Plus Lumiere and Surfaces
PHIGS	Programmer's Hierarchical Interactive Graphics System
RP	Rapid Prototyping
RP&M	Rapid Prototyping and Manufacturing
SDK	Software Development Kit
SL	StereoLithography
SLA	StereoLithography Apparatus

SLS	Selective Laser Sintering
STEP	Standard for The Exchange of Product model data
STL	STereoLithography (exchange format)
UI	User Interface
VA	Virtual Assembly
VDVAS	Virtual Design and Virtual Assembly System
VM	Virtual Manufacturing
VP	Virtual Prototyping
VPAI	Virtual Prototyping of Automotive Interiors
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
VS	Virtual Sculpting
WISL	Workspace Instance Speech Locator
WWW	World Wide Web

CHAPTER ONE

Introduction

This chapter introduces the research presented in this thesis. It begins by explaining the research background and introduces the research focus that is addressed. The aim of the research is established along with the research questions that the study aims to answer. The research methodology is outlined, and an overview of the thesis structure is also provided.

1.1 Research background

A range of computer-based technologies have become widely used in the product design process over the past decade. These include parametric computer aided design (CAD) systems, virtual prototyping, non-contact scanning systems and rapid prototyping and manufacturing (RP&M). In general, these technologies have been developed to assist product designers and engineers in specific problem-solving tasks. Generally, the product design process can be classified into four main phases that may be summarised as: i) clarification of the task, ii) conceptual design, iii) embodiment design and iv) detail design [McMahon and Browne 1998]. The use of traditional CAD tools has been fruitful, yet mainly confined to the later stages of the product design process, namely, embodiment design and detail design. Most commercial CAD systems currently available on the market, such as Parametric Technologies' Pro/ENGINEER, Electronic Data Systems' Unigraphics and IBM/Dassault Systems' CATIA, while providing increasingly sophisticated means of manipulating CAD model shape and form representation in the computer, are poor or limited at supporting natural and intuitive interactive capabilities critical at the conceptual design stage.

Conceptual design is considered to be the crucial stage of the whole product design process. It plays a vital role in the success of the product because, once conceptual design is complete, up to 75% of the total life cycle cost of the product is committed and the product quality is largely determined at this stage [Ullman 2002]. During conceptual design, product specifications are not yet rigidly defined and designers have much freedom to change and modify the product configuration so as to meet the design requirements. The use of CAD tools in conceptual design should allow designers to concentrate on the creative design aspects instead of paying more attention to the interaction with the computer.

The need to integrate new emerging computer-based technologies into the product design process is generally recognised, especially at the conceptual design stage [McLundie 2002]. However, the capability for designers to fully exploit current CAD systems to support conceptual design has not been realised yet. A major obstacle, which restricts current CAD systems from being used in an active role within conceptual design, is the lack of sufficient natural and intuitive human computer interfaces (HCIs). These HCIs can provide designers with more familiar interactive capabilities for creating and representing their design intents efficiently and effectively. On the basis of awareness that designers can benefit substantially from computer support during conceptual design, there is an increasing need for new techniques for making the HCIs natural and intuitive in dealing with three dimensional (3D) digital product model data.

Despite the rapid advancements in CAD technologies such as hardware processing speeds and powerful design functions, one aspect has not changed very much at all – designers still use only a two dimensional (2D) mouse, a keyboard and a 2D screen to communicate with most CAD systems. Therefore, the interaction paradigm between human and computer in most CAD systems is often complex and makes use of complex user interfaces (UIs). These often tend to be command and/or menu driven and are completely foreign to anyone who has not received in-depth training. Case studies have illustrated that industrial designers could perform their design activities more efficiently and effectively if they used more natural and intuitive interaction approaches instead of the mouse/keyboard and 2D display interaction method [Sener and Wormald 2001]. Hence, this research focused on investigating new technologies and methodologies to provide more natural and intuitive HCIs to support 3D CAD applications that could bring a new sense and meaning to conceptual design in particular. It is crucial in the next generation of product design systems to seamlessly integrate powerful conceptual design supporting tools into some form of existing CAD systems that can effectively aid designers in creating and managing their design intents during the new product design and development process [McLundie *op cit*].

1.2 Aim of the research

The aim of this research was to explore how much further industrial designers could be supported by new CAD HCIs in the initial stages of the product design process. The research emphasis was to concentrate on: i) investigating the potential of new emerging virtual reality (VR) technologies such as haptic interaction and stereoscopic display, ii) integrating and implementing these new VR-based interfaces into a computer aided conceptual design application and iii) exploring the efficacies of these new VR-based HCI technologies during the early stage of the product design process. Therefore, this research work can be considered as an investigation into the application of VR-based technologies to CAD tools in the context of the product design process.

1.3 Research objectives

The research needed to investigate the application of CAD techniques for the conceptual design process so as to better understand the limitations of current CAD systems and then to overcome the shortcomings of the traditional keyboard/mouse and 2D display interaction paradigm. Therefore, a series of research objectives was set in the form of research questions.

The objectives of the research were to answer the following questions:

1. What geometric modelling representations are best for construction of 3D models within the conceptual design process?
2. What are the strengths and weaknesses associated with using VR-based interaction techniques within the conceptual design process?
3. What new user interface specifications need to be adopted in the conceptual design process?
4. What types of input and output devices can be employed to support the conceptual design process?
5. What kinds of new human computer interface paradigms can be fully integrated into the conceptual design process?
6. How will these technologies improve the conceptual design process?

1.4 Research methodology

A comprehensive literature review was carried out, particularly in relation to CAD geometric modelling techniques and VR-based product design issues (methodologies, technologies, levels of interaction). This led to identifying and classifying existing data/information on CAD geometric modelling techniques and VR-based interaction technologies especially within the computer aided digital product design field. From the outcomes of the literature review, best geometric modelling approaches for conceptual design were formed and the strengths and weaknesses of existing VR-based interaction technologies within the product design process were obtained.

Based on the literature review and the outcomes of human factor analysis of CAD techniques through case studies [*ibid*], a deeper understanding of the limitations of current CAD systems for conceptual design was identified and the designers' requirements for a new conceptual design system were defined. This led to developing the system characteristics (new user interfaces and design functions) of a new conceptual design system. Several hardware devices and software components were chosen to create multiple user-friendly HCIs as defined above.

In order to demonstrate the advantages of the new HCIs involved in the conceptual design process, a level of design functionality was defined based upon the designers' requirements. A new VR-based desktop non-immersive conceptual design system called the Loughborough University Conceptual Interactive Design (LUCID) system that would integrate and implement the defined HCIs, geometric modelling techniques and design functions into one practical design application was developed.

User evaluation tests were conducted to measure the LUCID system performance against the evaluation objectives. The limitations of traditional CAD systems, the efficacies of four VR-based HCIs and the strengths and weaknesses of the LUCID system were gained from data analysis of the user evaluation test. Finally, conclusions were drawn from the research and suggestions for future work were made.

1.5 Structure of the thesis

The thesis consists of a further nine chapters, the content of which is briefly summarised below.

Chapter Two: The product design process and the role of geometric modelling

This chapter contains the literature review on the product design process and geometric modelling techniques in CAD applications. It begins by identifying the product design process, conventional and digital techniques involved in the conceptual design process and then introducing the concept of CAD and its brief history. The state-of-art understanding about different geometric modelling techniques (strengths, weaknesses and their specific application fields) is investigated.

Chapter Three: Virtual reality technologies

This chapter reviews the literature surrounding virtual reality (VR) technologies and their useful applications. It introduces the fundamentals of VR, existing VR immersive and non-immersive techniques and also some VR application systems. Existing desktop VR-based design systems are investigated with a clear analysis of their strengths and weaknesses.

Chapter Four: New interaction techniques and design functions for CAD applications

This chapter first discusses the results from human factor analysis of case studies which lead to a deeper understanding of the limitations of traditional CAD systems and identifying designers' requirements for new generation CAD tools. It then presents the system characteristics of a new conceptual design system drawn from the designers' requirements found above. Several new user interfaces such as two-handed operation, 3D haptic interaction, stereoscopic display and sound feedback are outlined. A level of design functionality and a CAD model data transfer issue are also discussed.

Chapter Five: Developing a new conceptual design system: Applying VR-based interaction techniques to CAD applications

This chapter introduces the system components of a new VR-based desktop non-immersive conceptual design system – the LUCID system developed from the system characteristics defined in Chapter Four. Detailed descriptions of selected hardware devices, application software components, design function configuration and CAD model data formats are presented. A brief description of the overall interface architecture of the LUCID system is also provided.

Chapter Six: Human computer interface design

This chapter presents the user interface design of the LUCID system. It describes the graphical user interface and four new VR-based HCIs (two-handed operation, stereoscopic display, haptic interaction and sound feedback) focusing on their interactive concepts, working modes and advantages in design applications. Detailed software processing diagrams and procedures for their integration and implementation in the LUCID system are also discussed.

Chapter Seven: Geometric modelling method and algorithm design

This chapter describes the CAD geometric modelling using the NURBS representation. It introduces an efficient cubic-degree NURBS algorithm for 3D freeform curve design which is also applied to ellipse curve creation in the LUCID system. Mathematical algorithms for 3D freeform surface design using the NURBS method including cylinder surfaces, sphere surfaces and 3D freeform surfaces created from feature-based approaches are developed and implemented in the LUCID system.

Chapter Eight: Design functions and model data exchange

This chapter introduces the design functions which are implemented in the LUCID system. A 3D freehand sketching design tool is developed to support a true 3D design capability. Four freeform feature-based design functions (sculpting feature, sweeping feature, lofting feature and blending feature) are presented along with demonstration examples. The model data exchange facilities available in the LUCID system are also described.

Chapter Nine: User evaluation tests and analysis

This chapter describes the user evaluation test and associated data analysis. The results have confirmed the author's findings about the limitations of traditional CAD systems and designers' expectations of new generation CAD tools. The outcomes also exhibit the efficacies of the four new VR-based HCIs involved in the conceptual design process and reveal the strengths and weaknesses of the current LUCID system.

Chapter Ten: Conclusions and suggestions for future work

Finally, this chapter draws together the overall conclusions for the research work presented in this thesis in relation to the research objectives. It also considers the limitations of the research work and makes suggestions for future research.

CHAPTER TWO

The product design process and the role of geometric modelling

2.1 The product design process

Product design is concerned with the process of definition and development of a product that will be commercially successful [Wright 1998]. Although there is a debate over a formal description of the stages involved in the design process, it is generally agreed that the product design process begins with a need through identification of the problem (the specification of requirements), and follows through a conceptual design process (which mainly focuses on the generation of the ideas and concepts of the product) to a detailed design stage (in which the dimensions, tolerances, materials of the design are specified in detail for subsequent manufacture) [McMahon and Browne *op cit*]. One typical product design process flow was introduced by French [1998], as shown in Figure 1. This design process is linear with permitted feedback iterations. Other non-linear or cyclic approaches exist, which undertake design, development, analysis and the preparation of manufacturing information in parallel [McMahon and Browne *op cit*]. This has usually been referred to concurrent engineering or simultaneous engineering. Ferguson [1992] argued that, in practice, all design stages occur simultaneously, and that French's design scheme was an idealisation.

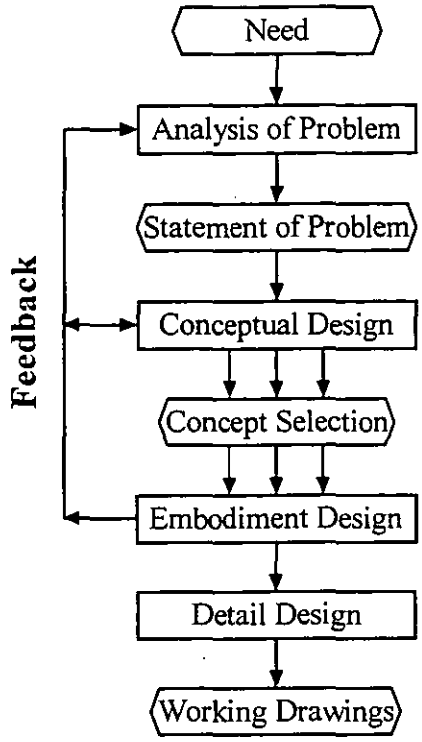


Figure 1: An ideal product design process [French *op cit*]

For the purpose of this research, product design is taken as an all-inclusive term. It includes input from all the design professions (including industrial design, mechanical, electronic and other engineering design) that engage in designing products. More specifically, the Industrial Designers Society of America defines industrial design as the profession of creating and developing concepts and specifications that optimise the function, value and appearance of products for the mutual benefit of both user and manufacturer [Idsa 2002]. Based upon this definition, Evans [2002] stated that the industrial designer mainly concentrates on defining product form and ensuring effective use with awareness of the manufacturing processes that would be employed in its production. Compared to engineering designers who mainly deal with applying the basic sciences, mathematics and engineering knowledge to convert resources optimally to meet a specific engineering process, industrial designers have a broader focus on the overall shape, style and appearance of the product, the production process, the choice of materials and the way the product is presented to the consumer with aesthetic and ergonomic considerations [Localcolor 2004].

In recent years, although there has been little change in the nature of the product design cycle, what have changed are the tools used to implement the design process and an awareness among engineering professionals of the value of industrial design [Davis 2004]. Therefore, the use of industrial design within a product design and development process may lead to added value through improved usability, lower production costs and more appealing products.

2.2 Conceptual design techniques

At the conceptual design stage, industrial designers are concerned mainly with the generation of ideas and concepts for the development of products [Roozenburg and Eekels 1995]. Although it constitutes a relatively short period in the whole design process, conceptual design plays a crucial role in the success of the product because it has many important implications (e.g. the overall cost of the product and the product quality) for the later design phases such as embodiment design and detail design [Ullman *op cit*]. Conventionally, industrial designers draw and sketch, make physical models and prototypes in the conceptual design phase.

It is interesting to watch how an industrial designer, when given a design task, instinctively reaches for a pencil and paper. The importance of conventional drawing, both formal drafting and informal sketching, has been widely recognised particularly during the early product design process [Lipson 1998]. Powell [1994] further introduced a more sophisticated form of sketching called sketch rendering. This technique involved the application of colour, light and tone to create the realism of a product form without excessive detail. Fang [1988] summarised the importance of sketching and drawing by identifying its six primary uses: to achieve the geometric and topologic form of a design; to communicate ideas between designers; to act as an analysis tool; to simulate the design; to serve as a completeness checker and to act as an extension of the designer's short term memory. Therefore, conventional sketching is considered an ideal design tool for fast creation and evaluation of concepts because of its close relationship with the creative process [Gribnau 1999]. An example of sketches during conceptual design for a car can be seen in Figure 2.

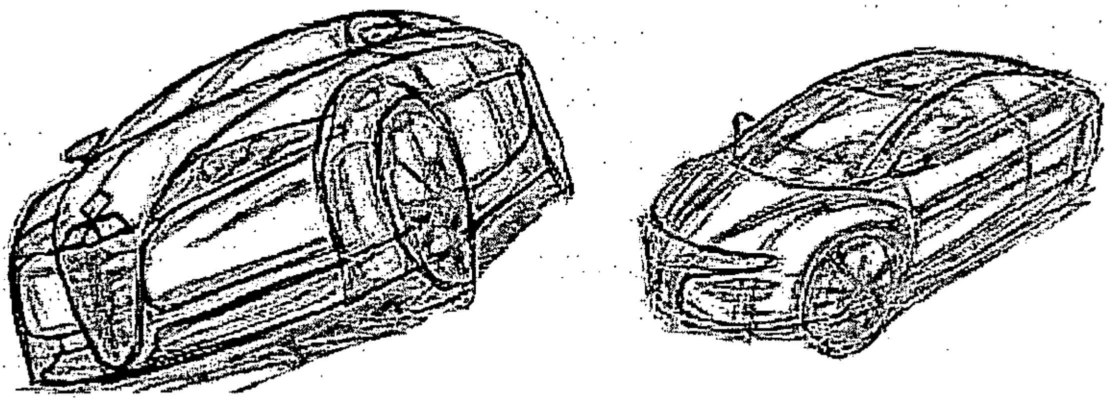


Figure 2: Sketches of a concept for a car [*ibid*]

Regarding conventional model making, there are two general approaches to produce physical models and prototypes: the building up and the carving away approach [*ibid*]. When building up, an industrial designer typically builds models up out of planar pieces cut out from paper, cardboard or thin styrene plastic. These pieces are taped or glued at the edges to form a rough three dimensional (3D) shape. When carving away, on the other hand, the designer usually starts with a solid material such as blue foam or clay from which parts are cut away or reshaped by hand using different tools. Industrial designers are known to use a wide range of materials, such as clay, wood, plaster, cardboard and foam. In most cases, they can use a variety of tools for working with one material. Figure 3 gives an example of a set of tools used for modelling with clay. When working with clay, for example, designers can use both hands and work directly with the form of the model with rich sensory information. With most computer aided design (CAD) systems however, the designers can only use a mouse, which limits the interaction with the model to sequential single-handed movements in two dimensions.

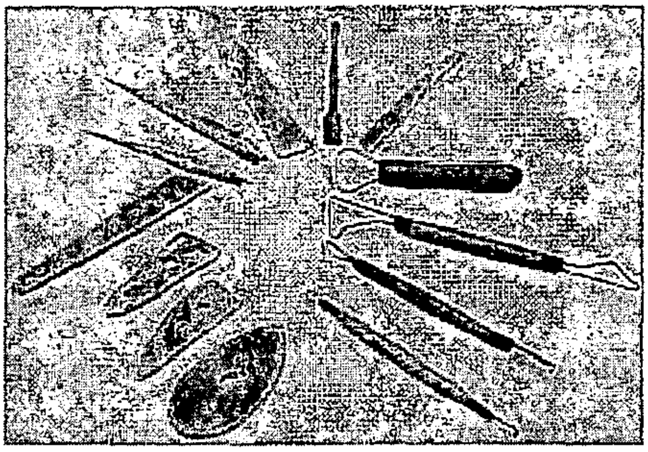


Figure 3: A set of tools for modelling with clay [Molteni 1989].

In contrast to conventional techniques, digital techniques are also used extensively in the conceptual design process. These include two dimensional (2D) digital drawing and image manipulation software (e.g. CorelDraw and Photoshop) and 3D CAD software (e.g. Alias Studio) applications for sketching and drawing, laser scanning approaches for gathering digital design data from a physical object and computer numerical control (CNC) and rapid prototyping (RP) technologies for physical model generation.

Sketching using 2D CAD systems provides an alternative method to conventional manual paper-based 2D drawing approach. However, it cannot yet match the speed and intuitive nature of manual sketching. Although 2D CAD remains a useful design tool, mainstream CAD has now evolved from simple 2D drawing to complex 3D geometric modelling (different geometric modelling techniques in CAD will be explored in detail in the following sections). Although CAD systems have great potential for conceptual design, the use of such systems for this purpose is limited. One reason for this might be that although the modelling within CAD has become 3D, sketching has remained 2D. This brought forth the observation that for sketching, it is still the age of the continuing reign of 2D "Paper Aided Design" [Stappers and Hennessey 1999]. Therefore, it is argued that new computer-based 3D sketching design tools should be developed so as to provide a true 3D design capability for the design process, especially at the early conceptual design stage.

Conventional techniques and digital techniques are not mutually exclusive. For example, in graphic design, conventional tools and materials such as brushes and paper are combined with digital tools with the aid of 2D scanners and printers. The advent of 3D laser scanning and printing tools could promote the same combined use of conventional and digital tools for conceptual design [Gribnau *op cit*]. It is feasible to capture the design intent by laser scanning a physical object that was created using conventional model making techniques. The resulting digital data can then either be refined within a CAD system to reproduce a new artwork, or used directly by RP and CNC machines to manufacture a replica [Evans *op cit*]. Currently, the bottleneck of 3D laser scanning lies in the complicated post-process of a large set of scanned data. The final goal of 3D laser scanning is to acquire a whole 3D image in a way like to acquire a 2D image with a digital camera without any complex data processing.

Despite the capability of obtaining a photo-realistic rendering of a product using CAD, there is still a need to verify the appearance of a product with a physical model during the conceptual design process. To achieve this, CAD model data can be used to create physical objects using CNC machining and RP technologies. CNC machining is a subtractive process, using CAD data to generate the cutter-path codes to control a variety of machines to produce the object modelled. Its efficiency depends on the complexity of the object being produced, usually requiring cutters to be changed and the model to be re-orientated to gain access to all surfaces on the object. In contrast, RP is an additive process and it normally has no sensitivity to the complexity of the object being built once the CAD data has been post-processed such as transferring to a STereoLithography (STL) file and slicing the STL file. From this point of view, it would be advantageous if the digital techniques involved at the conceptual design stage have direct supporting facilities to drive RP equipment or CNC machines.

2.3 Computer aided design

2.3.1 Introduction to CAD

As the name suggests, computer aided design (CAD) refers to a design process with the assistance of computers in the creation, modification, presentation analysis or optimisation of a design [Majchrzak, Chang *et al* 1987]. The characteristic of CAD that distinguishes it from other computer-based applications is its use of interactive computer graphics with design functions. Interactive computer graphics allow the product design to be created, viewed, modified and analysed by designers using a visual display device. CAD is sometimes translated as "Computer Assisted Design", "Computer Aided Drafting" or another similar phrase. Despite different words to represent CAD, all these terms are essentially synonymous. Although it does not change the basic nature of the design process, the use of CAD helps to improve the efficiency and productivity of the design process by generating easily modifiable model presentations, providing better documentations with quality improvements, performing complex design analysis at high speeds and storing and recalling model data with consistency [Singh 1996]. Despite the fact that it has been commercially available to industrial applications for just several decades, CAD has been regarded as one of the most significant advancements in industry. In short, CAD is a powerful tool for design and plays an important role in the product design process.

2.2.2 A brief history of CAD

The first CAD application could be traced back to the development of numerical control (NC) programming around the mid 1950's. It wasn't until the 1980's that microcomputer-based CAD packages were introduced, for example, the popular AutoCAD software from AutoDesk. During that period, the computer mouse was not yet an integral part of desktop computers, so a large number of keyboard operations needed to be remembered before an individual became proficient in the use of such software. These early 2D programs only allowed designers to use the computer to create and modify models in the form of simple points, lines and curves. The output from these 2D systems was printed drawings of models in 2D orthographic projection.

Wireframe modelling emerged as the first 3D method to describe 3D objects on computers. A wireframe model was described by its edges in an isometric or other 3D views. Surfaces were open represented and designs were open to visual misinterpretation. The output from 3D wireframe modelling systems was still limited to 2D printed images, just the same as from 2D drafting programs.

The introduction of 3D surface modelling and solid modelling had a huge impact on CAD applications. While surface modelling excels at defining complex shapes of objects, solid modelling is good at quickly building simple primitive geometries of objects. Both surface modelling and solid modelling support subsequent engineering applications such as finite element analysis (FEA) and multi-axis CNC cutter-path programming. More importantly, however, solid modelling even creates data on the physical properties, such as the volume, mass and centre of gravity. At this point, a part created in solid modelling on the computer could, in theory at least, be directly manufactured on either RP equipment driven by STL format data output or an NC machine driven by CNC code format data exportation.

As the sophistication of solid modelling evolved, such innovations as parametric modelling, variational modelling and feature-based modelling were developed. Current solid modelling systems have come a long way from the early CAD programs both in capabilities and ease of use.

To sum up, CAD has grown from a simple 2D drafting aid into a comprehensive and indispensable system for total product modelling in just several decades.

2.4 Introduction to geometric modelling

Extensive use of computer technologies is generally recognised as one of the driving forces in the current industrial revolution taking place in product design and other industrial applications. Geometric modelling technologies play a critical role in this progress by providing complete and accurate geometric data on the parts to be manufactured by various modern computerised tools [Mantyla 1988].

Normally, geometric modelling is concerned with describing the shape of an object (such as polygons, triangles, vertices and splines) as well as its appearance (such as surface texture, surface illumination and surface colour) using a valid computational representation. The goal of geometric modelling in CAD is to provide an approach capable of maintaining a model's complete geometric information using an efficient representation and to provide the tools to define the geometry by easily and accurately capturing the designer's creation intent. Therefore, geometric modelling is an integral part of any CAD system.

Geometric modelling can also be characterised as dealing with computer-based representation of geometry and other related information needed for supporting various computer-based applications in engineering design, analysis, manufacturing, assembly and other areas with similar requirements [Shah and Mantyla 1995]. This involves the study of the data structures, modelling algorithms and file formats for creating, representing, communicating and manipulating geometric information for physical parts and processes appearing in these applications. Today, geometric modelling has evolved from simple 2D drafting to 3D solid modelling. Various methods have been developed over the last several decades for representing 3D objects. Among them, wireframe modelling, surface modelling and solid modelling are the three principal and most successful types of 3D geometric representation in CAD applications. More recently, feature-based modelling has been considered to be a natural extension of solid modelling which can provide an additional layer of information for the physical product so as to make it more useful for design and to integrate design with downstream applications [*ibid*]. Other hybrid modelling techniques have also been used in many CAD systems which combine several of the above approaches such as surface modelling and solid modelling. As a matter of fact, each CAD modelling technique has its own applications. The introduction of 3D wireframe modelling did not do away with 2D drafting systems. Nor did the creation of solid modelling replace the need for surface modelling. Geometric modelling allows designers to represent physical objects in computerised digital forms. Based on the representation of the object in the digital form, a variety of useful shape operations such as union, difference, and intersection can be performed easily on the computer (see Figure 4). Most CAD systems use multiple representations because they are more efficient and effective than one representation. The disadvantages of one representation are often the advantages of other representations and vice versa.

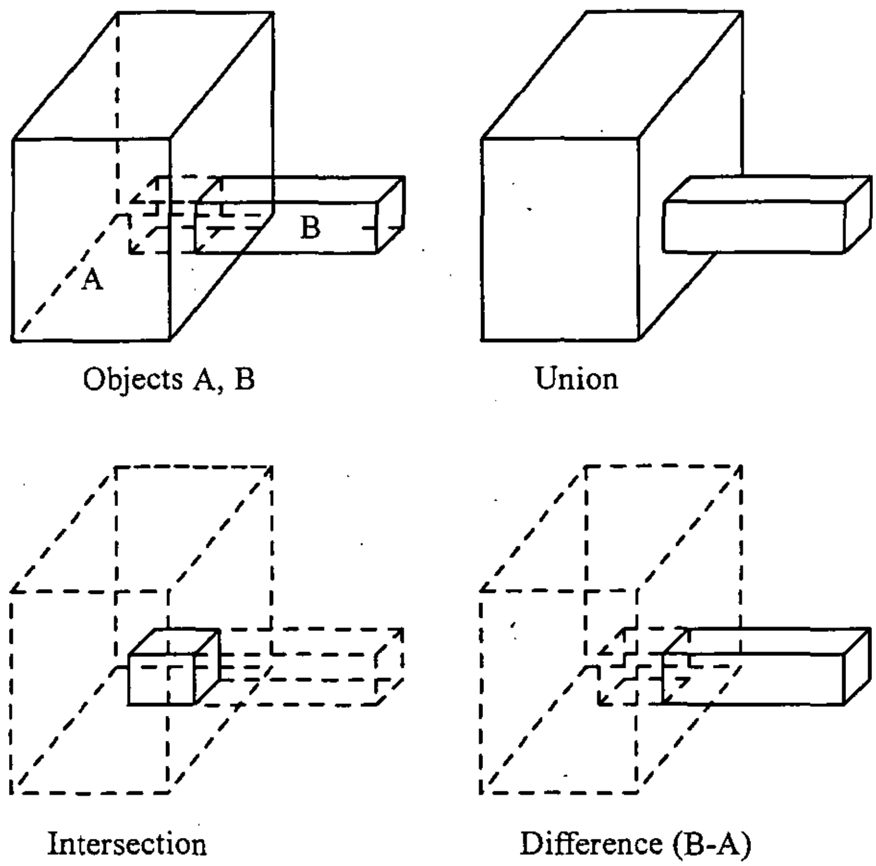


Figure 4: Shape operations on the computer

2.5 Two dimensional modelling

Two dimensional (2D) geometric modelling is the basic representation method needed to support the generation of 2D engineering drawings and illustrations which was widely used in early CAD systems. Sometimes these early 2D CAD tools are referred to as computer aided drafting systems. 2D drafting systems provided designers with simple electronic drawing boards that were more productive than traditional manual drawing boards, considering that it was much easier to recoup and to modify an electronic drawing instead of a drawing carried out in a conventional manual way. Figure 5 gives an example of a 2D drafting approach. The 2D drafting method is very simple and easy to work with. The existence of well established standards for the 2D drafting method makes it still used in CAD applications. However, a 3D model represented using a 2D drafting approach needs a number of different views (such as plan view, front view and side view) in order to describe its geometric and topological information completely (as shown in Figure 5). Moreover, the 2D drafting method has its inherent proneness to drawing errors and the time consuming impact of incorporating model changes. Furthermore, it suffers from the fundamental weakness to avoid ambiguous representations of 3D shapes. All these led to the creation and acceptance of 3D modelling technologies, which are discussed in detail in the following sections.

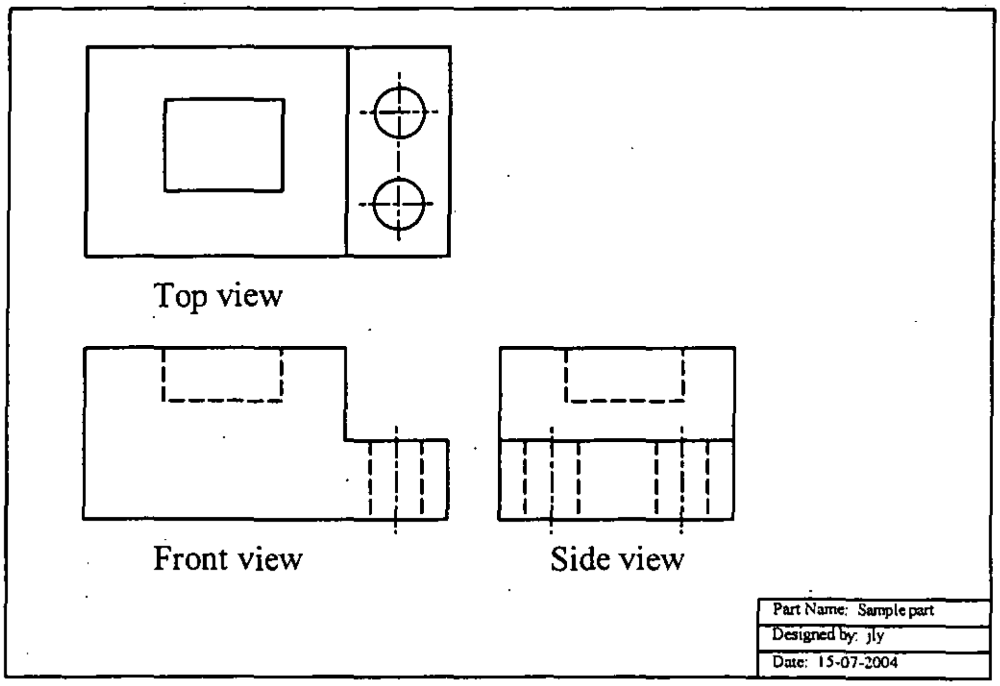


Figure 5: Example of a model in 2D drafting

2.6 Wireframe modelling

In CAD applications, wireframe modelling is defined as a technique for representing 3D objects transparently with a simple skeletal description consisting only of points, lines and curves. Wireframe modelling was the first 3D geometric modelling technique that originated from the earlier 2D geometric design. Wireframe modelling is one of the most basic approaches for geometric representation. Figure 6 shows an example of a wireframe 3D CAD model.

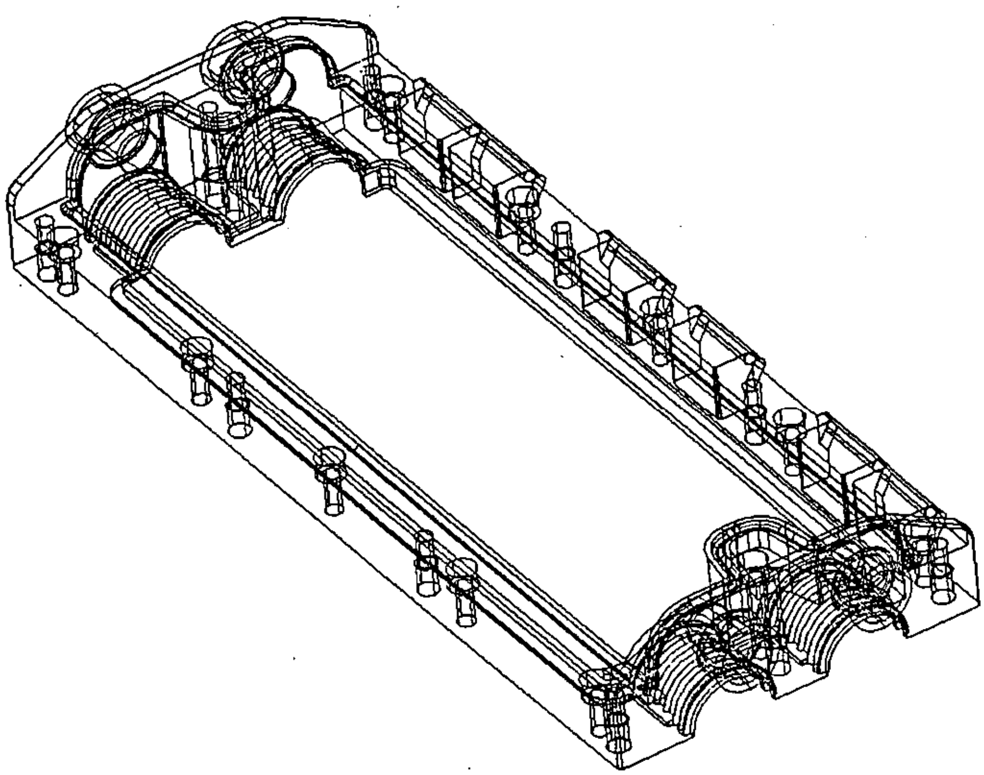


Figure 6: Example of a 3D wireframe model [Qmi 2002]

Although it is straightforward and simple in concept, and it is easy and efficient to generate in terms of using computing time and memory compared with other 3D geometric modelling techniques such as surface modelling and solid modelling, wireframe modelling exhibits a number of disadvantages when used to model some types of complex parts [McMahon and Browne *op cit*]. These included

- *Ambiguities in representation.* Wireframe modelling sometimes creates ambiguous representations of real objects. For example, a cylinder represented by a wireframe method may be recognised as a hole instead of a cylinder.
- *Deficiencies in representation.* In a wireframe representation, the whole profile of a model is not usually provided. There is no information on the surfaces or the inside or outside of the model, and the notion of solidity is not conveyed. For example, a cylinder may be represented by four edges, that is, two circles and two straight lines. But the straight lines are not enough to represent the profile of the cylinder's surface.
- *Limited abilities to calculate mechanical properties and geometric intersections.* From an engineering application point of view, wireframe modelling is difficult to calculate volume and mass properties of the object designed. Other applications, such as CNC cutter-path generation, cross-sectioning creation and interference detection also encounter problems when wireframe modelling is used.
- *Limited values as a basis for downstream applications.* Because a wireframe model database contains only low level information such as points and lines, the wireframe modelling method is very limited in scope when high level information is required by particular applications such as FEA and product process planning.
- *Inability to easily represent freeform surfaces.* Because wireframe modelling only uses points, lines and curves to describe the geometric form of the object, it is difficult to precisely represent freeform surfaces in CAD applications.

Other 3D geometric modelling solutions such as surface modelling and solid modelling can overcome many deficiencies that exist in wireframe modelling and are therefore widely used in most CAD applications.

2.7 Surface modelling

Surface modelling overcomes many of the ambiguities of wireframe modelling by precisely defining the geometry of an object in the form of bounding surfaces. A surface modelling method contains definitions of surfaces, edges and vertices. Surface modelling goes further than wireframe modelling. For example, a surface model of an object can be used to generate CNC cutting-path codes, whereas a wireframe model usually cannot. Figure 7 demonstrates a surface model with a freeform surface feature. Surface modelling is a widely used modelling technique in many industries such as ship building, aircraft manufacture and automobile production.

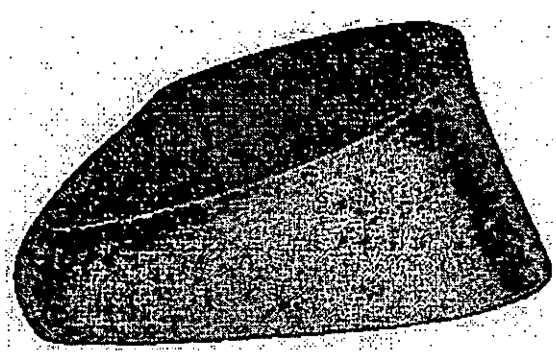


Figure 7: Example of a surface model

A plane surface is the simplest surface which may be defined in a number of ways including by two parallel lines, through three points or through a line and a point. Other surfaces are defined in one of the following three ways [*ibid*]:

- *The surface is fitted to arrays of data points.* In this way the surface is generated either to interpolate (pass through) or to approximate the data points. For example, the Bezier surface and the non-uniform rational B-splines (NURBS) surface are constructed from this method.
- *The surface is created from curves.* In this method the surface can be imagined as forming a skin on the top of the wireframe skeleton of curves. For example, the lofted (sometimes also termed as ruled or blended) surface is created from this approach.

- *The surface is designed from the interpolation between other surfaces.* For example, the fillet surface and the chamfer surface are produced from this function.

Research in geometric modelling has led to the development of some interactive and intuitive deformation methods for freeform surfaces [Zheng, Chan *et al* 1999a]. Most deformation techniques are closely related to the model representation methods, which can be classified as follows:

- Purely-geometric representation, such as the NURBS method and the free form deformation (FFD) approach.
- Physics-based geometric representation, such as the FEA method and the physics-based NURBS method.

These techniques are discussed in detail in the following sub-sections.

2.7.1 Non-uniform rational B-splines

The non-uniform rational B-splines (NURBS) description has become an industry standard for freeform curve and surface representation in computer graphics, CAD and computer aided manufacturing (CAM) communities due to its many properties that are beneficial to geometric modelling. Since a NURBS curve or surface is defined by its control points, weights and knot vectors, any modification of these parameters can produce a shape change of the curve or surface. Some examples of these modification operations are demonstrated in Figure 8 and Figure 9 respectively.

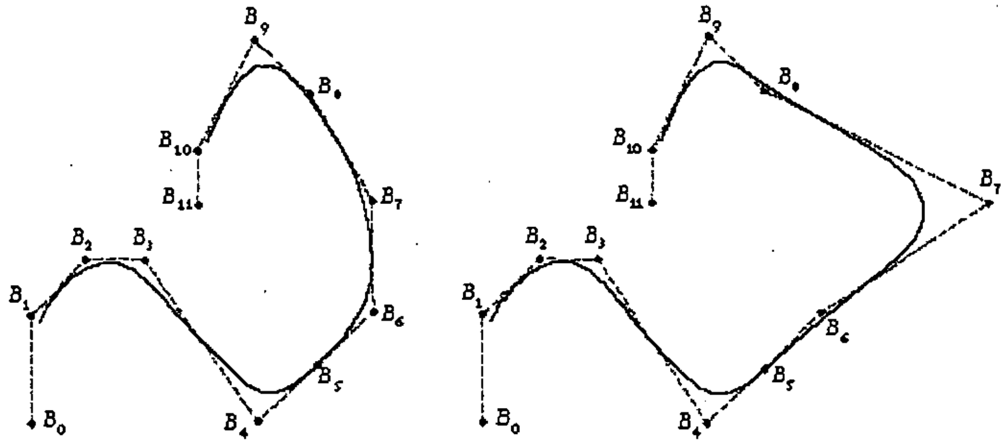
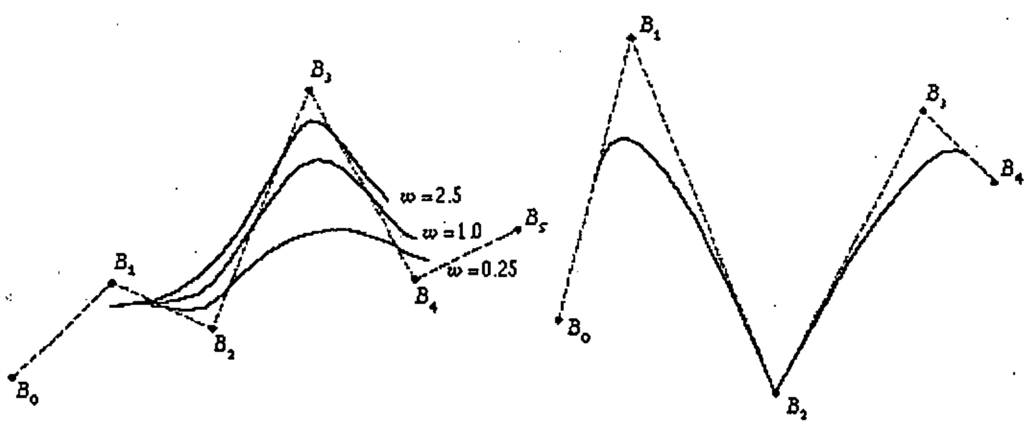


Figure 8: A NURBS curve shape changed by moving control point B_7
[Schneider 1996]



(a). Different weights of B_3 (b). Multiple identical knots at B_2

Figure 9: A NURBS curve form changed by its weights and knots [*ibid*]

The rapid proliferation of NURBS is due to its excellent geometric properties and characteristics. Piegl and Tiller [1997] have provided a comprehensive summary of the advantages of NURBS which are presented here:

- NURBS provide a unified mathematical form for representing and designing both standard analytic shapes, such as conics, quadrics and surfaces of revolution, as well as freeform curves and surfaces.

- NURBS are invariant (form-constant) under common geometric transformations such as scaling, rotation, translation and parallel and perspective projections.
- NURBS offer several degrees of freedom (such as manipulating the control points and the weights) to create a large variety of shapes.
- NURBS have a clear and easy-to-understand geometric interpretation, making them particularly useful for designers.
- NURBS have a powerful toolkit including knot insertion, knot refinement, knot removal, degree elevation and degree reduction which can be used throughout to design, analyse and interrogate the geometries of models.
- NURBS algorithms are fast and computationally stable.
- NURBS are genuine generalisations of non-rational B-spline forms as well as rational and non-rational Bezier curves and surfaces.

However, NURBS also have several drawbacks [*ibid*]:

- NURBS representations need extra data storage to define some traditional curves and surfaces. For example, a sphere in conventional mathematical representation only needs the position of its centre and a radius whereas the NURBS description for it needs more parameters.
- NURBS representations require careful attention to the processing algorithms to ensure a good quality result.
- Some interrogation techniques work better with traditional forms than with NURBS.

There is a lot of literature reporting on NURBS and their applications in geometric modelling. Au and Yuen [1995] proposed an approach for modifying the shape of NURBS curves by altering the weights and the location of the control points simultaneously. These shape operators could be used for rough sculpting of curves and surfaces. Piegl and Tiller [*op cit*] discussed a fundamental property of NURBS curves, called the cross ratio, which quantified the push/pull effect of weights for NURBS curves. Juhasz [1999] provided a weight-based shape modification method with points and tangent constraints for NURBS curves. Hu *et al* [2001] investigated shape modification of NURBS surfaces with geometric constraints, such as point, normal vector, and curve constraints. Two new methods were presented by constrained optimisation and energy minimisation. Liu and Wang [2002] presented two matrix representation formulations for arbitrary degree NURBS curves and surfaces explicitly other than recursively. Ravi Kumar *et al* [2003] proposed an approach for the offsetting of a trimmed NURBS surface. The approach was developed mainly to meet the stringent accuracy requirements in the simulation of composite laminate design and manufacturing processes.

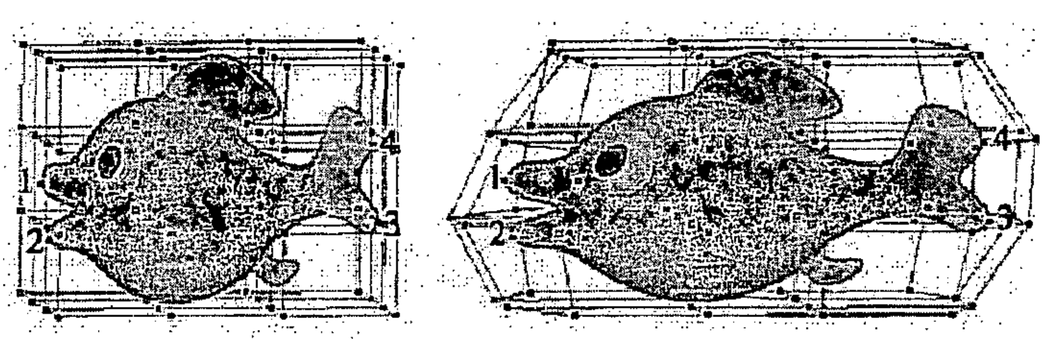
However, conventional geometric design using the NURBS representation can be problematic for the following reasons:

- Designers are often faced with the tedium of indirect shape manipulation through a bewildering variety of geometric parameters, for example, by repositioning control points, adjusting weights and modifying knot vectors. It is difficult to use them to achieve the exact shape and it is also difficult to know which group of control points or knot vectors or weights should be used to achieve the desired shape.
- Shape design to the required specifications by manual adjustment of available geometric degrees of freedom is often difficult because relevant design requirements are typically shape-oriented and not control point/weight-oriented. A particular shape can be represented non-uniquely with different values of knot vectors, control points and weights. This geometric redundancy of NURBS tends to make shape refinement ambiguous.

2.7.2 Free form deformation

Free form deformation (FFD) [Sederberg and Parry 1986; Hsu, Hughes *et al* 1992] is a powerful technique for the deformation of free form surfaces or volumes. FFD is defined by placing the surface or volume to be deformed into a regular lattice (sometimes also termed as grid). Deformations are applied by moving the points of the lattice and the embedded object is modified accordingly. These points are actually the coefficients of a trivariate Bernstein polynomial (also referred as the Bezier basis functions). The value of the trivariate Bernstein polynomial defined by the lattice control points can be calculated by the Bezier formulae. Hence, the edges of the volume contained by the lattice are deformed along Bezier curves, and the faces of the volume are mapped to Bezier surfaces. Thus, the output of a deformation can be reliably performed. Figure 10 gives an example of an FFD approach. However, using this technique is sometimes difficult. The deformations are defined by parametric functions (Bezier basis functions) whose values are determined by the locations of control points. Similarly, using FFD to manipulate deformation via control points has several problems [Hsu, Hughes *et al op cit*]:

- Exact shape is difficult to achieve since the deformation object does not follow the control points exactly.
- Exact placement of object points is difficult to achieve.
- Designers who are unfamiliar with splines do not understand the purpose of the control points and the results of their movements.
- The control points become difficult to manipulate when hidden by the object being deformed.



(a) Original model (b) Result of an FFD manipulation

Figure 10: Example of an FFD approach [Hu, Zhang *et al* 2001]

One effective way for improving this technique is to move control points in groups. However, it still does nothing to alleviate the shape and placement problems and it is unclear which control points should be moved in groups and how the transformation will affect the object.

2.7.3 Physics-based modelling

The use of physics is not new to computer graphics applications. It was introduced as physics-based modelling about two decades ago [Armstrong and Green 1985; Wilhelms 1987; Terzopoulos, Platt *et al* 1987]. Physics-based modelling approaches are becoming more and more attractive for geometric representation and graphics animation. Users interact with the model by exerting virtual forces, to which the system responds subject to the active constraints. The physics-based NURBS approach [Hong and Terzopoulos 1994; 1995; 1996] is a non-purely geometric representation for freeform curves and surfaces. The user's dynamic behaviour can produce physics-meaningful, and hence intuitive shape alteration. This allows users to interactively manipulate the object shape not only through the traditional indirect mode, such as adjusting control points and setting weights, but also through direct physical manipulation, such as exerting simulated forces and by using the local and global shape constraints. The main drawback of the non-purely geometric methods for modelling is the long computational time involved and the complex algorithm employed. Currently, they are still not widely used in most commercial CAD systems.

The physics-based modelling approach normally requires an FEA structure and a complex computational algorithm, and therefore it generally does not meet the basic requirements for a conceptual design application.

2.7.4 Summary of surface modelling

Although it is more advanced than wireframe modelling, surface modelling still has some drawbacks. Surface modelling contains no information about connections between surfaces, nor about which side of the surface is solid material. As a result, with surface models, designers may still not be able to distinguish the interior and exterior of an object on the computer. It still lacks some of the physical properties of the model. For example, the volume or mass of the model cannot be obtained easily from the surface modelling information. As a matter of fact, surface modelling may not even guarantee that the designer has designed a realisable object since the collection of surfaces may not define a physically realisable part [Singh *op cit*].

More and more algorithms are contributing to the modelling of complex freeform surfaces. Techniques for deforming shapes during sculpting operations aim to increase the users' ability to manipulate them effectively using a rich set of sculpting tools. Successful approaches for human computer interaction should have two characteristics: those involving less computation and those offering user interaction developers the ability to develop friendly user interfaces (UIs). Physics-based modelling can theoretically offer natural shape deformation operators, for example, a virtual force, for the users. However, its disadvantage is also obvious. Due to the complexity of computation involved in finite element data structures, contemporary computing hardware has difficulty in providing comfortable, natural interaction in 3D space. The FFD approach is difficult to achieve the exact deformation shape of the model due to its sole indirect movement of control points implied in its lattice. The NURBS method offers a substantial room to support interactive algorithms and intuitive UIs because it exhibits many advantages for representing freeform curves and surfaces, and it has several freedoms to deform the shape of the designed model.

2.8 Solid modelling

Solid modelling is another representation approach widely used in most CAD applications. In solid modelling, objects are either defined by solid shapes or faces with their boundaries connected topologically. This means that an independent surface, line or point does not have any meaning in solid modelling. A desirable solid representation for an object should have the following characteristics [Requicha 1980]:

- *Accuracy.* The accuracy property means that the modelling representation method should allow an object to be represented without any approximation.
- *Domain.* The domain of a representation method should be large enough to include a useful set of physical objects to be represented in geometric modelling.

- *Uniqueness*. The uniqueness property refers to the fact that the modelling representation should be unambiguous and complete, and the representation should be used to encode any given solid in only one way.
- *Validity*. The characteristic of validity in geometric modelling requires that the representation should allow the shape of an object to be physically realisable.
- *Closure*. The closure property means that the object should maintain closure under any transformations such as rotation, translation and other operations.
- *Compactness*. The representation should be compact to save computer memory space, which in return may reduce the computation time in complex modelling operations.
- *Efficiency*. The representation should allow the system developers to employ efficient algorithms and methods for creating digital models on the computer.

So far there are a number of representation methods for solid modelling which were reported in the literature [Mantyla *op cit*; Shah and Mantyla *op cit*; McMahon and Browne *op cit*]. These typical approaches can be classified by three main geometric foundations: Constructive solid geometry (CSG), Boundary representation (B-rep) modelling and voxel-based modelling. Each is discussed in detail in the following sub-sections.

2.8.1 Constructive solid geometry

Constructive solid geometry (CSG) is a popular solution in solid modelling. In the CSG method, a solid model is created by combining simple solid objects. The simplest solid objects are called primitives or solid primitives. These primitives are arranged in a tree structure using regularised Boolean operators such as union, intersection and difference in order to construct a physically realisable solid model. The data structure for a CSG model can be considered as a binary tree that stores an object with regularised Boolean operators at the internal nodes and simple primitives at the leaves. Nodes are connected to a root node by its branches. Any node may have one parent node and two child nodes. The root node of the tree has no parent and represents the complete solid model. The leaf nodes which have no child nodes represent simple primitives, such as a cylinder, a sphere, a cone or a cube. The intermediate nodes may be used either to represent regularised Boolean operators or to perform transformations, such as translation, rotation and scaling. Rather than using the ordinary Boolean set operators, CSG employs the regularised Boolean set operators in order to ensure that such operations on solid models always yield physically realisable solid models [Foley, Dam *et al* 1996]. For example, when two solid cubes perform an ordinary set operation intersection, several results may be generated including a null set, a point, a line, a surface or a cube. Since any independent point, line and surface is not a realisable solid object in the physical world, their presence leads to problems in CSG modelling. Figure 11 shows a simple model using the CSG representation in a binary tree structure.

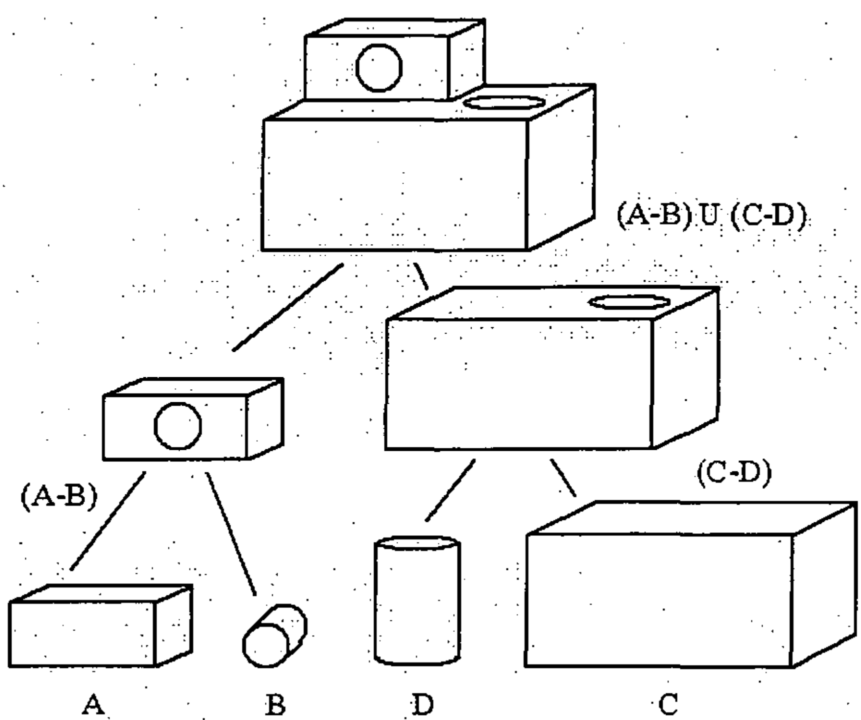


Figure 11: Binary tree for a CSG model

In CSG, the general processing strategy for creating a solid model is a depth-first (from the lowermost leaf node to the topmost root node) tree walk that combines the nodes beginning from the leaf primitives. Therefore, the modelling history can be kept within the model. This history information is useful for further processing in order to perform basic operations, such as determining an object's boundary. Consequently, the advantages of CSG include i) its compactness, ii) the ability to record Boolean operations, iii) changes of transformations quickly and iv) undo all of these operations quickly since they involve only tree-node building. Since the leaf primitives are accurately described by their positions and dimensions and the nodes are accurately created by regularised Boolean operations or transformations, CSG can allow an object model to be represented without any approximation.

By using the CSG method, complex solid models may be developed relatively quickly. But CSG is limited by the set of both solid primitives and regularised Boolean operations that are available within a CAD environment. In addition, the CSG method faces a severe inherent limitation. CSG cannot guarantee the uniqueness of a representation, as there are many different ways by which the primitives, Boolean operations and transformations can yield the same product. This non-uniqueness of representation makes recognition of shapes from a CSG approach difficult. Furthermore, it is difficult to deal with freeform surface modelling using CSG.

2.8.2 Boundary representation modelling

Boundary representation (B-rep) modelling is based on the previously existing, surface modelling technique. B-rep modelling describes an object in terms of its surface boundaries like vertices, edges and faces. The definition of a solid model comes from combining the geometric information about vertices, edges and faces of an object with their topological data structures on how these geometric entities are connected. Figure 12 shows a simple solid model in B-rep description along with its data structure.

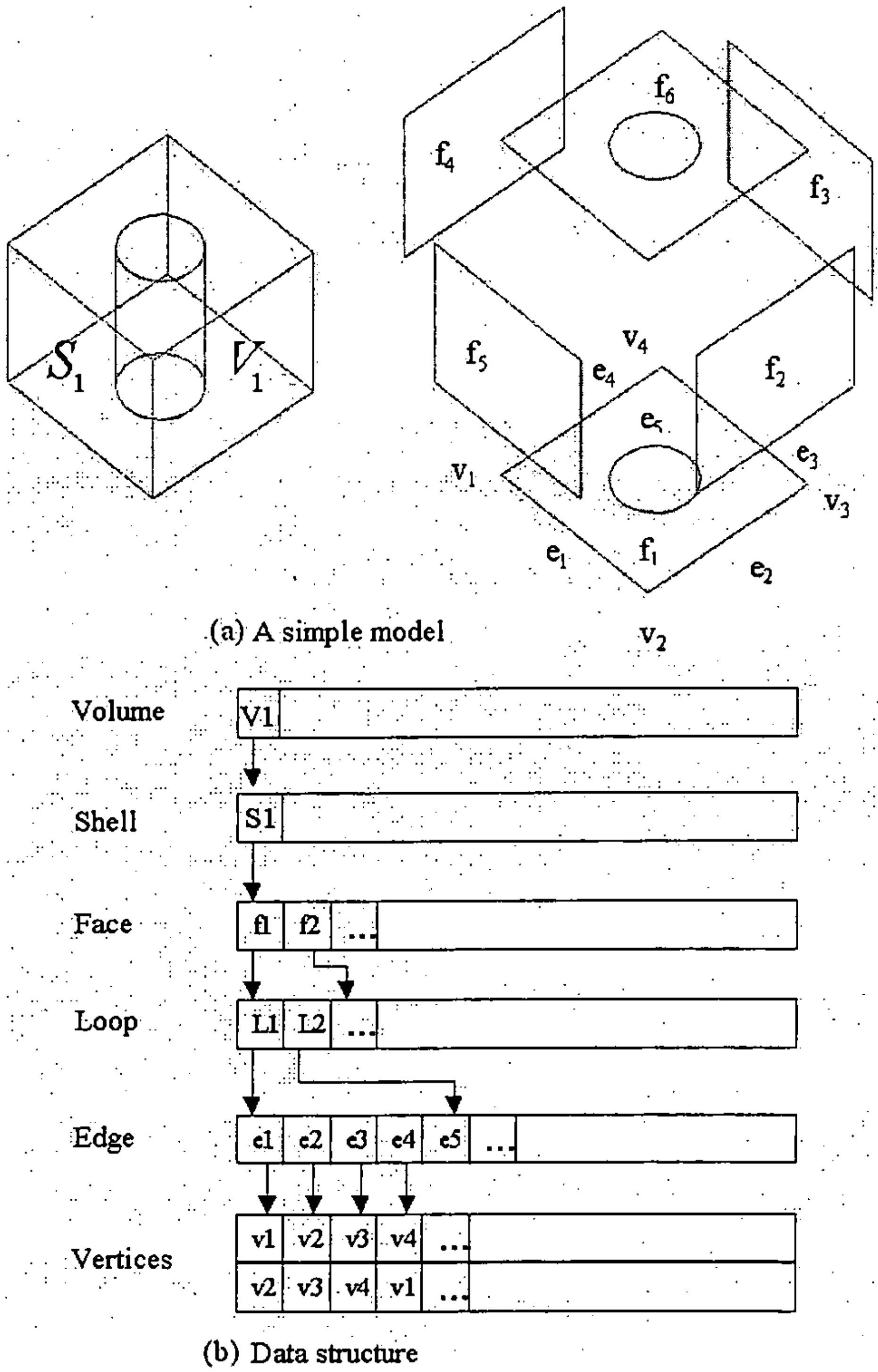


Figure 12: A simple model and its B-rep data structure [Zheng 2000]

In a B-rep method, curved faces are often approximated with polygons. Alternatively, curved surfaces can also be represented as surface patches if the modelling algorithms that process the representation can handle the resulting intersection curves, which generally are of higher order than the original surfaces [Foley, Dam *et al op cit*]. In order to ensure that a model defined by the B-rep method always remains a topologically valid solid during interactive modification, an appropriate data structure must be defined, and the model must conform to a set of mathematical rules such as each edge must connect two vertices and be shared by exactly two faces, at least three edges must meet at each vertex and Euler's formula must apply. For example, for a convex model without holes, Euler's law states that

$$F - E + V = 2 \qquad (2.1)$$

where F is the number of faces, E is the number of edges and V is the number of vertices.

For a model containing holes, protrusions from faces and re-entrant faces, a modified version of Euler's law known as Euler-Poincare formula must apply. This states that, if L is the number of interior edge loops or holes in faces, G is the number of passageways or through-holes and B is the number of separate bodies, then:

$$F - E + V - L = 2\,(B - G) \qquad (2.2)$$

The way that Euler-Poincare formula is used to ensure the topological consistency is to restrict the way the model may be manipulated during construction. It may not ensure the validity of such solids with passageways in all cases. For example, for an object with curved surfaces such as cylinders, spheres and cones, it is not so easy to apply Euler-Poincare's law. In such cases, new modelling structures for objects with curved surfaces must be defined. For example, a spherical surface must be approximately represented by small polygon meshes.

The data structure of the B-rep method must record both geometric and topological information of the object modelled. Typically this is achieved by means of a hierarchical structure where faces are represented in terms of their bounding edges, and these in terms of their bounding vertices. In addition to these basic types of objects and their relations, other information such as face and curve equations and vertex coordinates must be presented. The boundary data structure is more like a graph-based structure since the vertex, edge and face data are stored as nodes in a graph structure with pointers (see Figure 12). In addition, branches and the relational connectivity can also be indicated by a graph structure. These graphs are known as directed graphs because the direction of the links between nodes is important.

B-rep modelling has some advantages when compared with CSG modelling, mainly in terms of versatility in the generation of complex shapes and the speed of verification of topological relations. This is due to the way the B-rep method registers model information and stores model parameters in an explicit form. One of the major disadvantages of B-rep modelling is the large information requirement imposed by explicit storage for the model boundary. In addition, the B-rep approach does not guarantee that a group of boundary surfaces (often polygons) form a valid solid (physically realisable model). Therefore, the B-rep method is used as a basic approach for topologically representing vertices, edges and faces. Most CAD systems have a hybrid data structure, using both CSG and B-rep modelling at the same time.

2.8.3 Voxel-based representation

A voxel represents a volumetric element in volume form, just as a pixel denotes a picture element in planar form. Voxel-based representation is also termed as spatial occupancy enumeration in much solid modelling literature [Mantyla *op cit*; Shah and Mantyla *op cit*; Foley, Dam *et al op cit*; McMahon and Browne *op cit*]. A voxel-based modelling system naturally provides *what you see is what you get* information, whereas other solid modelling systems display smooth, shaded objects that give designers no feedback on the actual surface finish of the models after fabrication. In voxel-based representation, a solid model is decomposed into a collection of adjoining, discrete small solids called voxels. Figure 13 shows a sphere approximately represented in the voxel-based modelling method.

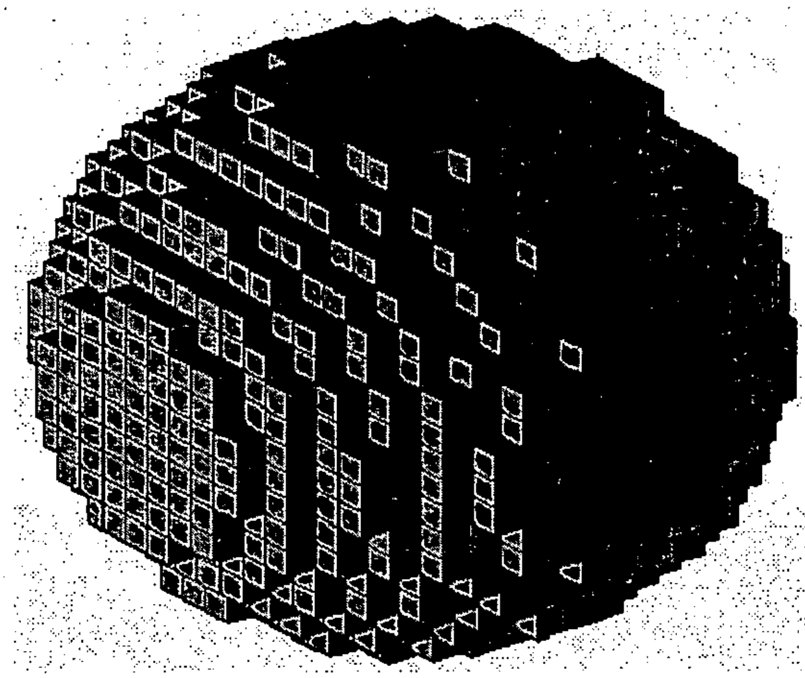


Figure 13: Voxel model of a sphere [Foley, Dam *et al op cit*]

The powerful aspect of voxel-based modelling is that it allows designers to selectively modify individual or group voxels so that the resulting object meets the design specifications whereas other conventional CAD modelling methods do not support this capability. However, voxel-based geometric modelling produces only approximated objects for product models. A detailed summary of the advantages and weaknesses of voxel-based modelling was provided by Kaufman *et al* [1993], which is summarised here:

Advantages of voxel-based modelling include

- *Insensitivity to complexity.* All objects are represented as collections of voxels in an ordered grid, allowing direct rendering without concern for intersections between polygons (as in surface models).

- *Inner information.* Voxel-based modelling has the ability to represent the interior of an object and amorphous phenomena.
- *Sampled and simulated datasets.* Voxel-based modelling is suitable for describing objects that are reconstructed from sampled datasets (such as in 3D medical imaging) and simulated datasets (such as in computational fluid dynamics). The most compelling examples of this application are the construction geometric models from datasets generated from computed tomography (CT) technology and magnetic resonance imaging (MRI) technology in the medical application field.

Disadvantages of voxel-based modelling include

- *Discrete form.* Voxel-based modelling provides finite resolution, approximating surfaces and volumes as discrete primitive volume elements. The artifact created by voxel-based modelling also complicates transformation manipulations and results in information loss during the manipulation operations.
- *Loss of geometric information.* Since a model is represented as discrete information, information about specific surfaces and features is not readily available for design algorithms.
- *Memory and processing.* In order to represent models more precisely, large amounts of memory are normally required, though this can be reduced by employing subdivision methods. In addition, processing huge amounts of voxel data also need a high speed computer in order to achieve a real-time effect.

2.8.4 Summary of solid modelling

The wireframe and surface modelling approaches, as mentioned earlier, have some inherent limitations for CAD applications. Solid modelling finds widespread applications that cut across functional boundaries, such as generating information for computer aided processing planning (CAPP) and driving RP applications. Furthermore, solid models can be used to evaluate the physical properties (such as the mass and the volume) and the interference detection of models early in the design process.

In CSG modelling, a solid model geometry is generated by solid primitives such as cubes, cylinders, spheres, cones and tori. In B-rep modelling, a solid model geometry is formed by its boundary elements such as faces, edges and vertices along with their topological relations. The computerised representation of solid geometry is required to be accurate, valid, compact and efficient. Multiple representations are more efficient than one representation in most CAD applications. The composite representations of CSG and B-rep modelling are popular in current commercial CAD systems due to their many advantages and will still be the predominant representations for CAD software applications. For example, B-rep modelling is more suitable for representing complex shapes, whereas CSG models are easy to create but are usually used in representing relatively simple objects. While interest is steadily growing, the area of voxel-based modelling is still in its infancy and currently there are few techniques and little expertise available.

2.9 Parametric and variational modelling

In the early stage of design, not all the data needed is known and designers are often not sure what specifications will satisfy the design requirements. This leads to various modifications in product configurations and inevitably causes changes often in the geometric shapes and dimensions. It is therefore important for CAD applications to provide automation tools to support such changes. However, earlier traditional CAD systems were based mainly upon building geometry with specific dimensions and creating geometry with specific initial relationships to existing geometry. To overcome the inflexibility in earlier traditional CAD systems, two new methods, known as parametric and variational modelling approaches, have emerged. During the past decades, parametric and variational modelling were examined in detail, developed and employed in many commercial CAD systems. Most solid modelling CAD systems available on the market are now parametric and variational as well.

2.9.1 Parametric modelling

The term parametric modelling denotes the use of parameters such as dimensions and formulae to control the geometries of CAD models. The parameters may be modified later, and the model will update to reflect the modification. The idea behind parametric modelling is that designers may want to adjust model parameters, for example a dimension to explore the effects of different sizes without recreating the model geometry. From this point of view, parametric modelling is powerful and intuitive. Parametric modelling also lends itself to data re-use. For example, a whole family of capscrews can be contained in one model. But parametric modelling requires more skill in model creation. Parametric modelling CAD, originally pioneered by the Parametric Technology's Pro/Engineer system more than ten years ago, has become an accepted paradigm for all major CAD systems [Hoffmann and Kim 2001].

In fact, parametric modelling enables a new CAD model design methodology that employs special case searching and solution techniques to provide dimension-driven capability that is applied to geometric and algebraic constraints [Chung and Schussel 1990]. In parametric modelling, dimensional-driven capability means that an object defined by a set of dimensions can vary in size according to the dimensions associated with it at any time during the design process. Geometric constraints specify certain relationships between geometric entities, such as parallelism, tangency, offset and alignment. These constraints can be applied to many different types of geometric entities such as lines, planes and surfaces. Algebraic constraints are simple engineering equations that designers add to ensure that product sizes and shapes meet the design requirements. For example, a part cross-section may have to be a certain area. Figure 14 gives a framework of a parametric modelling process.

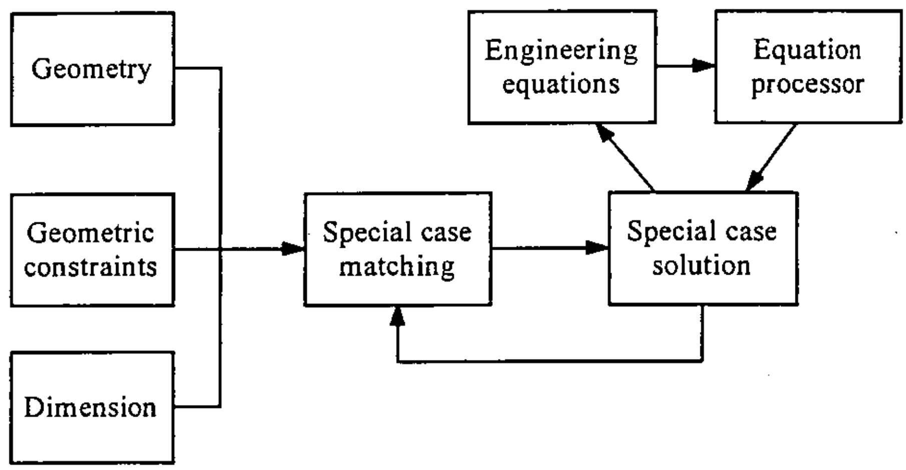


Figure 14: Schematic framework of a parametric design system [*ibid*]

2.9.2 Variational modelling

Variational modelling is an approach that uses fundamental graph theory and robust constraint-solving techniques to provide a constraint-driven capability that is applied to a combination of geometric constraints and engineering equations [*ibid*]. As this definition indicates, although parametric modelling and variational modelling have much in common, the differences are also significant. In parametric modelling, the model is limited to solutions in a procedural manner based on parameters of geometry, possibly even simple equations, to define those parameters. In variational modelling, the model is based on a set of simultaneous equations that calculate the size and orientation of the model [Kurland 1994]. In variational modelling, geometries, equations and dimensions of the design are all considered as constraints. This provides variational modelling with a constraint-driven capability which encompasses the dimension-driven capability of parametric modelling. Thus, parametric modelling can be considered as a subset of variational modelling.

All the geometric constraints and engineering equations in variational modelling are presented in the form of constraint networks. Techniques from graph theory are used in the variational design process. By using graph theory, a large constraint network may be decomposed into smaller simultaneous equation sets so that the networks can be solved efficiently. A schematic framework of a variational modelling process is shown in Figure 15.

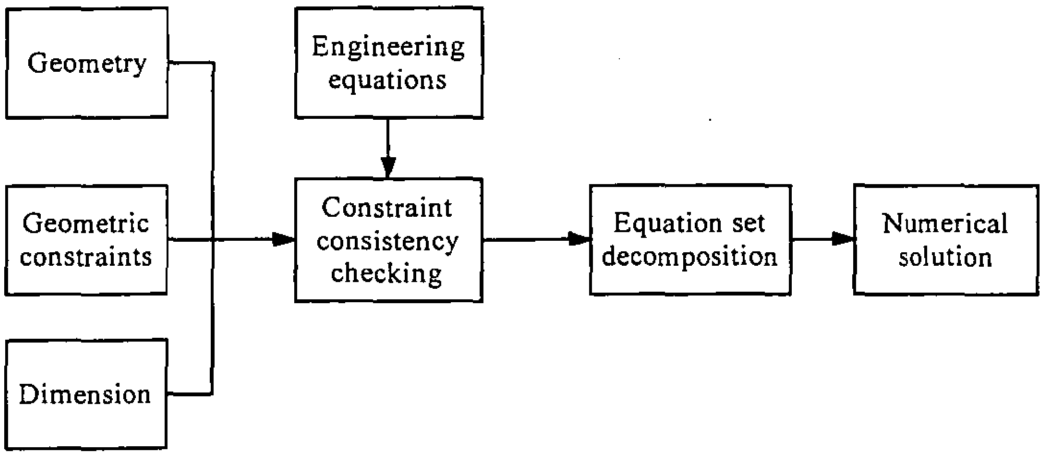


Figure 15: Schematic framework of a variational design system
[Chung and Schussel *op cit*]

2.9.3 Summary of parametric and variational modelling

Both parametric modelling and variational modelling provide variable-driven solutions to representing geometric constraints and relationships during CAD model creation. Parametric modelling solves constraints by applying sequential values to model variables, where each assigned value is computed as a function of the previously assigned values. Its use is limited to dimension-driven design. On the other hand, variational modelling deals with constraints using sets of complex equations, and solves all these equations simultaneously to evaluate the dimensions for models [Shah and Mantyla *op cit*]. It is a generic approach for dimension-driven design as well as for advanced applications such as tolerance analysis, mechanism analysis and design optimisation. From a technical viewpoint, the line between parametric and variational modelling is blurred, because many CAD applications employ a hybrid of both types of these approaches.

2.10 Feature-based modelling

2.10.1 What is a feature?

There are many published definitions of the concept of a feature. Even though these definitions seem to be dissimilar, they all consider features as entities which are of a semantically higher level than the pure geometric elements typically used in solid modelling [Shah, Sceevalsan *et al* 1988]. Shah and Mantyla [*op cit*] viewed features as information sets that referred to aspects of form or other attributes of a part, in such a way that these sets could be used in reasoning about design, performance and manufacture of the part or the assemblies they constituted. In other words, features need to contain different information as they are used for different application purposes. Features in geometric modelling are high level geometric elements which have some engineering significance or meaning. Shapes such as drilled holes, ribs or bosses in castings, grooves in shafts and so on are regarded as typical form features. The engineering meaning in many features is mainly related to machining operations which include the manufacturing process planning that determines the sequence of operations required to fabricate the model.

Normally, the definition of a feature includes three main parts listed below [*ibid*]:

- The parametric geometry.
- The attribute of a feature and the relationship between features.
- The mapping from the definition into an application and the feature knowledge, such as topological-reasoning rules and consistency-verification rules.

The main advantages of using features include [Ovtcharova, Pahl *et al* 1992]

- A feature vocabulary is more natural for expressing the product when compared with a purely geometric one.
- There is a possibility of using features as a basis for modelling product information in different phases such as design, analysis, process planning and manufacturing.
- The use of features can lead to an increase in designer's productivity and cost effectiveness.

Typically there are two main feature creation approaches in feature-based modelling applications known as feature recognition and design by features respectively [McMahon and Browne *op cit*]. The task of feature recognition is to take an existing solid model and to search its data structure for combinations of geometric elements that correspond to prototypical features. In the design by features process, a product model is created either from a library of features (rather than geometric primitives) or from defining form features on the existing model. Each of these solutions has distinct advantages and inherent weaknesses, and sometimes it may be necessary to use them simultaneously to complement each other (also called as hybrid feature-based modelling).

2.10.2 Feature recognition

A feature-based model is created by the feature recognition technique in such a way that the features are extracted from the model geometry directly. In other words, a geometric model is first created by conventional CAD systems and then a computer program processes the resulting model to find features. Normally, the feature recognition solution is mainly used in CAPP applications. The feature recognition approach is based most often upon B-rep modelling because the adjacency relationships between geometric entities are explicitly represented in such modelling systems [*ibid*]. The recognition of features in CSG models is potentially more difficult than in B-rep models, because a CSG model is non-unique in its representation. There have been limited experiments in feature recognition based on voxel-based representation models.

2.10.3 Design by features

A model's geometry can be created directly in terms of features. This is known as design by features. Design by feature modelling systems use features as building blocks to create the model geometry just like the solid primitives in CSG modelling. Designers can start either with a more or less complete geometric model and define form features on it, or one can start from selecting form features from a standard feature library. Design with pre-defined form features can reduce the number of input commands substantially. This is especially advantageous in re-design. In this way, features can serve as functional elements for designers in their design processes. However, the design by feature approach has distinct limitations [Shah, Mantyla *et al* 1994]. In the design process, sometimes geometric features may interact and form unintended geometric features. The design by feature approach also limits designers to select from a finite set of geometric features so as to inhibit their freedom of design creativity.

2.10.4 Freeform feature-based modelling

Freeform feature-based modelling can be regarded as an extension of the previous feature-based modelling approach, in which only regular-shaped features can be used. Freeform features are similar to regular-shaped features, the only difference being that there is more modelling freedom for the geometric shape of the feature. Typically, their geometric shapes can be modelled with freeform curves and freeform surfaces which are normally represented using the NURBS method [Fowler and Bartels *op cit*]. In freeform feature-based modelling, the general outline of a model is usually created first by sketching several freeform elements such as freeform curves and surfaces. Later, based upon the defined freeform elements, a freeform feature can be created by design functions such as sweeping, cutting, blending and lofting. Figure 16 illustrates an example of a freeform feature created by a sweeping design approach.

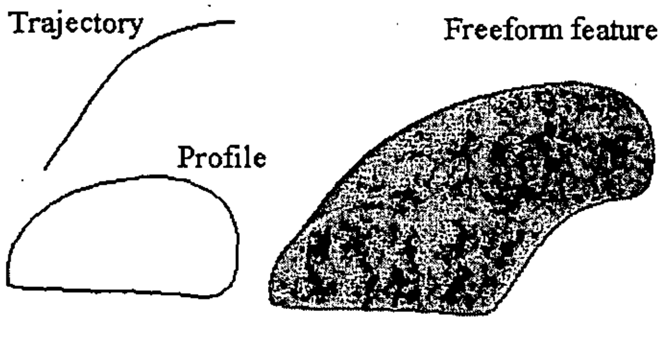


Figure 16: Example of a freeform feature

Although many attempts were made for freeform feature class definition [Poldermann and Horvath 1996; Fontana, Giannini *et al* 1999; Berg, Bronsvoort *et al* 2002], it has turned out to be very difficult to make a general classification of freeform features. It is therefore very important that new types of freeform features should be introduced in advanced freeform feature-based modelling systems. The definition of a new freeform feature class is, however, rather complicated: not only does the generic shape have to be modelled with NURBS, for example, but also a set of parameters has to be chosen that makes intuitive instantiation and modification of the feature possible; and a mapping between these parameters and the low level definition entities using the NURBS method has to be established.

Currently, freeform feature-based modelling is still in its infancy and requires much more attention from both academic research and industrial applications. Yet freeform feature-based modelling has shown much potential for the future of advanced CAD systems.

2.10.5 Summary of feature-based modelling

Features are application specific as they are used for different application purposes. From the design point of view, feature-based modelling has much better potential for computer support of the design process than current non-feature-based CAD systems do. Features are meaningful elements for designers and the use of them can speed up the design process as well as provide a means for standardisation, thus reducing design cost and accelerating time to market. Other advantages which can be expected from feature-based modelling are improvement of the quality of design and a better interface with applications such as process planning and engineering analysis.

In most CAD applications, feature-based modelling systems offer designers a fixed set of features, so called feature libraries, to choose from. The elements in the feature library can be classified as simple features that cannot be decomposed into simpler features, composite and compound features that can be further subdivided into simple features, and user defined features. Feature-based modelling could provide an effective way for designers to create product shapes, for example, less design variables and consideration of manufacturing process during the design process.

Freeform feature-based modelling is a relatively new research area. Much research carried out so far has shown that there are good prospects in this new field. However, much research is still to be done before freeform feature-based modelling becomes mature.

In short, feature-based modelling provides enhanced design tools and directs new paradigms and methodologies for product design and other relevant engineering applications.

2.11 Hybrid modelling

As stated earlier, each solid modelling method introduced above has its limitations. Therefore, in order to create more complex and stylish solid models, the idea is to combine several solid representation methods together (such as B-rep modelling and CSG modelling) for efficient and effective modelling. Such representation techniques are normally referred as hybrid modelling approaches. Most commercial CAD systems are hybrid using two or more solid modelling approaches at the same time.

Compared to other individual solid modelling solutions, hybrid modelling approaches provide the flexible facility that is crucial to efficient and effective model design. This useful concept can be extended from solid modelling to the whole geometric modelling field. For example, CAD applications using both surface modelling and solid modelling approaches are also called as hybrid modelling systems. Therefore, hybrid modelling solutions make meaningful sense by giving the ability to use the most appropriate modelling technologies for different design processes.

2.12 Summary

In this chapter, the product design process and conventional and digital techniques involved in the conceptual design process have been identified. CAD systems, as a technology, try to assist and improve the design process. The heart of a CAD system is its ability to create a computerised model that represents the shape of the product designed. Today's CAD technology has already evolved from 2D drafting to 3D modelling. The mainstream 3D modelling approaches include 3D wireframe modelling, surface modelling and solid modelling. There are alternative methodologies for the creation and manipulation of solid geometry at the solid modelling level of the CAD technology. These varied techniques include the CSG approach, the B-rep method, the voxel-based representation and other modelling techniques such as parametric modelling, variational modelling, feature-based modelling and a mix thereof. Clearly, each CAD modelling solution has its own strengths, weaknesses and specific application areas. Thus, hybrid modelling approaches would be best for creating 3D CAD models within the product design process. Figure 17 gives a summary of CAD modelling technologies which were presented and analysed in this chapter.

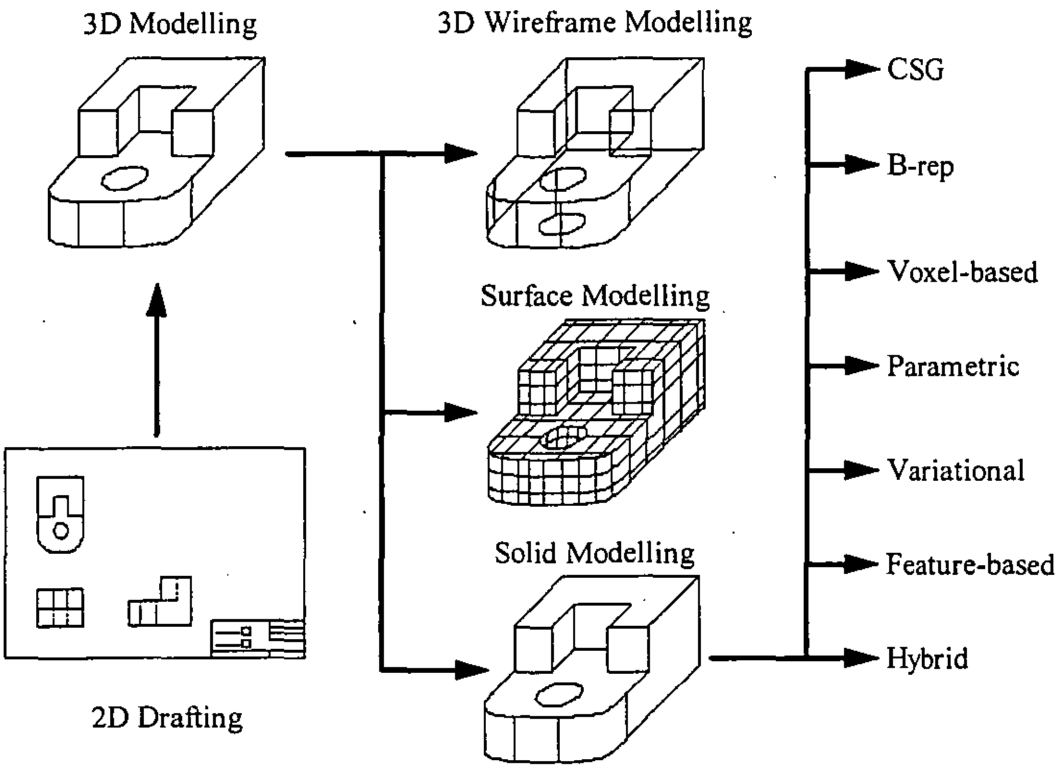


Figure 17: Summary of CAD modelling technologies

CHAPTER THREE

Virtual reality technologies

3.1 What is virtual reality?

Virtual reality (VR) is not a new invention. Scientific research has been working in the field of VR for decades, having recognised it as a very powerful tool for creating more natural and intuitive human computer interfaces (HCIs). VR can be described as an interactive, computer-generated three dimensional (3D) environment with which users can interact using specialised peripherals such as electrical data gloves and haptic force feedback devices. VR is also interpreted as a natural extension to 3D computer graphics with advanced HCIs that simulates a functionally realistic environment. Therefore, in a VR environment, users normally have multiple feedback senses rather than only vision information available in most computer graphics applications and can interact with virtual objects naturally and intuitively.

The term "Virtual Reality" was first introduced by Jaron Larnier, founder of VPL Research [Pimentel and Teixerra 1997]. Other related words include "Artificial Reality" coined by Krueger *et al* [1985], "Cyberspace" initiated by William Gibson in his science fiction novel and more recently, "Virtual World". VR is also closely associated with an environment commonly known as a virtual environment.

Burdea and Coiffet gave a more scientific definition of VR as:

> Virtual reality is a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell and taste [2003].

As the technologies of VR evolve, the applications of VR become literally unlimited. It is assumed that VR will reshape the interaction interfaces between user and computer technology by offering new approaches for the communication of information, the visualisation of processes and the creative expression of ideas. Today, VR technologies are widely used in the applications of flight simulators, collaborative product and process design, "walkthroughs", human factors and ergonomic studies, simulation of assembly sequences and maintenance tasks and virtual surgery. Moreover, recent advances in broadband networks are also opening up new applications for tele-collaborative virtual environments in these application fields.

3.2 Fundamentals of virtual reality

In a VR system, an important new concept is immersion, which refers to the fact that the user gets the feeling that he or she is fully immersed in an artificial, 3D world that is completely generated by a computer. This is a huge step forward compared to traditional 3D computer graphics animation and CAD modelling packages, which inherently impose major limitations especially on natural and intuitive user interaction. Today, the term "Virtual Reality" is also used for applications that are not fully immersive since the boundary between immersion and non-immersion is becoming blurred. VR systems currently have many forms due to different terms used in different applications, such as cyberspace, synthetic environment, artificial reality, virtual world, virtual environment and augmented reality. In all such VR-related systems the common features (also called the basic components) include a natural or intuitive interface for user interaction, real-time 3D graphics for synthetic presentation and a sense of immersion.

There are two main groups in VR-based systems based on the interactive means used. The first group is immersive VR systems, which are based on immersive display technologies such as head mounted displays (HMDs) or stereo projections. In an immersive VR system, devices such as HMDs and head position trackers are difficult to use for extended periods of time, and are quite expensive as well. The other group is desktop non-immersive VR systems, which have emerged from the 3D CAD animation technologies. A desktop non-immersive VR system, which is typically more economical than an immersive VR system, lets users view and interact with objects in a 3D environment using technologies such as stereoscopic display and haptic interaction.

For interaction with the 3D world, devices like 3D tracking devices, electrical hand gloves and haptic force feedback devices can be used. Additional features like voice input recognition and sound feedback output can further enhance the usability of a VR system, without the use of significant expensive additional hardware devices.

3.3 Existing virtual reality immersive techniques

A major distinction of VR systems is the mode with which they interface to the users. There are several techniques available for creating immersion in current immersive VR systems which include

- *Head mounted displays* (HMDs) [Keo 2002]. A spatial tracking device incorporating liquid crystal displays (LCDs) or cathode ray tubes (CRTs) mounted on the head of the user provides 3D information on head movements to update the visual images (see Figure 18). However these devices are cumbersome to wear and have uncomfortable intrusive viewing problems. Furthermore, users may not have the freedom of unlimited motion as their mobility is restricted by the cables attached to HMDs.

Figure 18: A head mounted display system

- *Binocular omni-orientation monitor* (BOOM) [Fakespacelabs 2002]. Another kind of personal head-coupled immersive display device which was introduced by Fakespace Inc., as shown in Figure 19. The device can offer stereoscopic visualisation on a counterbalanced, highly accurate, motion-tracking support structure for practically weightless viewing with high resolution. The drawbacks of the BOOM device are the encumbrance of the device and its restrictions on motion by its infrastructure and cable connection.

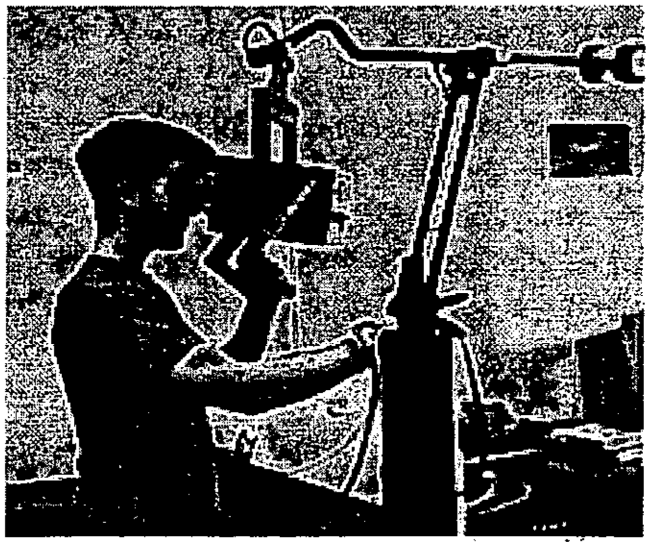


Figure 19: A binocular omni-orientation monitor system

- *Cave automatic virtual environment* (CAVE) [Fakespacesystems 2002]. A 3D illusion of immersion is obtained from projecting stereoscopic images on the walls or floors of a room-sized cube (see Figure 20). Unlike an HMD, multiple users wearing lightweight stereoscopic glasses can share the same experience using stereoscopic projectors. A head tracking system continuously adjusts the stereoscopic projection to the current position of the leading viewer. However, the system is quite complex and the amount of money needed to equip a company with this environment makes an obstacle for widespread industrial application.

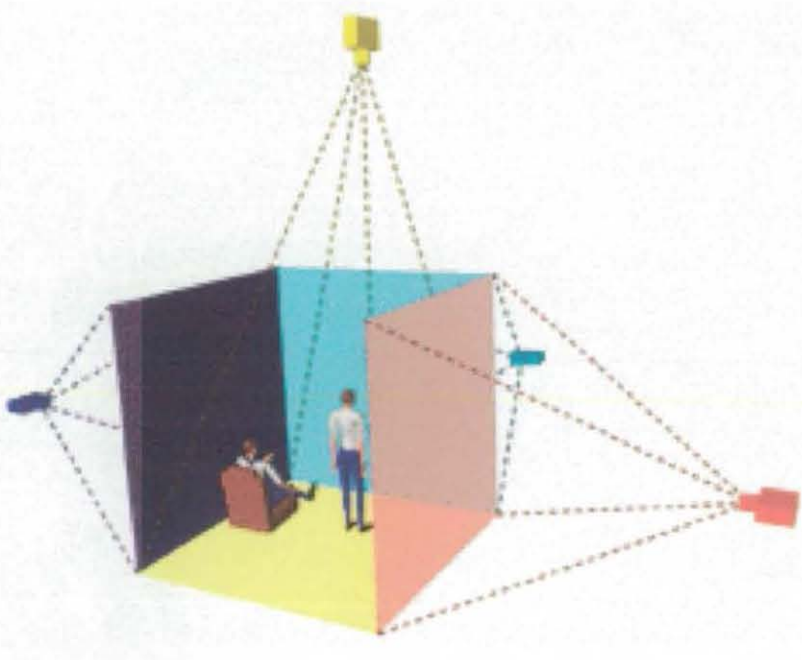


Figure 20: A cave automatic virtual environment system

- *Retinal display* [Banerjee and Zetu 2001]. Such a display is based on a laser microscanner technology, and it uses tiny solid state lasers to scan colour images directly onto the retina. The laser microscanner display, however, still faces substantial technical obstacles. Furthermore, there is still a long way to go before its commercial application.

3.4 Hardware and software in virtual reality systems

A VR system is a combination of hardware devices and software components that enable users to interact with virtual objects in a more natural and intuitive way. The hardware devices of a VR system receive input information from user-controlled devices and convey multi-sensory output information to create the illusion of a virtual environment. The software components of a VR system manage the hardware devices that make up a VR system for users' specific applications.

The first duty of VR system hardware devices is to receive input information from the user or from external input sources. In other words, a VR system receives input information from position tracking devices, electrical data gloves, digital input facilities, haptic force feedback devices and a wide variety of other devices.

The second duty of VR system hardware devices is to provide multi-sensory output information to the user. To give the user feedback about the virtual environment, VR applications employ a wide range of output technologies such as visual and auditory output devices. Visual presentation devices include projection-based systems, HMDs, BOOM, CRTs and LCDs. In addition to visual feedback, many VR application systems also provide auditory feedback using localised sounds. Some VR application systems also make use of tactile and haptic force feedback to enhance the virtual environment. In the future, there may be output devices for the remaining senses as well (for example, olfactory and gustatory senses).

VR system software components provide an access to all these types of input and output devices to successfully create a virtual environment for users. VR applications need to make full use of many software technologies (such as 3D graphics display, real-time data acquisition and multiple thread processing) not only to manage VR systems themselves but also to create and present information to users. The integration of all these technologies makes VR applications not only powerful, but also complex.

3.5 Desktop virtual reality systems

Desktop virtual reality systems, which are normally recognised as non-immersive VR systems, are the most basic type of VR systems. They are also regarded as a subset of traditional VR systems. A desktop non-immersive VR system is a natural extension of a traditional desktop computer system metaphor. In most desktop non-immersive VR systems, a traditional graphics workstation is used with various other input and output devices. Even in this simplest kind of VR system, there are many complexities in software programming and hardware integration. For example, the software system has to capture the tracking information and integrate that positional information into the running application to present the dynamic view images or other direct feedback to users in real-time.

Because it is composed of hardware that is part of commodity computer systems, a desktop non-immersive VR system is relatively inexpensive compared to an immersive specific VR system. In addition, a desktop non-immersive VR system only adds a few hardware devices to a normal desktop computer system, this makes it easy for users to setup and run such a system reliably. Furthermore, a desktop monitor commonly has higher resolution graphics than a VR display unit such as an HMD. All the above advantages make a desktop non-immersive VR system a popular choice for users of VR applications though it has the main drawback of lacking full sensorial immersion.

The best way to compensate for the missing spatial awareness in a desktop non-immersive VR system is to give users a greater sense of natural and intuitive interaction so as to block out other distractions and focus just on the specific object with which users want to work. This is also the main scheme to follow for developing any desktop non-immersive VR system application.

3.6 Virtual reality in industrial applications

As mentioned earlier, VR is often regarded as a natural extension to 3D computer graphics with advanced input and output hardware devices. This technology has only recently matured enough to warrant serious industrial applications. The integration of this new technology with software systems for industry, engineering, design and manufacturing will provide a new boost to the field of computer aided engineering (CAE).

3.6.1 Virtual product design and development

At present, accelerating worldwide market competition has become evident. Industry has more pressure to reduce product life cycle costs, maintain product quality, improve product performance and decrease time to design and fabricate the product [Banerjee and Zetu *op cit*]. Virtual product design and development can be considered as one of the enabling technologies for the rapid development of information technology infrastructure in this area by speeding up the product development process, improving the quality of the product and reducing the product design errors. It is now possible to develop products almost completely in a digital form. For example, Boeing introduced their 777 aircrafts without the need for any physical mock-up [Boeing 1996]. Design, visualisation, manufacturing analysis, assembly analysis and marketing images were all undertaken in a 3D digital environment. Successful examples were already found from the major automobile manufacturing companies such as Daimler Chrysler, Ford Motors and General Motors. At Daimler Chrysler, design engineers employed a BOOM-based VR system as an effective tool for a new vehicle product design and design review application [Brooks 1999]. At Ford Motors, product engineers simulated their new automobile assembly cycles by applying a VR system containing VPL's EyePhone and DataGlove devices [Fakespacesystems *op cit*]. According to the practical results from their applications, the VR processes they employed have reduced significantly their product design and development both in terms of time and costs.

3.6.2 Virtual reality based design systems

VR-based design systems are the most significant application in the field of virtual product design and development. VR technologies bring new potential tools into traditional CAD systems by providing more natural and intuitive ways to interact with 3D digital models and real-time 3D graphics design presentation during the initial product design stage. The idea behind them is to develop the future CAD systems for product design. Design systems employing VR-based techniques are generally referred to as VR-based design systems. According to their interactive abilities and functionalities involved in the design process, current VR-based design systems can be further classified into two main categories, namely, VR-enhanced 3D visualisation and analysis tools and VR-based CAD systems [Dani and Gadh 1997]. VR-based CAD systems are regarded as the direction in which new paradigms of CAD systems are evolving. With the in-depth maturing of VR technologies and conventional CAD techniques undergoing further development, the combination and integration of these technologies will lead to the next generation of powerful CAD systems for product design which industries are hungry for all the time.

In VR-enhanced 3D visualisation and analysis systems, product models are first designed in conventional CAD modelling systems and then appropriately translated into a VR-based environment. Such systems only allow designers to visualise and analyse CAD objects in a 3D virtual environment. Designers cannot directly create or modify CAD models and so when any change or modification is required, they must go back to the conventional CAD modelling systems. Obviously, as far as the modelling function and the modification of the model is concerned, such a system is more or less the same as the conventional CAD system. Virtual Design II [Astheimer, Dai *et al* 1995], developed by the Fraunhofer Institute for Computer Graphics in Germany, lets designers import data from various sources, pre-process and enhance data, interact with and manipulate data in real-time, and present the application using various audio-visual facilities including HMDs and dataglove devices (see Figure 21).

Figure 21: The Virtual Design II system

Researchers at the University of North Carolina at Chapel Hill in America introduced a system called Immersive Simulation Animation And Construction (ISAAC) for users to interactively construct virtual worlds [Mine 1997]. ISAAC allowed building designers to position, orient and scale architectural objects in a virtual environment using direct and indirect manipulation techniques (see Figure 22). Other examples of VR-enhanced 3D visualisation and analysis systems included the Interactive Virtual Environment for the Correction of STL files (IVECS) at Clemson University [Fadel, Grane *et al* 1995].

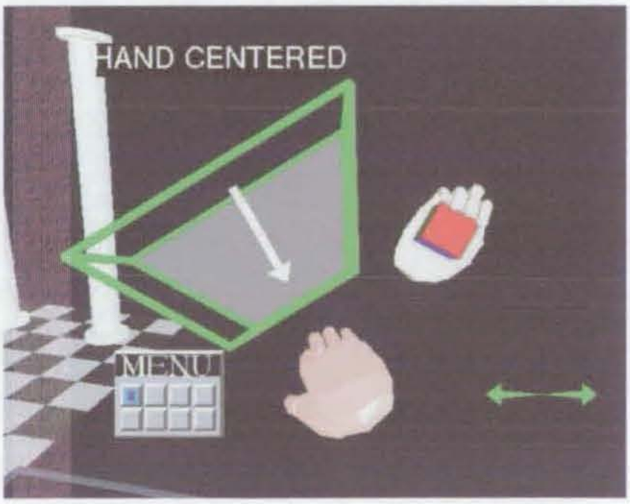


Figure 22: The ISAAC system

In contrast to 3D-enhanced visualisation and analysis tools, VR-based CAD systems allow designers to create, modify and manipulate 3D models directly in a 3D VR-based environment. Compared to most conventional CAD systems that only employ the traditional mouse/keyboard and 2D display-based interaction metaphor, VR-based CAD systems not only offer more natural and intuitive 3D interfaces for design and interaction, but also provide enhanced designing tools for model manipulation and functional experimentation. Moreover, VR-based CAD systems also support alternative methods of user input and output, such as voice commands, hand gestures and haptic interactions.

One known example was called the COnceptual VIRtual Design System (COVIRDS) which was developed by the I-CARVE Laboratory of the University of Wisconsin at Madison in America [Dani and Gadh *op cit*; Chu, Dani *et al* 1998]. COVIRDS introduced a new paradigm for CAD systems to use the hand and voice instead of the keyboard and mouse to create, edit and visualise designs of products in aerospace and automotive industries. The natural and easy-to-use interface was based on what was called the Workspace-Instance-Speech-Locator (WISL) approach that enabled the designer to operate in a 3D virtual workspace and generate 3D concept shapes by instancing primitives via speech and 3D locator (hand) inputs. The designer's stereoscopic visual feedback was provided by 3D glasses that allowed hologram-like 3D images to free-float in a space in front of the designer's field of vision. In addition, 3D position trackers attached to the hand allowed the computer to follow the motion of the designer's hand so as to determine the intended size, spatial location and orientation of the product geometry. Figure 23 gives the design environment of COVIRDS. However, the voice input had limited command vocabularies and the gesture interaction had poor recognition rate and capability. In addition, model data sharing facilities between COVIRDS and other commercial CAD systems were not provided. Furthermore, there were limited sketching functions and design tools for freeform curve and surface creation.

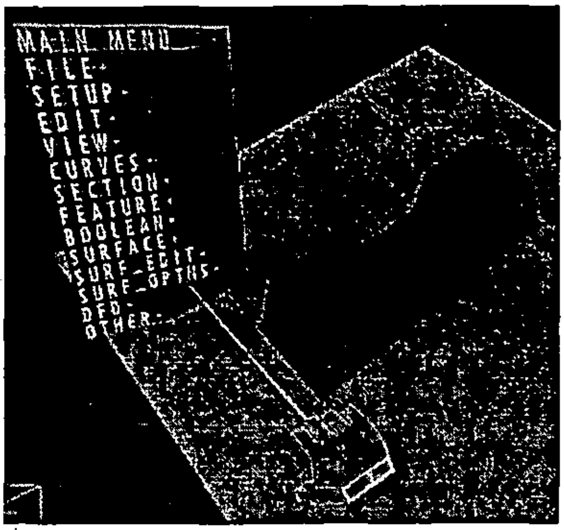


Figure 23: The COVIRDS system

Another VR-based CAD system called JDCAD [Liang and Green 1994] was produced by the University of Alberta in Canada. JDCAD was equipped with a pair of Polhemus Isotrak six degree-of-freedom (DOF) input devices. One was used to dynamically monitor the user's head position and provide the kinetic 3D effect, and the other was used as a hand-held bat which was the main input device for 3D direct manipulation through a so-called "ring menu" selection technique in a 3D virtual environment, as shown in Figure 24. The system made it possible to sketch 3D shapes in a highly interactive manner, just like the CSG approach in solid modelling (see Section 2.8.1 in Chapter Two). However, the solid model created by JDCAD was usually not precise. The JDCAD system had no tools and functions for other sketching designs, in particular, for freeform curve or surface creation. Furthermore, JDCAD did not provide the model data sharing ability with other commercial CAD systems.

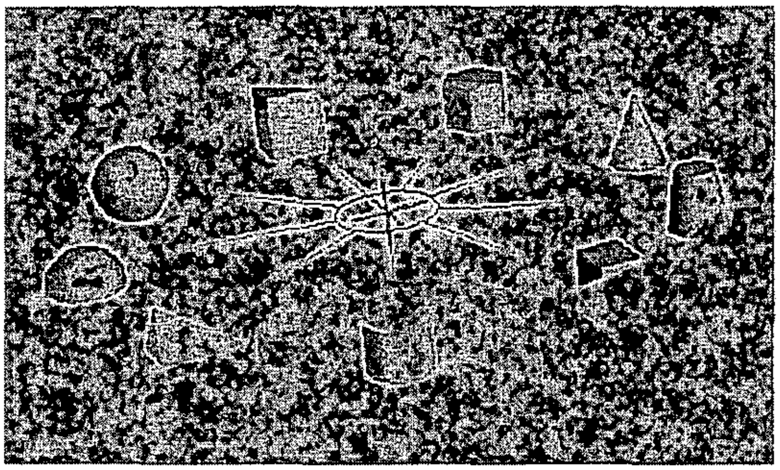
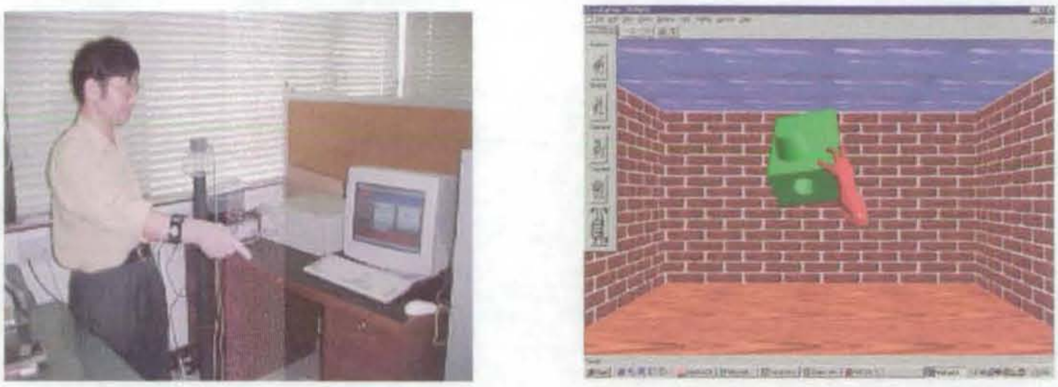


Figure 24: The JDCAD's ring menu

Another example of VR-based CAD systems could be found from the Department of Mechanical Engineering at the University of Hong Kong (HKU) in China [Zheng, Chan *et al* 1999b]. The system used an electrical hand glove called the CyberGlove as an input device to provide designers with a more natural and intuitive interface to create and manipulate 3D models, as shown in Figure 25 (a). The system also employed an advanced 3D graphics user interface technology to enhance the gesture-based user interface functions (see Figure 25 (b)). One point noted was that the system introduced some new mathematical algorithms and methods for freeform surface modelling and manipulation based on existing known freeform surface models during the conceptual design process. In addition, the HKU VR-based CAD system also included feature-based modelling techniques for constructing product models. However, human user interface based on slow discrete gesture recognition was still not very natural to use and needed further improvement with precise recognition. In addition, latency in the operation loop was one of the main problems in this VR-based CAD system. Furthermore, the model data exchange ability between the HKU VR-based CAD system and other CAD systems was not considered.



(a) System framework (b) System design environment

Figure 25: The VR-based CAD system from HKU

Researchers in the Computer Graphics Group at Brown University in America developed human-centred, powerful and interactive 3D graphics tools for modelling, scientific visualisation, tele-collaboration, and interactive illustrations in a shared visual, spatial and auditory environment [Zeleznik, Herndon *et al* 1996; Bloomenthal, Zeleznik *et al* 1998; Forsberg, LaViola *et al* 1998; Cohen, Markosian *et al* 1999]. Their many ongoing projects included using the Phantom haptic force feedback device, made by SensAble Technologies Inc., to provide force feedback for 3D haptic widgets in a polygonal modelling system testbed. One of them, called the ErgoSketch system offered simple tools, such as pencil and paper, for designers to freely sketch their design intent. The hand-drawn-representation could be used to rapidly conceptualise and edit approximate 3D scenes. To achieve this, the ErgoSketch system used simple non-photorealistic rendering and a purely gestural interface that was based on simplified line drawings of primitives and allowed all operations to be specified within a 3D world. The ErgoSketch system could offer a natural and intuitive user interface and even support two-handed interaction and speech recognition. However, all geometry could only be created using a 2D lightpen, which caused problems when supporting the generation of both freeform and precise 3D geometry. Furthermore, the modelling tools for product design were still limited.

Researchers in the State Key Laboratory of CAD&CG of Zhejiang University in China presented a prototype VR-based CAD system called the Virtual Design and Virtual Assembly System (VDVAS) [Wan, Gao *et al* 1999; Gao, Wan *et al* 2000]. VDVAS enabled designers to create and edit constraint-based 3D solid models completely in a 3D virtual workspace through voice commands and direct 3D manipulations. In VDVAS the accuracy of the created 3D model was guaranteed by a constraint recognition and constraint solution scheme. Virtual assembly which could fully integrate with virtual design was regarded as one of the main functions in the system and both assembly modelling and assembly planning based on direct 3D manipulations were included in VDVAS. However, VDVAS's emphasis was only on solid model creation from limited predefined primitives (very similar to the CSG approach in solid modelling) and 3D sketching and 3D freeform geometry creation functions were not provided. Furthermore, the model data exchange ability between VDVAS and other downstream CAD applications was not taken into consideration.

DesignSpace [Chapin, Lacey *et al* 1994], a system presented by the Center for Design Research in the Department of Mechanical Engineering at Stanford University in America, allowed designers to perform conceptual design and assembly using voice and gestures in a networked virtual environment. DesignSpace employed three head-tracked rear projection images, head-coupled binaural audio, hand instrumentation, electromagnetic position tracking devices for users' interactive simulation, dexterous manipulation and remote collaboration within a conceptual design environment. However, DesignSpace just served as an experimental testbed for design theory and methodology research. Its design functions and tools were poor and very limited for 3D modelling design and creation.

3-Draw [Sachs, Roberts *et al* 1991], a system for interactive 3D shape design was introduced by the researchers at Massachusetts Institute of Technology in America. 3-Draw was based on a pair of Polhemus Isotrak six DOF tracking devices. The designer could hold a palette-like sensor in his/her left hand to specify a moving reference frame, and used a stylus-like sensor in his/her right hand to draw and edit 3D curves in space, which made it much easier to design freeform curves and surfaces in a 3D environment. But the solid modelling functions and other issues such as the model data exchange ability with other conventional CAD systems were not mentioned.

Researchers at the University of North Carolina in America also contributed a VR-based CAD system called the three dimensional modeler (3DM) [Butterworth, Davidson *et al* 1992]. 3DM used an HMD to put the designer in a virtual modelling environment. The input device consisted of a Polhemus Isotrak 3-space mounted in a hollowed out billiard ball having two buttons on it. The hand-held tracker was used by the designer to select functions from a toolbox, and to create and manipulate objects in a 3D virtual environment. However, 3DM only supported modelling primitives, i.e. just triangles and tessellated shapes. In addition, 3DM did not have enough modelling facilities to create solid models. It remained in a demonstration state.

The Conceptual Understanding and Prototyping (CUP) system [Anthony, Regli *et al* 2001] which was introduced by the Geometric and Intelligent Computing Laboratory at Drexel University in America allowed users to author, in a 3D virtual environment, the structural, behavioral and functional knowledge about a design. CUP presented a new approach to CAD that united ideas from traditional mechanical design with 3D sketching and knowledge engineering in a virtual environment. However, CUP provided users with what was more like an environment for CAD process and tools for product data management (PDM) than a 3D design system. From the designer's point of view, CUP was poor at 3D model construction and manipulation.

The Conceptual Design Space (CDS) [Gatech 2002], developed at Georgia Technical College in America, offered a real-time 3D immersive virtual environment and an interactive, intuitive manner for 3D architectural design. The designer could use the CDS system to create conceptual building designs and modify them, add details or create new designs all immersed in a virtual world.

However, the CDS system was mainly designed for an architectural application and many features were not suitable for mechanical product design.

Despite the significant amount of research in this area, none of these VR-based CAD systems have made an impact on conventional CAD systems' evolution. This is partly due to the VR-based techniques they have chosen to use. Although it gives freedom to use hands for other operations and has the flexibility to specify verbal commands, the voice input method still has many disadvantages, including limited recognition capability both for languages and pronunciations, forcing users to remember arbitrary commands and the inappropriateness of the technique for specifying compound commands correctly. Despite its flexibility and number of degrees of freedom of the human hand, the glove type gesture interaction suffers from inherent weaknesses, including a poor recognition rate, needs for a gesture language and a user-specific calibration and a complex structure. Table 1 briefly summarises the advantages and major drawbacks of the main VR-based interaction paradigms currently used in most VR-based CAD systems. Any future VR-based design system should avoid these drawbacks as much as possible. Figure 26 gives a brief summary of the VR-based design systems which are reviewed in this section.

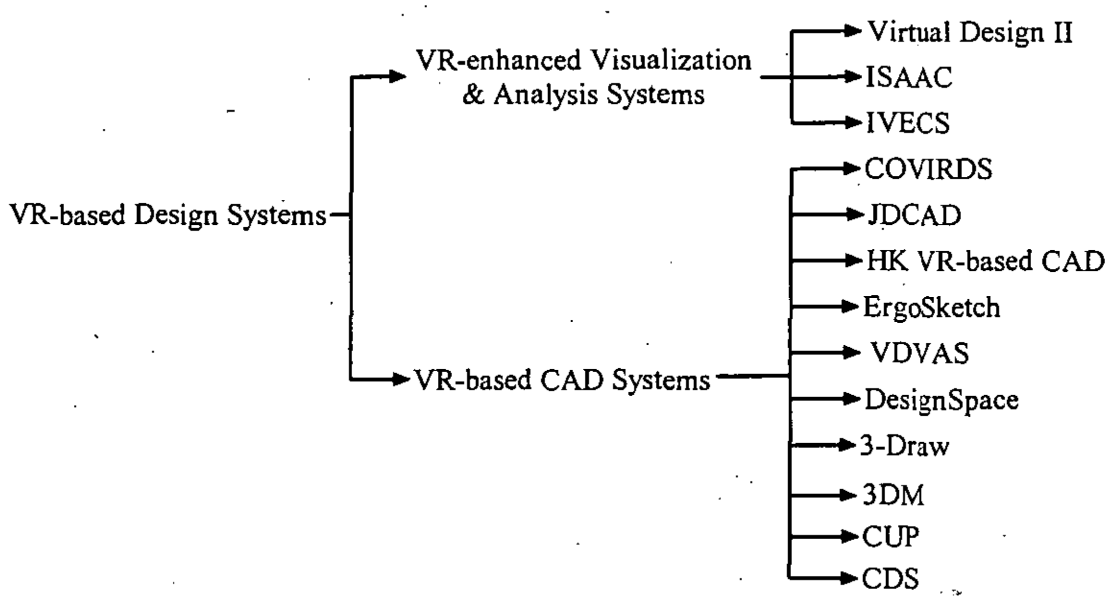


Figure 26: VR-based design systems

VR-based interaction paradigms	Main advantages	Main drawbacks
1. Glove type device method	• Enable to use both hands. • Use the hand with more degrees of freedom • Allow a natural interaction by gesture input	• Need pre-defined complex gesture language • Need fast and precise gesture recognition • Need user-specific calibration to work
2. Voice input method	• Free both hands for other operations • Need simple hardware devices (i.e. a microphone) • Specify verbal commands flexibly	• Need different language support • Need different pronunciation recognition • Need different accent recognition
3. Position tracking device method	• Provide spatial information for interaction (i.e. view control, object selection and manipulation) • Allow users to feel "presence" in a virtual world	• Need comprehensive position calibration • Need complex algorithm to reduce noise disturbance • Cable connections limit freedom of operation
4. Fully immersive virtual environment	• Create a more realistic environment • Increase the user's feeling of immersion	• Make the system infrastructure more complex • Cause uncomfortable intrusive viewing problems • Make the system more expensive to use

Table 1: Main advantages and drawbacks of VR-based interaction mechanisms

3.6.3 Virtual prototyping

Another useful application of VR technologies in the product design and development field is virtual prototyping (VP). VP is also regarded as virtual simulation in a computer-based environment in the early stages of the product design and manufacturing. Currently, different VP applications have different VP interpretations. From the product design point of view, VP can be referred to as the construction and testing of a virtual prototype, or in other words called a digital mock-up, in which a computer simulation of a physical product can be presented, analysed, and tested for product lifecycle aspects such as design, manufacturing, service, maintenance and recycling as on a real physical prototype [Wang 2002].

In general, VP has been widely used in an effort to reduce the product development time and cost. VP also enables designers to explore more design alternatives in a short time and assist design validation or testing. With the VP technology, users can design, test and debug a product before it is built in the physical world. Once a virtual prototype is finished, the design can be sent directly for physical prototyping on one or more of the available rapid prototyping (RP) technologies such as StereoLithography (SL), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM), or on other manufacturing technologies such as CNC machining.

The ultimate goal of VP is to completely substitute the physical prototype to greatly reduce the development cost and time. As new technologies such as VR techniques are applied to VP systems, VP has extended its functions from just a conventional engineering simulation to a simulation of all the interested aspects of a product, including the product function, manufacturability, ergonomics, market and even aesthetic features.

A commercial VP application example could be found from Mechanical Dynamics Inc. [Adams 2002]. A system called the Functional Virtual Prototyping Process could enable users to experiment with innovative design variations, gain insight earlier in the development cycle, make quantifiable improvements and make sure the products would work as intended before the customers invested a large amount of time and money creating physical systems. By simulating the performance of mechanical systems on the computer, the system enabled users to troubleshoot problems within existing designs and to reduce the risk associated with developing new designs.

Researchers in the Virtual Reality Laboratory at the University of Michigan in America introduced a VP system called the Virtual Prototyping of Automotive Interiors (VPAI) [Umich 2002]. In the VPAI system, a virtual prototype could replace a physical mock-up for the analysis of design aspects including layout and packaging efficiency, visibility of instruments, controls and mirrors, reachability and accessibility, clearances and collisions, human performance, aesthetics and appeal and more. Their other research projects have focused on VP applications in engineering design especially in automobile and marine industries.

3.6.4 Virtual manufacturing

Manufacturing is an important sector in most countries and represents the transition of products from the concept shape to production and sales. Virtual manufacturing (VM) is just one of the most useful VR applications in manufacturing. VM can be considered as the use of computer models and simulations of manufacturing processes to aid in the design and production of manufactured products. Lawrence Associates Inc., in its virtual manufacturing users workshop report, defined VM as an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control. Three paradigms of VM were proposed in their report, including design-centred VM, production-centred VM and control centred VM [Lin, Minis *et al* 1995].

Generally speaking, VM refers to the modelling of manufacturing systems and components with effective use of audio, visual and other sensory features to simulate alternatives for an actual manufacturing environment, mainly through effective use of computer-based technologies. The motivation of VM is to enhance the ability to predict potential problems and inefficiencies in product functionality and manufacturability before real manufacturing occurs.

The key point to which more attention is being paid in VM is to develop an interface between VR technologies and manufacturing, automation theory and practice. VR technologies could support the development of this interface for VM, and thus enhance the integration of VR technologies into VM applications.

It is well recognised that over 75% of the total cost of a product is committed at the product design stage [Ullman 2002]. From a product-life cycle viewpoint, VM provides design, processing and production engineers with an ability to validate their designs, associated processing plans and operational plans with respect to technical feasibility and cost. This is done early in the product development process before committing to real production.

There are a number of academic research and industrial application projects on VM. For example, the Interactive Manufacturability Analysis and Critiquing System (IMACS) [Lin, Minis *et al op cit*], developed by the Institute for System Research at the University of Maryland in America, made a good contribution to the computer aided manufacturability analysis. IMACS provided the user a new way to speed up the evaluation of new product designs in order to decide how to manufacture them easily.

Researchers in the Industrial Virtual Reality Institute of the University of Illinois at Chicago in America, developed many tools and carried out many applications in VM [Uic 2002]. Interesting examples included i) manipulation of objects using sensor data and real-time control inputs in a CAVE environment, ii) integration of factory layout, material handling and manufacturing equipment control models and iii) electronic collaboration between geographically dispersed factory designers: using high speed communication links and the world-wide-web (WWW), models were developed for collaborative manufacturing systems layout design.

3.6.5 Virtual assembly

Virtual assembly (VA) is regarded as a key component of VM and one of the largest challenges for VR-based technologies in engineering applications [Jayaram, Connacher *et al* 1997]. Normally, VA refers to the use of computer tools to make or assist with assembly-related engineering decisions through analysis, predictive models, visualisation and presentation of data without physical realisation of the product or supporting processes.

VA mainly consists of assembly process simulation, real-time collision detection, tolerance analysis and assembly process planning. In a VA system, a combination of several technologies such as advanced visualisation, real-time simulation, decision making theory, assembly and manufacturing procedures, and assembly and manufacturing equipment development are integrated together to provide support for VA process structures.

One VA application example could be found from the known automobile manufacturer – Ford Motors [Nist 2002]. In the Ford VA system, the vehicle parts were first designed in a conventional CAD system. The CAD files were transferred to the VA system with VR equipment. A user then manipulated the virtual part and attempted to assemble it into the virtual vehicle. The equipment used for the VR experiments were a VPL's EyePhone and a DataGlove running on a Silicon Graphics workstation. The user put all the equipment on and attempted the part insertion. The VA system checked for interference and collision between the part and the vehicle. The simulation process could be used to evaluate process installation feasibility. For example, it could be used to evaluate the human ergonomics of various assembly operations.

Currently, VA is still in its infancy and attracts much attention from both academic research and industry practice. Yet VA has shown great potential for the new product design and development process. With the rapid development of VR and other related technologies, VA activities such as assemblability evaluation and assembly planning can be done completely within a computer-generated virtual assembly environment.

3.6.6 Virtual sculpting

A large amount of work has been done in computer graphics to provide an intuitive design metaphor. In practice, there are still a lot of parameters to tune and limitations on the object's topology and geometry due to the underlying mathematical description. Designers are hungry for tools for sculpting design where they could deposit material wherever they desired in space, and then iteratively deform, carve or paint it with a tool, without any consideration on its underlying description. The emerging technology called virtual sculpting (VS) is regarded as one of the possible solutions to realising the designer's dream. There are many academic research and industrial application activities on intuitive and direct interaction with freeform surface creation in order to apply them to creating whatever shapes designers have in their minds.

Researchers at Colorado State University in America developed a prototype sculpting software package, called the CySculpt system for editing and reshaping 3D polygonal mesh surface models [Colostate 2002]. These surfaces could be imported from 3D digitising systems, medical imaging surfacing software or surface modelling CAD systems. Editing and sculpting could be applied to individual vertices or facets, to user-defined areas or to an entire model. Operations included selective smoothing, roughening, stretching, decimation and refinement. The CySculpt system also offered utilities for preparing a surface with a thickness for rapid prototyping (RP) production. Major applications of the CySculpt system were targeted for visualising, verifying, repairing and performing calculations with digitised models and performing working-with-clay type sculpting/modifications. Since the CySculpt system was a polygonal-based system, the surfaces or solid faces of the design model were represented in an approximate non-precise way.

The Manchester Visualisation Centre (MVC) at the University of Manchester in England [Manchester 2002] has conducted various research projects in the use of non-uniform rational B-splines (NURBS) for creating high-quality computer graphics. In one of their research projects, they developed a NURBS Surface Editor which allowed designers to create and manipulate 3D NURBS surfaces and place them within a 3D scene. The "motif widgets" were used to provide user interfaces and a Hewlett Packard-Programmer's Hierarchical Interactive Graphics System Plus Lumiere and Surfaces (HP-PHIGSPLUS) model was used to produce the output. The interactive methods included primitive selection and surface skinning through curves. The project involved the application of free form deformation (FFD) algorithms to the NURBS Surface Editor, thereby allowing the usual editing tools to be augmented by using an FFD lattice. Another contribution from MVC was that they developed a NURBS library of functions which could assist designers in the creation, manipulation and rendering of NURBS curves and surfaces in 3D CAD applications.

Researchers in the Department of Computer and Information Sciences of De Montfort University in England [Noble and Clapworthy 1996] presented a virtual sculpting system called Gargoyle for designers to locally modify a NURBS surface by varying the weight parameters. The method led to the use of a simple "point and click" metaphor for shape manipulation. The Gargoyle system could provide designers with some degree of convenience in virtual sculpting.

SensAble Technologies Inc. introduced the FreeForm Modeling system [SensAble 2002] which provided virtual carving tools, smudging tools, tugging tools and tooth-pasting tools in order to mimic manual modelling methods like clay and plaster carving or wood and marble sculpting processes with which many designers were familiar at the conceptual design stage. The FreeForm Modeling system was also one of the first commercial design products to successfully use a haptic force feedback device for product development. However, the FreeForm Modeling system still suffered from a number of problems such as the inconvenience caused by the collaboration of 2D mouse input and 3D Phantom device input on a 2D planar visual display, most of the operations were performed by only one hand, a large amount of memory and a high computing speed were needed due to its volumetric modelling technique and its model data was harder to transfer to other CAD platforms.

However, most sculpting tools in these systems were implemented with traditional mathematical formulations. Although the shape operators were more intuitive than traditional CAD systems, they were still very limited and needed to be further improved. Except for the FreeForm Modeling system, most systems did not use

VR-based input and output devices to offer a virtual environment, and consequently, designers still worked in a traditional CAD environment.

3.6.7 Collaborative virtual environment

Collaborative virtual environment (CVE) is an extension to traditional single-user or standalone VR applications [Hartling 2001]. In a CVE application, two or more users can interact with each other in the same virtual environment. Communication between users should be clear and intuitive which often means that users can "speak" to each other directly. Figure 27 gives an example of multiple designers collaborating in a virtual environment. In order for designers to feel that they are sharing the same virtual world and potentially working together on the same task, concepts of information sharing and cooperative manipulation of the information must exist. Visually, the shared world should be the same for all sites, or it must be similar enough that no user is lacking crucial environmental elements such as landmarks that could be used as reference points. At present, there are two CVE approaches used in such applications: local collaboration or remote collaboration.

Figure 27: Multiple designers collaborating in a virtual environment

Basically, the CVE technology includes and emphasises the wide use of internet/intranet communication networks for virtual component sourcing, collaborative design and testing. Moreover, recent advances in broadband networks are also opening up new applications for tele-collaborative virtual environments in these fields. Using the most advanced CVE systems, users can dramatically shorten the time to market for new products, cut the cost of prototyping and pre-production engineering, enable many more variations to be tried out before committing to manufacture and increase the effectiveness of quality assurance testing.

3.7 Virtual reality in medical applications

VR technologies bring numerous advantages to the medical community. These include improved medical training (errors made on virtual, rather than real patients; modelling of unusual and rare cases), more realistic certification procedures (for example, objective measures of surgical skill) and more pleasing treatments (in the case of virtual rehabilitation) [Burdea and Coiffet *op cit*]. Not only do VR technologies have great potential to revolutionise the teaching and practice of medical applications, but they also encompass some of the greatest computer visualisation challenges of state-of-the-art: real-time interaction with complex 3D data, photo realistic visualisation and haptic feedback modelling. What is more, they require that all of these be achieved in the same application [Earnshaw, Vince *et al* 1995].

In a virtual surgery application, the virtual model is usually built from actual patients' data, using scanning techniques such as magnetic resonance imaging (MRI) and computed tomography (CT). This kind of virtual surgery system can be used not only as an assistant to surgeons during operation, but also for training young surgeons and other inexperienced surgeons for unusual surgeries. Lately, augmented reality systems have been able to combine computer-generated imagery with a view of the real world. A typical application would be to overlay information on real world objects, such as showing the location of an organ on the inside of a body in an immersive environment instead of navigating inside the body.

3.8 Virtual reality in telepresentation applications

Recently, many new words are coming out with the applications of VR technologies in some specific areas. They include tele-presentation, tele-operation, tele-presence and tele-robotics. Whatever way they appear in the literature, the key feature behind them is the same: using VR technologies for achieving natural man-machine interfaces for specified remote activities.

The best example one can imagine is where virtual tele-presentation is used in hazardous environments such as a nuclear reaction station and space exploration. But the applications of virtual tele-presentation are not restricted to hazardous environments which were originally designed for intervention by humans. Recently, the new and exciting field of nanotechnology employs VR-based nanopresence technologies for non-destructive testing, visualising and inspecting materials at an atomic level [Earnshaw, Gigante *et al* 1993].

3.9 Summary

Computing technology, especially the personal computer (PC) has seen dramatic improvements, and has laid a solid foundation for mature VR applications in different fields. The aim of VR technologies used in the product design process is to allow faster and more natural ways of interaction with the computer and to overcome the communication bottleneck presented by 2D interaction (both input and output) which has prevailed in most commercial CAD systems. Therefore, VR technologies are regarded as the next generation of advanced HCIs. Despite the significant amount of research in VR-based design systems, none of them has made an impact on mainstream CAD systems' evolution. This is partly due to the techniques they have used having more or less inherent weaknesses. Future new VR-based design systems should take full advantage of existing VR technologies and avoid their drawbacks as much as possible.

Although it is argued that the emerging VR-based CAD systems provide the direction for the next generation of CAD, integration of new VR-based techniques into 3D CAD applications indeed plays a crucial role especially at the initial stages of the product design process. Rapid advances in digital technologies for interaction and visualisation offer the potential to bring the active, exploratory, manipulative and expressive approaches in which designers work with real objects using hands and tools, into the visual digital world. It is anticipated that through the development of new design systems that use VR techniques and other new emerging technologies, designers can significantly reduce design time and costs, and improve design quality and reliability. Therefore, it is essential that a full understanding of VR-based interactions should be formed and the new HCI requirements to support conceptual design should be defined. This is the subject of the next chapter.

CHAPTER FOUR

Interaction techniques and design functions for CAD applications

4.1 Human factor analysis of CAD techniques

While citing CAD applications, one should never forget one key factor that affects the functionality and usability of such applications in a very deep way: the human factor. As discussed in Chapter Three, Virtual reality (VR) technologies provide much potential to achieve more natural and intuitive human computer interfaces (HCIs) for a specific task such as the conceptual design process. More attention should be paid to the human computer interaction in the design process in order to develop user interfaces (UIs) from which designers benefit based on the features of naturalness and intuitiveness.

Recent improvements in computer technologies provide advanced tools in the field of CAD. Many CAD research activities have focused on the development of enhanced computer aided conceptual design systems to fully support different phases of the product design process. In order to provide more friendly UIs for designers in the design process, there is a need for high level, understandable and effective UI specifications from practical case studies with usability testing. These UI specifications should not only establish more effective and usable HCI mechanisms, but also reveal the real needs from industrial designers when they perform design work using CAD tools.

Sener and Wormald [2001] conducted several case studies that revealed the needs and expectations of industrial designers when they carried out their design work using current CAD systems. These case studies covered several subjects including i) exploring the capability of current CAD systems for supporting conceptual design activities, ii) identifying user expectations of new generation computer aided industrial design tools, iii) understanding the needs of professionals involved in the design process such as industrial designers and engineering designers and iv) producing improved computer aided conceptual design tools that can be used from conceptual design to total product design. Their observations could be regarded as the future expectations from industrial designers of a new generation of CAD systems. The following presents a brief summary of their findings in relation to this research that deliberately focused on HCIs rather than modelling techniques.

- A new CAD system should be less complicated so that designers could learn to use it in a much shorter time without having difficulty. When using the CAD software, it should be easy to find which tool to use for which purpose, easy to locate the tool, easy to create complex shapes and easy to remember which level of modelling is being used.
- Sketching on the computer should create lines without any need to complete all the lines. It should be done as quickly as by a free hand; it should allow sketching in 3D space; it should be using similar tools as in traditional sketching such as a pen; it should not limit but allow them to draw exactly what they want to draw; it should keep records of sketch work as layers that allow designers to see previously created ones; it should allow designers to define drawings in their own styles.
- A new CAD system should enable designers to shape and sculpt the object by hand, to interact with the model by touching, feeling, holding and manipulating if needed just the same as in real life.
- A new CAD system should provide strong tools for free and fast control of the freeform shape construction under certain constraints. New modelling representations and new processing algorithms should be employed to achieve this goal.

An intuitive interface between human and computer is one which requires little training and offers a working style most like that used by users when interacting with environments and objects in their day-to-day life. In other words, users interact with elements of their task by looking, hearing, holding, feeling and manipulating using as many of their natural skills and experience as appropriate, or can reasonably be expected to apply to a task. Haptics or force feedback technology opens the door to a new level of interactivity between users and computers. Prior to haptics, users only have the chance to interact with the computer through vision and sound. The sense of touch has been conspicuously absent in traditional computer interfaces like the keyboard and mouse. The introduction of haptic technology could bring significant changes to the way designers interact with information and communicate ideas, by permitting designers to touch and manipulate virtual computer-generated objects in a way that creates a compelling sense of tactile realness.

In order to better understand the role of haptic interaction in CAD applications, a case study on haptic modelling was performed by Sener [2002]. Another aim of this case study was to find out the potential strengths and weaknesses of haptic modelling systems currently available on the market and to explore the level of usability that the existing haptic application system would provide for a 3D modelling solution to conceptual design or industrial design. The observations drawn from the case study provided a definite indication of how haptic technology should evolve in order to satisfy the needs of industrial designers and how this technology could be integrated into the conceptual design process.

The information collected from this case study was very useful for providing first hand data from designers on the potential and drawbacks of haptic modelling in 3D object design, especially at the initial stages of the product design process. Moreover, the findings from the case study greatly helped CAD application designers to better combine the advantage of different manual modelling techniques (for example, sculpting, wire cutting, clay shaping and deforming) with CAD technologies in order to enhance the usability of CAD tools. The following summarises the results which come from Sener's case study [*ibid*].

- The haptic FreeForm Modeling system from SensAble Technologies was introduced as a tool which let designers sculpt and form virtual clay-based or foam-based models using similar tools and techniques to those employed in the physical world, yet with most of the advantages of a CAD tool. However, the haptic FreeForm Modeling system was not an accurate CAD system, and it would not be used in the later stages of product design. It was also an insufficient modelling system for making final design decisions. It was still a step away from completely satisfying industrial designers and replacing their conventional tools and other CAD modelling systems.

- Haptic technology offered a revolutionary approach for combining physical and digital modelling techniques in the industrial design phase. In spite of recent progresses, the incorporation of haptics into product design was in its infancy. New sophisticated 3D modelling techniques were typically needed to master traditional 3D modelling. Advanced haptic interfaces could create entirely new opportunities for computer aided conceptual design. Given the continued rapid development of 3D modelling and visualisation with computers, the challenges for future CAD were likely to be the seamless integration of haptic interaction into the product design process.
- Work was still needed which would focus mainly on the characterisation and classification of industrial designers' 3D manual working techniques, such as the tools used and the ways for form creation. A set of recommendations would show how manual techniques could be better duplicated or mimicked within a computer aided industrial design environment.
- The Phantom haptic device was an easy and straightforward input device to use. Using the Phantom haptic device as a carving tool also let it rotate freely in 3D space, as they would do with the actual carving tool. There existed a need for more research on its design which offered a form with hand support and allowed designers to use it without getting tired very quickly. There was also a need for research to improve its functions in relation to other input devices being used in the same system such as the keyboard and mouse.
- The interface was generally simple and easy to use. The interface should be more flexible so that designers could arrange their own working environments as if they were working in a real workplace. Using similar keyboard/mouse shortcuts available with other CAD systems should also be taken into consideration to make the interface less confusing.

- One of the advantages while working with the haptic FreeForm Modeling system was being able to go back a few steps after making a mistake unlike blue foam-based modelling in the physical world. However, the accuracy and being able to get engineering drawings from the CAD model appeared as important issues which the haptic FreeForm Modeling system was not able to deliver.
- In general, parts built using FreeForm Modeling system have a somewhat unique, organic appearance compared with models designed directly using other CAD systems. This can be achieved by using virtual sculpting techniques along with the haptic interface support rather than employing conventional modelling methods with standard user interfaces.

Table 2 gives a brief summary of the needs and expectations of new CAD systems found from both the author's and Sener's research work. This summary is based on the findings from a range of industrial designers.

Relevant issues	**Preliminary results**
1. Interactive devices	• Easy and straightforward to use in 3D space • Mimic the normal way that designers interact with the nature world • Provide direct sensory feedback in operation
2. Preferred human computer interfaces	• Simple, easy and flexible to use • Require little training and offer a natural working style • Interact with models by seeing, hearing, touching, holding and manipulating in an intuitive way • Enable two-handed operation to work in the design process
3. Functional modelling tools	• Less complicated to learn and use • Allow sketching in 3D space which is done as quickly as that by a freehand operation • Provide strong tools for free and fast control of the freeform shape creation
4. CAD data formats	• Provide import/export CAD data format options

Table 2: Needs and expectations of new CAD systems for conceptual design

4.2 Characteristics of a new conceptual design system

Drawing upon the previous section, it is possible to define the aim of a new conceptual design system as follows:

> To integrate VR-based HCIs into the design process in order to maximise its interactivity and efficiency so as to provide better support to conceptual design.

The overall aim of the conceptual design system was expanded into ideal system characteristics using a matrix approach, similar to that used within the quality function deployment process (see Figure 28). The designers' requirements obtained from the same case study results are listed down the left-hand side of the matrix and the characteristics of a new conceptual design system needed to meet them are listed along the top. The correlations between designers' requirements and system characteristics are shown by crosses entered in the matrix.

		System characteristics						
		Two-handed operation	Haptic interaction	Stereoscopic display	Sound feedback	3D input and 3D output	Design functions	CAD data transfer
Designers' requirements	Simple, efficient and flexible to use	x					x	
	Offer a natural working style	x						
	Easy and straightforward to use in 3D space			x		x		
	Provide direct sensory feedback in operation		x		x			
	Provide an intuitive interaction method		x		x			
	Allow 3D sketching			x		x	x	
	Provide fast freeform shape creation						x	
	Support import/export file format options							x

Figure 28: Correlation matrix between designers' requirements and system characteristics

Since the research focuses mainly on the interactivity and efficiency of HCI for conceptual design so as to provide a more effective modelling environment, other objectives such as to enhance and improve the capability to achieve more unique designs are not considered in this research. The defined system characteristics would provide both a starting point for system configuration and a yardstick against which system performance could be measured. Each characteristic is described in detail below.

4.2.1 Two-handed operation

In their everyday lives, people are constantly confronted with tasks that involve physical manipulation of real objects. They typically perform these tasks with little cognitive effort, using both hands and with total confidence in their movements. For CAD applications, a familiar 3D user interface is needed to offer an equally natural interaction which takes advantage of existing skills and experience in manipulating real objects in the physical world. Two-handed operation interfaces were found to be faster and easier to use than conventional interfaces that were based on a keyboard and a mouse [Raisamo 1999]. In addition, a well-designed two-handed interaction interface should have a physical form which gives clues to the way it works, making it more intuitive and easier to learn than traditional techniques for manipulating virtual objects. Though the traditional mouse/keyboard operation is normally performed by two hands in a serial order, it is important to emphasise that here the two-handed operation refers to using both hands simultaneously instead of in series.

4.2.1.1 Psychological analysis of two-handed operation

Human two-handed control has been extensively analysed in psychology. Much of this research specialised in defining which parts of the brain controlled which hand, and how to determine the handedness of the subjects. Many of these results were not directly applicable to building user interfaces, but there were some useful theories that explained the differences between the hands and the way both hands cooperated in bimanual tasks. Among this research, Guiard presented a kinematic chain theory [Guiard 1987]. According to his model, the functions of both hands were related serially so that the non-preferred hand acted as a base link and the preferred hand as the terminal link. Based on this theory and observations of people performing bimanual tasks, Guiard proposed three high-order principles governing cooperative and asymmetric functions of the two hands, which could be summarised as follows (here assuming a right-handed person):

- *Right-to-left reference.* Motion of the right hand typically found its spatial references in the results of the motion of the left hand. Often the non-preferred hand played a postural role in keeping an object steady while the preferred hand executed a manipulative action on it. For example, when writing, the non-preferred hand controls the position and orientation of the page, while the preferred hand performs the actual writing by moving the pen relative to the non-preferred hand.
- *Asymmetric scales of motion.* The movement of the left hand usually had a low spatial accuracy compared to the right hand. The preferred hand was capable of producing finer movements than the non-preferred. During handwriting, for example, the movements of the left hand adjusting the page are infrequent and coarse in comparison to the high-frequency, detailed work done by the right hand.
- *Left hand precedence.* Usually the action started with the non-preferred hand and ended with the preferred hand. For example, in handwriting, a sheet of paper is first positioned with the left hand and then the right hand is used to write on it.

Clearly, analysing the division of labour between two hands helps people to understand more about two-handed operation in harmony in the physical world. This also leads people to a better understanding of two-handed operation with computers as well in order to meet the requirement for designing two-handed interfaces for CAD applications.

4.2.1.2 Two-handed operation in CAD applications

There are a number of research activities where two-handed operation computer-based applications use both hands to give continuous operation in an integrated manner.

ToolGlass and Magic Lenses [Bier, Stone *et al* 1993] was a desktop system in which the tools were controlled with both hands. This metaphor consisted of a semi-transparent menu which users superimposed upon a target using a trackball in the non-preferred hand. The preferred hand then moved the mouse cursor to the target and clicked through the menu to apply an operation to the target.

Two-handed operation with 2D input devices could be applied not only to 2D applications but also to 3D CAD systems. An example of such an application was the SKETCH system [Zeleznik, Herndon *et al* 1996] developed by Brown University in America. The SKETCH system's two 2D devices together provided four degrees of freedom and allowed users to perform a number of CAD operations with two hands. Objects could be moved, rotated and scaled, the viewpoint and other camera-based display parameters could be manipulated and several other editing operations were supported.

A notable two-handed operation interface was the T3 system, which was introduced by Kurtenbach *et al* [1997]. T3 was a graphical user interface paradigm that was based on tablets, two-handed manipulation and transparent user interface components, hence the name T3 represented. This paradigm was used in a sophisticated drawing application. The tools were controlled with two multi-sensor tablets that both had a puck that sensed rotation in addition to their position. Tablets could potentially simplify between-hand coordination, but multi-sensor tablets presented their own quirks, such as the possibility for multiple input devices to collide with one another.

Hinckley *et al* [1998] developed a two-handed operation interface in which a doll was used to control neurosurgical visualisation, as shown in Figure 29. Their experiment system showed that two-hand operation provided more than just time savings over one hand manipulation. They found that two hands together provided sufficient perceptual cues to form a frame of reference that was independent of visual feedback.

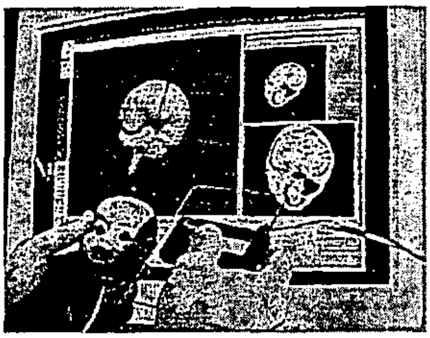


Figure 29: The neurosurgical visualisation two-handed operation interface

Sachs' 3-Draw system [Sachs, Roberts *et al op cit*] was a two-handed operation CAD tool which facilitated the sketching of 3D curves (see Figure 30). In 3-Draw, the designer held a stylus in one hand and a tablet (similar to a painter's palette) in the other hand. These tools served to draw and view a 3D object which was seen on a desktop monitor. The tablet was used to view the object, while motion of the stylus was used to draw and edit the curves making up the object.

Figure 30: The 3-Draw System

Shaw and Green [1994] introduced a two-handed operation CAD system for creating hierarchical quadrilateral polygon-based surfaces. The interface of the system used two hands to interact with the surface, with the left hand setting geometric and other contexts and the right hand manipulating the surface geometry.

4.2.1.3 Potential of two-handed operation

As mentioned earlier, most everyday tasks or working skills are two-handed in nature. Using two-handed operation in the design process mimics the way people use both their hands for their everyday tasks. Hinckley *et al* [*op cit*] argued that the common-sense conclusion for why two-handed operation might offer advantages for UIs, (for example, "two hands save time by working in parallel") was not always true in two-handed manipulation. They believed that using both hands could indeed help users to perform tasks more quickly than using one hand. Furthermore, two hands were not just faster than one hand, but two hands together could provide the user with additional information such as the position and kinaesthetic sensory feedback between the two hands that one hand alone could not. Using both hands rather than a single hand could also change how users thought about a task, and this influenced the user's problem-solving behaviour as well.

According to a report on ergonomic efficiency testing of two-handed versus one-handed CAD working styles from Ergonomic Technologies Corporation [3dconnx 2004], using two-handed operation could reduce both hand motions rapidly and alleviate muscle activity significantly. 90% of the subjects who participated in their evaluation tests would prefer to have a two-handed approach for their CAD use. Many other researchers have indicated that two-handed interfaces have many potential benefits over one-handed interfaces. The potential benefits can be summarised in three main points which are listed below:

- *Two-handed interfaces are natural*. Just thinking of everyday living, both hands are used frequently to assist each other in performing many tasks. For example, it is very natural and easy to perform a drawing operation with a pencil in one hand and a ruler in the other. In contrast, only a conventional 2D mouse held in one hand can be used to interact with models in most commercial CAD applications.
- *Two-handed interfaces are efficient*. By dividing the labour between two hands, based on a deeper understanding of the difference between the preferred and the non-preferred hands, two-handed interfaces can save time dramatically in

performing tasks. For example, in physical modelling activities, one hand is used for holding and navigating the model, while the other hand is used for selecting a tool and applying the tool operation to the model. In this way, dividing the navigation task and the operation action between two hands can make the work much more efficient.

- *Two-handed interfaces are more flexible.* Compared to one-handed interfaces, two-handed interfaces have more degrees of freedom, thus providing users with more alternative solutions and operations to support their activities in performing tasks. Moreover, when working with two hands, users can feel greater sensory feedback such as the haptic force sense and kinaesthetic sense between two hands.

4.2.2 Haptic interaction

Rapid advances in digital technologies for interaction and visualisation offer the potential to bring out new natural and intuitive approaches in which people work with real objects, using both their hands and tools, into the digital space [McLundie *op cit*]. Among these advances, haptic technology offers many benefits to designers for interacting with virtual objects in a 3D digital environment. Haptic technology provides force feedback sense while the digital model is modified by tools such as sculpting, cutting and smudging. Also haptic technology includes tactile sense about the digital object that is touched such as surface texture and surface lineament or boundaries. The potential of such technology to allow a less constrained, more naturalistic interaction with virtual models has increased the drive towards computer support for the whole design process, in particular for conceptual design.

4.2.2.1 Introduction to haptics

Haptics is a Greek word meaning "the science of touch". Haptics is the study of how to couple the human sense of touch with a computer-generated application [Smith 1997]. Haptic feedback can be further divided into two sub-fields, force (kinesthetic) feedback and tactile feedback.

Force feedback deals with the devices that interact with the muscles and tendons that give the human a sensation of a force being applied. These devices mainly consist of robotic manipulators that push back against a user with the forces which correspond to the environment that the virtual effector is in.

Tactile feedback deals with the devices that interact with the nerve endings in the skin which indicate heat, pressure, and texture. These devices typically are used to indicate whether or not the user is in contact with a virtual object.

4.2.2.2 Haptic interaction devices

Haptic interaction devices allow users to experience a sensation of touch and physical properties when they interact with virtual objects in a 3D digital environment. They exert force in response to a user's action, and they enable active two-way interaction with virtual objects, where action and perception are brought together.

Haptic interaction devices can be categorised in two distinct classes: impedance controlled devices and admittance controlled devices [Thurfjell, McLaughlin *et al* 2002]. The essential control paradigm of impedance controlled devices is as follows: the user moves the haptic device, and the device will react with a force if a virtual object is contacted.

One prime example of the impedance control paradigm was the SensAble's six degree-of-freedom (DOF) Phantom haptic device, as shown in Figure 31. The Phantom haptic device was a desktop haptic feedback system which provided single point, 3D force feedback to the user through a stylus attached to a moveable arm. The position of the stylus point was tracked, and a resistive force was applied to it when the device came "into contact" with the virtual model, providing accurate, ground-referenced force feedback. The physical working space was determined by the extent of the arm, and a number of different models were available to suit different application requirements.

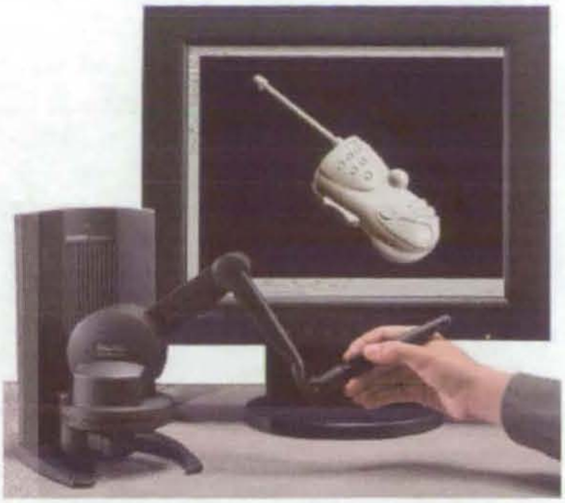


Figure 31: Impedance haptic device: The Phantom haptic device

Another impedance controlled device was the Delta haptic device from Force Dimension, as shown in Figure 32. The Delta's key design feature was a symmetric tripartite structure. Compared to the Phantom's serial kinematics, the Delta's parallel kinematics ensured lower inertia, which was a crucial element for rendering of realistic forces. High stiffness and higher forces could be applied to were other characteristics that followed from using the Delta device structure. The Delta haptic device had three translational DOF end effectors, but could be equipped with an extra three rotational DOF end effectors.

Figure 32: Impedance haptic device: The Delta haptic device

A French company called HAPTION also introduced its impedance controlled haptic interaction device named VIRTUOSE haptic devices, as shown in Figure 33. The VIRTUOSE haptic device provided six DOF force feedback with a large working volume and high torques. It was particularly suited for virtual object handling operations at a real scale during the engineering process, to simulate assembly, disassembling, or maintenance training.

Figure 33: Impedance haptic device: The Virtuose haptic device

Admittance control is the inverse of impedance control. In admittance control, the device first measures the force exerted by the user via a sensitive force sensor, then calculates the acceleration, velocity and displacement, which the object touched in virtual space would experience as a result of this force. Admittance control has been used for control sticks in the flight simulator field for many years. A recent example of a generic haptic device using the admittance control paradigm was the FCS HapticMaster device shown in Figure 34.

Figure 34: The FCS Haptic Master used in a gear shift simulator

All of the above haptic interaction devices provided at least a 3D haptic force (some of them even provide 3D torques). Because they normally worked in a two-way communication (both input and output) between the user and the computer, these haptic devices provided not only a force feedback interaction but also a direct 3D input mechanism.

There are other types of force feedback interaction devices commercially available in the world. Among them, glove-like force feedback devices are used commonly in some specific applications. Their main feature is the glove structure that wraps around the hand and fingers to support kinaesthetic sensors from the fingers and hand. The glove consists of resistors or air pockets distributed across the finger or the underside of the hand. Sequential inflation and deflation of the pockets convey virtual object feedback to the wearer.

Immersion Corporation (formerly Virtual Technologies, Inc.) [Immersion 2002] produced a family of products based around its CyberGlove, a tethered, instrumented glove that could sense the position and movement of the fingers and wrist. With the appropriate software, it could be used to interact with systems using hand gestures, and when combined with a tracking device to determine the hand's position in space, it could be used to manipulate virtual objects. The CyberTouch package provided a sense of tactile feedback through the addition of vibrotactile stimulators to the palm and fingers of the CyberGlove. These produced a buzzing vibration when the wearer came into contact with the virtual object. While not true tactile feedback, it could give the perception of touching an object. The CyberGrasp (as illustrated in Figure 35 (a)) was a full hand force-feedback exoskeletal device, which was worn over the CyberGlove. When the wearer made contact with a virtual object, a resistive force was exerted on the fingers through a series of tendons controlled by actuators, allowing them to feel the object. This force was hand-referenced: it could prevent the user from crushing a virtual object in their hand, but it could not prevent them pushing through a wall, nor allow them to feel weight, for example. This could be achieved through the CyberForce (as shown in Figure 35 (b)), a moveable, force-feedback arm on a fixed base which, when used with the GyberGrasp, provided the hand and arm with force-feedback relative to the ground.

(a) (b)

Figure 35: The CyberGrasp and CyberForce system

Another example of a glove-like force feedback device was the Rutgers Master II-New Design (ND) glove [Bourad, Popescu *et al* 2002], as shown in Figure 36. Research at the Rutgers Human-Machine Interface Lab was aimed at unifying the sensing and force feedback in a single glove. This resulted in the Rutgers Master

II prototype developed in the mid 1990s. This glove design was problematic since it had sensors placed at the fingertips, and exposed pneumatic tubes and wiring. The follow-up Rutgers Master II ND glove was then developed. However, this glove device was not commercially available on the market as it was still at the research stage in the laboratory of the State University of New Jersey in America.

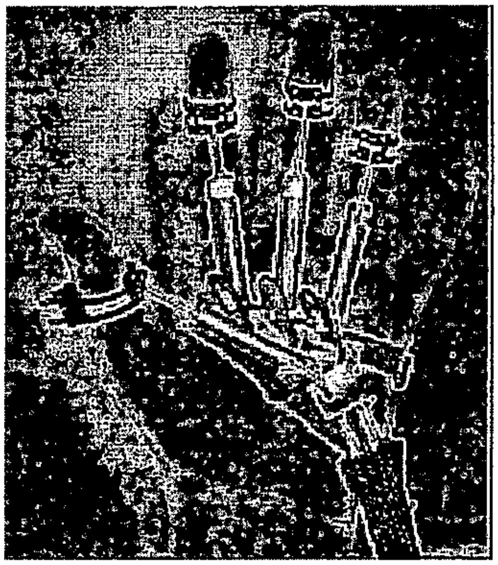


Figure 36: The Rutgers Master II-ND glove

4.2.2.3 Haptic interaction in CAD applications

Today there are already some commercial haptic application systems available on the market. Most of these application systems are accompanied by the widespread type of Phantom arm-like haptic devices which provide small resistive forces to users' index at a high bandwidth (see one example in Figure 31).

As mentioned in Section 3.6.6 of Chapter Three, the SensAble Technologies' FreeForm Modeling system [SensAble 2002] was one of the first commercial haptic interface-based CAD applications. By integrating a touch-enabled interface with a digital modelling tool, the FreeForm Modeling software provided industrial designers with familiar physical metaphors such as sculpting, wire cutting, clay shaping and deforming, which they have used for many years. Besides the

Figure 37: The Reachin Display system

Several years ago, SensAble Technologies created a joint project with Fakespace to develop a new modelling system which would provide designers not only the haptic force feedback through SensAble's Phantom devices but also 3D stereoscopic visions by Fakespace's MiniWorkBench displays. Figure 38 shows this concept system which was still under development. The eventual integration of haptics with 3D displays would introduce a new technology which enabled users to not only see their 3D data as if they were floating physically in front of them, but also feel and interact with them in the same way. Unfortunately, this system was not commercially released due to its complex infrastructure and several unsolved technological problems.

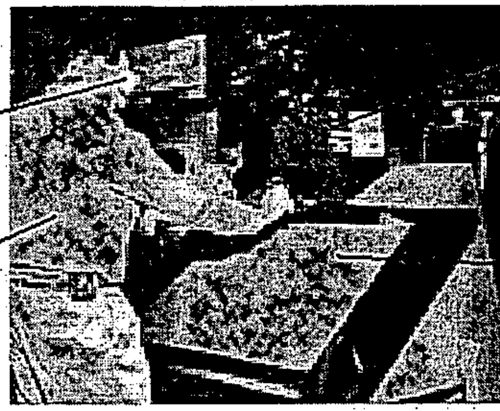


Figure 38: A new system combining haptics with stereoscopic display

Besides the above haptic application systems, there are other haptic interface research projects in the world. McDonnell *et al* [2001] presented Virtual Clay, a real-time sculpting system with a natural interface for direct haptic deformation. Dachille *et al* [1999] developed a haptic interface that permitted direct manipulation of dynamic surfaces. Balakrishnan *et al* [1999] developed ShapeTape, a non-uniform rational B-splines (NURBS) curve and surface manipulation technique that could sense bending and twisting motions with a haptic feedback interface. All of these application systems employed the Phantom haptic devices to provide haptic interfaces in their specific design processes.

4.2.2.4 Benefits of haptic interaction in CAD applications

In the evolution trends of CAD techniques, one of the main issues concerns the interaction between the designer and the computer [Massie 1998]. New emerging technologies create new interaction paradigms which overcome the drawbacks from conventional interfaces like a 2D mouse and keyboard with the complex skill and knowledge needed. Haptic technology brings out one attractive solution to providing designers with more natural and intuitive UIs to support their design activities when it is used in conjunction with a 3D visual display. In such a case, designers could not only view the design content in 3D immediately, but also touch and feel the design result directly. Furthermore, haptics provides many benefits to designers for interacting with models in a 3D digital environment.

Massie [*ibid*] provided a comprehensive summary of the advantages of haptics in the CAD process which is presented here:

- Haptic interaction provides feedback to help to position objects accurately in 3D space.
- Haptic interaction resolves visual ambiguities by letting designers feel the models.
- Haptic interaction communicates the physical properties of objects.
- Haptic interaction lets designers naturally and continuously manipulate models.

For these reasons, 3D CAD packages that incorporate even limited haptic interaction should have many benefits over traditional CAD software. More importantly, incorporating haptic interaction into model generation programs will let designers work more creatively by taking advantage of their existing skills and experience in manipulating objects in the real world.

4.2.3 Stereoscopic display

4.2.3.1 Introduction to stereoscopic display

One of the most amazing properties of the human vision system is its ability to perceive the depth of the scene being viewed. Humans see different images of the world with each eye because of a separable binocular depth sense. A stereoscopic display is an optical system whose final component is the human brain. It is the ability of the brain to process these two separate images together to generate a single 3D stereoscopic view that contains embedded information about depth and an improved resolution of detail [StereoGraphics 1997]. In much literature, a stereoscopic display interface is also termed as a 3D visual output channel.

Stereoscopic displays are distinctly different from conventional 2D displays because they can only truly be appreciated with both eyes open. If one eye is closed when looking at a stereoscopic image it will simply be like looking at an ordinary 2D computer-generated image.

4.2.3.2 Hardware and software in stereoscopic display

In order to view computer-generated images in a stereoscopic display mode, users must have both software application components that are capable of presenting two alternating images and hardware devices that can support this specific function. The necessary hardware devices include a computer with a stereo-support graphics card and stereo-ready screen monitor capable of providing a sync signal and stereoscopic visualisation eyewear, such as the StereoGraphics' StereoEyes liquid crystal shuttering eyewear or the MacNaughton's NuVision 60GX stereoscopic wireless glasses. The combination of these components allows users to take advantage of the benefit of viewing computer-generated images in a 3D environment.

New personal computer (PC) graphics cards which include built-in support for stereoscopic buffering, along with a standardised OpenGL interface to those cards' stereo-support features, now make them easier than ever to add stereoscopic display support to PC Windows-based applications. StereoGraphics Corporation [StereoGraphics 2002] provided many recommendations for selecting suitable graphics cards and screen monitors on which the stereoscopic display could be performed.

The stereoscopic software development kits (SDKs) from different vendors provided rich software development support tools in stereoscopic display applications. Sometimes even demonstration sample programming codes were available to users for quick code programming reference.

4.2.3.3 Benefits of stereoscopic display in CAD applications

Unlike 2D technologies, which attempt to display depth and perspective cue in a flat 2D environment, stereoscopic displays provide users with a more realistic 3D visual perception. Due to this fact it has already found many applications in engineering, architectural, scientific, entertainment and industrial fields. Stereoscopic display systems were already designed for 3D visualisation, remote control vehicles and tele-manipulators, 3D CAD applications, computational chemistry, biological microscopic investigations and air traffic control training and simulations [Edirisinghe and Jiang 2000].

Because it mimics the normal way that people view the nature world in three dimensions, stereoscopic visualisation can be much easier to interpret than 2D images that are normally displayed on computer monitors. From the design point of view, stereoscopic displays can enhance visual understanding of complicated on-screen digital objects. A design system which uses a stereoscopic display interface can deliver the ability to reduce errors in the design process, support design reviews in a 3D virtual environment and thereafter accelerate the time-to-market realisation.

The success or failure of a stereoscopic display system design largely depends on the visual comfort it provides to the user for long duration viewing of high quality stereo images. Thus, the human factor issue is an important part in the design of modern and future stereoscopic display applications.

4.2.4 Sound feedback

4.2.4.1 Introduction to sound feedback

People have visual, tactile, auditory and other sensorial modalities to interact with the physical world. As discussed earlier (see Table 1 in Chapter Three), the voice input method exhibited several fundamental weaknesses. Thus, this research focuses mainly on the sound feedback interaction rather than the voice input method. Sound output or auditory feedback technology plays an important role in increasing the simulation realism by complementing the visual feedback provided by graphics displays. Prior to the haptic feedback interaction introduced in the earlier section, the visual display tends to dominate the human computer interaction to convey information between users and computers. In this case, one might prompt such a question: Why not use touch and sound to provide feedback to other senses and so take the load off the eyes in the design process? Therefore, it is clear that the sound feedback interface could add another information channel to designers to increase their interactive quality in the design process.

4.2.4.2 Hardware and software in sound feedback interface

Today, advancements in multimedia technologies have made creating complex digital sounds common-place. Most desktop computers are equipped with audio input/output facilities as part of a standard configuration. Computer-supported speaker-based auditory systems can even be bought off the shelf in most computer hardware shops. There is no additional hardware needed in order to put the sound feedback interface into any application.

The Microsoft Speech SDK from Microsoft Corp. provided rich software development support tools in sound output applications. This shareware software SDK could be downloaded from Microsoft homepage freely through an internet connection service.

4.2.4.3 Benefits of sound feedback in CAD applications

Sound feedback has the advantage of being a channel of communication that can be processed in parallel with visual information. The most apparent use in CAD was to provide auditory feedback to users about their actions during the design process. Furthermore, 3D sounds, in which the different sounds would appear to come from separate locations, could be used to provide a more realistic VR experience.

In addition, the sound feedback interaction expands the information exchange between the designer and the virtual model, since designers gain the sound feedback directly during the design process. Moreover, the design process associated with sound feedback can give more feedback than that in the conventional CAD design process.

4.2.5 3D input and 3D output

In order to make the proposed conceptual design system easy and straightforward to use in a 3D environment and to provide a 3D sketching design function, 3D input and 3D output facilities would be needed to support the realisation of these demands. As discussed earlier, the stereoscopic display interface could act as a 3D visual output channel. While their main task was to provide force feedback interaction, most haptic interaction devices could support a 3D input mechanism because they normally worked in a bi-direction mode in their functions. Therefore, a combination of a haptic interaction interface and a stereoscopic display interface could provide a solution to the 3D input and 3D output requirements in the proposed conceptual design system.

4.2.6 Design functions

The main designers' requirements for design functions included 3D sketching design and free and fast freeform shape creation. The 3D sketching design function could be achieved in the proposed conceptual design system by the support of 3D input and 3D output devices. The emerging freeform feature-based design technologies could provide a practical solution to the freeform shape creation in the proposed conceptual design system. Other design functions such as traditional 2D paper-based sketching tools could be added so as to enrich the design functions in the proposed conceptual design system. Therefore, a level of design functionality could be defined to perform a certain extent of conceptual design work that could take full use of the 3D input and output devices in the proposed conceptual design system.

4.2.7 CAD data transfer

It was supposed that the proposed conceptual design system to be developed was not a fully-functional design system that would rival commercial CAD systems available on the market. Therefore, it was important to consider the CAD data exchange aspect in order to provide software connection facilities with other commercial CAD systems. The proposed conceptual design system could be treated as a part of the design programme used for providing a practical total solution to the whole product design and development process.

4.3 Summary

The findings from case studies have led to a better understanding that conventional CAD systems have not provided good interaction tools for the design process especially at the conceptual design stage. For a conceptual design application, the productivity bottleneck lies with users' abilities to communicate with the computer rather than with the computer's limitations. Whilst good and useful developments in the usability and effectiveness of 3D CAD systems have taken place rapidly over the last two decades, the interface between the user and the computer is almost always constrained to a keyboard/mouse and 2D visual display. In this chapter, the main designers' requirements, identified through human factor analysis of case studies, had been translated into ideal system characteristics of a new conceptual design system to be developed. This covered several new VR-based user interfaces (two-handed operation, haptic interaction, stereoscopic display and sound feedback), a level of design functionality and a CAD model data transfer issue. The next stage of the project was to define such a conceptual design system which would meet all the designers' requirements identified above.

CHAPTER FIVE

Developing a new conceptual design system: Applying VR-based interaction techniques to CAD applications

The main designers' requirements for the next generation of computer aided design (CAD) systems were defined in Chapter Four. These indicated the necessity of improving the interactive capabilities between designers and CAD systems by using more natural, familiar interaction mechanisms instead of traditional paradigms such as the mouse/keyboard and two dimensional (2D) display method. A new desktop non-immersive conceptual design system called the Loughborough University Conceptual Interactive Design (LUCID) system is introduced in this chapter that attempts to overcome the human computer interface (HCI) limitations prevailing in most CAD systems and to match as closely as possible the system characteristics developed in the previous chapter.

5.1 Components of the LUCID system

In order to define the configuration of the LUCID system to be developed to meet the system characteristics identified in Chapter Four, it was necessary to determine what various components of the system should be. Once again, a quality function deployment matrix approach was used (see Figure 39). This time, the system characteristics from the matrix in Figure 28 were used to generate solutions to possible system components. The system characteristics are now listed down the left-hand side of the matrix and components of the LUCID system are listed along the top. The correlations between characteristics and components are shown by crosses entered in the matrix. The system components were selected on the basis of knowledge gained about interaction techniques, VR technologies and geometric modelling as reported in previous chapters. Justification for the choice of components and a detailed description of how they work are now given.

System characteristics		System components												
		Non-immersive desktop system	SpaceMouse device	Phantom haptic device	NuVision GX60 stereoscopic toolkit	Speaker-based auditory system	GHOST SDK	3DWare SDK	OpenGL API	Microsoft Speech SDK	3D freehand sketching design	Freeform feature-based design	STL file format	VRML file format
	Two-handed operation	x	x	x			x	x						
	Haptic interaction	x		x			x							
	Stereoscopic display	x			x				x					
	Sound feedback	x				x				x				
	3D input and 3D output	x		x	x		x		x		x			
	Design functions	x									x	x		
	CAD data transfer	x											x	x

Figure 39: Correlation matrix between system characteristics and system components

As discussed before (see Table 1 in Chapter Three), a fully immersive design system tended to make the system infrastructure more complex, cause uncomfortable intrusive viewing problems and make the system much too expensive. Therefore, it was decided that the LUCID system should be a non-immersive desktop system and it would not employ any fully immersive equipment (such as HMD, BOOM or CAVE) in its construction. Another reason for this choice was that it would allow the design system to be more portable since desktop computers are abundant in both academia and industry. Therefore, the LUCID system would be developed on a high performance desktop computer. The LUCID system would consist of a variety of hardware devices and software components. There were several important issues to resolve when developing such an integrated VR based conceptual design system. The hardware devices should be carefully selected based upon their performance characteristics, ease of integration and flexibility for future enhancements. The software infrastructure would require a modular design, efficient cooperation between its elements and performance optimisation. More importantly, all these hardware devices and software components should cooperate well in an integrated synchronised environment to match the defined requirements as closely as possible.

In order to select the specific hardware devices and software components to enable the LUCID system to meet the above requirements, a detailed study was carried out including i) visiting the world-wide-web (WWW) homepages of different companies who could provide the components which the LUCID system might need, ii) directly contacting the vendors respectively for detailed technical specifications and product quotations, iii) collecting end-user feedback on their experience and lessons using the same components which might be employed in the LUCID system and iv) arranging evaluation opportunities with relevant hardware devices and software components as much as possible. A description of each component that would be used in the LUCID system is given in the following sub-sections.

5.1.1 Hardware specification

After a comprehensive comparison based upon the information collected, several VR-based interactive hardware devices were selected to construct the LUCID system hardware architecture. The list below describes the hardware components that would be employed in the LUCID system.

- A desktop computer with an Intel Pentium® 4 3.0 Giga hertz (GHz) central processing unit (CPU), 512 Megabytes high-speed memory, an integrated audio subsystem, a 3DLabs WildCat VP760 stereoscopic support graphics card, and a stereoscopic-ready displaying monitor.
- A six degree of freedom (DOF) SpaceMouse Classic device from 3Dconnexion, a Logitech Company.
- A three dimensional (3D) Phantom Desktop haptic feedback device from SensAble Technologies, Inc.

- A NuVision GX60 stereoscopic wireless liquid crystal display (LCD) glasses toolkit from MacNaughton, Inc.
- A universal computer-supported speaker-based auditory system.

The overall framework of the LUCID system to be developed is shown in Figure 40.

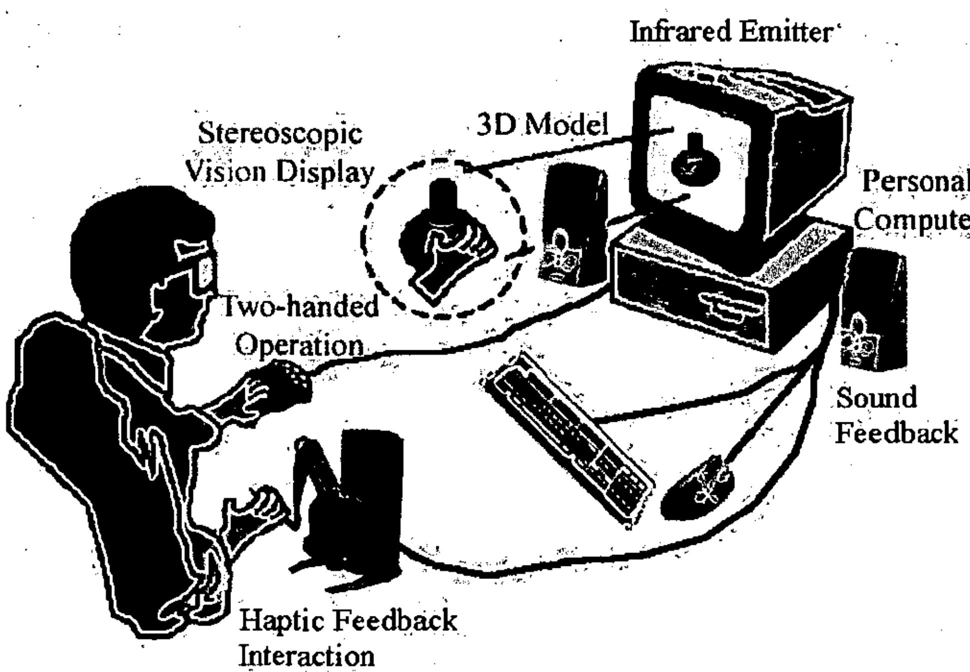


Figure 40: Framework of the LUCID system

5.1.2 Overview of selected hardware devices

5.1.2.1 SpaceMouse device

The SpaceMouse device is a six DOF input device that is used to directly control the position and orientation of graphical objects in a 3D virtual space. It controls three translational degrees of freedom (X, Y and Z) and three rotational degrees of freedom (A, B and C), as shown in Figure 41. The main component of the SpaceMouse device is a sensorised cylinder that measures three forces and three torques applied by the user's hand on a compliant element. Forces and torques are measured indirectly based upon the spring deformation law and then sent to a host computer over an RS232 serial cable. The input data information is processed by software tools to return a differential change in the controlled object position and orientation in most applications. Several pushbuttons are integrated with the SpaceMouse device support base, within the reach of the user's fingers. These pushbuttons work in a binary on/off method and can be pre-defined and pre-programmed by users according to the specific need of any application. However, the SpaceMouse device is not very easy to use for object selection and manipulation of object parameters due to its original function being defined as a 3D manipulation tool rather than a selection tool.

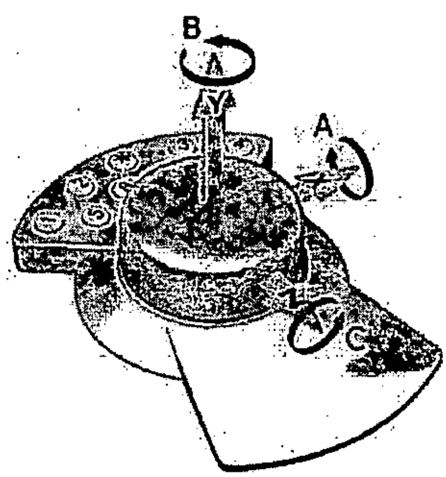


Figure 41: The six DOF SpaceMouse device

Compared to data gloves which exhibited poor recognition rates, needed gesture language definition and had complex structures for two-handed operation, the SpaceMouse device was quite easy and stable to use when a suitable force was applied to it. The small amount of movement was generally liked by users since it gave a sense of proprioceptive feedback. Therefore, it was decided that the SpaceMouse device should be selected to facilitate a two-handed interface in the LUCID system.

5.1.2.2 Phantom Desktop haptic device

The Phantom Desktop haptic device is a compact desktop-based device which has a serial feedback arm that ends with a stylus, as shown in Figure 42. Of the six degrees of freedom of the arm, three are active, providing translational force feedback (so called as a 3D force feedback device). The stylus orientation is passive, so no torques can be applied to the user's hand.

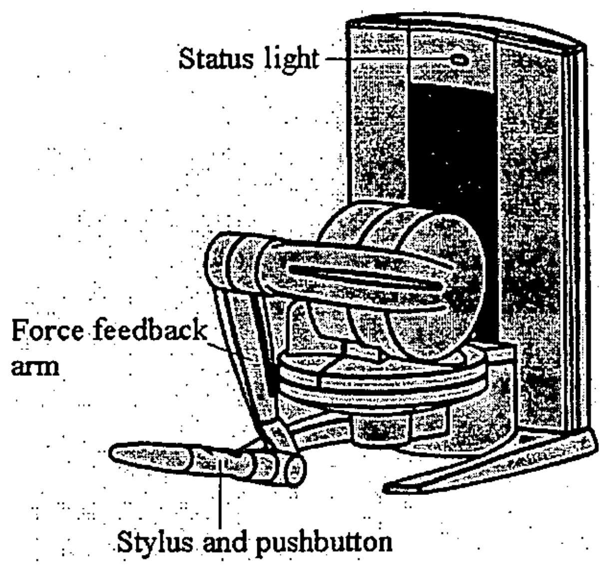


Figure 42: The Phantom Desktop haptic device

Since there was only one pushbutton on the stylus, it was very difficult to fully simulate the operation of a standard mouse (with two or three pushbuttons) when the Phantom Desktop haptic device was working in the "Phantom-Mouse" mode in most haptic applications. In addition, the Phantom Desktop device's inability to feed back torques limited the type of applications it could be used for. Besides, shoulder strain was induced by the Phantom Desktop haptic device on an unsupported arm over a long period of continuous use. Nevertheless, other types of haptic device suffer from several severe drawbacks such as fewer successful applications and high cost. With more than 1500 Phantom haptic devices in use, the Phantom Desktop haptic device has become today's *de facto* standard haptic device to create haptic interaction interfaces in most haptic-based applications. Due to this overriding reason, the Phantom Desktop haptic device was selected to provide a haptic interaction interface, to facilitate two-handed operation and to support 3D input within the LUCID system.

5.1.2.3 NuVision GX60 stereoscopic display toolkit

The NuVision GX60 stereoscopic display toolkit consists of a pair of wireless stereoscopic LCD glasses and an infrared emitter with a cable connection to a host computer, as shown in Figure 43. The NuVision 60GX stereoscopic wireless LCD toolkit makes it practical to include stereoscopic visualisation in economical desktop applications. Designed for comfort and convenience in most applications, the pair of lightweight glasses could be worn for an extended period without causing uncomfortable eyestrain. Viewing quality is preserved consistently over the entire display with stereoscopic images that are clear, crisp and flicker-free at a refresh speed of 120 hertz (Hz) or more.

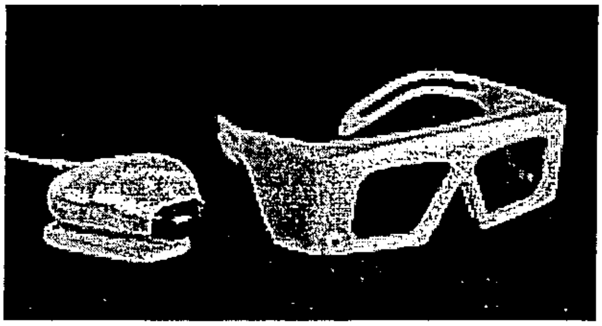


Figure 43: The NuVision GX60 stereoscopic display toolkit

The NuVision wireless stereoscopic LCD glasses were fully compatible with all of today's stereo-ready personal computers (PCs) and software. However, compared to auto-stereoscopic displays available for both laptop and desktop computers on the market, the NuVision GX60 stereoscopic display toolkit showed its disadvantage in that users had to wear vision apparatus to view the stereoscopic images on flat panel displays. But auto-stereoscopic displays suffered from several severe drawbacks such as lower resolution and high cost. As a result, its simple structure and low price made the NuVision GX60 stereoscopic display toolkit ideal for an economical desktop application. Therefore, the NuVision GX60 stereoscopic display toolkit was chosen to construct a stereoscopic display interface and to provide 3D visual output in the LUCID system.

5.1.2.4 Auditory system

As stated earlier, most of today's computers are equipped with audio input/output facilities as part of a standard configuration. Their cheap price and very simple implementation make computer-supported speaker-based auditory systems a commonly used item in sound-related applications. Therefore, it was decided that a universal computer-supported speaker-based auditory system should be selected to create a sound feedback interface in the LUCID system.

5.1.3 Software components

The first step for the LUCID system software design was to choose a suitable developing programming language. Considerations included data portability, data interchange and software development kit (SDK) tool support. Microsoft Visual C++ Version 6.0 was chosen as the programming language because Microsoft Visual C++ is the standard development environment for most popular Windows-based applications. It is easy to port data from various systems into the application by using the Microsoft Foundation Class (MFC) library provided by Microsoft Visual C++ Version 6.0. Besides, Microsoft Visual C++ Version 6.0 has been proved as the most stable and mature software development platform for Windows-based applications. Furthermore, both the General Haptic Open Software Toolkit (GHOST) SDK for haptic rendering and the 3DxWare® SDK for SpaceMouse manipulation have themselves been developed under the Microsoft Visual C++ Version 6.0 environment. This advantage greatly helped to integrate the software supporting tools seamlessly into the LUCID system development and implementation. The following is a list of the software packages that would be used in the LUCID system design and development.

- Microsoft Windows 2000 Professional from Microsoft Corp.
- Microsoft Visual C++ Version 6.0 from Microsoft Corp.
- GHOST SDK Version 4.0 for Windows from SensAble Technologies, Inc.
- 3DxWare® SDK Version 1.1 for Windows from 3Dconnexion Corp.
- Open source Graphics Language (OpenGL) application programming interface.
- Microsoft Speech SDK Version 5.1 from Microsoft Corp.

5.1.4 Overview of application software components

5.1.4.1 GHOST SDK

GHOST SDK from SensAble Technologies was the first commercial haptics application programming interface (API) that was designed for the development of applications using the Phantom haptic devices. GHOST SDK was a C++ software toolkit that supported the task of developing touch-enabled applications. It worked as a haptics engine which took care of complex computations for haptic rendering and allowed application developers to deal with simple, high-level objects and physical properties like location, mass, friction and hardness. However, GHOST SDK was solely used for haptic rendering and it did not support stereoscopic graphics rendering. Hence, application developers must use another software toolkit for graphics rendering, for example, a commercial graphics API such as OpenInventor and Direct3D. Therefore, it was left to application developers to handle the complex task of synchronising the graphic and haptic rendering of the designed object. Nevertheless, GHOST SDK was the most widespread haptic API used together with the Phantom haptic devices in haptic-based applications. Since the Phantom Desktop haptic device was selected as the haptic hardware, the GHOST SDK programme was chosen as the software supporting toolkit to support the haptic interaction interface, two-handed operation and 3D input within the LUCID system.

5.1.4.2 3DxWare® SDK

3DxWare® SDK from 3Dconnexion Corp. provided a single interface to the 3DxWare® driver software that gave an application software access to a six DOF input device such as a SpaceMouse or a SpaceBall. It was normally made available along with the SpaceMouse device. 3DxWare® SDK provided application developers with very detailed materials including

- 3DxWare® libraries, including the 3DxWare® input library and the 3DxWare® math library.
- All the files required to integrate with the 3DxWare® libraries.
- Installation for the libraries, documentation, demonstrations, and source codes.
- Full documentation explaining how to build and use the 3DxWare® libraries and demonstrations.

Therefore, 3DxWare® SDK was used to support the SpaceMouse device operation so as to create a two-handed interface in the LUCID system.

5.1.4.3 OpenGL API

OpenGL was a cross-platform standard for 3D graphics rendering and 3D hardware acceleration. This software runtime library worked with all Windows, MacOS, Linux and Unix systems. In other words, OpenGL was regarded as a software interface to graphics hardware. As a 3D graphics and modelling library, OpenGL was easily portable for coding and very fast for running. Using OpenGL, a system could not only create elegant and high quality 3D graphics, but also support real-time stereoscopic graphics rendering. Therefore, it was decided that OpenGL API should be chosen as the software toolkit to support the creation of a stereoscopic display interface and to support a 3D output function within the LUCID system.

5.1.4.4 Microsoft Speech SDK

Microsoft Speech SDK was a voice-based software development toolkit used for any Microsoft Windows-based application. Tools, information, and sample engines and applications were provided to help application developers to integrate and optimise voice recognition and voice synthesis engines using Microsoft Speech API. Microsoft Speech SDK also included updated releases of the Microsoft advanced speech recognition engine and Microsoft concatenated speech synthesis engine. Since the LUCID system would be developed under the

Microsoft Visual C++ Version 6.0 platform, the sound feedback function could be easily implemented and integrated in the system through the aid of Microsoft Speech SDK. For these reasons, Microsoft Speech SDK was selected to support the creation of a sound feedback interface in the LUCID system.

5.1.5 Design function configuration

In order to support the design functions specified in the previous chapter, the LUCID system needed to provide several useful design tools to perform a limited extent of conceptual design work. A 3D freehand sketching tool would be required to provide a true 3D design capability in the LUCID system. Other traditional 2D paper-based sketching functions would also be needed in the LUCID system. More importantly, the LUCID system would need to support 3D freeform surface creation functions employing freeform feature-based design technologies. Several freeform feature-based design functions such as the sculpting feature, the sweeping feature, the lofting feature and the blending feature would have to be defined and developed in the LUCID system. Implementation of these freeform feature-based design functions in the LUCID system would provide designers with enhanced functional tools for their design activities, in particularly for the free and fast freeform shape creation.

5.1.6 Model data formats

It was recognised that the LUCID system defined in this chapter would not be implemented as a fully-functional design system. Rather, there was a need for combining the LUCID system with other design systems so as to provide a practical total solution package for the whole product design and development process. In order to enable the model designed conceptually in the LUCID system to be shared seamlessly in most downstream CAD and CAM applications such as embodiment design, detail design and manufacturing planning, the LUCID system needed to provide certain CAD model data transfer facilities. Therefore, the LUCID system should consider this critical issue within its design and development.

5.1.6.1 Introduction to CAD data exchange

It is common knowledge that the primary cause of the CAD model data-sharing problem between two or more CAD systems is model data incompatibility. This is due to the fact that vendors of different CAD applications design different proprietary formats to store the model data required and produced by their own CAD systems. In order to solve this model data-sharing problem, many international standards, for example, the Initial Graphics Exchange Specification (IGES) and the Standard for the Exchange of Product Model data (STEP), have been developed for CAD model data representation. For the purpose of CAD model data sharing, various CAD systems could output their CAD model data using the same file format (called a neutral data exchange format) based upon one of the above international standards. Another way to tackle the CAD model data-sharing problem is to use direct data translation software.

Although they have already supported other CAD model data importing/exporting functions (for example, the StereoLithography (STL) file format to drive many RP machines), most commercial CAD systems available on the market often tend to define their own file formats to store their CAD model data, for example, the data exchange format (DXF) for the AutoCAD software and the 3DS file format for the 3D Studio MAX program.

5.1.6.2 STL file format

The STL file format was introduced for CAD software applications by 3D Systems in 1987 for moving 3D CAD models to its StereoLithography Apparatus (SLA). An STL file represents an object's 3D geometry by storing a set number of facets or 3D triangles. Each facet in an STL file is defined by the three points that make up the 3D facet and also the normal to the facet. The normal to the facet is redundant because the normal can actually be calculated from the three points that define the facet. This redundancy is a potential problem, because the large size of an STL file can be prohibitive. There are two types of STL file formats that are commonly used: the American standard code for information interchange (ASCII) format and the binary format. An ASCII STL file has one advantage in that it is easy to read with most text editors. This makes it easier to spot errors in the STL file, and the file can be used with computer applications that do not read a binary STL file. A binary STL file is more compact and faster for a computer to read. When an STL file is transferred over a network, a binary STL file is mostly used because of the smaller file size. Despite its smaller size, a binary STL file has a null space of two bytes for every facet which has no defined use. In the future, however, the null space may be used for something, like defining the facet's properties such as its colour or material.

The STL file format has become the *de facto* standard data format for most RP machines that produce 3D physical models directly from CAD systems. Some CAD systems (such as Pro/Engineer, AutoCAD and IDEAS) adopt the STL file format as a general import/export option. However, some CAD systems still do not directly support the STL file format, and conversion utilities must be used to transform the 3D models to the STL format. Conversion of other file formats into STL file formats, however, sometimes causes loss or distortion of information, making the STL file useless or difficult to read. One basic problem with STL file conversion is that the STL file format is facet-based, and this is very inefficient for storing some types of 3D models. Many CAD software systems store 3D information as 3D primitives in the form of cubes, cylinders, spheres, cones, or spline surfaces. To produce an STL file, the cubes, cylinders, spheres, cones, or spline surfaces must be converted into 3D facets. This conversion usually creates a much larger data file with less accuracy than the original 3D model data. Therefore, the STL file format does have some disadvantages, yet it is still an overall benefit for the RP industry. It was decided that the STL file format should be chosen as one of the supported CAD data file formats in order to create a design environment in which the designed object could also be manufactured directly using RP technologies.

5.1.6.3 Virtual Reality Modeling Language

The Virtual Reality Modeling Language (VRML) is an international standard for a file format used to describe interactive 3D objects [Carey, Bell *et al* 1997]. The VRML file format is designed to be used on the internet, intranets and local client systems. It is also intended to be a universal data interchange format for integrated

3D graphics and multimedia information. It may be used in a variety of application areas such as engineering and scientific visualisation, multimedia presentations, web pages, and shared virtual worlds.

Since the VRML file format is capable of representing both static and animated dynamic 3D and multimedia objects with hyperlinks to other media such as text, sounds, movies and images, VRML browsers, as well as authoring tools for the creation of VRML files, are widely used on many different platforms. The VRML file format supports an extensibility model that allows new dynamic 3D objects to be defined allowing application communities to develop interoperable extensions to the base standard [*ibid*]. In short, the VRML file format is widely supported by most applications employing VR technologies. For these reasons, it was decided that the VRML file format should also be chosen as one of the supported CAD data formats in the LUCID system so as to provide a solution to sharing CAD model data information freely and easily with other VR-based CAD applications.

5.2 Implementation of the LUCID system

The previous section described the configuration of the proposed LUCID system which was created from the specifications developed in Chapter Four. The main focus of the system development was to be on CAD HCIs rather than on design functions. The next task was to implement the LUCID system incorporating as many as possible of the components defined in the above section. As mentioned earlier, it was not the aim of this implementation to create a fully functional design system that would rival commercial CAD systems available on the market. Such a system would require an extensive amount of development work that was beyond the scope of this project. However, it was necessary to develop a level of design functionality that would adequately illustrate how the new VR-based HCIs could be used and the benefits they would yield when used for conceptual design.

Initially, the LUCID system consisted of four main HCI hardware components: a six DOF SpaceMouse Classic device for the two-handed operation interface, a 3D Phantom Desktop force feedback device for the haptic interaction interface (also for the two-handed operation interface and the 3D input method), a NuVision GX60 stereoscopic wireless LCD glasses toolkit for the stereoscopic display interface (the 3D visual output channel), and a universal computer-supported speaker-based auditory system for the sound feedback interface. The overall interface architecture of the LUCID system is illustrated in Figure 44. With its interface integration and implementation, the LUCID system would allow industrial designers to experience 3D force feedback from the Phantom Desktop haptic device via their dominant hand, and to navigate the virtual model easily and freely through the six DOF SpaceMouse device operated by their subdominant hand. At the same time, the stereoscopic display would allow designers to utilise a more realistic 3D space for their design efforts and the sound feedback would give designers useful notification on which design actions were being performed. All these components were to be handled by different processes running on the high performance desktop computer with a stereoscopic support graphics card and a stereoscopic-ready monitor.

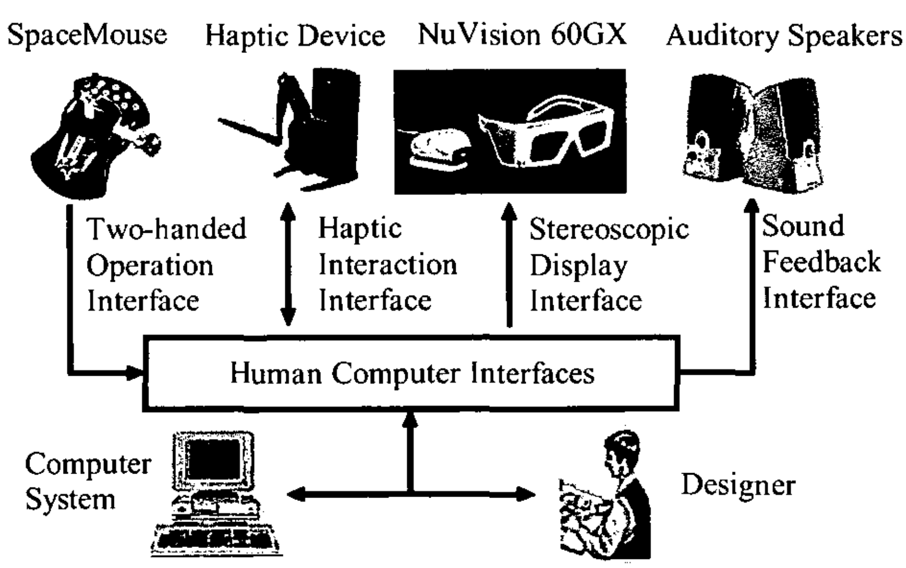


Figure 44: Interface architecture of the LUCID system

5.3 Summary

In this chapter, a new VR-based desktop non-immersive conceptual design system – the LUCID system has been designed to satisfy the characteristics laid down by the specifications described in Chapter Four. Detailed descriptions of the selected hardware devices, software components, design function configuration and CAD model data formats have been presented. A description of the overall system interface architecture has also been provided. The next three chapters discuss in detail the three main aspects of the LUCID system, i.e. human computer interface design, geometric modelling method and algorithm design and design functionality and model data exchange design.

CHAPTER SIX

Human computer interface design

In Chapter Five, the LUCID system components were defined based upon the system characteristics derived from the designers' requirements which were gained from case studies. This chapter describes the LUCID system graphical user interface design and its four new VR-based human computer interface (HCI) integration and implementation.

6.1 Graphical user interface design

Since designers are familiar with Windows-based graphical user interfaces through their daily computer operations, and other "innovative" graphical user interfaces require designers to master extra knowledge in order to use them correctly (for example, designers must learn the gesture-based language and its commands in order to use a hand glove-based interface), it was decided that the LUCID system should use the standard graphical interface layout which was employed in most popular Windows-based software applications. The graphical user interface of the LUCID system was divided into several functional areas comprising the sketching toolbar displayed on the left-hand side of the screen, the general menu bar and the useful functional toggle button toolbar displayed along the top, the freeform feature creation toolbar displayed on the right-hand side, the system status bar displayed along the bottom, the design history tree display area located in the left window and the design content display area located in the right window, as shown in Figure 45. The whole framework of the LUCID system was developed based upon the Microsoft Visual C++ Version 6.0 platform using the MFC application library and the OpenGL API on a high performance desktop computer running Windows 2000 Professional.

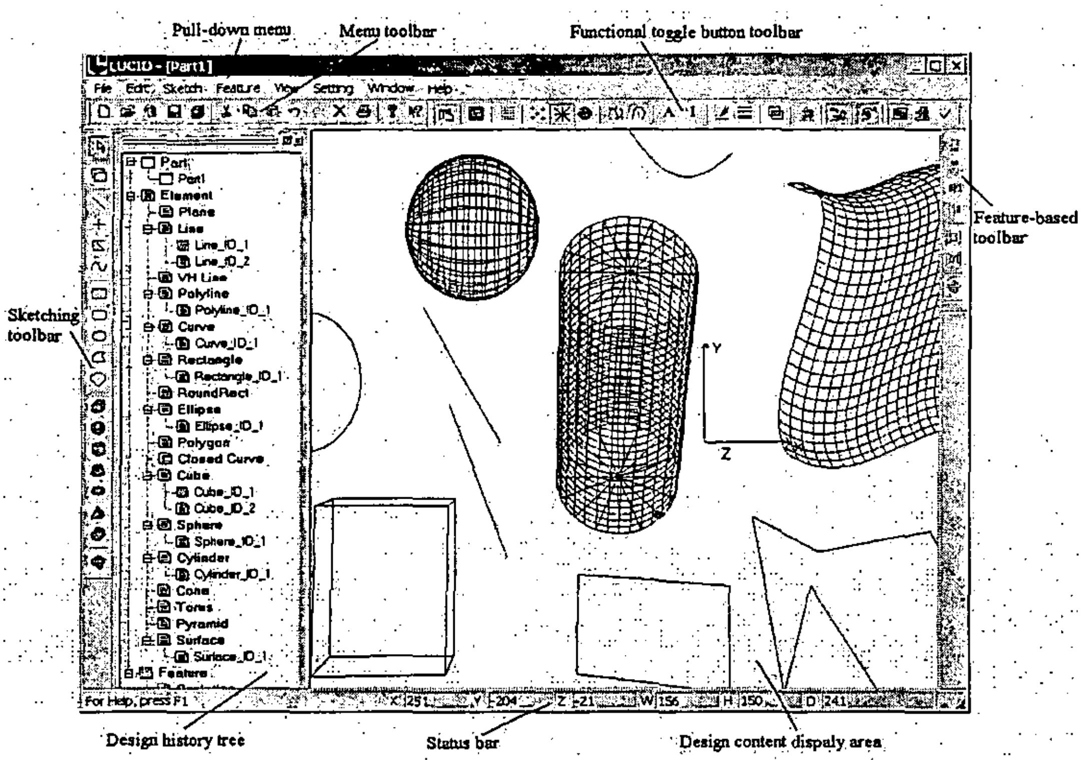


Figure 45: Graphical user interface of the LUCID system

When the LUCID system is started up, the main window opens on the desktop computer. All model designs are created in this window. The several distinct elements of the window are:

- *Pull-down menus*

  The pull-down menus in the LUCID system include the following items:

  File – Contains commands for manipulating files.

  Edit – Contains edit action commands.

  Sketch – Contains all sketching functions available.

  Feature – Contains all feature design functions available.

  View – Contains commands of toolbar viewing and model viewing.

  Setting – Contains commands of system and model configuration setting.

  Windows – Contains commands for managing various windows.

Help – Contains commands for accessing online help documentation.

- *Toolbars*

  The toolbars in the LUCID system contain icons for frequently used options from the pull-down menus, icons for functional toggle buttons, icons for sketching functions and icons for feature-based design functions (see Figure 45).

- *Display areas*

  Models created in the LUCID system are displayed in the design content window on the right side of the screen, and the design history tree is shown in the history tree display window on the left side of the screen (see Figure 45).

- *Status area*

  The status area of the LUCID system illustrates the information of the current designed model such as the width, height and depth of the model on the bottom of the screen (see Figure 45).

6.2 Two-handed operation interface: Integration and implementation

In the LUCID system, a two-handed operation interface was implemented using a six DOF SpaceMouse device together with a 3D Phantom Desktop haptic device. The two-handed operation interface works in the following way: Designers can navigate the onscreen model via the six DOF SpaceMouse manipulation using their subdominant hand and, at the same time, they can perform functional operations on the model through the 3D Phantom Desktop haptic device using their dominant hand. Two-handed interaction provides industrial designers with a more natural interaction method, which is very similar to the working style that uses both hands in their everyday tasks. In addition, two-handed operation makes the design work more efficient since both hands are involved in the design process instead of only one hand as in the past. Furthermore, two-handed operation makes the design work more flexible since different design tasks are done by different hands.

The integration of a six DOF SpaceMouse device operation into a CAD application was aimed at providing designers with an intuitive and familiar way to translate, rotate and zoom 3D models freely and easily within a 3D design environment. The software process procedure of the SpaceMouse input operation, developed with the aid of the 3DxWare® SDK, is shown in Figure 46.

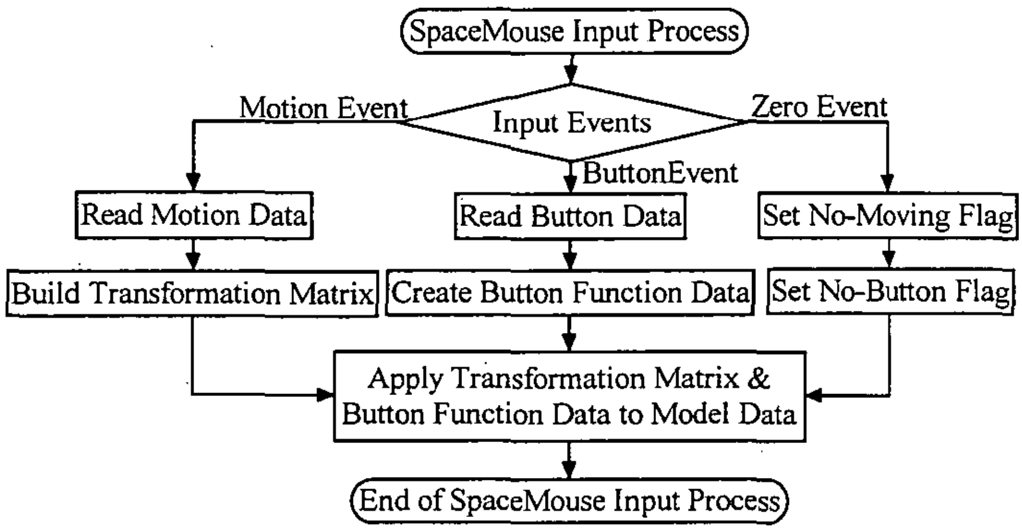


Figure 46: Flow diagram of the SpaceMouse input process

The six DOF SpaceMouse input interface works in the following ways to support the design process:

- Shift the SpaceMouse cap to different axis directions to move the onscreen designed object through space in the X, Y, Z directions, as shown in Figure 47.
- Rotate the SpaceMouse cap around the desired axis to rotate the onscreen designed object in the A, B, C directions, as shown in Figure 47.

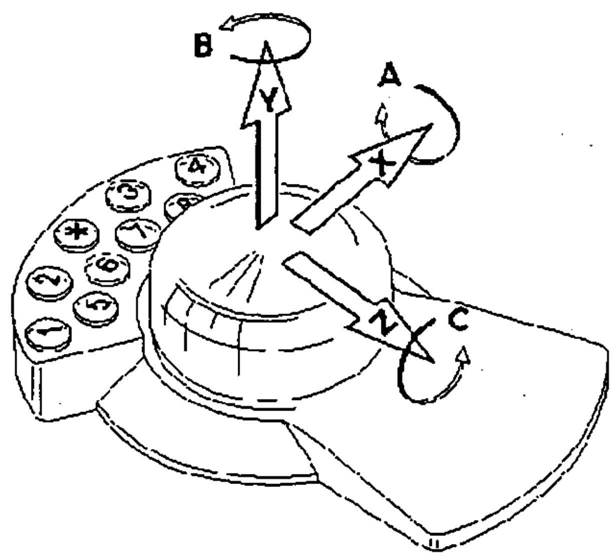


Figure 47: Operation of the SpaceMouse device

The various operation modes and sensitivities of the SpaceMouse input data could be manually configured using the additional eight keys provided for user pre-defined functions. Designers could use these function keys to turn the translational DOF on/off, to set the rotational DOF on/off, to increase/decrease the translational/rotational sensitivities and to return the translational/rotational sensitivities to the default settings so as to greatly support convenience in operation. In order to achieve a comfortable operation with the SpaceMouse in the LUCID system (e.g. avoiding "model flying" operation), the scale factor for the three translational input data is set as 0.025 and the scale factor for the three rotational input data is set as 0.00025 for the input data process from the SpaceMouse. Function key *1* was defined as a toggle switch to enable/disable the SpaceMouse translational input operation, and Function key *2* was defined as a toggle button to enable/disable the SpaceMouse rotational input operation. Function key *5* was defined as a press button to decrease the sensitivity for the SpaceMouse input operation, whereas Function key *6* was defined as a press button to increase the sensitivity for the SpaceMouse input operation. Function key *7* was defined as a switch to reinstall the default sensitivity for the SpaceMouse input operation. There were other function keys available for adding other user-defined functions in the future if needed for the operation of the SpaceMouse input device.

By default, the SpaceMouse input transformation was fixed to the design workspace coordinate system. This meant any input data from the SpaceMouse device operation would automatically synchronise with the change of the design workspace coordinate system. This method provided a more realistic effect for the two-handed operation in the LUCID system which complied with the Guiard's three high-order principles that were introduced in Chapter Four.

There were several technologies available to integrate the SpaceMouse operation interface into the LUCID system that were built upon Microsoft Foundation Class (MFC) applications. All of these methods were based on the Windows messages sent by the SapceMouse driver to the application. One approach to integrate the SpaceMouse support into an MFC application was based on overriding function calls within an MFC class. Another approach was to use an MFC message mapping technology that relied on the use of the *ON_REGISTERED_MESSAGE* message map macro in the Microsoft Visual C++ environment. This macro allowed an application to trap a specific registered Windows message and called a user defined message callback function. The LUCID system employed this approach to bring the SpaceMouse operation interface smoothly into the design application. The literature [LogiCad3D 2001] provided more information on the integrating procedures for the six DOF SpaceMouse input operation in most SpaceMouse-based applications.

6.3 Stereoscopic display interface: Integration and implementation

Most CAD systems display their models only on 2D planar screens. In order to understand 3D CAD models, more view ports are needed simultaneously to interpret both inside and outside structures. This normally needs additional brain work to reconstruct these complex structures from different view channels and thus leads to much confusion in the design process. To overcome this obstacle, NuVision GX60 stereoscopic wireless LCD glasses were employed to create a stereoscopic display interface in the LUCID system. The NuVision GX60 LCD eyewear was activated by an infrared emitter that connected to the user's computer. Compared with head mounted display (HMD) systems, which often caused uncomfortable intrusive viewing problems in a fully immersive virtual environment, the stereoscopic LCD glasses provided a comfortable way to view virtual models in a more realistic 3D environment. This also enhanced the information exchange between the designer and the digital model during the design process.

There were several software technologies available to display a stereo image on a desktop computer. Among them, the OpenGL stereo technology was an approach that worked best for professional applications, which usually involved a combination of windowed stereoscopic imagery alongside various non-stereo interface elements. For this reason, in the LUCID system design, the OpenGL stereo technology was investigated and used to support the stereoscopic visualisation function. Figure 48 gives the flowchart of graphics rendering including the stereoscopic and non-stereoscopic (orthographic) data processes. Currently, the LUCID system supports a graphics rendering cycle looping at about 30 Hz and a refresh rate of the monitor display running around 100 Hz or more to achieve a comfortable stereoscopic image display.

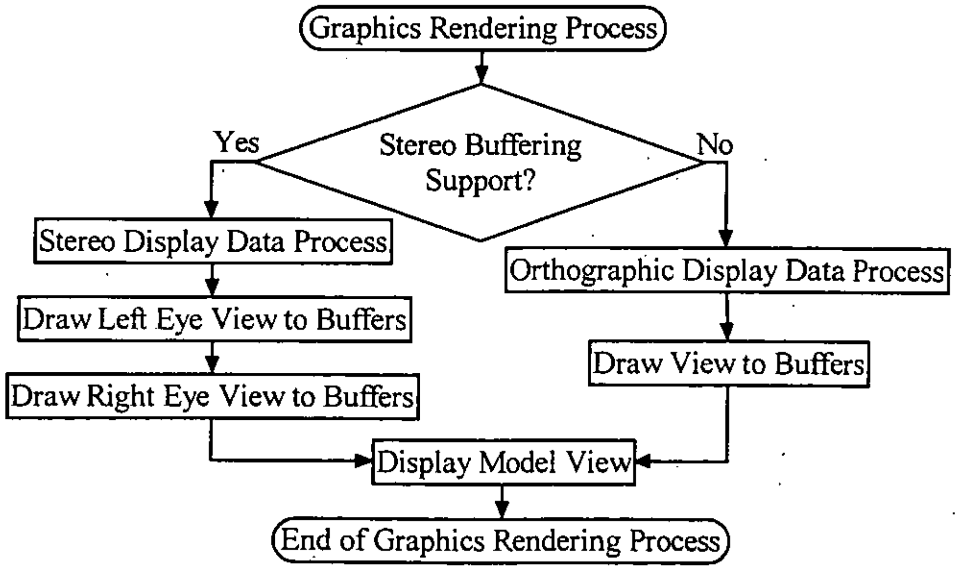


Figure 48: Flow diagram of the graphics rendering process

The steps for creating the stereoscopic display interface using the OpenGL API were:

- *Set up for stereo development environment.* This setting up of the graphics hardware to support stereo included selecting suitable graphics cards and monitors to support the output for stereoscopic display.
- *Query the graphics hardware for stereo buffering support.* The driver should respond appropriately when the application queried whether or not the OpenGL stereo support was available in the current display configuration.
- *Enable stereo buffering in a display window.* The driver should configure to permit stereo buffering in the current window if that window was set up with a pixel format descriptor structure that indicated stereo buffering.
- *Write to separate stereo buffers.* Once stereo buffering was successfully initialised for the current window, the application should be able to write to left-eye and right-eye buffers separately.
- *Do stereo perspective projections.* A good quality stereo image composed of two stereo pair elements, each of them being a perspective projection whose centre of projection was offset laterally relative to the other centre of projection position.
- *Set up projections for high quality stereo image.* This balanced the stereo positive and negative parallax by making the two perspective projections with different post-projection shifts in order to achieve a pleasing stereoscopic image.

The literature [Akka 1998; Akka 1999; Akka and Halnon 1999] provided more information on the development and implementation procedures for the stereoscopic display interface using the OpenGL API. Based upon the stereoscopic display interface integration and implementation, the LUCID system could achieve a CAD model viewing effect similar to the example illustrated in Figure 49.

Figure 49: Example of a stereoscopic vision display [StereoGraphics 2002]

6.4 Sound feedback interface: Integration and implementation

Human beings have visual, auditory, tactile and other sensorial channels to interact with the physical world. In the LUCID system, a sound feedback interface was implemented by using a universal computer-supported speaker-based auditory system. In this case, designers obtained auditory feedback when they performed certain design functions, touched or deformed the virtual CAD model within the design process. The design process associated with sound feedback gave much more auditory feedback information than that in a conventional CAD process. The sound feedback interaction added another sensorial channel to expand the information exchange between the designer and the virtual model generated by the computer. In the LUCID system, the sound feedback technology played an important role in increasing the interactive quality by complementing the visual feedback provided by the stereoscopic display and the tactile feedback provided by the haptic interaction.

In the LUCID system, the Microsoft Speech SDK Version 5.1 from Microsoft Corp. was used to implement the software process for integrating the sound feedback interface into the design application. Different sounds with different volumes were generated to give designers very useful auditory information when they either performed different design functions on the virtual model, touched the virtual model or directly deformed the virtual model via the 3D Phantom Desktop haptic device. Figure 50 shows the software programming diagram of the sound output process. Currently, the LUCID system supports the sound feedback interface mainly by using speech-based sounds rather than non-speech-based sounds, such as music sounds. Table 3 lists the sounds used in the LUCID system in which "model element" represents any individual design component such as line, curve, surface, cube and so forth. There is a need to further investigate non-speech-based sounds and apply them to give better support to the design process which is beyond the scope of this research.

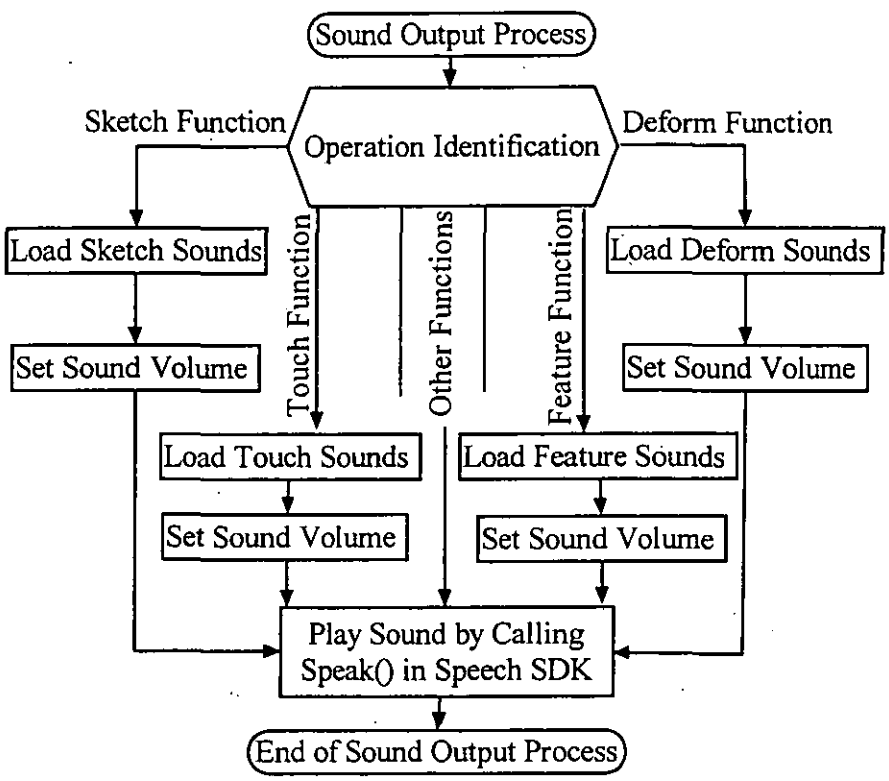


Figure 50: Flowchart of the sound output process

Sounds used in the LUCID system	Activated by which action
Speech-based sounds	
"Model element" copied	Copying operation
"Model element" cut	Cutting operation
"Model element" deformed	Form changing operation
"Model element" deleted	Deleting operation
"Model element" hide	Hiding operation
"Model element" moved	Moving operation
"Model element" pasted	Pasting operation
"Model element" rotated	Rotating operation
"Model element" selected	Selecting operation
"Model element" shown	Showing operation
"Model element" sketched	Sketching operation
"Model element" zoomed-in	Zooming-in operation
"Model element" zoomed-out	Zooming-out operation
Blended solid created	Blending feature creation
Lofted solid created	Lofting feature creation
Sculpted solid created	Sculpting feature creation
Swept surface created	Sweeping feature creation
Model opened	Opening an existing model file
Model saved	Saving an existing model file
Model transformed	SpaceMouse transforming operation
New file opened	Opening a new part file
Redo finished	Redoing operation
Undo finished	Undoing operation
Please input the new part file name	Inputting a new part file name
Welcome to the LUCID system	Starting the LUCID system
Are you sure to exit the LUCID system	Before existing the LUCID system
Thanks for using the LUCID system	After leaving the LUCID system
Music-based sounds	
"Ding ding"	Both haptic touching the model and haptic moving points on the model

Table 3: Sounds used in the LUCID system

6.5 Haptic interaction interface: Integration and implementation

Haptics or force feedback technology provides a new interaction paradigm between designers and computers. Prior to haptics, designers only had the ability to interact with models through visual and audio channels. In particular, there is only visual information available for designers in most CAD systems. However, haptic feedback interfaces bring profound changes to the way designers interact with virtual objects by feeling, touching and manipulating them in a way that creates a compelling sense of tactile realness [Sener, Wormald *et al* 2002]. A 3D Phantom Desktop force feedback device was used to support a haptic interaction operation in the LUCID system. The haptic interaction enabled designers to use their sense of touch to design and modify models in the same way as they would do in the physical world, and thus provided a more intuitive interaction method to support the design process. Assisted by the haptic feedback operation, designers could not only apply designing actions to the CAD model, but also touch and feel the created CAD model with 3D force feedback. Moreover, the design process associated with force feedback expanded the information exchange between designers and virtual models since designers obtained the haptic sense directly during the design process.

When integrating a haptic feedback operation into a design application, the most important issue is to render the designed CAD model both graphically and haptically. It is generally accepted that the update of a visually rendered model must be done with a frequency of about 30 Hz to avoid flickering [Bordegoni and Angelis 2000]. However, the haptically rendered model must be updated at approximately 1000 Hz so as to make the rendered forces appear more realistic. This obviously requires very efficient implementation of the haptic rendering algorithms. In the LUCID system, the GHOST SDK from SensAble Technologies was used to solve the difficulty involved in the implementation of the haptic interface design. In addition, the OpenGL API was employed to carry out the stereoscopic graphics displaying. Hence, this co-location task was implemented by having two different APIs, one for the haptic rendering and one for the stereoscopic graphics rendering. Using different APIs brought a great challenge to the LUCID system but it also provided much potential to further extend other functions for the design process in the future.

Since the GHOST SDK itself did not work with stereoscopic graphics rendering, a new effective method was developed and implemented to combine the haptic interaction with the stereoscopic graphics rendering in the LUCID system. This was achieved by calling low-level input/output functions to access the real-time position data from the Phantom Desktop haptic device together with displaying the received data in a stereoscopic visual environment using the OpenGL API. An effective collision detection algorithm was also employed to support the co-location rendering task since the GHOST SDK did not provide collision detection support for low-level data access and manipulation. Figure 51 gives the whole software process of haptic rendering in the LUCID system. A more detailed description of the techniques used for the haptic rendering implementation in the LUCID system is given below.

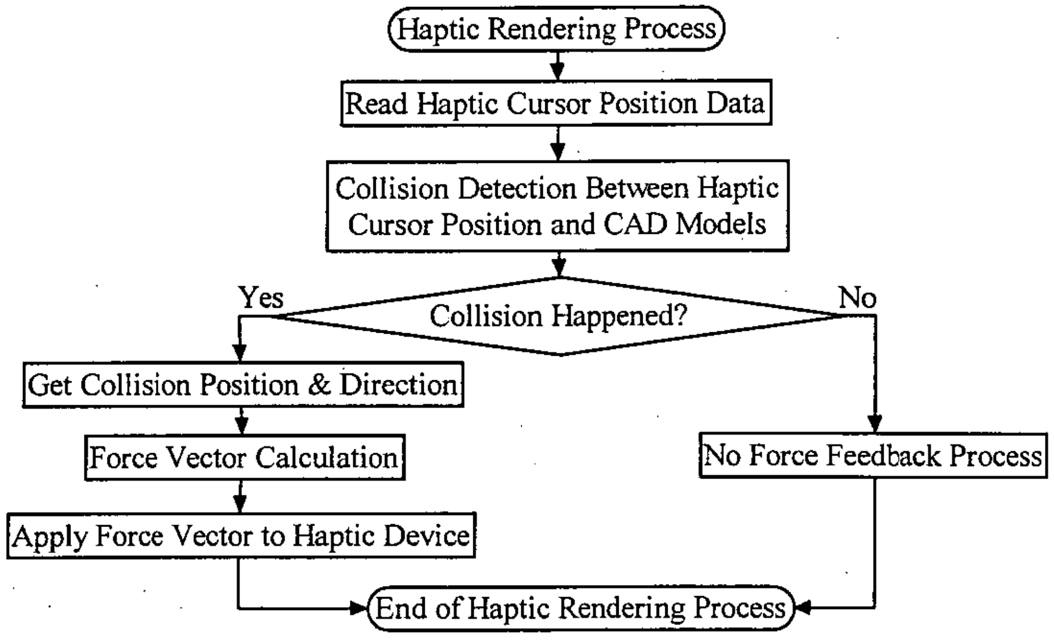


Figure 51: Flow diagram of the haptic rendering process

6.5.1 Haptic rendering rate

As mentioned before, different rendering cycle rates are used to give better support to haptic and graphics rendering whilst trying to create a haptic application. Graphics rendering loops commonly at a rate of approximately 30 Hz, but a much higher rate is necessary for haptic rendering. There can be additional advantages when using even higher haptic rendering rates. An intuitive description of why this is true comes from the nature of haptics and the fact that a haptic device presents forces to users. The motors in the haptic device cannot turn on instantaneously. When a haptic cursor touches a virtual object, a collision detection algorithm detects the contact and presents the haptic force to users. Commonly, as the haptic cursor moves into a solid object, the force increases quickly to the full force to simulate a stiff solid model. A fast haptic rendering cycle rate allows the motors in the haptic device to change quickly enough so that a consistent representation of a solid object is presented to users and so that the haptic device can remain stable when touching a stiff model. Eventually there will still be latency as a result of the inertia, backlash and other mechanical aspects of the motor mechanism that cannot be dealt with by fast processing.

To account for this in the LUCID system, a second process was used which controlled the haptic aspects of the rendering work. This effectively divided the overall visual and haptic rendering tasks into two interacting asynchronous loops, where the haptic process had the priority for system usage. The high cycle speed of the haptic process often required pre-processing of data to enable faster computations. Also, any computations that were done while the haptic process was running were put into the graphics loop process if possible as it was running at a slower rate and therefore required less computing time.

6.5.2 Low-level data access to the Phantom haptic device

As stated above, the GHOST SDK itself did not work with CAD models rendered in a stereoscopic display. A new method was needed to overcome this drawback so as to integrate the haptic feedback interface with the stereoscopic display interface seamlessly in the LUCID system.

There was a new addition to the GHOST SDK Version 4.0 called the gstDeviceIO class. This class allowed application developers to access the encoders and motors of the Phantom haptic device directly. The gstDeviceIO class offered a new tool to develop haptic applications using the GHOST SDK. Application developers could filter encoder values, directly send forces to the motors and test the motor temperatures. All of the functions in this new class were fairly self-explanatory in the GHOST SDK. These functions could be used in a haptic servo loop, started by calling the gstStartServoScheduling() function, which ran at the recommended 1000 Hz servo loop. If application developers would rather use a non-1000 Hz servo loop rate, the gstStartServoScheduling() function was not used. Instead, the application developers could design a loop that performed the specific tasks that were desired, and then called the gstUpdatePhantom() function to update the internal state of the Phantom haptic device.

In the LUCID system, the haptic servo loop ran at the recommended 1000 Hz cycling rate in order to have comfortable force feedback. The haptic servo loop process first recorded the stylus pushbutton state on the Phantom haptic device and then queried the current status of the Phantom haptic device. If the Phantom haptic device worked in a non-error mode, the haptic cursor position data was gained by calling the gstGetPhantomPosition() function in the gstDeviceIO class. Once the haptic cursor position data was available, collision detection was performed right away to find out whether the haptic cursor was touching the CAD model. If a collision was detected, the haptic force was determined from the relative positions of the haptic cursor and the CAD model. The generated haptic force was then sent to the Phantom haptic device by calling the gstSetPhantomForce() function in the gstDeviceIO class so users felt the force feedback through the Phantom haptic device. Detailed description about the haptic rendering software process is already shown in Figure 51.

6.5.3 Model geometry representation for haptic rendering

There are a number of advanced techniques available for haptic rendering such as volume-based methods, vector field-based methods, polygon-based methods and so forth [Novint 2002]. For example, the FreeForm Modeling system [SensAble 2002] employed a volume-based (also termed as voxel-based) method to represent its model data for haptic rendering. Vector fields could be modelled by mapping the vector field components directly to mechanical forces felt by users, or applied directly to the haptic cursor to visualise data sets that were otherwise not intuitive. For example, in one e-Touch application introduced by Novint Technologies [Novint *op cit*], point charges were put in the space which created an electric potential vector field that users could interact with by moving the haptic cursor. As the haptic cursor moved through the space as a probe, the vector field was mapped into forces that users could feel. This allowed a 3D method of interaction that could not be accomplished with traditional graphics alone. Another approach, common to haptics, involved using the polygons that were used to draw models in graphics as shown in Figure 52. In a simplistic implementation of this method, each polygon had a force direction associated with it in its normal direction, which was applied when the haptic cursor made contact. Hence, a real-time collision detection algorithm was needed for this representation method.

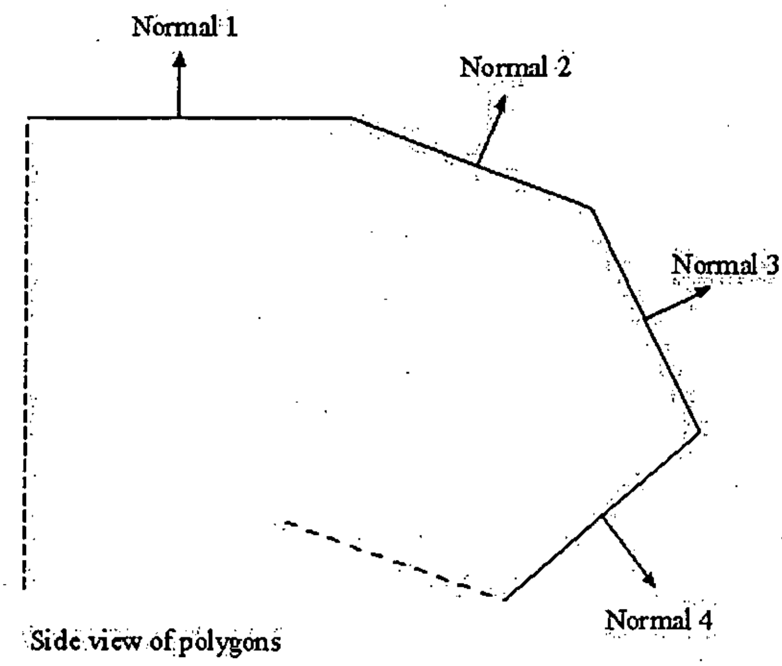


Figure 52: A simplified polygonal approach to haptic rendering

All of the above approaches had limitations in that they were specific to particular application situations. Volume or voxel-based methods demanded a large amount of memory to represent the model (normally at a gigabyte level), and needed a high processing speed (normally two CPUs at a GHz level working in a parallel processing mode) to perform haptic rendering in most haptic-based applications, such as the FreeForm Modeling system. Vector field-based methods were only implementable with vector field applications which could not be applied to product design situations at all. Polygon-based methods brought a complication when the haptic cursor was inside a model. Because the haptic cursor was already within the model (at some distance) there was no contact between the haptic cursor and the model and the force could not be generated by detecting a collision. Another problem with this method was that the corners of the polygons felt distinct, even on a surface that should in fact be smooth.

Thus, there was a need for a more coherent approach to haptic rendering and modelling interaction with complex models, in which a larger base of haptically renderable models could be obtained. There were other ways to render haptic models, such as spline-based methods, FEA methods or other advanced mathematical approaches which showed potential [*ibid*]. Polygon-based approaches, however, took advantage of a large database of models that were already existed within existing graphics hardware and software. Therefore, an efficient polygon-based method for creating haptic rendered forces was developed and implemented in the LUCID system. This polygonal algorithm first focused on determining whether or not the haptic cursor touched a model, which required a real-time collision detection algorithm. A culled collision detection algorithm was developed that worked in real-time with large data sets (see Section 6.5.5 for more detail). If the collision existed, then forces were generated based on the contact position and the normal vector of the contacted polygon in the model's facets.

6.5.4 Phantom-Mouse integration

In addition to providing a foundation for a standard haptic feedback application, the LUCID system provides support for interfacing with the Phantom-Mouse. The Phantom-Mouse is a mode of operation in which the Phantom haptic device emulates the ability of a standard 2D mouse. When the Phantom-Mouse was transitioned into the standard 2D mouse operation, users could use the Phantom haptic device in place of the standard 2D mouse, to interact with windows, menus, icons and so forth.

3D to 2D transitioning mechanism

The LUCID system currently provides the following 3D to 2D transitioning mechanism by which users can trigger a transition from the 3D haptic scene into a 2D mouse mode.

- Initiate a transition by moving the Phantom haptic device out of the design content view window while the view is active.

In such a case, the Phantom haptic device worked as a standard 2D mouse. All tasks once performed by the standard 2D mouse were now carried out by the Phantom haptic device. This feature was especially needed to give better support to the two-handed operation in the LUCID system since it could avoid the need for a hand change between the Phantom haptic device operation and the standard 2D mouse manipulation.

2D to 3D transitioning mechanisms

Since different users have different preferences for the Phantom-Mouse operation, the LUCID system currently provides three 2D to 3D transitioning mechanisms. The list below describes these three mechanisms by which users can trigger a transition from a standard 2D mouse mode back into the 3D haptic scene.

- *Fall through.* Allows users to fall back into the 3D haptic scene only after the mouse cursor has left the design content view window and then re-entered it.
- *Click through.* Causes a transition back into the 3D haptic scene only if users click the stylus button while the cursor is in the design content view window. (Note: the stylus pushbutton must be emulating a left mouse click function in order for the stylus click to work.)
- *Push through.* Simulates a mouse plane that behaves just like a thin ice. This allows users to cause a transition by pushing against the plane while the cursor is in the design content view window.

In order to customise this configuration, the following interface functions were developed and implemented in the LUCID system with the support of the GHOST SDK and its relevant documents.

Function Prototype: virtual void OnPhantomEntry ();

Function Description: The LUCID system calls this function when a 2D to 3D transition occurs.

Function Prototype: virtual void OnPhantomLeave ();

Function Description: The LUCID system calls this function when a 3D to 2D transition occurs.

Function Prototype: BOOL IsPHANToMMouseEnabled ();

Function Description: The LUCID system calls this function to query the current transitioning state.

Function Prototype: void EnablePHANToMMouse (BOOL bEnable);

Function Description: The LUCID system calls this function to enable or disable OnPhantomLeave () transitioning. Calling the EnablePHANToMMouse (FALSE) function would disable the mouse integration.

Function Prototype: BOOL SetWhichButton (UCHAR buttonMask);

Function Description: Allows application developers to modify the mouse buttons being emulated when a stylus click occurs. Application developers have the following three masks to use in their applications:

MOUSE_LEFT_BUTTON_MASK

MOUSE_MIDDLE_BUTTON_MASK

MOUSE_RIGHT_BUTTON_MASK

For example, to emulate a left mouse button click, pass the button mask as the MOUSE_LEFT_BUTTON_MASK in the function calling:

SetWhichButton (MOUSE_LEFT_BUTTON_MASK);

Function Prototype: void SetHapticEntryMode (HapticEntryMode mode);

Function Description: Allows application developers to specify the entry mechanism that should be detected in order to transition from 2D back to 3D. The possible modes are listed below:

PHANTOM_MOUSE_FALL_THRU

PHANTOM_MOUSE_CLICK_THRU
PHANTOM_MOUSE_PUSH_THRU

Function Prototype: void SetPHANToMMouseConfig (const PHANToMMouseConfig &config);
Function Description: This routine makes use of a data structure to maintain configuration settings for the Phantom-Mouse.

6.5.5 Collision detection algorithm

In any haptic application, creating a force for a contacted model consists of two basic operations — collision detection and force generation. The first step in creating a force for a contacted model is to find whether or not the haptic cursor is touching the model. This means that as the haptic cursor moves, collisions between the haptic cursor and the model's facets must be checked as fast as possible. After a collision is detected, the force is then determined and presented to users through the haptic hardware device that is employed in the application.

Since the GHOST SDK did not provide collision detection support for the low-level data access and manipulation to the Phantom haptic device, new collision detection algorithms were investigated to support haptic feedback rendering in the LUCID system. Gregory *et al* [1999] introduced a framework called H-Collide which used hybrid hierarchical representations and frame-to-frame coherence query algorithms for collision detection for haptic interaction with polygonal models. However, H-Collide did not open to outside use and it did not work with stereoscopic display. Another simple way to do collision detection is to check if the haptic cursor has moved through any of the polygons in a model. This can be accomplished by taking the line segment from the haptic cursor's current and previous positions each loop of the cycle, and comparing that segment with every one of the polygons in a model. If the line segment intersects any of the polygons then a collision has occurred. This can be extremely time consuming if the model consists of a large amount of polygons. It is inefficient to check every one of the polygons in a CAD model each cycle of the loop. The process can be speeded up by culling the polygons that are not in the cursor's vicinity and this allows real-time collision detection with large data sets to be achieved relatively easily.

In the LUCID system, a shareware 3D collision detection function library called ColDet V1.1 which was downloaded from http://photoneffect.com/coldet/ was used to perform the intersection calculation based on the condition that the collision model was represented in triangular meshes. The following describes the main steps needed to integrate the ColDet library into the LUCID system to carry out the collision detection task.

Model setup

- For each collision model mesh, first create a collision model by calling the function CollisionModel3D* model=newCollisionModel3D () in the ColDet V1.1 library (Shared collision model meshes can use as one model).
- Add all the triangles the collision mesh has to the model by calling the function model->addTriangle (vertex1, vertex2, vertex3) in the ColDet V1.1 library.
- Call the function model->finalize () in the ColDet V1.1 library to finish adding all triangles and process the information and prepare for collision test.

Collision test

- Assuming two models (model1, model2) are either set both of their transformation matrices by calling functions:
  model1->setTransform (model1_transformation_matrix);
  model2->setTransform (model2_transformation_matrix).
- Then call the function model1->collision (model2). The function returns a Boolean value indicating if a collision has occurred.

Collision test results

- Call the function getCollidingTriangles () to get which triangles have collided.
- Call the function getCollisionPoint () to find the exact collision point.

Other collision tests

- The ColDet V1.1 function library also provided rayCollision () and sphereCollision () functions to test the model against these primitives.

In the LUCID system, the haptic cursor was recognised as a small 3D sphere model, and all CAD models were interpreted as one collision object. Therefore, the sphereCollision () function in the ColDet V1.1 library was used to perform the contacting calculation. To make the collision detection work more efficiently, collision polygon meshes were culled using a new method that was integrated and implemented into the LUCID system. This was accomplished by creating a 3D voxel sphere boundary around the haptic cursor and pre-calculating which polygons should be checked when the haptic cursor was located in any 3D space position. As the algorithm ran, therefore, on each loop the current 3D voxel sphere boundary was determined and the list of active polygons were checked for the collision detection. Figure 53 gives a demonstration example about this new algorithm in a simple 2D view. The supposed collision model consisted of thirteen triangles as numbered 1 to 13 respectively. When the haptic cursor moved to the model, a 3D sphere boundary with a pre-defined radius R at the centre of the haptic cursor was established. As Figure 53 shows, only three triangles had intersections with the 3D sphere boundary, namely, Triangle 1, 11 and 12. Thus, only these three triangles instead of all thirteen triangles were pre-processed and put into the mesh list to perform the final contacting calculation. This new efficient algorithm was implemented in the LUCID system and achieved a good result for the fast collision detection used in the haptic rendering process. The evaluation tests of processing efficiency using this approach has shown that the model containing less than about ten thousand triangular meshes could achieve a good collision detection result in the LUCID system.

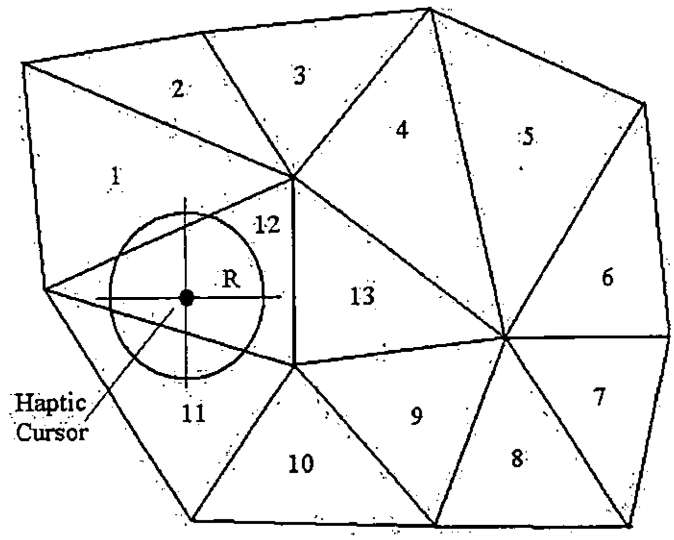


Figure 53: Voxel sphere-based culling of a triangular mesh model

To support this efficient collision detection method running in a real-time mode, some mathematical algorithms were needed to determine the intersection between the sphere boundary and the triangular meshes. These included the calculation algorithm for the 3D distance between a point and a triangle in 3D space. A straightforward method introduced in the literature [Jones 1995] was employed and implemented in the LUCID system to perform the 3D distance mathematical calculations. The following gives a detailed description of this mathematical calculation algorithm.

Finding the distance from a point P_0 to a triangle $P_1P_2P_3$ where P_i is a point in 3D space is a pure mathematical calculation process. There are three possibilities available for this calculation. The point P_0 might be closest to the plane of the triangle, closest to an edge, or closest to a vertex. Approaching the problem in 3D requires the projection of the point P_0 onto the plane of triangle $P_1P_2P_3$ to create the point $P_0^{'}$ (see Figure 54).

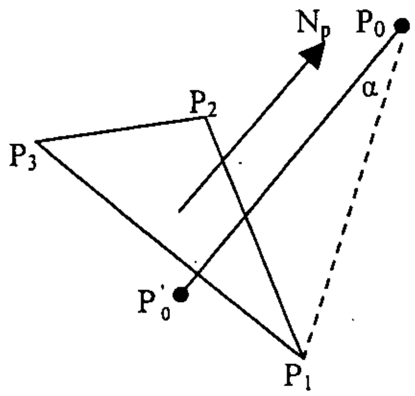


Figure 54: Calculation the distance of P_0 from $P_1P_2P_3$

The normal vector N_p of the plane of triangle $P_1P_2P_3$ can be calculated as

$$N_p = P_1P_2 \times P_1P_3 \tag{6.1}$$

The angle α between the normal vector N_p and the vector P_1P_0 can be calculated by

$$\cos\alpha = \frac{P_1P_0 \cdot N_p}{|P_1P_0||N_p|} \tag{6.2}$$

The length of the vector $|P_0P_0^{'}|$ can be found using

$$|P_0P_0^{'}| = |P_0P_1|\cos\alpha \tag{6.3}$$

The vector $P_0P_0^{'}$ can then be determined by

$$P_0P_0^{'} = -|P_0P_0^{'}|\frac{N_p}{|N_p|} \tag{6.4}$$

Then the point $P_0^{'}$ can be obtained from

$$P_0^{'} = P_0 + P_0P_0^{'} \tag{6.5}$$

If $P_0^{'}$ lies within the triangle $P_1P_2P_3$, the distance $|P_0P_0^{'}|$ calculated by Equation (6.3) is the correct distance of the point P_0 from the triangle $P_1P_2P_3$.

If $P_0^{'}$ falls outside the triangle $P_1P_2P_3$, the distance to the triangle $P_1P_2P_3$ is the distance to the closest edge or vertex to the point $P_0^{'}$. In order to determine which edge or vertex the point $P_0^{'}$ is closest to, the position of the point $P_0^{'}$ in relation to the three vectors V_1, V_2 and V_3 should be set up (as shown in Figure 55), where

$$V_1 = \frac{P_2P_1}{|P_2P_1|} + \frac{P_3P_1}{|P_3P_1|}, \quad V_2 = \frac{P_3P_2}{|P_3P_2|} + \frac{P_1P_2}{|P_1P_2|}, \quad V_3 = \frac{P_1P_3}{|P_1P_3|} + \frac{P_2P_3}{|P_2P_3|} \tag{6.6}$$

Let

$$f_1 = (V_1 \times P_1P_0^{'}) \cdot N_p, \quad f_2 = (V_2 \times P_2P_0^{'}) \cdot N_p, \quad f_3 = (V_3 \times P_3P_0^{'}) \cdot N_p \tag{6.7}$$

If $f_1 > 0$, the point $P_0^{'}$ is determined as anticlockwise of V_1. Similarly, f_2 and f_3 can be checked for the other vectors. Thus, using f_1, f_2 and f_3 described in Equation (6.7) the position of the point $P_0^{'}$ in relation to the vectors V_1, V_2 and V_3 is determined directly. Furthermore, it has to be determined whether the point $P_0^{'}$ is inside the triangle $P_1P_2P_3$ or not. If it is, the distance from the point P_0 to the triangle $P_1P_2P_3$ is the distance calculated in Equation (6.3).

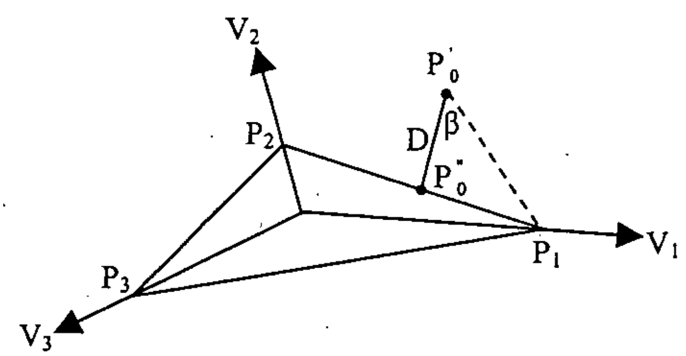


Figure 55: Determining the position of $P_0^{'}$ in relation to V_1, V_2 and V_3

As the example in Figure 55 shows, if the point $P_0^{'}$ is clockwise of V_2 and anticlockwise of V_1, it is outside the triangle $P_1P_2P_3$ if

$$(P_0'P_1 \times P_0'P_2) \cdot N_p < 0 \tag{6.8}$$

and similarly for the other cases.

If the point P_0' is found to be outside the triangle $P_1P_2P_3$, it is either closest to a vertex, or a side. For example, assume the point P_0' is closest to P_1P_2, and the point P_0'' is the projection of the point P_0' onto the line P_1P_2. The vector D of the point P_0' to the point P_0'' is given by

$$D = (P_0'P_2 \times P_0'P_1) \times P_1P_2 \tag{6.9}$$

and the angle β between the vector $P_0'P_0''$ and the vector $P_0'P_1$ is determined by

$$\cos\beta = \frac{P_0'P_1 \cdot D}{|P_0'P_1||D|} \tag{6.10}$$

The length $P_0'P_0''$ is calculated using

$$|P_0'P_0''| = |P_0'P_1|\cos\beta \tag{6.11}$$

and $P_0'P_0''$ is obtained from

$$P_0'P_0'' = |P_0'P_0''|\frac{D}{|D|} \tag{6.12}$$

The point P_0'' can then be calculated as

$$P_0'' = P_0' + P_0'P_0'' \tag{6.13}$$

Let

$$t = \frac{P_0'' - P_1}{P_2 - P_1} \tag{6.14}$$

If $0 \le t \le 1$, the point P_0'' is between P_1 and P_2, and the distance of the point P_0' from the line P_1P_2 is $|P_0'P_0''|$, as calculated in Equation (6.11). So the distance of the point P_0 to P_1P_2 is $\sqrt{|P_0'P_0''|^2 + |P_0P_0'|^2}$.

If $t < 0$, the point P_0 is closest to the vertex P_1. The distance can be calculated as $|P_1P_0|$. If $t > 1$, the point P_0 is closest to the vertex P_2. The distance can be calculated as $|P_2P_0|$.

The above algorithm can be easily applied to the remaining edges of the triangle so as to calculate the distance of the point P_0 to the triangle $P_1P_2P_3$ properly.

The steps for the collision detection in the LUCID system are summarised as follows:

- First create a collision model by calling the function newCollisionModel3D () in the ColDet V1.1 function library.
- Build the haptic cursor boundary by using the default empirical radius value R.
- Calculate the distance between the haptic cursor and the triangles in the CAD model's facets based on the above mathematical algorithm introduced.
- Perform the distance checking based on the condition that the calculated distance is less than R.
- If the statement "calculated distance is less than R" is true, add the triangle to the collision model by calling the function addTriangle () in the ColDet V1.1 library.
- Perform the collision detection calculation by calling the function sphereCollision () in the ColDet V1.1 library after the adding triangle process is finished.
- If the returned Boolean value is true, a collision is detected. Retrieve the collision information by calling functions getCollidingTriangles() and getCollidingPoint() in the ColDet V1.1 library. The collision force feedback is then generated based upon this information.

6.5.6 Haptic representation of lines

Since the haptic force feedback generated by the GHOST SDK was based upon the concept of "surface contact point" [Ghost 2002], an issue was encountered while trying to create a haptic feedback interaction with non-surface-based geometric elements such as lines and 3D freeform curves in CAD models. Ideally, lines could be simulated as small tubes so that the haptic feedback interaction could be achieved using small long-thin cylinder surfaces for contacting calculation. But this method created a large amount of polygons for presenting lines especially for 3D freeform curves, and thus led to an inefficient system usage. Therefore, an approximate method was introduced in the LUCID system to speed up the data processing for this matter. Figure 56 gives some possible approximate solutions with comparisons to the ideal processing method in a simple 2D cross section view. Considering trade-offs in the processing time and the storage memory usage, an octahedral representation method was used to represent the line elements in CAD collision models in the contacting detection algorithm in the LUCID system. This method gave more comfortable haptic force feedback than other solutions that could be used such as the quadrilateral representation and the trilateral representation, as shown in Figure 56.

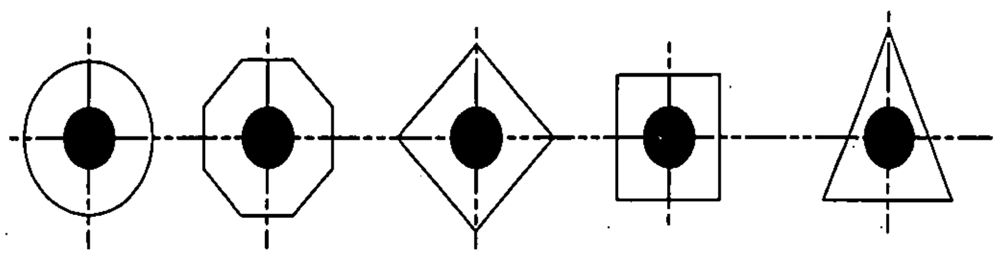


Figure 56: Solutions to the haptic interaction with lines

6.5.7 Haptic force generation

After a collision is detected, a force must be presented through a haptic hardware device used in the application. Usually, this generated force is in the normal direction and is proportional to the penetration depth into a collision model, which is measured from the currently active polygon. This means the collision detection method should discriminate which solid geometry element in the CAD model the contacted polygon belongs to. Unfortunately the ColDet V1.1 function library did not provide any support for this kind of function call. Therefore, in the LUCID system, the haptic rendered force was approximately generated by first finding out the contacting point and the normal vector of the contacted triangle, then multiplying an empirical factor for the force value along the normal vector direction. When the haptic cursor left the collision model, the force disappeared since the collision detection did not find any contact between the haptic cursor and the CAD model.

An initial problem arose because of the nature of a polygonal data set. The outward direction on a polygon is determined from the ordering of the points it contains. The direction that is considered outward is important for both graphics and haptic rendering. In graphics rendering, the outward direction is used to determine shading effects like the light property on the model. In haptic rendering, the outward direction is used in collision detection and force direction calculations. A typical way to overcome this problem, which has become a standard in graphics, is to pre-process the points and order them so that all the vertex listings are consistent based upon the right-hand rule that is used widely in processing an STL file format used in the RP field. This method was also applied to the LUCID system.

6.6 Summary

In this chapter, the LUCID system graphical user interface was presented first. Four VR-based HCIs in the LUCID system (two-handed operation, stereoscopic display, sound feedback and haptic interaction) have been described focusing mainly on their interactive concepts, working modes and advantages in design applications. Detailed software processing diagrams and procedures for their integration and implementation in the LUCID system were also provided. Further topics on haptic interaction and its relevant application problems that arose from the LUCID system design and development were also discussed in detail both theoretically and practically. Detailed mathematical algorithms were provided so as to allow interface design functions to work properly in the LUCID system.

CHAPTER SEVEN

Geometric modelling method and algorithm design

As discussed in Chapter Two, CAD geometric modelling allows designers to represent physical objects in computerised digital forms. Different geometric modelling techniques have their own strengths, weaknesses and specific applications, and hybrid modelling approaches possess the flexible facility for efficient and effective model creation. Therefore, it was decided that the LUCID system would use hybrid geometric representation solutions to describe CAD model form information. Non-Uniform Rational B-Splines, commonly referred to as NURBS, have become a *de facto* industry standard for freeform curve and surface representation in most CAD/CAM/CAE applications because NURBS can provide a unified mathematical basis for representing both analytic shapes, such as conic sections and quadric surfaces, and freeform entities, such as the shapes of cars, airplanes, ships and so forth [Piegl and Tiller *op cit*]. Also the NURBS algorithms are fast and numerically stable. There is substantial potential in NURBS for researchers to study interactive algorithms to support intuitive human computer interfaces (HCIs). Therefore, this research has explored effective algorithms to support intuitive interaction using the NURBS modelling technology. This chapter discusses in detail the NURBS modelling algorithms that are used in the LUCID system to represent CAD models when they contain freeform entities such as freeform curves and freeform surfaces.

7.1 Non-uniform rational B-splines representation method

7.1.1 NURBS curve representation

A p th-degree NURBS curve can be defined by

$$C(u) = \sum_{i=0}^{n} R_{i,p}(u) P_i \tag{7.1}$$

where P_i are the control points, and $R_{i,p}(u)$ are the piecewise rational basis functions defined as

$$R_{i,p}(u) = \frac{N_{i,p}(u) w_i}{\sum_{j=0}^{n} N_{j,p}(u) w_j} \tag{7.2}$$

where w_i are the weights (assume that all w_i>0), and $N_{i,p}(u)$ are the p th-degree B-spline basis functions defined on the non-periodic and non-uniform knot vector $U = \{u_0, u_1, u_2, \ldots u_n, u_{n+1}, \ldots, u_{n+p+1}\}$ as

$$\begin{cases} N_{i,0}(u) = \begin{cases} 1 & \text{if } \mathrm{u_i} \le \mathrm{u} < \mathrm{u_{i+1}} \\ 0 & \text{otherwise} \end{cases} \\ N_{i,p}(u) = \dfrac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \dfrac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u) \end{cases} \quad i = 0,1,\ldots.n+p \tag{7.3}$$

where u_i are called knots defined in the knot vector U.

There are several useful algorithms available which are fundamental in the implementation of NURBS curves and surfaces. These tools are known as knot insertion, knot refinement, knot removal, degree elevation and degree reduction. All these different fundamental geometric algorithms have their specific applications in the implementation and modification of curves and surfaces represented using the NURBS method. The literature [*ibid*] gave an exhaustive description of all these five algorithms including the statement of the problem, the list of applications, clarification of the problem and solution approaches, the list of references where more rigorous derivations and proofs could be found, the solution formulae, worked examples, computer algorithms and examples of applications.

7.1.2 NURBS surface representation

The following equation expresses a NURBS surface defined on $u \in [0,1]$ and $v \in [0,1]$:

$$S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} R_{i,j}(u,v) P_{i,j} \tag{7.4}$$

where $P_{i,j}$ are the control points, and $R_{i,j}(u,v)$ are the piecewise rational basis functions defined as

$$R_{i,j}(u,v) = \frac{N_{i,p}(u) N_{j,q}(v) w_{i,j}}{\sum_{k=0}^{n} \sum_{l=0}^{m} N_{k,p}(u) N_{l,q}(v) w_{k,l}} \tag{7.5}$$

where $w_{i,j}$ are the weights, $N_{i,p}(u)$ and $N_{j,q}(v)$ are the p th-degree and q th-degree non-rational B-spline basis functions

$$\begin{cases} N_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \le u < u_{i+1} \\ 0 & \text{otherwise} \end{cases} \\ N_{i,p}(u) = \dfrac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \dfrac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u) \end{cases} \quad i = 0,1,\ldots.n \tag{7.6}$$

and

$$\begin{cases} N_{j,0}(v) = \begin{cases} 1 & \text{if } v_j \le v < v_{j+1} \\ 0 & \text{otherwise} \end{cases} \\ N_{j,q}(v) = \dfrac{v - v_j}{v_{j+q} - v_j} N_{j,q-1}(v) + \dfrac{v_{j+q+1} - v}{v_{j+q+1} - v_{j+1}} N_{j+1,q-1}(v) \end{cases} \quad j = 0,1,\ldots.m \tag{7.7}$$

defined on the knot sequences

$$U = \{\underbrace{0,\ldots,0}_{p+1}, u_{p+1},\ldots, u_n, \underbrace{1,\ldots,1}_{p+1}\} \tag{7.8}$$

and $$V = \{\underbrace{0,\ldots,0}_{q+1}, v_{q+1},\ldots, v_m, \underbrace{1,\ldots,1}_{q+1}\} \tag{7.9}$$

Since a NURBS curve or surface is defined by its control points, weights, and knot sequences, any modification of these parameters leads to a change of the curve or surface shape (see Figure 8 and Figure 9 in Chapter Two). In the LUCID system, the curve or surface shape could be directly deformed by modifying the input data points so as to re-generate the control points for the new curve or surface shape based on the mathematical formulae introduced here.

7.2 3D freeform curve design

In the design process, there is more often a need to use freeform curves instead of direct lines to describe the model profile to be created. Most programming tools such as the Microsoft Foundation Class (MFC) application library only provide limited sketching tools for very simple curves such as circles and ellipses. A practical mathematical algorithm for 3D freeform curve design was investigated and implemented in the LUCID system. In particular, the LUCID system had to provide useful tools that allowed designers to fashion a larger variety of 3D shapes simply by specifying a small collection of input data points in 3D space.

Ideally, the curve generated by the defined mathematical algorithm should closely approximate the original curve the designer had in mind when specifying the data points required. If the curve that is generated does not provide an adequate approximation to the original curve, the designer will modify the entered data points by shifting them this way and that and regenerating the curve again several times. This interactive process continues until the designer is satisfied.

Figure 57 shows two main classes of curve generation algorithms commonly used in the field of computer aided geometry design. Figure 57 (a) indicates a curve P(t) generated by an algorithm that interpolates the input data points given by the designer. This algorithm returns points along a curve that passes exactly through the points input at specific instants and forms a smooth curve for points in between. Figure 57 (b) uses an algorithm that generates a curve R(t) that approximates the data points input by the designer. The points this algorithm returns form a curve that is attracted towards each input point in turn, but does not actually pass through all of them. In the computer aided geometry design literature, the input data points in Figure 57 (b) are termed as control points with their basis functions implied. In the literature [Hill 2001], the curve that interpolates the input data points is termed as the interpolation algorithm, whereas the curve that approximates the control points is named as the approximation algorithm.

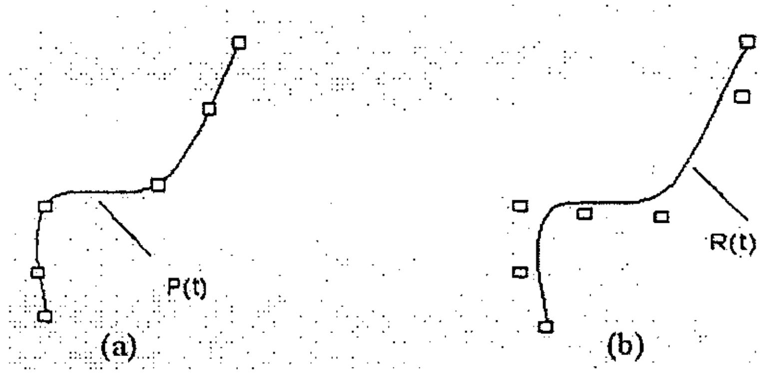


Figure 57: Curve design methods

The designer enters the data points on the basis of his/her experience, along with a clear understanding of the characteristics of the curve generation algorithm that will be used to regenerate the curve from the data points. In most cases the designer wants the curve creation algorithm to produce a curve that passes through all of the input data points. This seems more natural than using an algorithm that just attracts the curve to control points. In order to provide designers with natural and intuitive function tools and interfaces to support their design process, the interpolation algorithm is desired to generate the freeform curve. To achieve the created freeform curve with the desired continuity, an efficient natural cubic-degree spline interpolation algorithm was developed and implemented in the LUCID system.

Given a set of input data points Q_k, $k = 0,\ldots,n$, the desired freeform curve was created by interpolating these points with a cubic-degree (called a 3rd-degree) NURBS curve. For each Q_k, a parameter value $\bar{u}_k$ was assigned and an appropriate knot vector $U = \{u_0,\ldots,u_m\}$ was selected. The $(n+1)\times(n+1)$ system of linear equations was then setup

$$Q_k = \bar{C}(\bar{u}_k) = \sum_{i=0}^{n} N_{i,3}(\bar{u}_k) P_i \tag{7.10}$$

where the control points P_i were the $n+1$ unknowns. The problem of choosing the $\bar{u}_k$ and the knot vector U remained, and their choice affected the shape and parameterisation of the curve designed.

According to the literature [Piegl and Tiller *op cit*], there were three common methods available to determine the $\bar{u}_k$:

- *The equally spaced method.*

$$\bar{u}_0 = 0 \qquad \bar{u}_n = 1$$

$$\bar{u}_k = \frac{k}{n} \qquad k = 1,\ldots,n\text{-}1 \tag{7.11}$$

  This was the simplest way to define the $\bar{u}_k$ parameters. But it was not used practically, as it could produce erratic shapes or undesired shapes when the input data points were unevenly spaced.

- *The chord length method.*

  Let d be the total chord lengths calculated upon the input data points

$$d = \sum_{k=1}^{n} | Q_k - Q_{k-1} | \tag{7.12}$$

  then

$$\bar{u}_0 = 0 \qquad \bar{u}_n = 1$$

$$\bar{u}_k = \bar{u}_{k-1} + \frac{| Q_k - Q_{k-1} |}{d} \qquad k = 1,\ldots,n\text{-}1 \tag{7.13}$$

  This was the most widely used method, and it was generally adequate. It also gave a good parameterisation to the curve, in the sense that it approximated a uniform parameterisation.

- *The centripetal method.*

  Let d be the total square root of the chord lengths computed on the input data set

$$d = \sum_{k=1}^{n} \sqrt{| Q_k - Q_{k-1} |}$$

then

$$\bar{u}_0 = 0 \qquad \bar{u}_n = 1$$

$$\bar{u}_k = \bar{u}_{k-1} + \frac{\sqrt{|Q_k - Q_{k-1}|}}{d} \qquad k = 1,\ldots,n\text{-}1 \tag{7.14}$$

This method gave even better results than the chord length method when the input data set took very sharp turns in space. The literature [Lee 1989] gave more detailed description of this newer method.

There was a simple method to determine the knot vector U. It could be equally spaced (based upon the degree $p = 3$), that is,

$$u_0 = u_1 = u_2 = u_3 = 0 \qquad u_{m-3} = u_{m-2} = u_{m-1} = u_m = 1$$

$$u_{j+3} = \frac{j}{n-3+1} \qquad j = 1,\ldots,n\text{-}3 \tag{7.15}$$

where m is defined as $m = n + 3 + 1$. However, this method was not recommended. If it was used in conjunction with Equation (7.13) or (7.14) it could result in a $(n+1)\times(n+1)$ system of linear equations which could not be solved directly by some mathematical approaches so as to obtain the control points P_i in Equation (7.10). Therefore, the following technique of average was employed:

$$u_0 = u_1 = u_2 = u_3 = 0, \qquad u_{m-3} = u_{m-2} = u_{m-1} = u_m = 1$$

$$u_{j+3} = \frac{1}{3}\sum_{i=j}^{j+3-1} \bar{u}_i \qquad j = 1,\ldots,n\text{-}3 \tag{7.16}$$

With this method the knots reflected the distribution of the $\bar{u}_k$. Furthermore, using Equation (7.16) combined with Equation (7.13) or (7.14) to compute the $\bar{u}_k$ led to a simple $(n+1)\times(n+1)$ system of linear equations which could be solved by the Gaussian elimination algorithm relatively easily.

Once the $\bar{u}_k$ and the knot vector U were determined, the $(n+1)\times(n+1)$ coefficient matrix of the linear equations was setup by evaluating the nonzero basis functions at each $\bar{u}_k$, $k = 0,\ldots,n$. Afterwards, the control points P_i in Equation (7.10) could be obtained from the $(n+1)\times(n+1)$ system of linear equations solution.

The solution process in the 3D freeform curve design in the LUCID system is summarised as follows:

- Compute parameters $\bar{u}_k$ corresponding to the input data points Q_k using Equation (7.14).
- Calculate the knot vector U using Equation (7.16).
- Evaluate the basis functions to setup a $(n+1)\times(n+1)$ coefficient matrix of the linear equations, with the control points P_i as unknowns.
- Solve the $(n+1)\times(n+1)$ system of linear equations by the Gaussian elimination algorithm to obtain the control points P_i described in Equation (7.10).

Once the curve parameters $\bar{u}_k$, knot vector U and control points P_i were determined by the input data points Q_k, the inner interpolation points of the freeform curve were obtained from Equation (7.10). The whole freeform curve was then generated by joining all these inner interpolation points together. The finished freeform curve could be displayed via many polylines defined by all these interpolation points to provide a close approximation in the LUCID system. In the code programming, drawing tools such as line drawing and polyline drawing functions provided by the OpenGL API were called to display the curve result stereoscopically on the screen in the LUCID system.

7.3 Ellipse design using NURBS

In most Windows-based application programming, ellipses can only be drawn as axis-aligned figures, as shown in Figure 58. If one wants to design rotated or skewed figures under Windows-based applications, it is necessary to need additional calculation work.

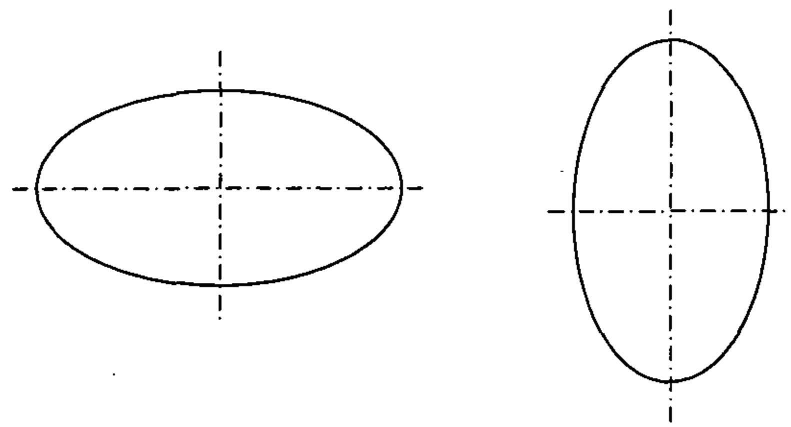


Figure 58: Ellipses generated by normal Windows applications

Basically, there were two alternatives that could be used to implement this task:

- *Use a basic mathematical equation to create an ellipse via line segments.*

  The mathematical equation for an ellipse was relatively simple. The approximation of an ellipse could be performed by dividing an ellipse into many short line segments and then connecting these line segments to form the ellipse.

- *Use cubic-degree NURBS curves to approximate an ellipse.*

  Using four simple NURBS curves, each representing ninety degrees of an original axis-aligned ellipse, a fair approximation with a minimal error could be arrived at.

In the LUCID system, the NURBS approach was employed to implement the ellipse design. Because NURBS curves were invariant under rotation, scaling and translation, it was only necessary to transform the control points to apply the same transformation to the ellipse curve. More precisely, since each point on a cubic-degree NURBS curve was a combination of a set of piecewise rational functions with control points, the relationship of the curve to the control points was not changed under any affined application.

Figure 59 shows the thirteen NURBS control points (labelled in number 0 to 12 respectively) defining the four NURBS curves making up the ellipse which could be calculated relatively easily using an empirically derived magical constant which was set to 0.552 in the LUCID system. The cubic-degree (the 3rd-degree) four control point NURBS representation for the ellipse curve was defined as

$$C(u) = \sum_{i=0}^{3} R_{i,3}(u) P_i \tag{7.17}$$

where the knot vector was defined as $U = \{0,0,0,0,1,1,1,1\}$ and the weight vector was defined as $\{w_i\} = \{1,1,1,1\}$. Control points labelled 0, 1, 2 and 3 were used to create the first NURBS curve as the first part of an ellipse through a NURBS curve calculation. Similarly, control points labelled 3, 4, 5 and 6 were used for the second NURBS curve creation, control points labelled 6, 7, 8 and 9 were used for the third NURBS curve computation and control points labelled 9, 10, 11 and 12 were used for the final NURBS curve creation.

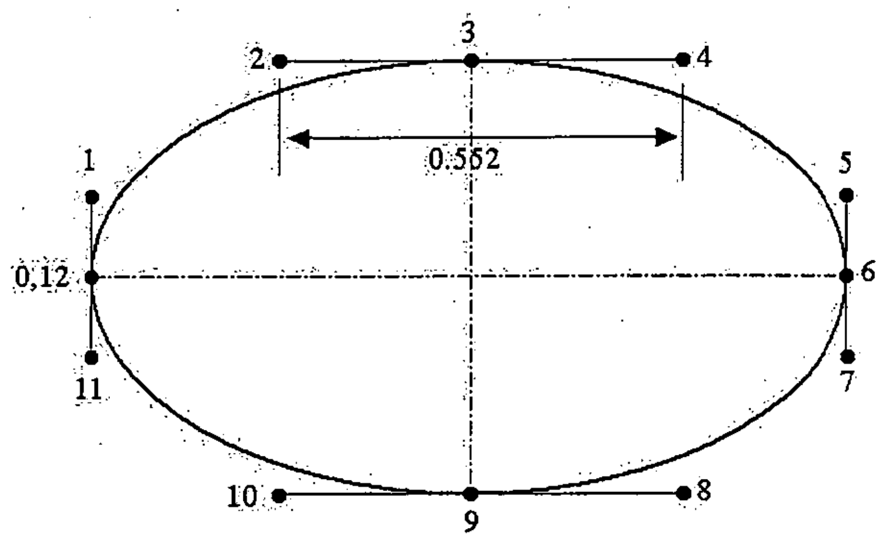


Figure 59: NURBS control point configuration for creating an ellipse

Figure 60 gives two example ellipses created using the above NURBS algorithm in the LUCID system by applying the SpaceMouse device transformation operation.

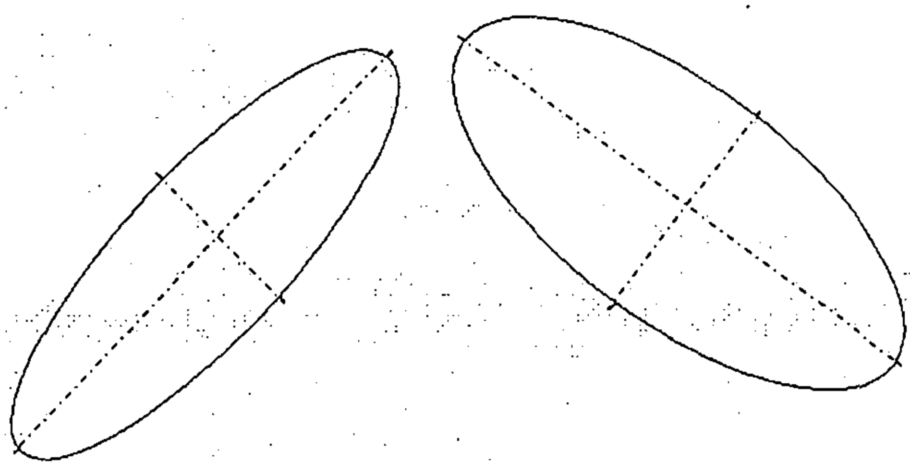


Figure 60: Rotated and skewed ellipses in the LUCID system

7.4 Cylinder and sphere surface design

In the LUCID system, cylinder and sphere creation were provided in the solid geometry sketching functions defined as the basic design tools. Both a cylinder surface and a sphere surface were standard freeform surfaces that could be represented efficiently and stably using NURBS methods.

7.4.1 Cylinder design

Normally, a full cylinder can be created by translating the NURBS circle a specific distance along a vector normal to the plane on which the circle is located. There are several methods available for creating a full circle using the NURBS representation algorithm. One simple solution, using a nine-point square-degree (also termed as a 2^{nd}-degree) control polygon NURBS representation was introduced in the LUCID system. That was,

$$C(u) = \sum_{i=0}^{8} R_{i,2}(u)P_i \tag{7.18}$$

where the knot vector was defined as $U = \{0,0,0,\frac{1}{4},\frac{1}{4},\frac{1}{2},\frac{1}{2},\frac{3}{4},\frac{3}{4},1,1,1\}$, the weight vector was defined as $\{w_i\} = \{1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1\}$ and the control points P_i were defined as (here described in terms of the unit dimension in 2D just for the purpose of simplicity)

$\{P_i\} = \{(1,0),(1,1),(0,1),(-1,1),(-1,0),(-1,-1),(0,-1),(1,-1),(1,0)\}$, as shown in Figure 61.

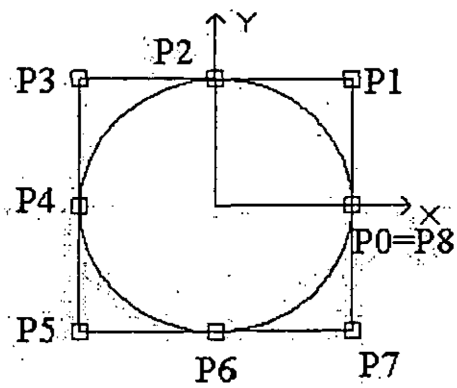


Figure 61: A nine-point square-based NURBS circle

In order to create a full circle in any position in 3D space, coordinate transformation calculations including translation and rotation were applied to the control points' P_i computation in a practical design application.

Therefore, a cylinder surface is defined using the NURBS method by

$$S(u,v) = \sum_{i=0}^{8}\sum_{j=0}^{1} R_{i,2;j,1}(u,v)P_{i,j} \tag{7.19}$$

where the knot vector $V = \{0,0,1,1\}$, the knot vector U and weights $w_{i,0}$ and $w_{i,1}$ are those given for the nine-point 2nd-degree control polygon representation circle creation. They can be described as follows:

$U = \{0,0,0,\frac{1}{4},\frac{1}{4},\frac{1}{2},\frac{1}{2},\frac{3}{4},\frac{3}{4},1,1,1\}$, $\{w_{i,0}\} = \{w_{i,1}\} = \{1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1,\frac{\sqrt{2}}{2},1\}$.

The control points are given by $P_{i,0} = P_i$ and $P_{i,1} = P_i + dW$ in which W is the vector of unit length which is normal to the plane of the construction circle, d is the distance along W and P_i are the control points of the construction circle (see Figure 62).

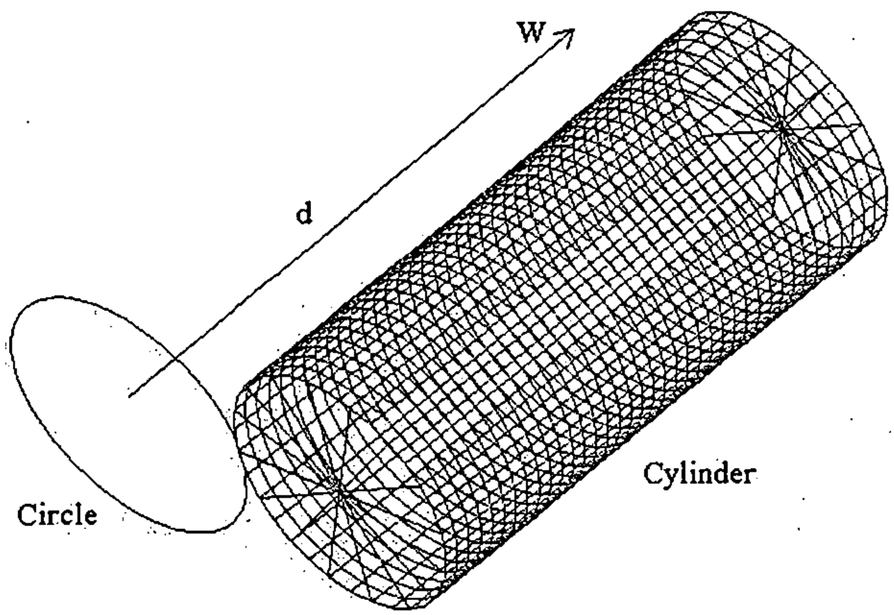


Figure 62: A cylinder designed using NURBS

Once a full circle is constructed using Equation (7.18), a cylinder surface or solid could be easily created by using Equation (7.19) in the LUCID system, as shown in Figure 62.

7.4.2 Sphere design

For the sake of simplicity, a sphere can be obtained by revolving a semi-circle about any axis where the two endpoints lie on that axis (see Figure 63 and the axis is defined as the Z axis, for example).

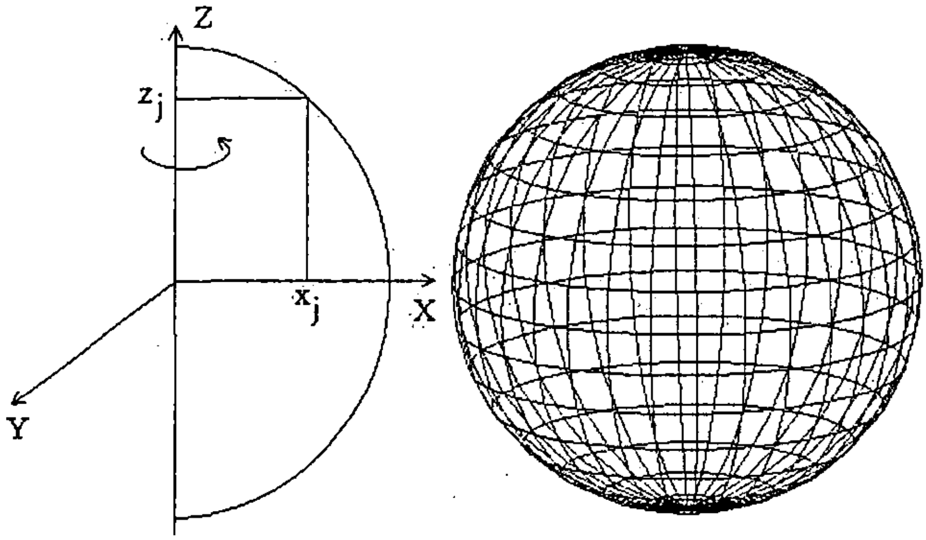


Figure 63: A sphere as a surface of revolution using NURBS

A sphere surface can be defined using a NURBS representation as

$$S(u,v) = \sum_{i=0}^{8} \sum_{j=0}^{4} R_{i,2;j,2}(u,v) P_{i,j} \tag{7.20}$$

where for the knot vectors U and V, $U = \{0, 0, 0, \frac{1}{4}, \frac{1}{4}, \frac{1}{2}, \frac{1}{2}, \frac{3}{4}, \frac{3}{4}, 1, 1, 1\}$ and $V = \{0, 0, 0, \frac{1}{2}, \frac{1}{2}, 1, 1, 1\}$, the weights $\{w_i\} = \{1, \frac{\sqrt{2}}{2}, 1, \frac{\sqrt{2}}{2}, 1, \frac{\sqrt{2}}{2}, 1, \frac{\sqrt{2}}{2}, 1\}$ and $\{w_j\} = \{1, \frac{\sqrt{2}}{2}, 1, \frac{\sqrt{2}}{2}, 1\}$, $w_{i,j} = w_i \times w_j$ (for the sphere surface), and the control points $P_{i,j}$ are determined as follows: For i = 0, $P_{i,j} = P_{0,j} = P_j$. Because of the circular nature of $S(u, \bar{v})$ for the fixed $\bar{v}$, the $P_{i,j}$ for the fixed j, $0 \le i \le 8$, all lie in the plane $z = z_j$. They lie on a square of width $2x_j$, with its centre on the Z-axis. Notice that the control points at the north and south poles of the sphere are repeated nine times respectively: This means that $P_{0,0} = \ldots = P_{8,0}$ and $P_{0,4} = \ldots = P_{8,4}$.

Therefore, a sphere surface or solid could be relatively easily created by using Equation (7.20) in the LUCID system, as shown in Figure 63. Also the NURBS algorithm guarantees that the continuous forms can be achieved both at the north and south poles of the sphere.

7.5 3D freeform surface design

Currently, the 3D freeform surface design in the LUCID system is implemented by feature-based design functions such as the sweeping feature, the lofting feature, the sculpting feature and the blending feature. All models involved in freeform feature-based design functions were represented using NURBS methods in the LUCID system. Due to the limitations of the LUCID system, all these NURBS approaches are applicable to full (uniform) patches only.

7.5.1 Freeform surface design by sweeping feature

Using the sweeping feature technology, a 3D freeform surface could be created by first sketching both a 3D freeform profile curve and a 3D freeform trajectory curve and then sweeping the sketched profile curve along the sketched trajectory curve, as shown in Figure 64.

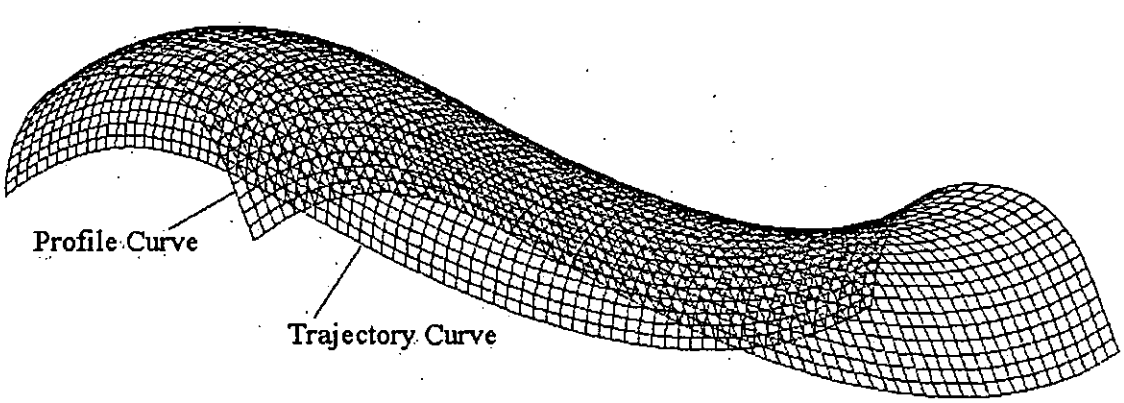


Figure 64: Example of a swept surface

If the profile curve is defined using NURBS as

$$C(u)=\frac{\sum_{i=0}^{n}N_{i,p}(u)w_i^C Q_i}{\sum_{i=0}^{n}N_{i,p}(u)w_i^C} \tag{7.21}$$

and the trajectory curve is defined using NURBS as

$$T(v)=\frac{\sum_{j=0}^{m}N_{j,q}(v)w_j^T T_j}{\sum_{j=0}^{m}N_{j,q}(v)w_j^T} \tag{7.22}$$

then the swept surface can be obtained by

$$S(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}} \tag{7.23}$$

which is defined on the knot vectors U and V, and has control points

$$P_{i,j}=T_j+Q_i \qquad i=0,\ldots,n,\ \ j=0,\ldots,m \tag{7.24}$$

and weights

$$w_{i,j}=w_i^C\times w_j^T \qquad i=0,\ldots,n,\ \ j=0,\ldots,m \tag{7.25}$$

Using Equations (7.23), (7.24) and (7.25), a closed 3D swept surface or solid was generated by first sketching a 3D freeform closed profile curve and a 3D freeform opened trajectory curve and then sweeping the closed sketched profile curve along the open sketched trajectory curve, as shown in Figure 65.

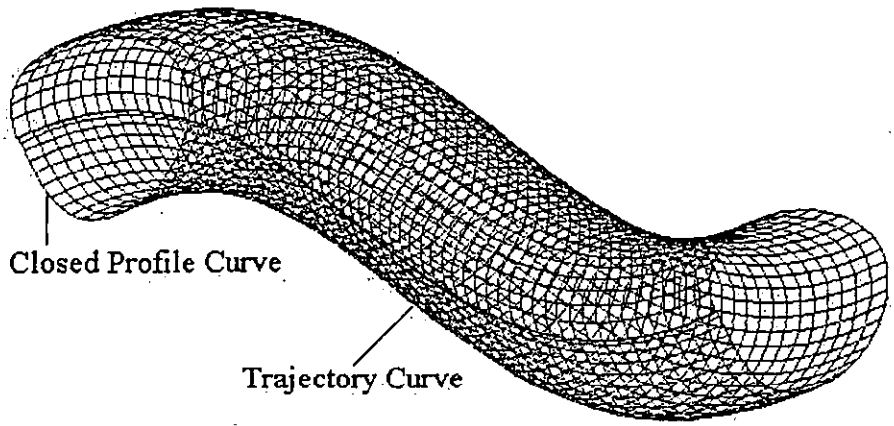


Figure 65: Example of a closed swept surface

7.5.2 Freeform surface design by lofting feature

Using the lofting feature technology, a skinned surface could be created by first sketching a set of section curves, and then smoothly lofting these section profiles together in a defined direction. Figure 66 gives an example of a freeform surface or solid created by lofting between four elliptical section profiles.

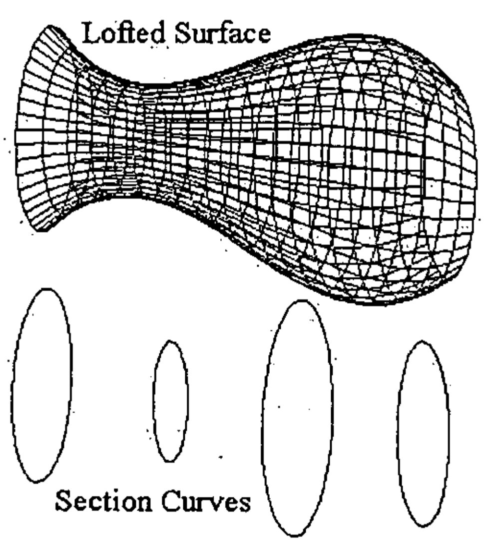


Figure 66: A lofted model created by ellipse section profiles

Let

$$C_k^w(u) = \sum_{i=0}^{n} N_{i,p}(u) P_{i,k}^w \qquad k = 0, \ldots, K \tag{7.26}$$

be the NURBS section curves. For the sake of simplicity, all $C_k^w(u)$ are defined on the same knot vector *U*, and have the same degree *p*. Then for the lofting direction *v* a degree *q* is chosen as 3 (the cubic-degree), parameters $\{\bar{v}_k\}$, $k = 0,\ldots,K$, and a knot vector *V* are computed using Equations (7.14) and (7.16). They are then used to do *n*+1 curve interpolations across the control points of the section curves, yielding the control points $Q_{i,j}^w$ of the lofted surface. Figure 67 demonstrates another example of the lofted surface, this time constructed by using a set of rectangles as the section profiles.

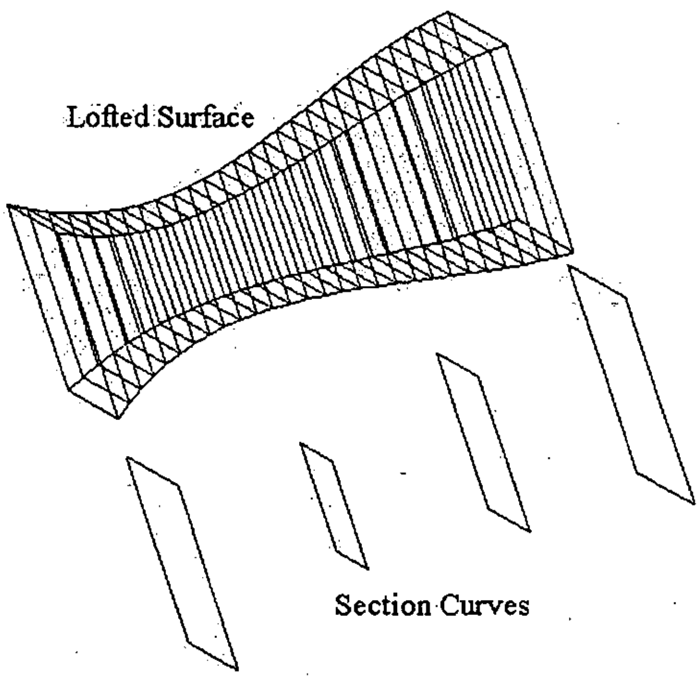


Figure 67: A lofted model created by rectangle section profiles

7.5.3 Freeform surface design by blending feature

The blending feature is sometimes considered as a kind of lofting feature in much literature. Here the difference between a lofting feature and a blending feature is defined as a blending feature being one that is created by a linear ruled construction whereas a lofting feature is obtained by a smooth ruled creation.

Let Equation (7.26) describe the NURBS section curves. Again for the sake of simplicity, all $C_k^w(u)$ are defined on the same knot vector U, and have the same degree p. Then for the blend direction v a degree q is chosen as 1 to perform the linear blending operation. In such a way, it is possible to simply combine the control points of different section curves to form the needed control points of the blended surface. Figure 68 demonstrates an example of the blended surface created by using a set of rectangles as the section profiles.

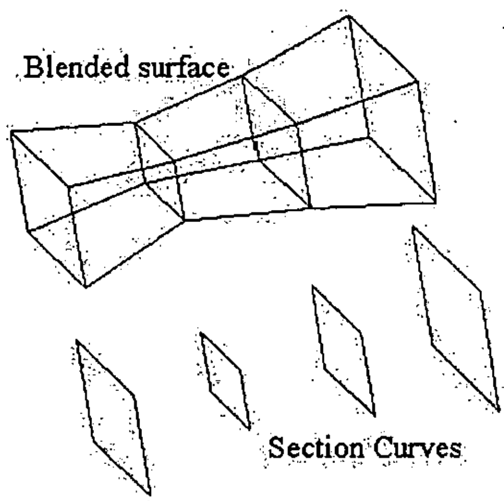


Figure 68: A blended model created by rectangle section profiles

7.5.4 Freeform surface design by sculpting feature

The sculpting feature is sometimes named as the cutting feature which allows traditional physical model making skills to be used directly in a digital design environment. Trimmed freeform surfaces are often produced during the sculpting feature creation. As mentioned before, the focus in this research is on new CAD UIs rather than on design functions. Therefore, the LUCID system does not employ a third party CAD modelling kernel package such as the Spatial's ACIS or the Electronic Data Systems' Parasolid to carry out the complex calculation of trimmed freeform surfaces. It uses the following methods to demonstrate the trimmed freeform surface reconstruction when the sculpting feature function is applied to the designed model.

In the LUCID system, the sculpting feature could be created by applying either a freeform curve or a freeform surface as the sculpting tool profile to a solid model. If the sculpting tool profile was defined as a freeform curve as in Equation (7.1), the sculpting surface could be obtained by the freeform curve sweeping along the defined sculpting direction (perpendicular to the screen plane by default). The sculpting surface formed could be calculated using Equation (7.4). If the sculpting tool profile was defined as a swept freeform surface, the sculpting surface could be obtained using Equation (7.23). Later, the intersection points between the sculpting freeform surface and the solid model were calculated using pure mathematical algorithms introduced in the literature [Schneider and Eberly 2003]. If the obtained intersection points could form a uniform set of $(n+1)\times(m+1)$ data points $\{Q_{k,l}\}$, $k=0,\ldots,n$ and $l=0,\ldots,m$, then the trimmed freeform surface could be calculated by a 3rd-degree NURBS surface interpolating all these points,

$$Q_{k,l}=S(\bar{u}_k,\bar{v}_l)=\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,3}(\bar{u}_k)N_{j,3}(\bar{v}_l)P_{i,j} \tag{7.27}$$

Again the first order of work was to compute reasonable values for the $(\bar{u}_k,\bar{v}_l)$ and the knot vectors U and V. Here an approach for computing the $\bar{u}_k$ is followed. The computation of $\bar{v}_l$ was analogous to $\bar{u}_k$. A common method was to use Equation (7.14) to compute parameters $\bar{u}_0^l,\ldots,\bar{u}_n^l$ for each l, and then to obtain each $\bar{u}_k$ by averaging across all $\bar{u}_k^l$, $l=0,\ldots,m$, that is

$$\bar{u}_k=\frac{1}{m+1}\sum_{l=0}^{m}\bar{u}_k^l \qquad k=0,\ldots,n \tag{7.28}$$

where for each fixed l, $\bar{u}_k^l$, $k=0,\ldots,n$, was computed by Equation (7.14).

Once the $(\bar{u}_k,\bar{v}_l)$ were computed, the knot vectors U and V could be obtained by Equation (7.16). Clearly, Equation (7.27) represented a $(n+1)\times(m+1)$ linear equations with the unknowns $P_{i,j}$. However, since $S(u,v)$ was a tensor product surface, $P_{i,j}$ could be obtained more simply and efficiently as a sequence of curve interpolations. For fixed l, Equation (7.27) could be re-written as

$$Q_{k,l} = \sum_{i=0}^{n} N_{i,3}(\bar{u}_k)\left(\sum_{j=0}^{m} N_{j,3}(\bar{v}_l)P_{i,j}\right) = \sum_{i=0}^{n} N_{i,3}(\bar{u}_k)\, R_{i,l} \tag{7.29}$$

where $$R_{i,l} = \sum_{j=0}^{m} N_{j,3}(\bar{v}_l)\, P_{i,j} \tag{7.30}$$

Notice that Equation (7.29) was just a curve interpolation through the points $Q_{k,l}$, $k = 0,\ldots,n$. $R_{i,l}$ were the control points of the freeform curve on $S(u,v)$ at fixed $v = \bar{v}_l$. Similarly, fixing i and letting l vary, Equation (7.30) was a curve interpolation through the points $R_{i,0}$, ... , $R_{i,m}$, with $P_{i,0}$, .. , $P_{i,m}$ as the computed control points. Thus, the algorithm to obtain all the control points $P_{i,j}$ is summarised as follows:

- Using U and the $\bar{u}_k$, do $m+1$ curve interpolations through $Q_{0,l}$, ... , $Q_{n,l}$ (for $l = 0,\ldots,m$) to obtain $R_{i,l}$.
- Using V and the $\bar{v}_l$, do $n+1$ curve interpolations through $R_{i,0}$, ... , $R_{i,m}$ (for $i = 0,\ldots,n$) to obtain $P_{i,j}$.

If the intersection points obtained in the sculpting feature creation could not form a uniform set of data points for a NURBS surface solution, a triangular mesh was created using these intersection data points to approximately represent the trimmed freeform surface in the LUCID system.

Figure 69 shows an example of the trimmed freeform surface created using the NURBS algorithm. In Figure 70, a triangular mesh simulated the trimmed freeform surface since the intersection points could not result in a uniform data set for the NURBS solution.

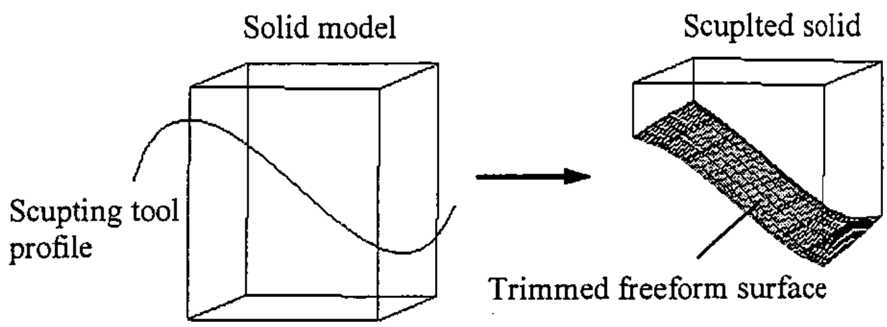


Figure 69: Example of a trimmed freeform surface using a NURBS solution

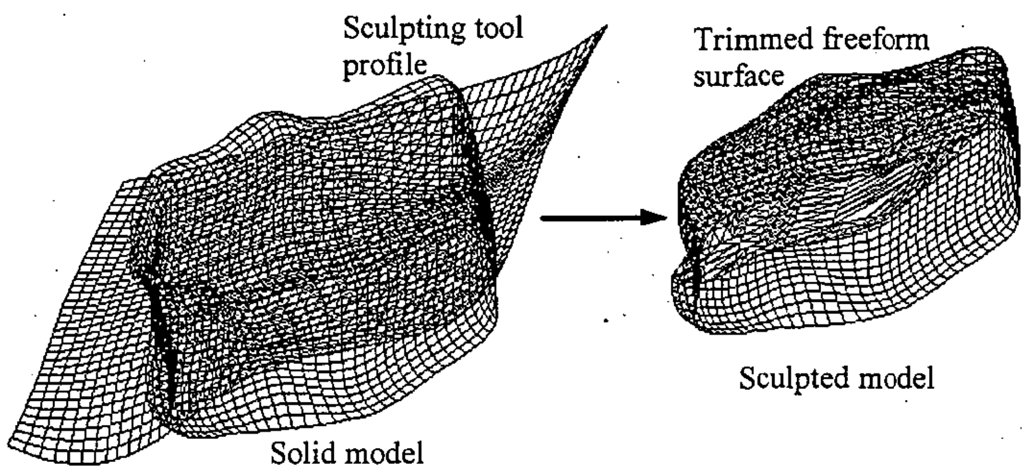


Figure 70: Example of a trimmed freeform surface using a triangular mesh solution

7.6 Summary

In this chapter, geometric modelling using the NURBS algorithm was discussed. An efficient cubic-degree NURBS algorithm for 3D freeform curve design has been developed and implemented. This freeform curve NURBS solution has also been successfully applied to ellipse curve design in the LUCID system. As special freeform surface design cases, cylinder and sphere creations using NURBS solutions have been developed and implemented. Other freeform surface design methods using NURBS algorithms for several feature-based design approaches have also been presented in detail along with demonstration examples.

CHAPTER EIGHT

Design functions and model data exchange

As stated before, the focus of this research is on new CAD human computer interfaces (HCIs) rather than on design functions. However, it is necessary to develop a level of design functionality that will demonstrate the advantages of the new user interface (UI) methods involved in the design process. Therefore, it was decided to select and develop functional tools that would be of most benefit to conceptual designers whilst using the LUCID system. Furthermore, in order to facilitate better integration of the LUCID system within a total product design and development process, it was decided that the LUCID system should provide practical CAD model data sharing facilities as much as possible.

8.1 Sketching tool design

As stated earlier, the importance of drawing, both formal drafting and informal sketching, has been widely recognised particularly during the early product design process. A survey among designers from different enterprises indicated that besides CAD systems, handmade paper-based sketches still played a crucial role during the product design process, in particular, in the early stages of the product design process [Pache, Weisshahn *et al* 1999]. According to the results they found, more than half of the designers indicated that they frequently used handmade paper-based sketches at least before the use of CAD systems. Also while working with CAD about 35% of the designers used sketches frequently or always. Over 90% indicated that the development of new solutions during conceptual design was a primary reason for the use of sketches. Since sketching offers ease of use, fast access and quick production of design results, most designers use sketches frequently while working with commercial CAD systems.

Therefore, an integration of a series of sketching design tools into a practical CAD application would be very important, in particular during the conceptual design stage.

8.1.1 Sketching tool design and implementation

After observation of the tools used and the operations performed by industrial designers in order to create their physical models, the LUCID system was outlined first with design tools to perform sketching functions in the design process. These sketching design functions were classified into several groups respectively: the line geometry section, the closed line geometry section, the 3D solid geometry section and most importantly, the freeform surface geometry section. In the line geometry section, using sketching design functions one could create generic lines, vertical/horizontal lines, polylines and more importantly, freeform curves. An effective algorithm for a natural cubic-degree spline interpolation was developed to create 3D freeform curves (see Section 7.2 in Chapter Seven for the mathematical algorithm). In the closed line geometry section, sketching design functions needed to generate rectangles, polygons, rounded rectangles, ellipses and closed freeform curves were developed and implemented in the LUCID system. Cube, sphere, cylinder and pyramid creation functions constituted the 3D solid geometry section. More importantly, the LUCID system also supports 3D freeform surface creation functions employing freeform feature-based design technologies (see Section 7.5 in Chapter Seven for their mathematical algorithms). Figure 71 shows an image created by some of these sketching design functions in the LUCID system. The LUCID system supports not only traditional paper-based 2D sketching functions which are prevailed in most commercial CAD systems, but also new 3D freehand sketching design tools. These 3D freehand sketching functions provide a true 3D design capability in a CAD application which is lacking in most commercial CAD systems. Here the true 3D design capability means the model is designed completely in 3D (both input and output) and it gives several sensorial feedbacks when it is manipulated (such as touched or deformed), which is quite similar to a true model existent in the physical world.

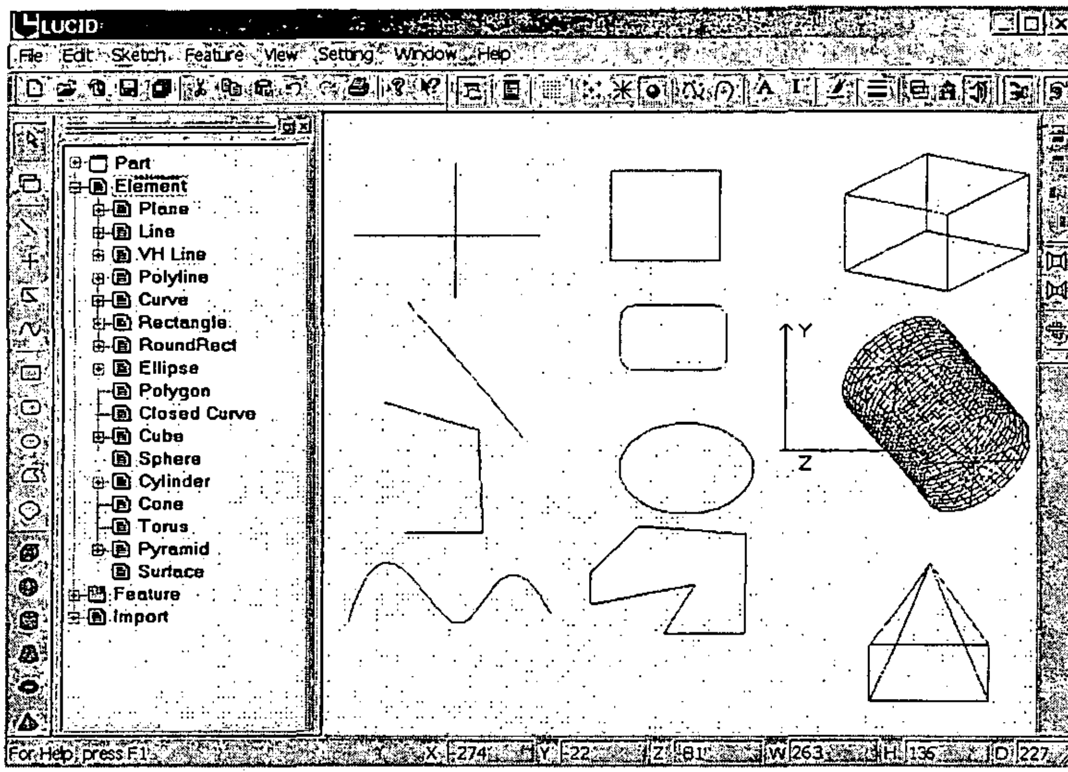


Figure 71: An image of sketching using the LUCID system

8.1.2 Requirements for 3D freehand sketching

Since CAD offers many advantages in contrast to traditional handmade paper-based sketches such as the spatiality of the CAD models and the transformation of the CAD models (panning, rotating and zooming), a computer-based freehand sketching tool should combine the creativity-supporting characteristics of traditional freehand sketches together with the advantages of digital system environments. Furthermore, a digital freehand sketching tool only makes sense if the sketch can be done completely in 3D rather than in 2D. The findings from case studies indicated that designers very much expected a 3D freehand sketching tool to perform their design work more efficiently and effectively during the product design process (see Section 4.1 in Chapter Four). Other design applications such as the artistic sculpture and design for rapid manufacture also need such a true 3D design capability. Therefore, it was decided that the LUCID system should provide a 3D freehand sketching design function to meet the designers' requirements as closely as possible.

8.1.3 3D freehand sketching tool design and implementation

The LUCID system provides several 3D freehand sketching design functions including the 3D line freehand sketching, the 3D polyline freehand sketching, the 3D polygon freehand sketching and more importantly, the 3D freeform curve freehand sketching. The LUCID system supports these 3D design approaches by using a 3D Phantom Desktop device for 3D input of the sketches and a stereoscopic display for 3D visual output.

Since a method for low-level data accessing to the Phantom haptic device was developed and implemented in the LUCID system (see Section 6.5.2 in Chapter Six), the 3D position data information of the stylus arm of the Phantom haptic device can be captured in real-time through the haptic rendering servo loop running at about a 1000 Hz cycling rate. The 3D position data obtained can be displayed using stereoscopic visualisation after some simple data processes such as the different coordinate systems' translation and the scale factors' multiplication. Therefore, in the LUCID system, the Phantom haptic device provides not only the force feedback interaction, but also the direct 3D input method which can be seen using the stereoscopic display output interface.

Figure 72 (a) gives an example of a 3D freehand polygon sketching created in the LUCID system. Furthermore, the LUCID system supports modification tools to directly deform the created polygon by moving the vertex of the polygon in a 3D freehand way exactly the same as that in the physical world (see Figure 72 (b) and (c)). Since the images in Figure 72 are shown in a 2D paper-based mode, the real effect of the 3D freehand design and deformation is not seen clearly.

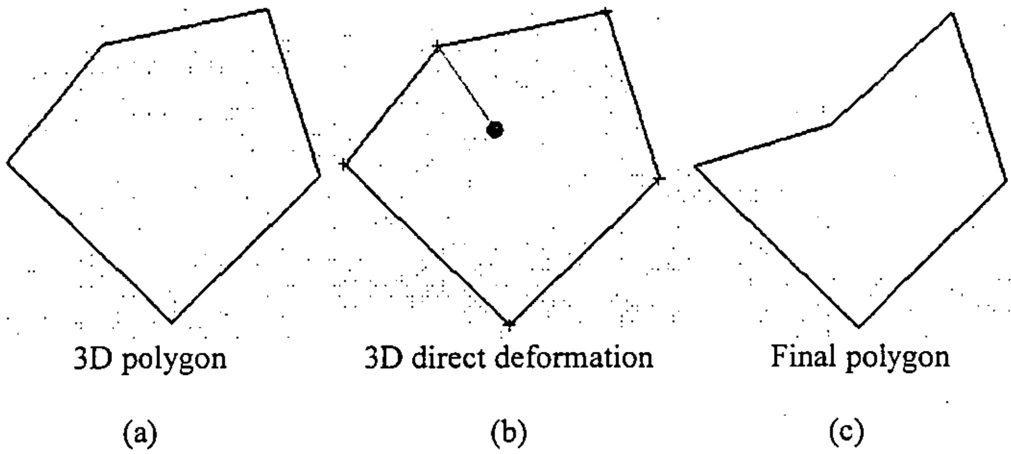


Figure 72: 3D freehand sketching and deformation of a polygon

As discussed earlier (see Section 7.2 in Chapter Seven), 3D freeform curve design was an important tool available in the LUCID system. A direct 3D freehand deformation tool could be used to modify the created curve in 3D space, even incorporating spring law-based force and sound feedback. This provided designers with a more natural working style so as to support a true 3D design capability rather than just a dragging operation as in most conventional CAD applications. Figure 73 (a) shows an example of a 3D freeform curve sketched in the LUCID system. Figure 73 (c) gives a typical result after a 3D freehand modification operation was performed on the created curve. Again, due to the images in Figure 73 being displayed in a 2D paper-based mode, the real effect of the 3D freehand design and deformation is not seen clearly.

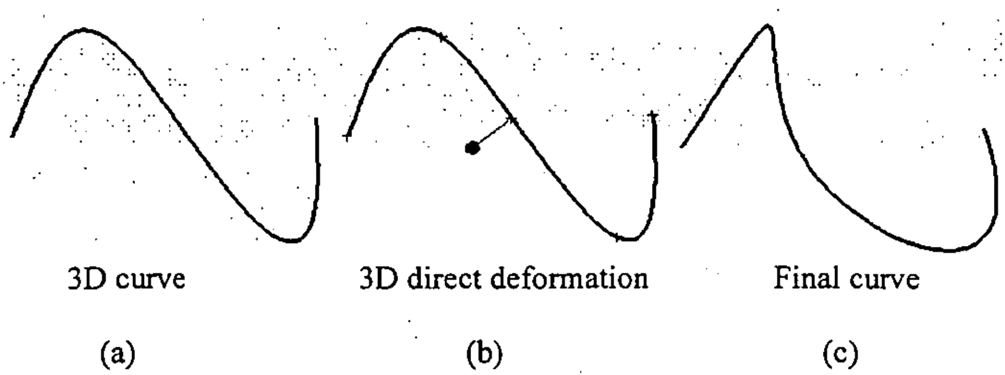


Figure 73: 3D freehand sketching and deformation of a curve

8.2 Freeform feature-based function design and implementation

As stated before, the feature-based modelling approach is considered to be an attractive technique which provides enhanced design tools in CAD modelling especially for fast freeform shape creation. In order to meet the designers' requirements developed in Chapter Four (see Table 2 and Figure 28), several freeform feature-based design functions were abstracted and developed in the LUCID system. These included the sculpting (cutting) feature, the sweeping feature, the lofting feature and the blending feature. Implementation of these freeform feature-based design functions in the LUCID system provided designers with enhanced functional tools for their design activities supported by the integration and implementation of the four VR-based innovative HCIs.

8.2.1 Sculpting feature design and implementation

As discussed earlier, the sculpting feature is sometimes termed as the cutting feature which allows traditional physical model making skills and experience to be used directly in a digital environment. The NURBS algorithm for the sculpting feature design was discussed in detail in Section 7.5.4 of Chapter Seven. The sculpting tool profile such as a freeform curve and a freeform surface could be directly sketched by designers using the 3D freehand sketching tool available in the LUCID system.

Currently, the sculpting feature can be created by applying a freeform curve or a freeform surface as a sculpting tool profile to a solid model such as a cube or a lofted solid. Since a line was normally considered as the simplest case of a freeform curve, a sculpting tool profile could be defined as a line by creating a freeform curve that contained only two input points. Figure 74 gives an example of a sculpted model created by a line tool profile.

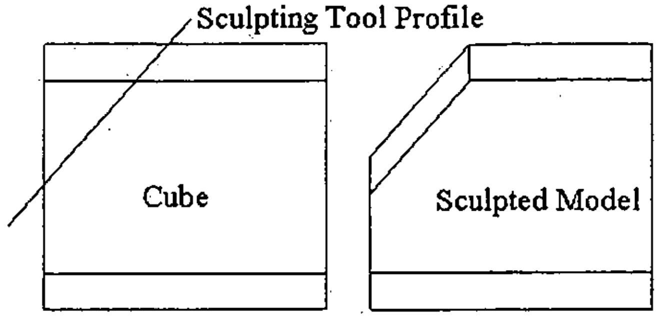


Figure 74: A sculpted model created by a line sculpting tool profile

In Figure 75, a sculpted model is obtained by first sketching a cube as a solid model and a 3D freeform curve as a sculpting tool profile, then performing the sculpting feature creation function provided in the LUCID system.

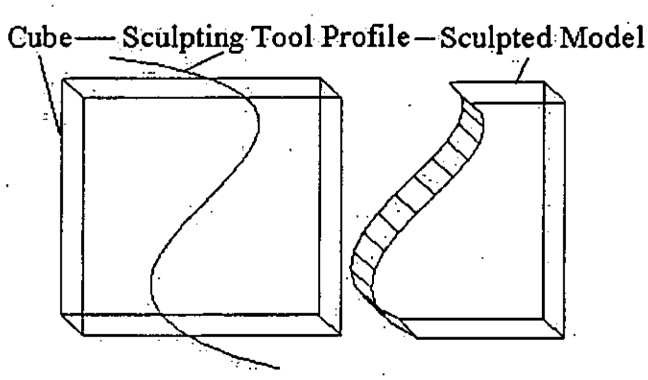


Figure 75: A sculpted model created by sculpting feature design

In the LUCID system, due to the complex algorithm calculation, the sculpting feature creation function can be performed only on the condition that the sculpted model contains one sculpting tool profile. This means only one sculpting feature can be created on a solid model at the moment. Furthermore, all sculpted models can generate force and sound feedback when they are touched by the Phantom haptic device.

As mentioned above, the LUCID system also supports sculpting feature creation using a 3D freeform surface as a sculpting tool profile. For example, a sculpted solid can be gained from applying a 3D freeform surface to cut through a solid model such as a 3D cube or a lofted solid (see Figure 76).

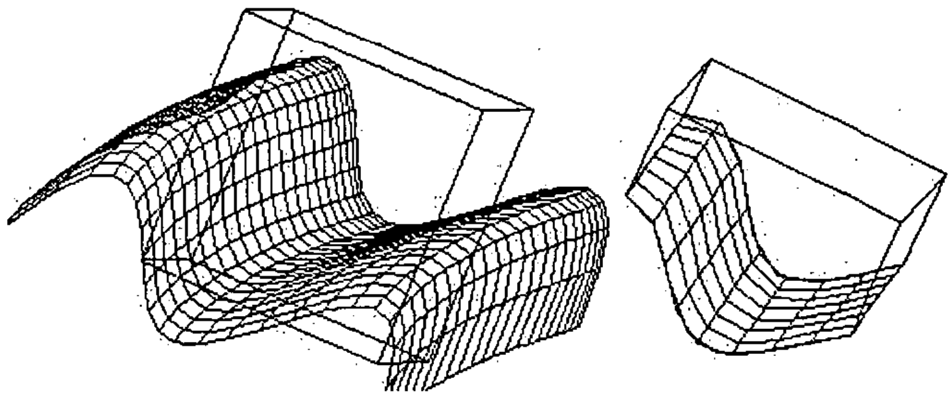


Figure 76: A sculpted model created by using a freeform surface cutting tool

8.2.2 Sweeping feature design and implementation

The sweeping feature function allows designers to create 3D freeform surfaces relatively easily and directly using the 3D freehand sketching tool provided in the LUCID system. The NURBS algorithm for the sweeping feature design was discussed in detail in Section 7.5.1 of Chapter Seven. Several examples of creating 3D freeform surfaces using the sweeping feature design method were also demonstrated. Figure 77 gives another example of a 3D freeform surface created by the sweeping feature design approach supported in the LUCID system.

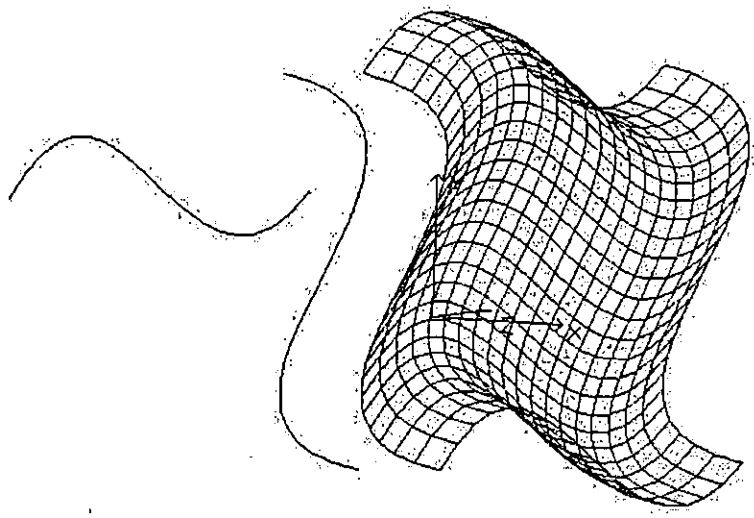


Figure 77: A 3D freeform surface created by sweeping feature design

Using the sweeping feature design function, designers can create not only freeform surfaces, but also freeform solids. One solid model is created as an example of this method and shown in Figure 78.

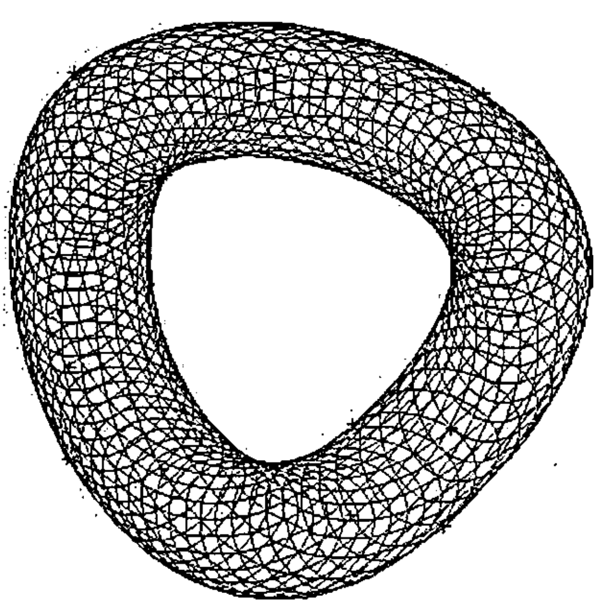


Figure 78: A solid model created by sweeping feature design

One characteristic of the sweeping feature design function is that it provides direct haptic modification on the swept model created. This means that designers can improve or modify their design contents after the swept model is created. This performance can be relatively easily achieved by moving and rotating the swept model directly via the SpaceMouse device operation to locate the desired model position, and then changing the positions of the sample points displayed on the swept model directly through the 3D Phantom Desktop device operation. When the swept model is touched or points on the swept model are moved, designers can feel the haptic feedback in their hand via the 3D Phantom haptic device and hear volume-variable sound through the computer supported speaker-based auditory system. Compared to traditional CAD systems, more information feedback is gained to increase interactive abilities while using the LUCID system.

8.2.3 Lofting feature design and implementation

The lofting feature function is another useful design tool for creating freeform surfaces and solids in the LUCID system. The NURBS algorithm for the lofting feature representation was provided in Section 7.5.2 of Chapter Seven. Several examples of creating 3D freeform surfaces using the lofting feature design approach were also demonstrated. Figure 79 gives another example of a 3D lofted model created by the lofting feature design method using several ellipse profiles.

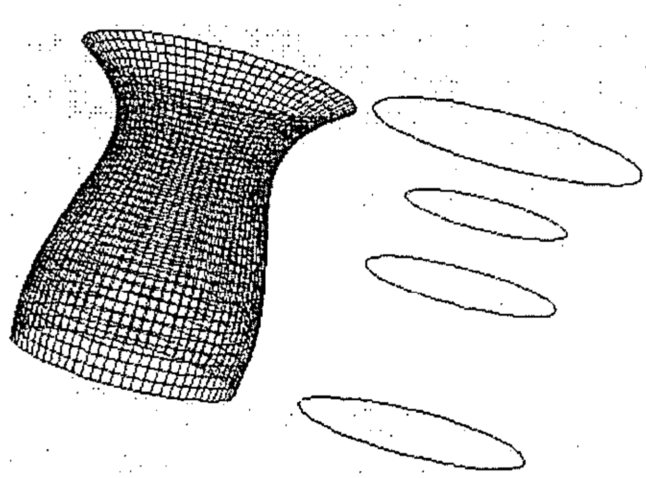


Figure 79: A lofted model created by ellipse profiles

Using the lofting feature tool, designers can create as many freeform surfaces as they require for their design process. All lofted models can generate force and sound feedback when they are touched by the Phantom Desktop haptic device in the LUCID system. Furthermore, a lofted model can be used as a base solid to create a sculpting feature on the model if needed thereafter (see the demonstration example model used for the user evaluation test in Chapter Nine).

8.2.4 Blending feature design and implementation

The LUCID system also supports the blending feature design function for creating freeform surfaces and solids. In some literature, this feature is also considered as a special kind of lofting features as was discussed in the previous section. Figure 80 gives an example of a 3D freeform model created by the blending feature design approach in the LUCID system.

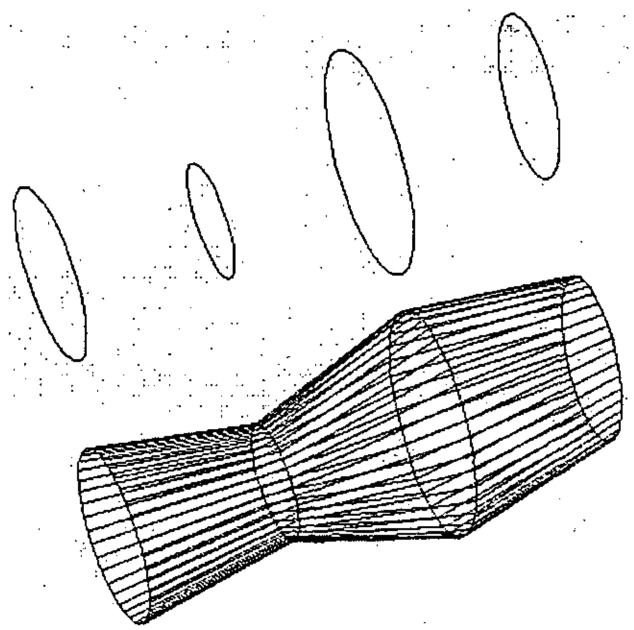


Figure 80: A blended model created by ellipse profiles

Similar to the lofting feature design function, the blending feature design function provides designers with another useful design tool for creating as many freeform surfaces as they require for their design process. Force feedback and sound feedback interactions are also applicable to all blended models designed in the LUCID system.

The current LUCID system only supports simple freeform feature-based design operation functions since the research focuses mainly on HCI design rather than complex functional designs.

8.3 Model data exchange in the LUCID system

The LUCID system currently has its own file format used to store its model data. The file extension is defined as ***.prt*** for models created in the LUCID system.

In order to provide certain CAD model data sharing facilities and to extend the LUCID system to be used for other useful applications such as product design evaluation, model data in other file formats such as the STL file format and the VRML Version 2.0 file format needed to be imported into the LUCID system seamlessly. In this case, very complex product models could be first designed in other commercial CAD systems and then imported into the LUCID system to be evaluated thoroughly using its four VR-based interaction tools. Figure 81 gives an example of using the LUCID system to evaluate a CAD model in the STL file format (a spider model seen often in the RP field). Figure 82 shows a VRML file format model (a human heart from the medical field) that was loaded into the LUCID system so that examination could be performed intuitively and directly with the four VR-based user interfaces.

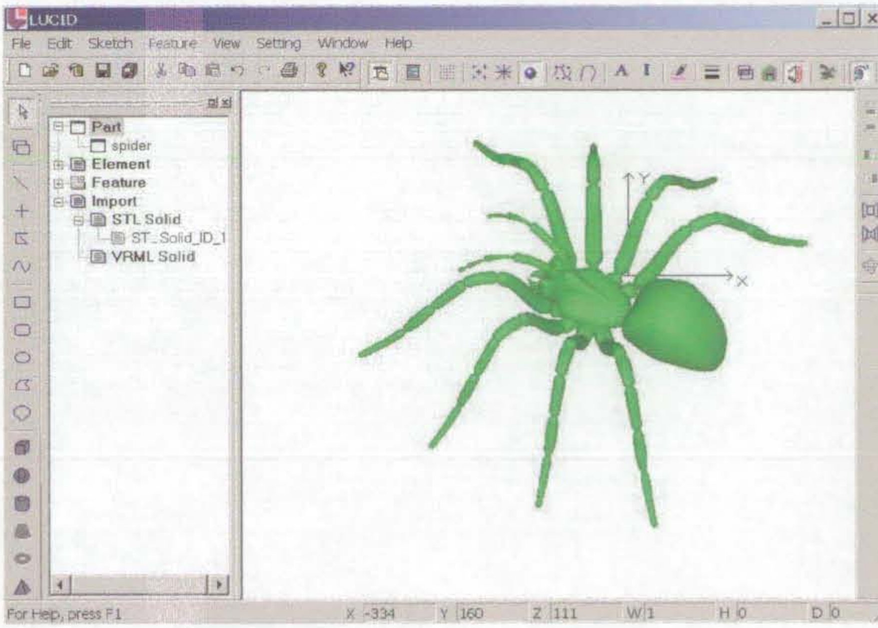


Figure 81: Evaluation of an STL model using the LUCID system

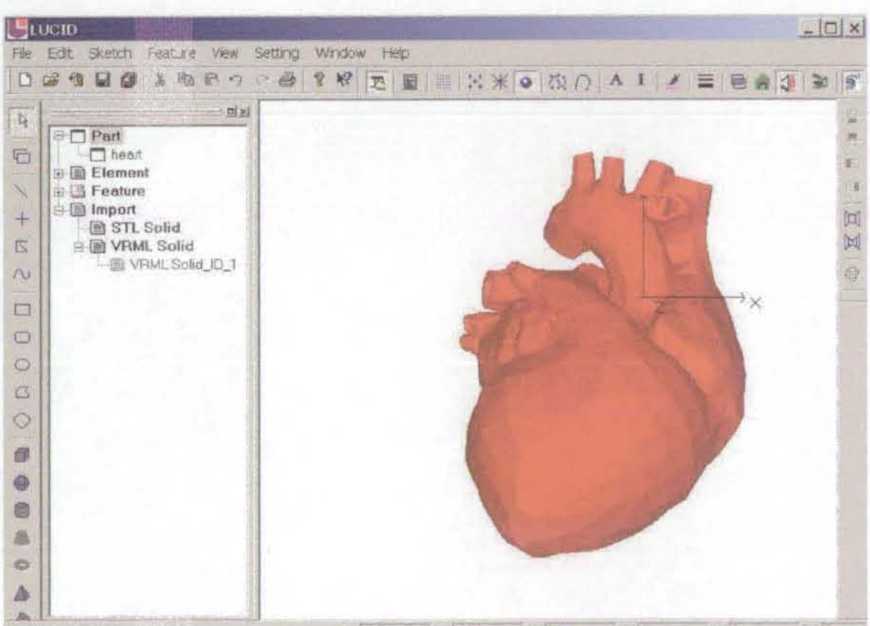


Figure 82: Examination of a VRML model using the LUCID system

More importantly, the LUCID system also supports the export of its CAD model data in either the STL file format or the VRML file format so as to enable other CAD software packages to share the model data conveniently. In Figure 83, a CAD model created in the LUCID system was first exported as an STL file format model and then reloaded as a "reflection test" of the translation algorithm. Figure 84 demonstrates a model which was exported and re-input as a VRML file format model. These useful data import/export facilities enable the LUCID system to be connected to other commercial CAD systems easily so as to create a new solution to product design and evaluation in a fully digital and virtual environment. In particular, the STL file format supporting function of the LUCID system makes it possible to manufacture the designed model directly on a variety of computer controlled RP machines.

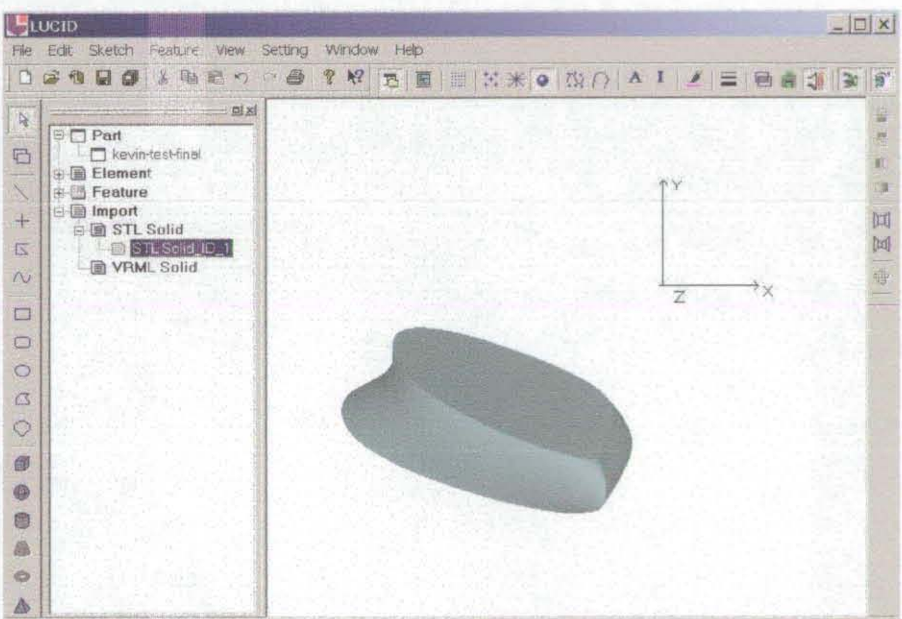


Figure 83: A CAD model exported and re-loaded in the STL file format

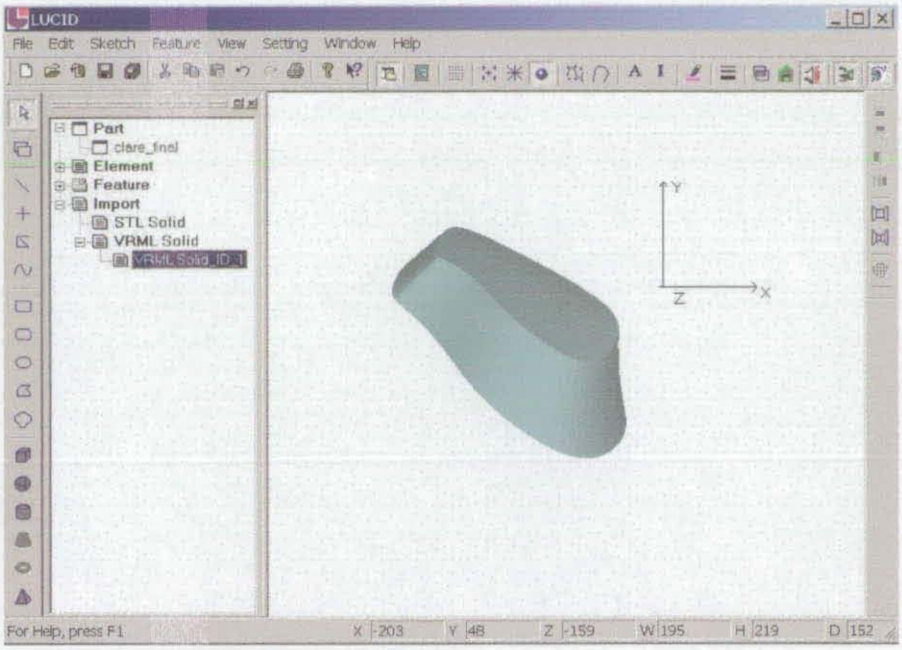


Figure 84: A CAD model exported and re-loaded in the VRML file format

8.4 Summary

In this chapter, design functions that were implemented in the LUCID system have been presented. In particular, a 3D freehand sketching tool has been developed to provide a true 3D design capability in a CAD application. Four freeform feature-based design functions (sculpting feature design, sweeping feature design, lofting feature design and blending feature design) have been described along with demonstration examples. CAD model data exchange facilities available within the LUCID system were also presented. Currently, there are limited design functions available in the LUCID system since the research focused more on CAD HCIs rather than on design functions. However, the level of design functionality provided was sufficient to enable evaluation of the LUCID system by designers from both academia and industry, as described in the next chapter.

CHAPTER NINE

User evaluation tests and analysis

The aim of the LUCID system is to give better support to conceptual design through its multiple VR-based user interface integration and implementation which is completely realised in one practical design application. User evaluation tests of the LUCID system were designed and conducted in order to assess whether this objective had been met.

The user evaluation test consisted of a demonstration example modelling task to be undertaken and a formal questionnaire to be completed. Each participant was asked to design a computer mouse model using the LUCID system. Considering the fact that the timescale was not very long and the participants had no previous experience in using either the SpaceMouse device or the Phantom haptic force feedback device, they were not expected to come up with refined designs at the end of the user evaluation test. However, they were able to judge several aspects of the usefulness of HCIs in the design process after using the LUCID system. Their comments were valuable for providing data on the potential and drawbacks of the LUCID system.

9.1 Objective of user evaluation test

In order to test whether the LUCID system could give better support to conceptual design through its multiple innovative VR-based HCIs, an example of creating a computer mouse model is selected to demonstrate the LUCID system's interactive abilities and design functions. Although the LUCID system has limited design functions, the computer mouse model design example gives a full demonstration of using the design functions available at present, focusing mainly on the four new VR-based HCI operations (two-handed operation, stereoscopic display, haptic interaction and sound feedback), the 3D freehand sketching tool and the freeform feature-based design functions (sculpting feature function, sweeping feature function and lofting feature function). The main objectives of the user evaluation test were: i) to evaluate the limitations of current CAD systems used by designers, ii) to identify designers' expectations of new HCIs that could give better support to design activity, iii) to determine the advantages and drawbacks of the four new VR-based HCIs used in the LUCID system and iv) to find out the strengths and weaknesses of the LUCID system.

9.2 Participants of user evaluation test

The user evaluation tests involved eight design researchers, five industrial designers and three engineering designers. All participants were experienced CAD users and were proficient in using Pro/Engineer, AutoCAD or some other CAD systems. It was important to ensure this fact, since the LUCID system let designers carry out their design work using VR-based innovative HCIs that were quite different from those used in most commercial CAD systems. Their design background along with their design knowledge and experience in CAD made the data collection more efficient since they could compare the LUCID system with other conventional CAD systems they had used and thus gave their valuable comments.

9.3 Venues and equipments used in evaluation test

The user evaluation tests were conducted either at the research office in the Department of Design and Technology, Loughborough University or at company sites with industrial designers and engineering designers. The LUCID system including a high performance desktop PC, a Phantom Desktop force feedback device, a six DOF SpaceMouse input device, a stereoscopic display toolkit and a computer-supported speaker-based auditory system was utilised to perform the user evaluation test. During the user evaluation test, photographs of the participants were taken with a digital camera to illustrate how they used the

LUCID system. Demonstration model data files were recorded in the computer for each participant in different sessions. Therefore, any problem encountered during the user evaluation test could be traced back and an improvement modification on the LUCID system could be made afterwards.

9.4 User evaluation test technique

Before each user evaluation test, relevant documents were distributed to each participant including i) *Introduction to the LUCID system,* ii) *Example Demonstration of Using the LUCID System* and iii) *Questionnaire – The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process*. During the user evaluation test, all participants were given a brief demonstration on how to use the Phantom Desktop force feedback device, the six DOF SpaceMouse input device, the stereoscopic display toolkit and the speaker-based auditory system. Design functions such as the 3D freehand sketching tool and freeform feature-based functions were also introduced to attendees so that they could perform their demonstration model design using the LUCID system. During the user evaluation test, they were free to ask the observer for further help if they had difficulties in operations. On average, the user evaluation test was finished within one hour. After the demonstration modelling operation, a formal questionnaire was used to collect valuable comments from all participants based on their evaluation experience focusing especially on the four new VR-based HCIs used in the LUCID system.

9.5 Selecting the design model for user evaluation test

It was decided that the design model should be suitable for 3D construction using the 3D freehand sketching design and freeform feature-based creation. A computer mouse model was chosen since today every desktop computer is equipped with a standard mouse and keyboard interface. At first glance the computer mouse model is small and simple, but its shape consists of many freeform surfaces and freeform curves which are tedious to design even in most conventional commercial CAD systems. All participants could explore their demonstration modelling design interactively using design functions available in the LUCID system.

9.6 Design method for the mouse model

After carefully studying the mouse model geometry, an easy and simple method for creating its basic shape was found in order to use the LUCID system. First, sketching different freeform curve profiles on different cross-sections (or planes) based on the mouse shape changed in its height direction. Secondly, generating a 3D freeform surface-surrounded solid model through the lofting feature creation technology based upon these sketched sectional profiles. Next, by using the sweeping feature design function, creating a 3D freeform surface with the desired shape form of the upper freeform surface of the mouse model. This could be achieved by the 3D freehand direct haptic modification of the sampling interpolation points on the surface. Then positioning the 3D freeform surface onto the 3D lofted solid model, setting the 3D freeform surface as the cutting tool and the 3D lofted solid model as the base solid to be cut, and performing the sculpting feature function provided by the LUCID system. This generated the basic geometry of the mouse model to be designed (see Figure 85).

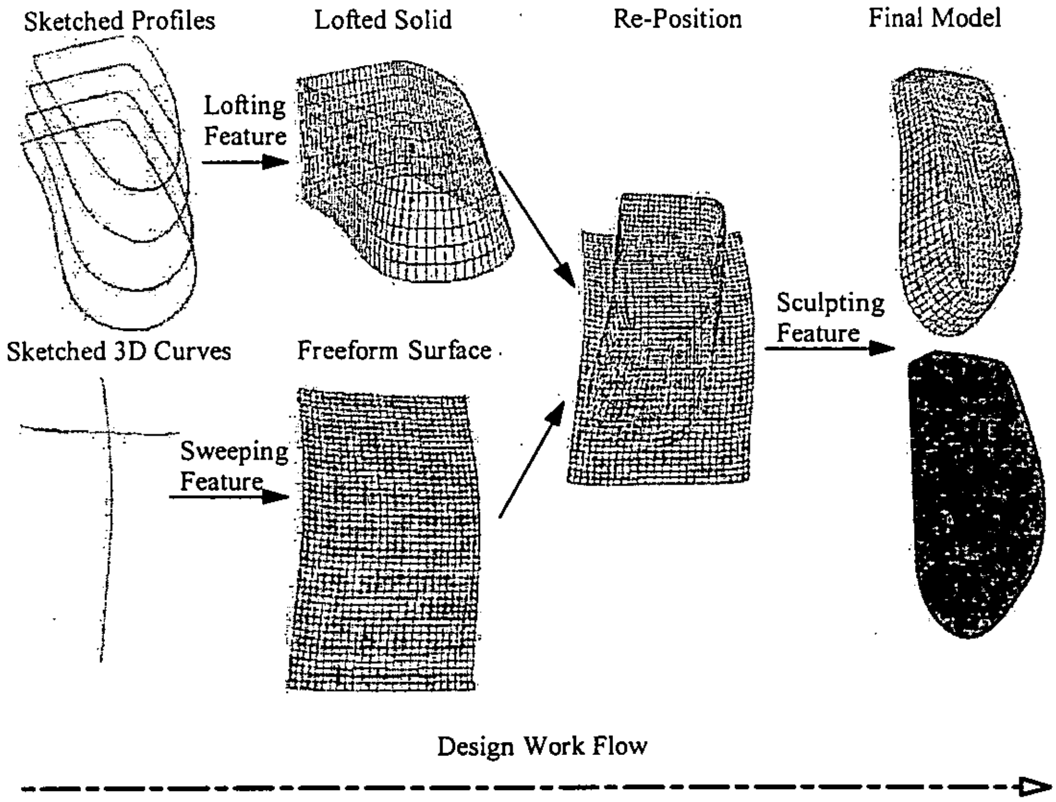


Figure 85: The example mouse model for user evaluation test

Since the LUCID systems supports the stereoscopic display, haptic interaction and sound feedback functions, a more realistic 3D mouse model can be viewed on the screen and be touched with haptic force feedback and sound feedback. More importantly, the SpaceMouse operation mimicked the two-handed operation and thus makes the model navigation relatively easy, free and quick.

9.7 Questionnaire of user evaluation test

A formal questionnaire document was designed to investigate the extent to which the VR-based technologies being employed were giving better support for HCIs used in conceptual design. The questionnaire document along with other relevant documents were distributed to all participants so that they could fill in some sections such as CAD systems and VR technologies before their evaluation tests, and the others such as the four VR-based HCIs used in the LUCID system and the strengths and weaknesses of the LUCID system after their trial operations. This was to enable a qualitative comparison to be made between designers' opinions of existing CAD user interfaces and the new HCIs of the LUCID system. For the detailed content of the questionnaire document, please refer to Appendix I of this thesis.

9.8 Outcomes of user evaluation test

Sixteen user evaluation tests were conducted by design researchers, industrial designers and engineering designers who were experienced CAD users and proficient in using either Pro/Engineer or AutoCAD or some other CAD systems. Two of the participants performing their evaluation tests using the LUCID system are shown in Figure 86. Each participant produced a different design outcome. Some of their design results are illustrated in Figure 87. Very useful feedback comments were collected through the questionnaire survey after the user evaluation test. Data analysis has been performed and the final results are illustrated in the following sub-sections.

Figure 86: User evaluation tests using the LUCID system

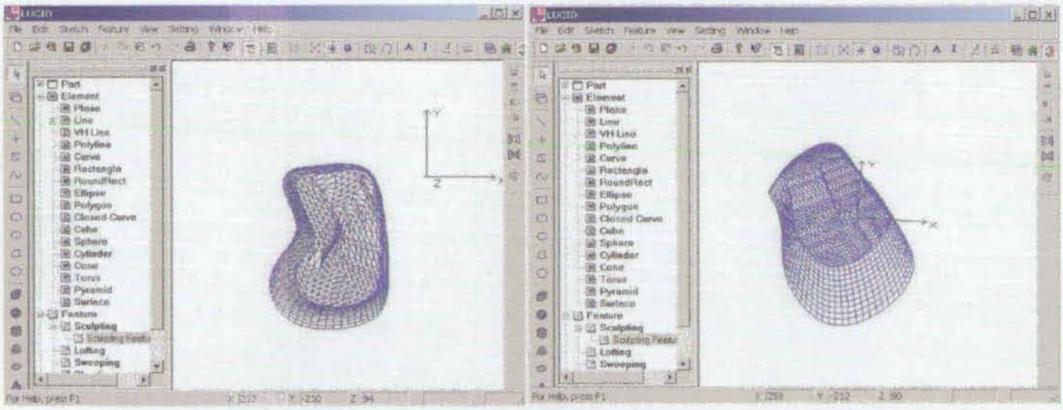


Figure 87: Design results from user evaluation tests

9.8.1 Data analysis of CAD systems

In order to collect user evaluation comments on the LUCID system which employs four new VR-based HCIs to give better support to conceptual design, a background survey on several aspects including CAD systems, VR technologies and HCIs in CAD was conducted before starting the demonstration example modelling using the LUCID system.

User evaluation participants covered many aspects of the design field including design researchers, industrial designers, engineering designers, design teachers, design students and design consultants. For the sake of simple clarification, here design researchers, design teachers and design students are classified as a design academics group and design consultants are recognised as industrial designers. Figure 88 gives the user evaluation participants' distribution.

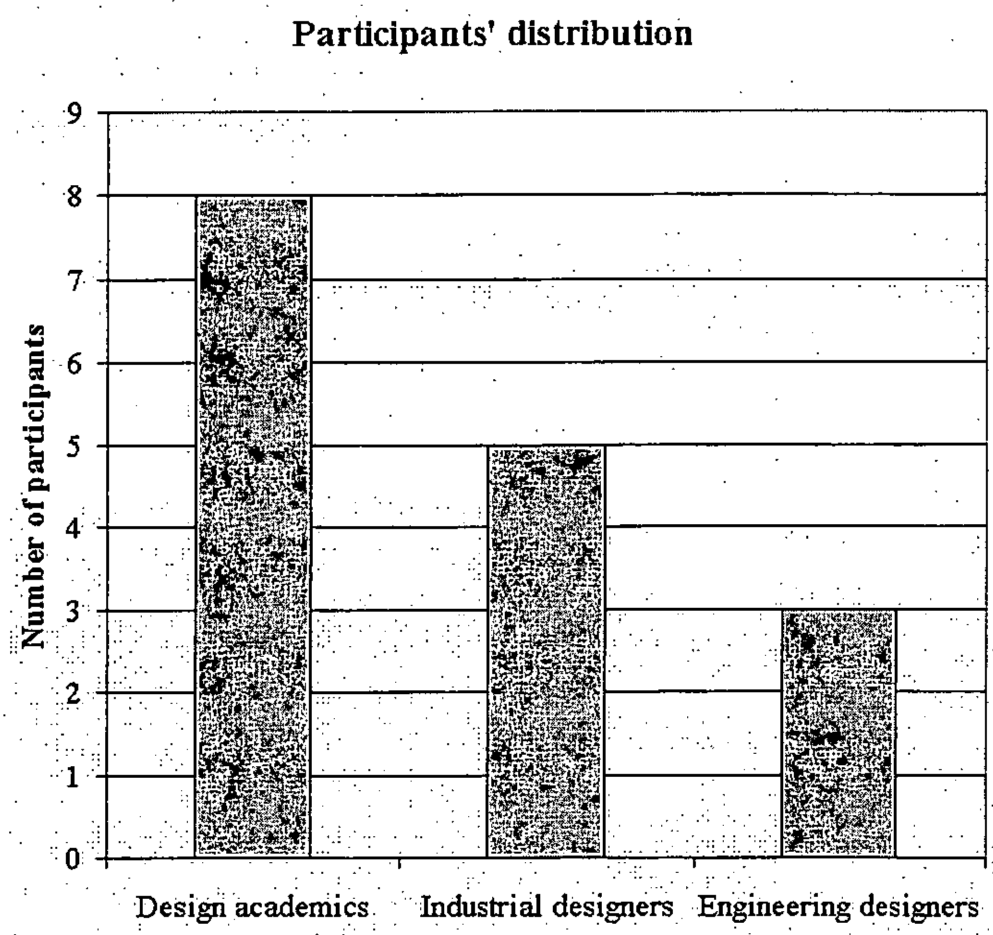


Figure 88: Participants' distribution

The participants' knowledge and skills with commercial CAD systems were first surveyed in the questionnaire. Figure 89 shows the number of participants experienced with each CAD system. Note that there are overlaps here since attendees may be familiar with several CAD systems like Pro/Engineer, AutoCAD, SolidWorks and so on.

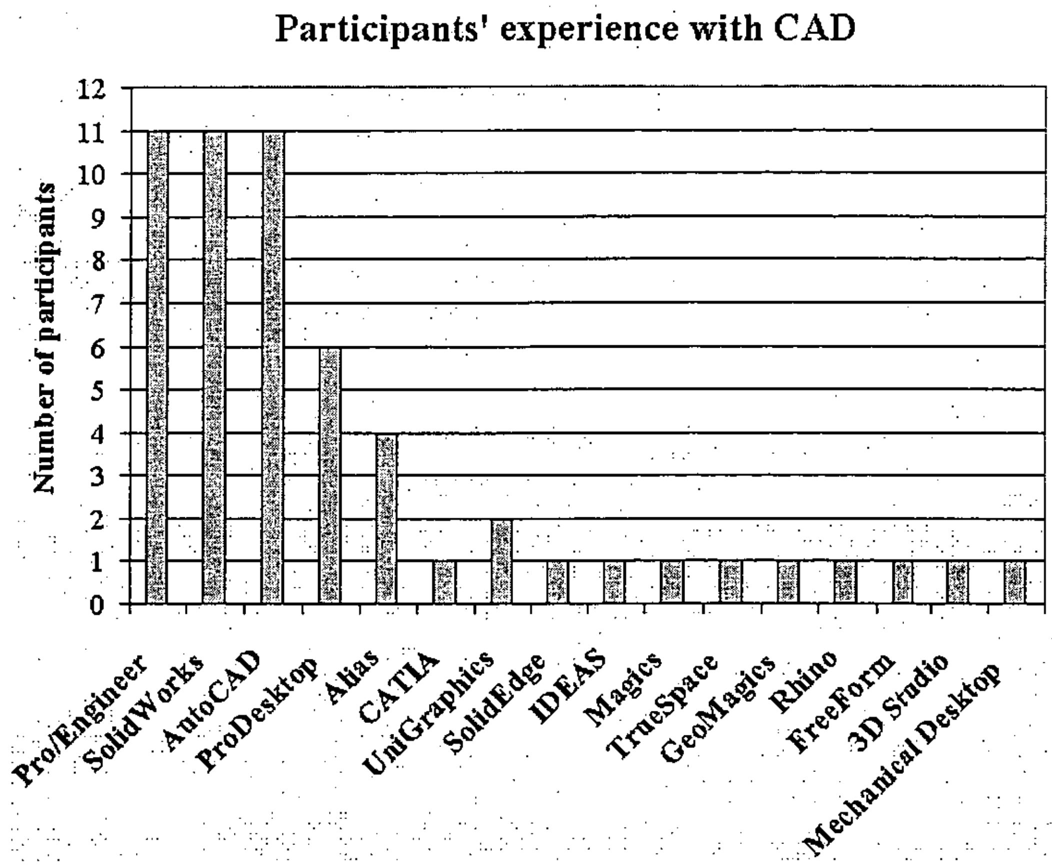


Figure 89: Participants' experience with CAD systems

On the basis that all participants had experience with one or more commercial CAD systems, their comments on the overall design functions and tools of the CAD system they have used most for their design work were assessed. For a simple comparison of the evaluation results discussed in the following sections, all values were produced on a scale of 1 to 5 (values originated from the questionnaire on a scale of 1 to 10 were divided by two for this calculation). Figure 90 gives the assessment result and an average value of 3.31 was received. It was noted that designers from industry were more satisfied with current CAD design functions than those from academia. There might be misunderstandings in the questionnaires for design engineers from industry due to the limited time scale allowed for the user evaluation test conducted at company sites. For example, some design engineers made confusing comments on this question between the commercial CAD system they have used for most for their design work and the

LUCID system that was under evaluation. Another reason was due to the different occupations and different preferences between them. On the one hand, designers from industry had received more training for their preferred CAD system and had used it for a long time. They had also accumulated more experience and knowledge with that CAD system through their daily work. But they had fewer opportunities to access and learn new technologies which are still at a research level because of their job position. It was not an easy matter to persuade them to use new technologies that they are unfamiliar with. On the other hand, designers from academia were more open-minded to all new technologies even at a research level. They preferred to explore new technologies to provide alternative solutions or better approaches for their research work. The participants also commented that most commercial CAD systems currently available on the market were not good for organic freeform shape creation, and they neither allowed 3D freehand sketching type usage nor let designers follow their own design paths. These findings indicated that current CAD technologies could be improved further in the future and designers were still looking forward to new design methods that could meet their specific requirements.

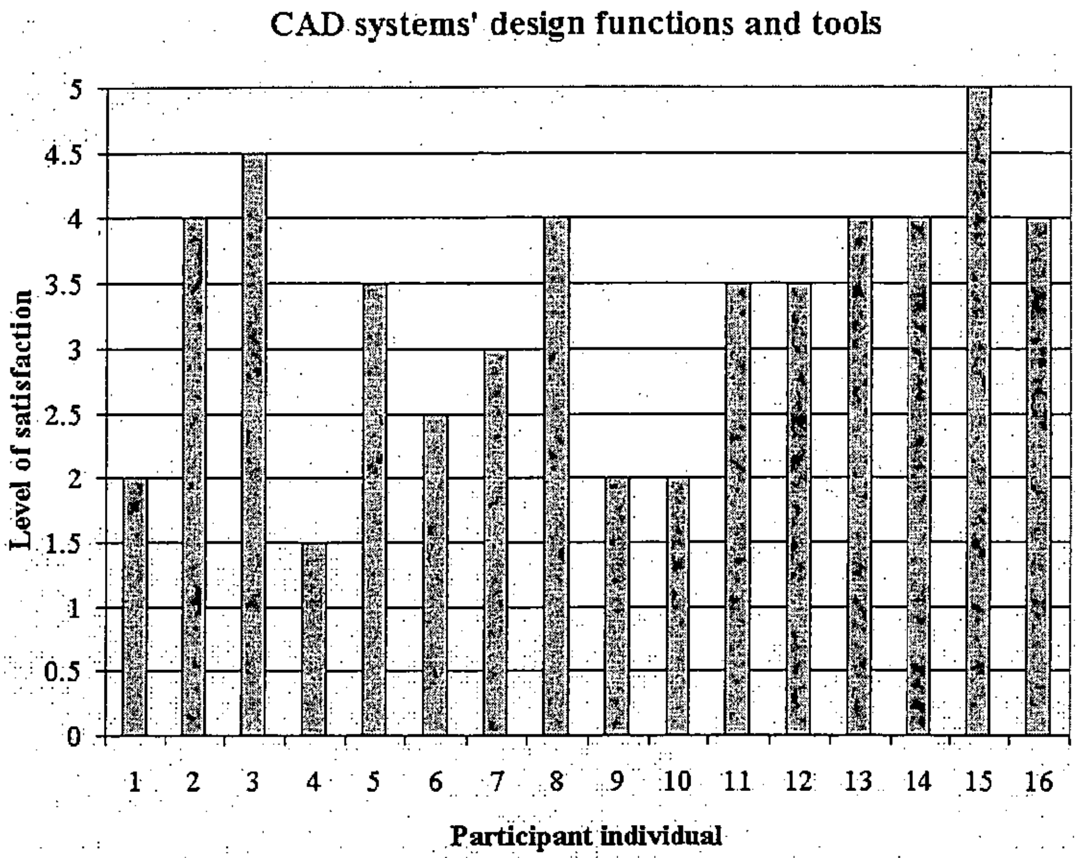


Figure 90: Satisfaction with CAD systems' design functions and tools

Along with the evaluation of the satisfaction with commercial CAD systems' design functions and tools, comments on satisfaction with UIs provided by these commercial CAD systems were also identified. Figure 91 shows the result that an average value of 3.12 was obtained on a scale of 1 to 5 (values originated from the questionnaire on a scale of 1 to 10 were divided by two for this calculation). The lower value indicated that designers have not been fully satisfied with the UIs (the mouse/keyboard and 2D display interface) which most commercial CAD systems currently employ. These results also revealed that there was an increasing need for techniques for improving UIs to support designers in interacting with 3D digital product data. It could be recognised that designers could perform their design activities more efficiently and effectively if they use more natural, familiar interaction mechanisms instead of the traditional mouse/keyboard and 2D planar display paradigm. It was also noted that designers from industry were more satisfied with current CAD UIs than those from academia. The reasons for this are thought to be similar to those provided in the previous paragraph which were related to the question of the overall CAD design functions and tools they have used most for their design work. This difference might need further investigation in the future, but is beyond the scope of this research.

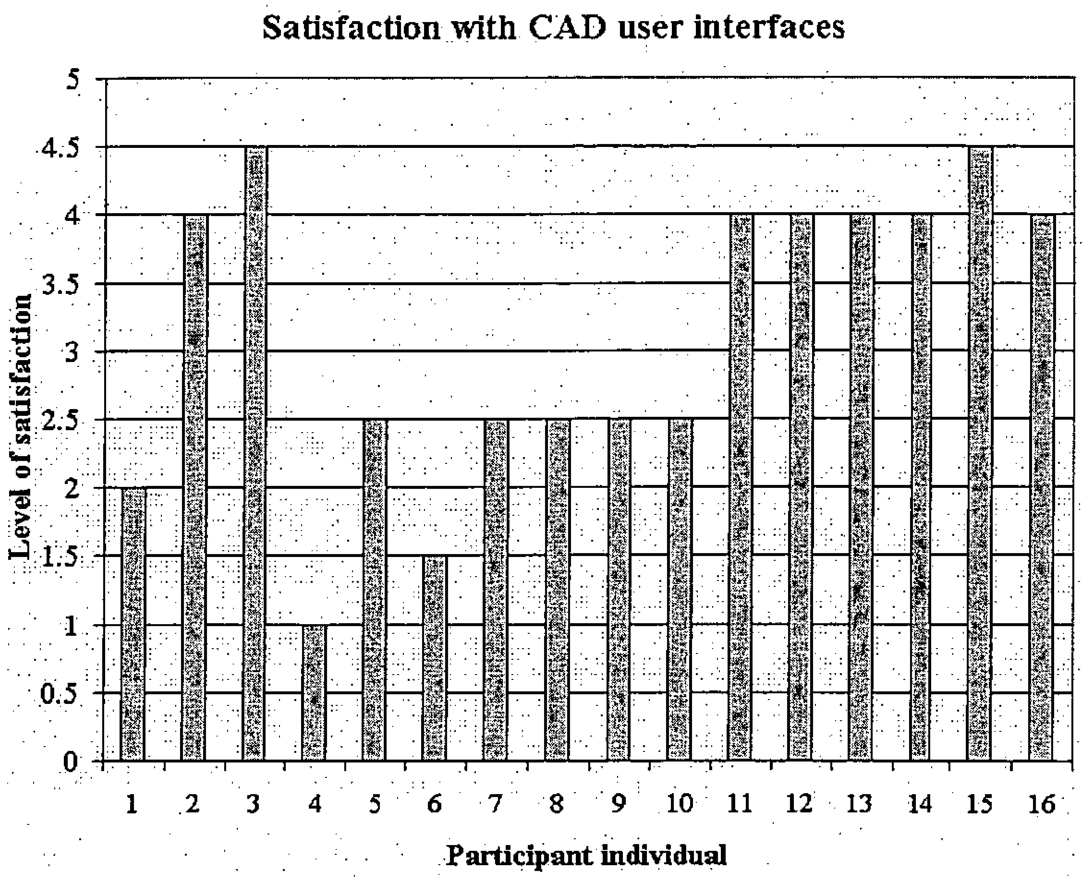


Figure 91: Satisfaction with CAD systems' user interfaces

9.8.2 Data analysis of VR technologies

Since the LUCID system employed several VR-based HCIs to increase designers' interaction during conceptual design, the participants' VR experience and knowledge was acquired as a base for evaluating the data feedback more meaningfully.

All participants taking part in the user evaluation test had already heard about VR technologies. Most participants had experience with VR technologies, and only 25% of the participants (four out of sixteen) had not used VR-based input/output hardware devices for their design work in the past. Figure 92 gives a basic summary of VR technologies which the participants had previously used. Note that there are overlaps here since the participants may have had experience and knowledge with several VR-based technologies such as haptics and stereoscopic displays.

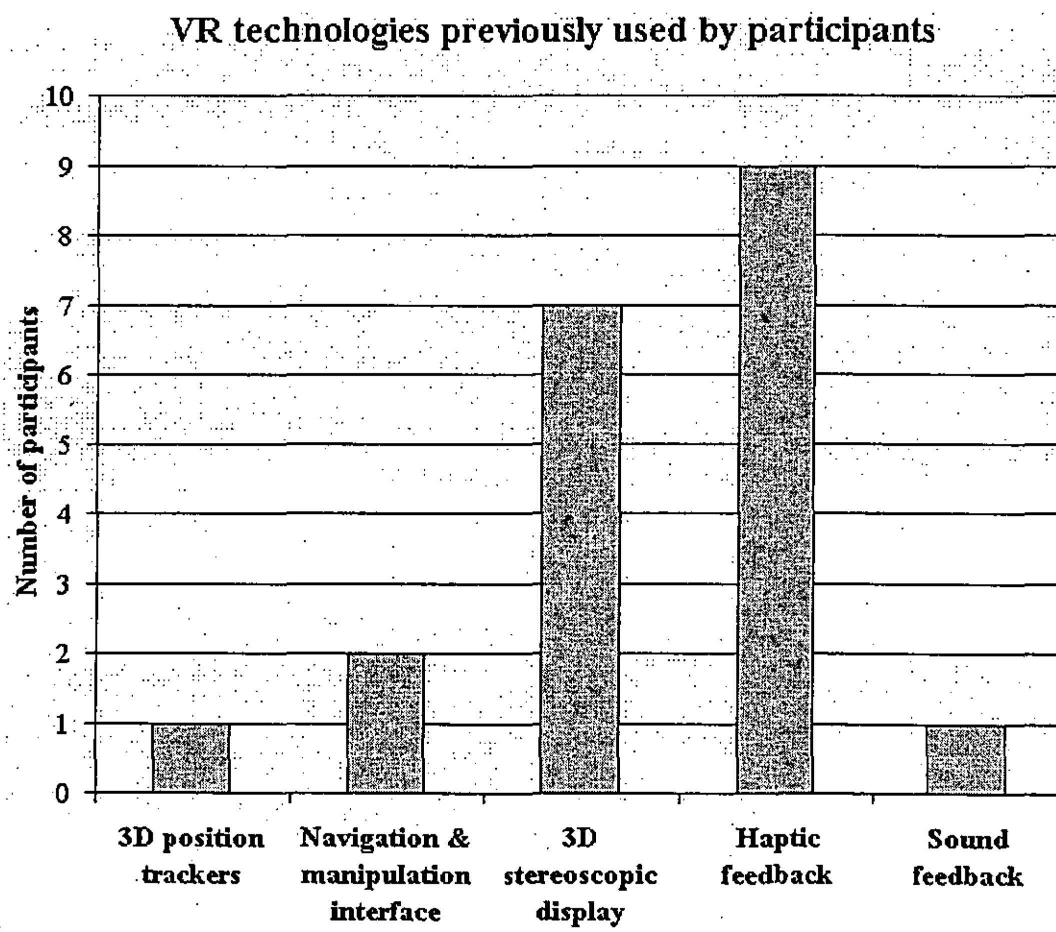


Figure 92: VR technologies previously used by participants

With respect to how they thought VR technologies could be employed to provide better support to HCIs in the product design process, the participants commented that i) VR-based technologies should create a more natural design environment and more realistic and intuitive HCI interactions. This would make it easier and more comfortable to create model geometry without having to refer to manuals or a help desk, ii) VR-based technologies should provide different methods of clearly viewing and manipulating models and iii) VR-based technologies should replicate the scale of the designed model at a real size. All these findings showed that VR-based technologies were believed to have much potential in providing new HCI interactions so as to give better support to product design.

9.8.3 Data analysis of human computer interfaces

With respect to the HCIs, the level of satisfaction with the traditional mouse-keyboard interface used in most commercial CAD systems was gauged next. Figure 93 shows the result that an average value of 2.91 was obtained on a scale of 1 to 5 (values originated from the questionnaire on a scale of 1 to 10 were divided by two for this calculation). The lower value indicated that designers have not been fully satisfied with the traditional mouse-keyboard interface. New UIs that could provide more natural, more intuitive and more realistic interaction methods needed to be developed and used in CAD systems to meet the requirements prompted by the user evaluation test.

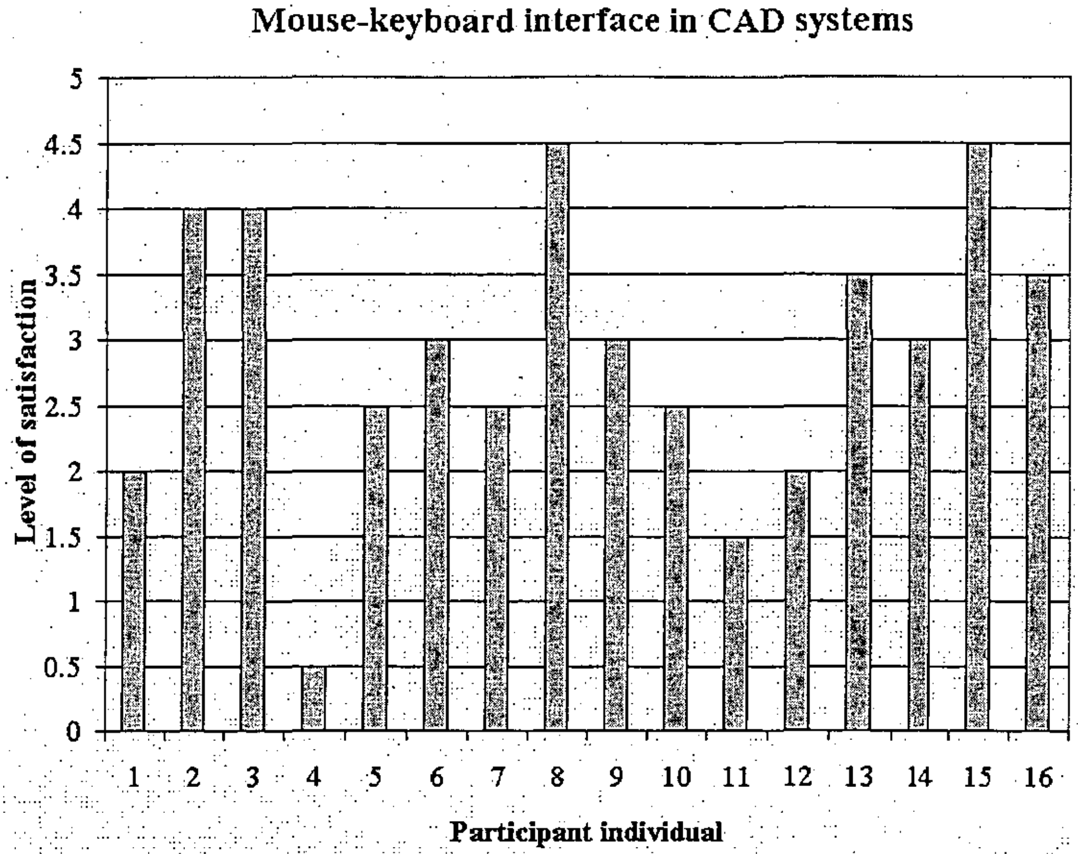


Figure 93: Mouse-keyboard interface used in CAD systems

Apart from the mouse-keyboard interface, only 37.5% of the participants (six out of sixteen) used other HCIs in the past. This information indicated that new HCI design and development was still in its infancy and it has not matured enough to be used widely in design activity.

With respect to the expectation for new HCIs to be used in the design process, the participants commented that i) new HCIs should better mimic the way designers use modelling tools with real objects, ii) new HCIs should be easy, comfortable, friendly and adaptive to use, iii) new HCIs should provide the facility to feel the model physically, iv) new HCIs should allow designers to quickly manipulate and freely view the object and v) new HCI hardware should be cheap and they should be easy to include in mainstream CAD packages. These findings together with the results from previous sections made it clear that designers could perform their design activities more efficiently and effectively if they used more natural, familiar interaction mechanisms instead of the traditional mouse/keyboard and 2D planar display paradigm.

9.8.4 Data analysis of new VR-based interfaces

After the background information survey on CAD systems, VR technologies and human computer user interfaces, four new VR-based HCIs comprising two-handed operation, stereoscopic display, haptic interaction and sound feedback that are employed in the LUCID system were evaluated. The evaluation outcomes are discussed in the following.

9.8.4.1 Two-handed operation evaluation

Figure 94 gives the evaluation results of the two-handed operation interface. An average value of 3.94 was received on a scale of 1 to 5 for the usefulness of the two-handed operation in the design process. With respect to whether the two-handed operation could provide a more natural interaction method in the design process, an average value of 4.13 was obtained. An average value of 3.94 was gained for the usefulness of the two-handed operation in the LUCID system.

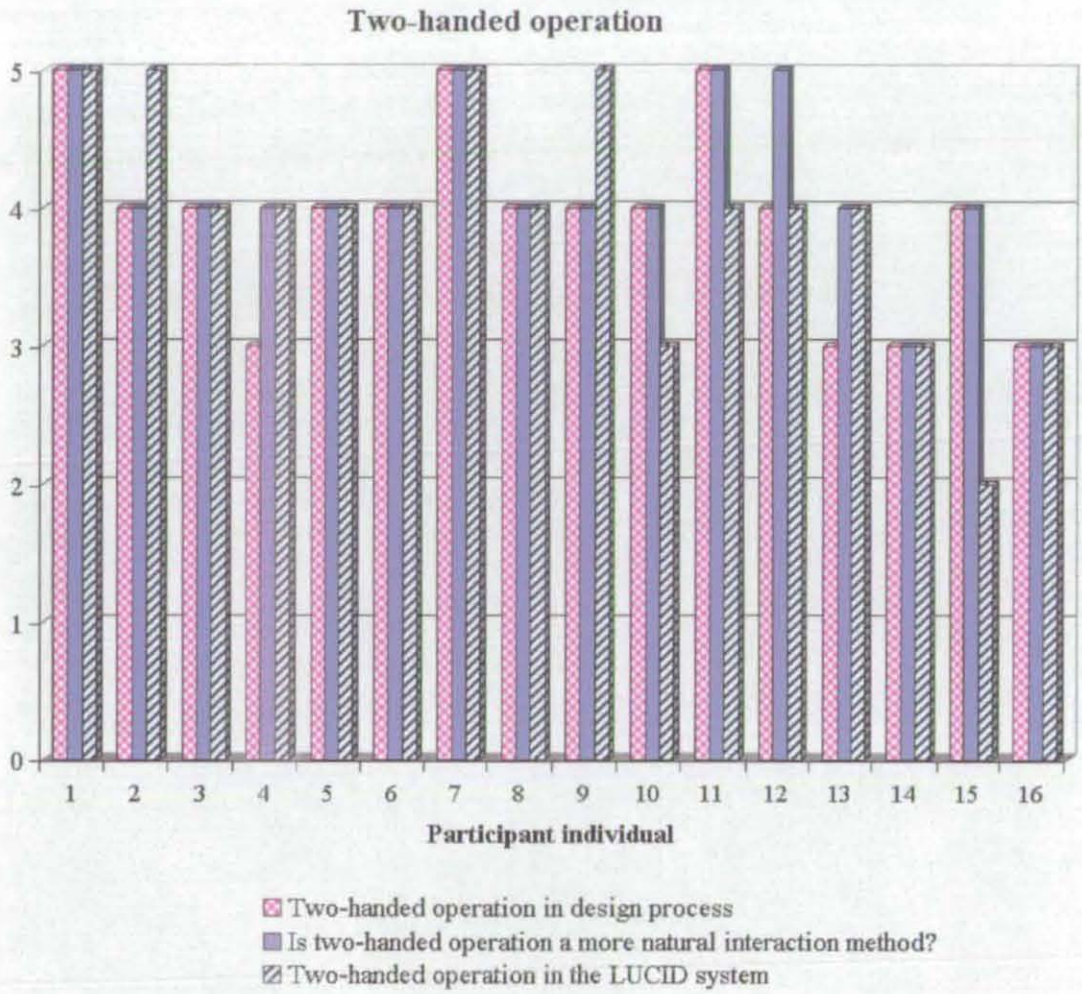


Figure 94: Two-handed operation interface evaluation

With respect to whether the two-handed operation could be used to make the design process more efficient and flexible, the participants commented that i) using two hands at the same time was a good idea and enjoyable, ii) it was useful to be able to zoom/pan/rotate the CAD model with one hand, while using the other hand for working on the model, iii) it was a lot quicker using two hands because designers could manipulate and design the model at the same time and it was flexible because designers could make changes to the model easily from different viewpoints and iv) it was a faster method to perform the design work. These outcomes led to a better understanding of two-handed operation methods used in CAD applications.

9.8.4.2 Stereoscopic display evaluation

Figure 95 shows the evaluation results of the stereoscopic display interface. An average value of 4.19 was received on a scale of 1 to 5 for the usefulness of the stereoscopic display in the design process. With respect to whether the stereoscopic display interface could provide a more realistic 3D environment in the design process, an average value of 4.19 was obtained. An average value of 3.81 was achieved for the usefulness of the stereoscopic display in the LUCID system.

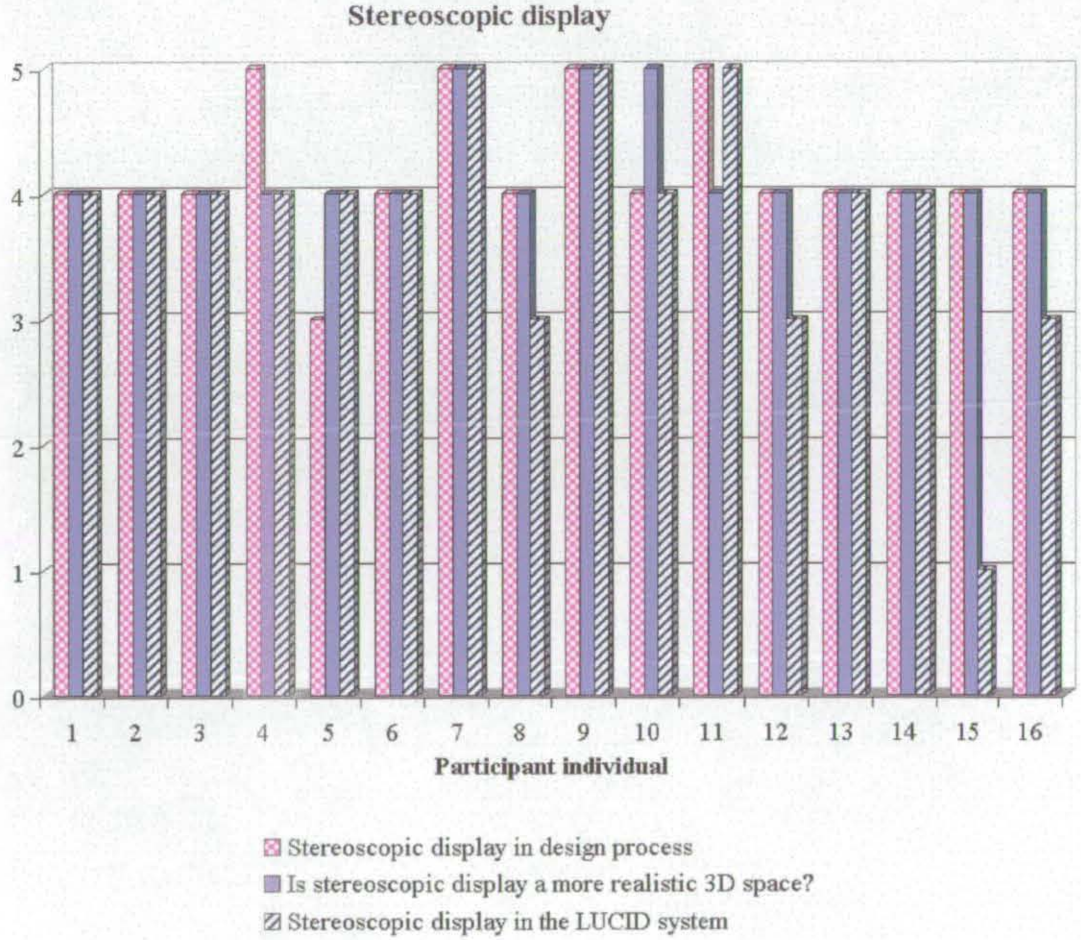


Figure 95: Stereoscopic display interface evaluation

The participants also commented that i) using the stereoscopic display could remove the need for additional view ports (such as side/top/front views), ii) using the stereoscopic display could allow a clearer 3D viewing of the CAD model that was more true to life and iii) it would be even better to use the stereoscopic display technology together with large screens to give an appreciation of real size models. These useful findings validated the advantages of using stereoscopic display technologies in CAD systems.

9.8.4.3 Haptic interaction evaluation

Figure 96 gives the evaluation results of the haptic interaction interface. An average value of 3.88 was received on a scale of 1 to 5 for the usefulness of the haptic interaction in the design process. With respect to whether the haptic interaction could provide a more intuitive method in the design process, an average value of 3.88 was obtained. An average value of 3.38 was gained for the usefulness of the haptic interaction in the LUCID system.

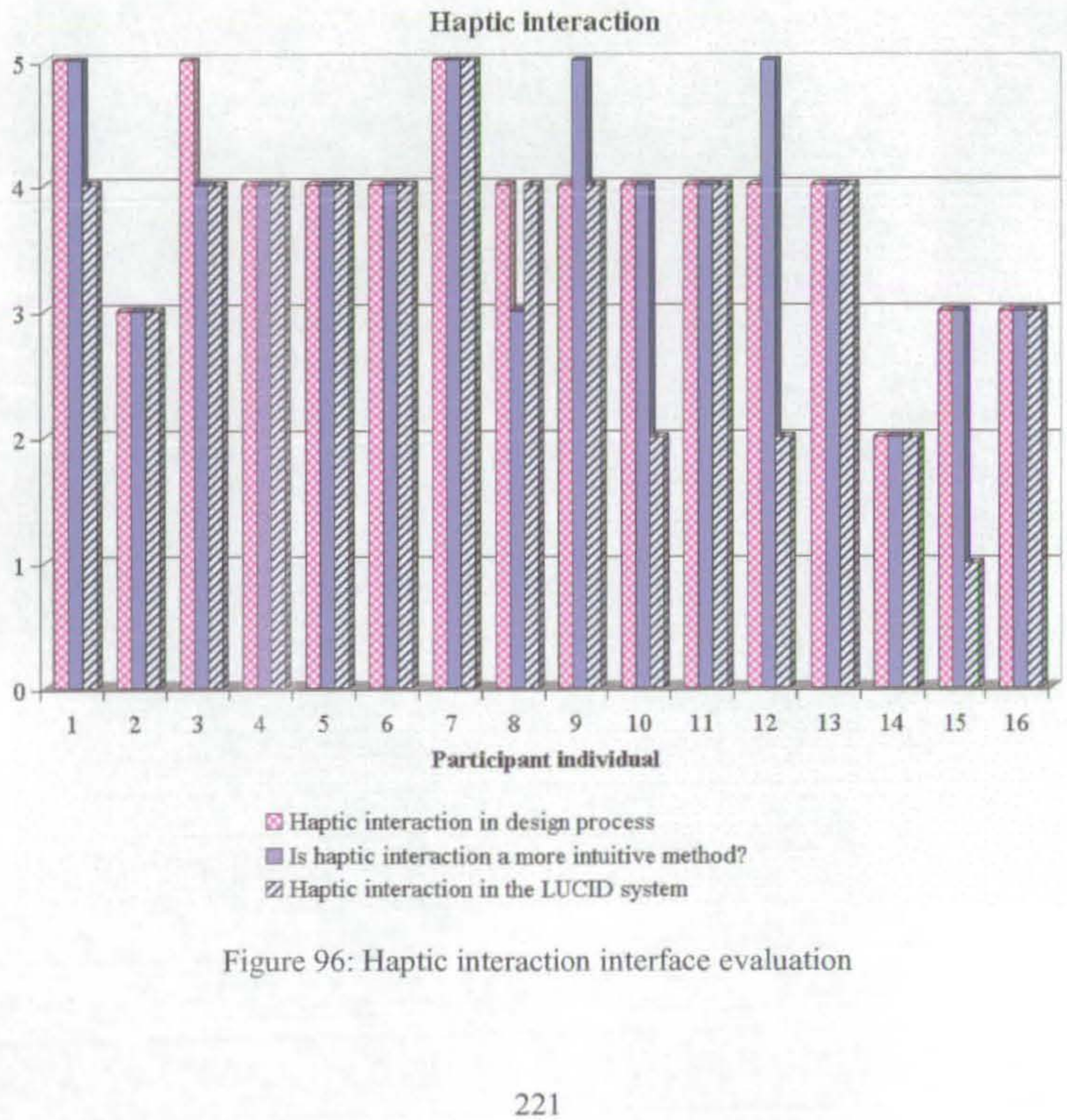


Figure 96: Haptic interaction interface evaluation

The participants also commented that the haptic feedback information was too coarse at the moment and it was sensed only from the tip of the haptic device rather than both hands and all fingers simultaneously which was necessary to simulate a real life sense. This showed that current haptic interaction technologies were not seen as being totally satisfactory, but had particular benefits to designers.

9.8.4.4 Sound feedback evaluation

Figure 97 shows the evaluation results of the sound feedback interface. An average value of 3.47 was received on a scale of 1 to 5 for the usefulness of sound feedback in the design process. With respect to whether sound feedback could enhance the information exchange during the design process, an average value of 3.47 was obtained. An average value of 3.0 was achieved for the usefulness of sound feedback in the LUCID system. Please note that there was no sound feedback interface available in the LUCID system when the participant named No. 3 took part in this user evaluation test. All values calculated above were based on fifteen users.

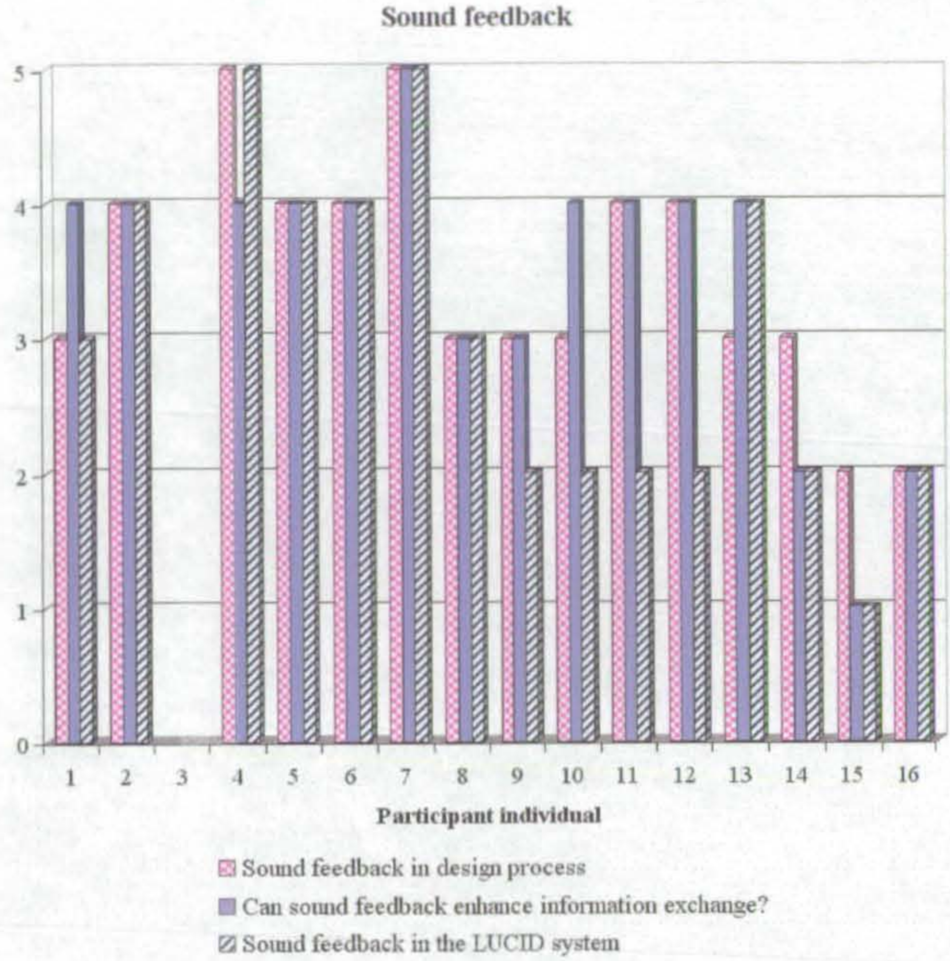


Figure 97: Sound feedback interface evaluation

Again, the participants commented that i) the sound feedback was very informative for knowing when a design action was being performed and when the model was being touched, ii) using the sound feedback to provide instruction and warning information would be quite useful, iii) the sound feedback should be adjustable and optional since different designers had different preferences for the sound feedback and iv) it would be better to provide music-based sound feedback rather than speech-based sound feedback. These findings indicated that current sound feedback technologies were still a step away from completely satisfying different designers.

9.8.4.5 Summary of VR-based HCI evaluation

The four new VR-based HCIs employed in the LUCID system have received positive responses through the user evaluation test. Figure 98 gives the final evaluation values on a scale of 1 to 5, respectively. All VR-based HCIs had higher values than the traditional mouse/keyboard interface. Figure 99 illuminates the HCI comparison result between them. High values for both the two-handed operation and the stereoscopic display indicated that these two technologies have become more mature whereas the haptic interaction and the sound feedback still needed further development and improvement in CAD applications.

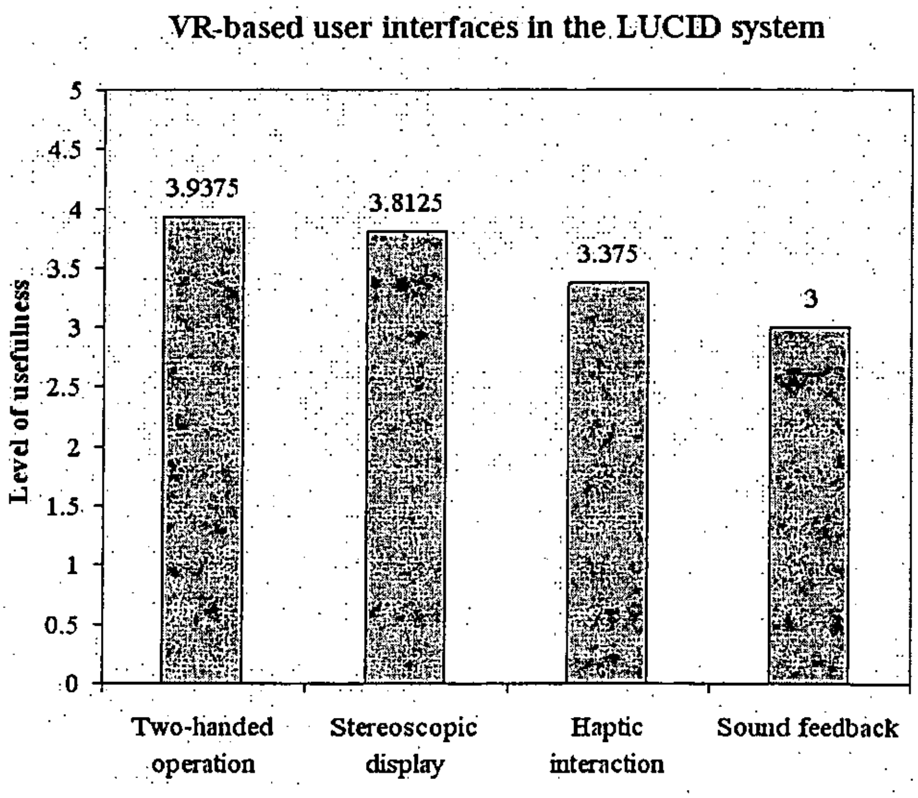


Figure 98: Four VR-based user interface evaluation in the LUCID system

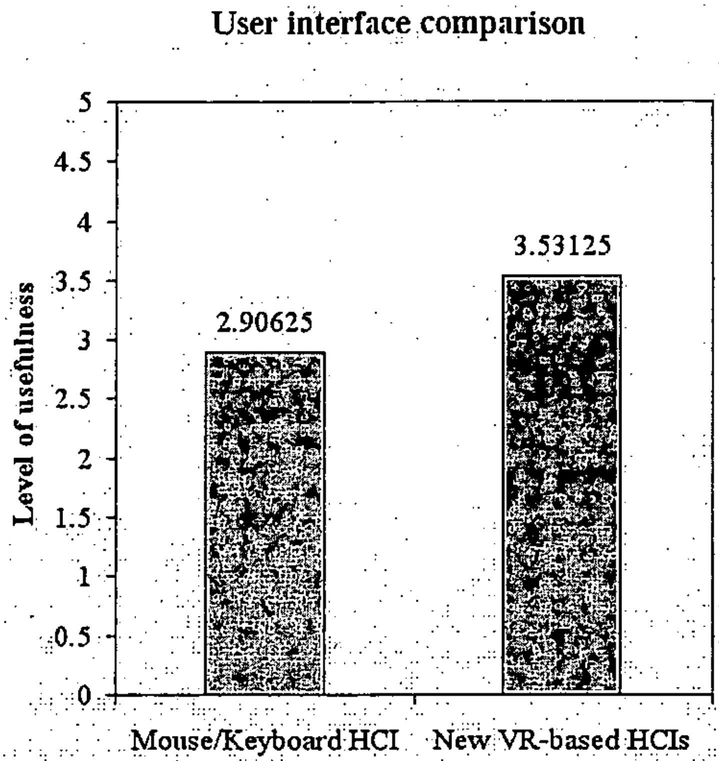


Figure 99: User interface evaluation comparison

9.8.5 Data analysis of strengths and weaknesses of the LUCID system

After the information survey on the four new VR-based HCIs currently used in the LUCID system, a comprehensive list of strengths and weaknesses of the LUCID system for supporting the conceptual design process was compiled. Table 4 and 5 give a summary of the findings from the user evaluation test respectively.

• Provides many user interfaces to enable the use of both hands, feeling models with haptic force feedback, viewing models in stereoscopic display and to manipulating models with sound feedback.
• Provides abilities to work quickly and more naturally by using both two hands in 3D space instead of 2D planes with both haptic and sound feedback.
• Provides simple and efficient 3D freeform surface creation functions by using feature-based technology and thus leads to greater flexibility and interactivity for product design.
• The SpaceMouse device provides a more intuitive way to zoom/pan/rotate the models.
• The sound feedback is very informative for knowing when the design operation is being performed and when the model is being touched.
• Would be a useful way to present design models to users for evaluation.

Table 4: Main advantages of the LUCID system from participants' evaluations

• Shoulder strain is induced by the haptic device on an unsupported arm over a long period of continuous use.
• Tiring of eyes exists when using the stereoscopic view due to screen flickering.
• Lack of data exchange interfaces to share the model data with other commercial CAD systems.
• Limited design functions available.
• Lack of lighting effects in shaded model view.
• Does not provide icon-menus in a float mode.

Table 5: Main weaknesses of the LUCID system from participants' evaluations

Shoulder or arm strain could be alleviated by a new design of the haptic force feedback device taking more ergonomic aspects into consideration, for example, by providing a comfortable stand for the hand/arm movement. The Eye-tiredness problem could be removed by using a high performance monitor which supports a high refresh rate to avoid flickering. Another solution to this matter would be to decrease the screen resolution of the currently used monitor so as to support a higher refresh rate to reduce flickering. This method was realised in the LUCID system by reducing the screen resolution of the monitor from 1280×1024 at a 75 Hz refresh rate to 1024×768 at a 100 Hz refresh rate. It was also noted that auto-stereoscopic display technology has recently been available on the market. In an auto-stereoscopic system, all of the stereoscopic display work is done by the display screen. Users do not need any eyewear to view 3D images. However, its high cost and lower resolution currently prevents its widespread use. The LUCID system supports the STL file format and the VRML file format to provide certain model data exchange facilities with other mainstream CAD systems. Since the focus of this research is on new CAD UIs rather than on design functions, the main reason for the limited design functions available in the LUCID system is that the LUCID system currently uses its own codes for model representation instead of using any commercialised solid modelling kernel package such as the Spatial's ACIS or the Electronic Data Systems' Parasolid. The function of lighting effects in shaded model view was developed and added in the LUCID system. The function of the icon-menu working in a float mode will be investigated in the future.

Besides the problems highlighted in Table 4, another issue was encountered during the user evaluation test. Since the Phantom stylus only has one pushbutton, it was very difficult to take over the set of jobs that are carried out by a standard mouse with three buttons in the design process when the Phantom Desktop device worked in the Phantom-Mouse mode (see Section 6.5.5 in Chapter Six for more detail). In this case, designers could change from the Phantom haptic device operation to the standard mouse operation in order to carry out design functions. This was contrary to the two-handed operation and thus caused some inconvenience in the design process using the LUCID system. This obstacle could be relieved when SensAble takes this situation into consideration for their future Phantom device design.

9.9 Summary

In conclusion, the results from the user evaluation test have confirmed the author's findings about the limitations of most commercial CAD systems and designers' expectations of new generation CAD tools. The outcomes have also exhibited the efficacy of the four new VR-based HCIs involved in the design process and revealed the strengths and weaknesses of the current LUCID system. Though it was not seen as being totally satisfactory, the LUCID system had particular HCI benefits to designers. The findings from the user evaluation test were valuable especially to further improve the LUCID system in the future.

CHAPTER TEN

Conclusions and suggestions for future work

This chapter presents the conclusions drawn from the research work, discussion on the limitations of the research work and suggestions for future work.

10.1 Conclusions

The conclusions of the project are assessed in regard to the objectives stated in Section 1.3 of Chapter One. Also, the main contributions made by the research are listed.

10.1.1 What geometric modelling representations are best for conceptual design?

In Chapter Two, geometric modelling in CAD applications was described in detail. Each CAD geometric modelling technology has its own strengths, weaknesses and specific application areas. Therefore, in the creation of more complex CAD models, the best solution is to combine several modelling approaches together for easier and more efficient geometric representation. For example, in the LUCID system, a NURBS modelling method was used to represent 3D freeform curves and surfaces (see Chapter Seven) whereas a feature-based modelling approach was employed to describe high level feature design functions (see Section 8.2 in Chapter Eight). From the conceptual design point of view, CAD geometric modelling should allow designers to represent object geometric information efficiently and effectively without the need of advanced modelling knowledge and complex mathematical algorithms, since the focus in conceptual design is on concept creation rather than on detailed model geometry. Currently, there is no single CAD modelling technique available to fully match this requirement for conceptual design. Hence, hybrid modelling approaches (using two or more individual modelling techniques together) have offered a practical solution to modelling issues involved in conceptual design. The implementation of hybrid CAD modelling in the LUCID system has confirmed this viewpoint.

10.1.2 What are the strengths and weaknesses of VR-based interfaces for the conceptual design process?

A deeper understanding of the strengths and weaknesses of VR-based interaction techniques for CAD applications was gained based upon a comprehensive literature review of VR-based technologies and their applications in product design and development (see Table 1 in Chapter Three). Each VR-based interaction technique for CAD applications has its potential and limitations. For example, a voice command-based interface has several advantages including its simple input device (a microphone) and freedom to use hands for other operations. But it also suffers from fundamental weaknesses including limited recognition capability and difficulty in specifying continuous and complex commands. Therefore, any new VR-based interaction technique to be developed should take full advantage of existing VR-based interfaces' strengths and avoid their inherent drawbacks as much as possible. This was the criterion which gave the overall guidance for the LUCID system design and development during this research work.

10.1.3 What new user interface specifications need to be adopted for conceptual design?

In order to create new VR-based interaction interfaces from which designers could derive most benefit for conceptual design, new user interface specifications were defined from human factor analysis of the designers' requirements for new CAD systems (see Table 2 and Figure 28 in Chapter Four). These new user interface specifications formed both a starting point from which the LUCID system configuration could be defined and a yardstick against which the LUCID system performance could be measured. They were discussed in detail in Chapter Four with their fundamentals, CAD applications and specific potential for the product design process.

10.1.4 What input and output devices can be employed to support conceptual design?

In order to support the new user interface specifications defined in Chapter Four, new input and output hardware devices were selected based upon their performance characteristics, ease of integration and most importantly, abilities to match the HCI requirements as closely as possible. A SpaceMouse input device was chosen to create a two-handed operation mechanism as it was relatively easy and stable to use in CAD applications. A Phantom Desktop haptic device was selected to implement a haptic interaction channel as it was the *de facto* standard haptic device used in most haptic-based applications. A NuVision GX60 stereoscopic display toolkit was employed to create a stereoscopic display interface due to its simple structure, lower cost and comfort and convenience in use. A computer-supported speaker-based auditory system was used to provide a sound feedback interface since most of today's computers are equipped with audio input/output facilities as part of a standard configuration. The LUCID system that integrated these input and output hardware devices into one practical conceptual design application was described in detail in Chapter Five.

10.1.5 What new HCI paradigms can be fully integrated into conceptual design?

Four new VR-based human computer user interfaces (two-handed operation, haptic interaction, stereoscopic display and sound feedback) were developed and implemented in the LUCID system in order to provide industrial designers with improved interaction capabilities along with more natural and intuitive model manipulation and more efficient and effective function experimentation. Detailed procedures for their integration and implementation in the LUCID system were provided in Chapter Six both theoretically and practically.

10.1.6 How will these technologies improve the conceptual design process?

New design functions such as 3D freehand sketching design and freeform feature-based design were developed to demonstrate the advantages of using the new HCIs within the conceptual design process (see Chapter Eight). Compared with the traditional mouse/keyboard and 2D display paradigm used in most conventional CAD systems, all four new HCIs employed in the LUCID system provided particular benefits to designers during conceptual design based upon the results drawn from the user evaluation test (see Section 9.8.4 in Chapter Nine). The outcome of the user evaluation test also showed that these four HCIs were not seen as being totally satisfactory and further improvements and developments would be needed in the future (see the following Section 10.3 for more detail).

As the result of this research work, a new VR-based desktop non-immersive conceptual design system called the LUCID system has been developed. It uses four VR-based innovative user interfaces, 3D freehand sketching tools and freeform feature-based design functions to provide better support capabilities for conceptual design. Unlike most traditional CAD systems that provide designers with only 2D visual information, the LUCID system supports stereoscopic display along with other sense information provided by haptic interaction and sound feedback, as shown in Figure 100. Furthermore, the LUCID system can be used for product evaluation to extend its usability as it supports several other model data file formats. As an approach to the next generation of HCIs for use in the design activity, the LUCID system user evaluation test results have indicated that it could provide better support to conceptual design through its innovative interface integration and implementation.

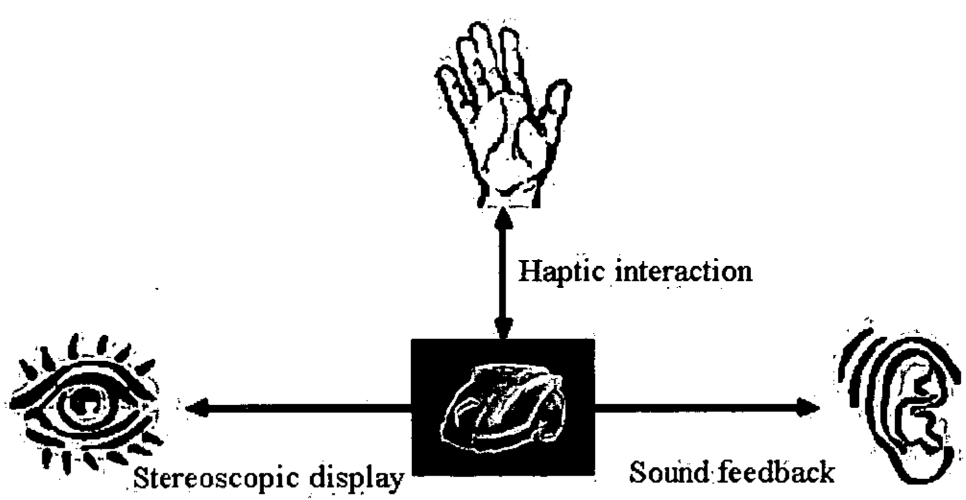


Figure 100: Three sensorial modalities used in the LUCID system

The outcomes of the research have made several contributions to both technological knowledge and design practice which are listed below:

1. A deeper understanding of both the limitations of current CAD systems and designers' expectations of the HCIs for the next generation of CAD systems has been obtained through case studies and user evaluation tests. The information gained has not only made a contribution to the state of technological knowledge in the fields of CAD and associated HCI design and development, but will also be valuable to future researchers in the areas of CAD software design and HCI hardware device design.

2. A new direct, more natural and more intuitive interaction paradigm has been introduced which enables designers to take fuller advantage of their visual, auditory and tactile sensorial channels to create, view, touch, manipulate and listen to 3D CAD digital models easily and freely in one practical design application. This interaction method has been implemented in a more realistic 3D environment through convenient interface hardware device operation. The new interaction paradigm has made a positive contribution to the design of interactive HCIs, especially for the conceptual design practice. This indicates that a significant change in established practice is required because novel interactive technologies can make the communication between the designer and the CAD system more fluent and natural. This challenge should be met by system developers in the areas of CAD and associated HCI design and development.

3. A new 3D freehand sketching design tool has been created to support a true 3D design capability for CAD applications. This design tool has been realised by using a 3D Phantom Desktop device for 3D input of the sketches and a stereoscopic display for 3D visual output. This capability has overcome the communication bottleneck of 2D interaction (both input and output) which has prevailed in most commercial CAD systems, and thus made a significant contribution to CAD operational competence and practice. Design practitioners who become aware of this capability will want to explore more creative design

possibilities which are difficult to realise using conventional 2D HCI environments.

4. Freeform feature-based design functions have been developed for operation inside a 3D environment with both direct haptic and sound feedback operations. Compared with traditional design functions, these approaches have increased the speed of the information exchange between designers and virtual models, and led to greater design flexibility and interactivity for conceptual design.

This research project has been successful in that it has identified the requirements for conceptual design interactivity, investigated the weaknesses of available approaches and provided a new innovative solution to the problem. From the results of this research work, several journal and conference papers have been written and published are listed in Appendix III of this thesis.

10.2 Discussion

As an approach to the next generation of HCIs for use in the design process, the user evaluation test has shown that the LUCID system presented in this thesis could provide better support capabilities for conceptual design through its multiple innovative interface integration and implementation. However, there are some limitations to the LUCID system. The following gives a brief discussion of these issues.

10.2.1 Haptic interaction in the LUCID system

Haptic interaction technology has been successfully applied to CAD applications over the past decade. However, designers have not been fully satisfied with this new technology since there are several drawbacks existing in current mainstream haptic interaction devices. For example, high prices prevent their widespread use in many applications. With respect to the Phantom Desktop haptic device used in the LUCID system, some technology-based problems make it inconvenient to use. Only one pushbutton on the stylus arm of the haptic device could not fully simulate the standard mouse operation when the Phantom Desktop haptic device worked in a "Phantom-Mouse" mode (see Section 6.5.4 in Chapter Six). This caused an intrusive problem for supporting the two-handed operation used in the LUCID system. Arm strain is induced by the Phantom haptic device over a long period of continuous use because there is no support stand for the hand movement. Since the GHOST SDK does not support the stereoscopic display, the haptic interaction in the LUCID system has not achieved the desired level of satisfaction. For example, the rendered force only exists on the surface of the CAD model and there is no haptic feedback when the haptic cursor is located inside the CAD model. This result limited the intuitive haptic interaction method aimed for within the LUCID system. Any new design of haptic technology should avoid these drawbacks as much as possible.

10.2.2 Sound feedback in the LUCID system

Though it was successfully implemented in the LUCID system, the sound feedback interface has not reached the desired satisfaction level as expected. The outcomes from the user evaluation test revealed that more improvements would be needed in order to make the sound feedback interface more useful in the design process. This will include exploring non-speech-based sounds such as music sounds and applying them to the design process. For example, an increasing pitch sound would be useful to indicate an increasing deformation. Further research will be needed to identify what kind of sounds could be best used to support the product design process.

10.2.3 CAD technologies in product design applications

The results drawn from both the case studies (see Section 4.1 in Chapter Four) and the LUCID system user evaluation tests (see Sections 9.8.1 and 9.8.3 in Chapter Nine) indicated that designers have not been fully satisfied with current commercial CAD systems for their design work especially in regard to the nature of the HCIs. New technologies are still being awaited to overcome this obstacle so as to give better support to designers. As stated in Chapter Nine, there was a noticeable difference between designers from industry and academia in terms of their satisfaction with current CAD systems and the use of new technologies in the design process (see Section 9.8.1 in Chapter Nine). Further research will be needed to explore this difference so as to obtain a better understanding of the needs of designers in industry. Any new design technology developed to give better support to the product design process in the future should aim to meet these specific requirements.

10.2.4 VR-based technologies for product evaluation applications

In this thesis, VR-based technologies were used for providing more natural and intuitive HCIs to give better support to the product design process. However, VR-based technologies can also provide much potential in product design evaluation applications. Some examples demonstrated in Section 8.3 of Chapter Eight showed their strengths in product design evaluation applications. Extending VR-based technology applications from supporting CAD HCI design to enhancing product design evaluation abilities will provide a useful approach to the whole product design and development process. Further research will be needed to explore the ability of VR-based technologies to support efficient and effective product design evaluation applications in the future.

10.3 Suggestions for future work

Although the current implementation of the LUCID system provides better support to conceptual design with its multiple VR-based innovative interfaces, it can still be improved in several respects in the future:

- New geometric modelling representations and algorithms should be investigated to give better support to the LUCID system. Currently, the NURBS modelling algorithm is employed for representing freeform curves and surfaces and the feature-based modelling approach is used to support the freeform feature-based design functions in the LUCID system. Also the STL and VRML file formats are supported by the LUCID system for both importing and exporting options. Other representations and algorithms need to be investigated to support the model data exchange effectively and efficiently with mainstream commercial CAD systems. For example, STEP and IGES are able to support model data direct transfer of NURBS representation.

- Several freeform feature-based design functions are already outlined and implemented in the LUCID system. Other useful freeform feature-based modelling functions (for example, the protrusion feature, the rotating feature, the hole feature and so forth) should be developed and added to the LUCID system so as to enrich the design facilities as much as possible.

- Compared with commercially available CAD systems, the LUCID system does not possess a rich enough range of design functions to perform some very complex design tasks. This could be remedied by using an existing commercial 3D solid modelling kernel package such as the Spatial's ACIS or the Electronic Data Systems' Parasolid in the future.

- Since the auto-stereoscopic display technology has recently become commercially available on the market, further research should consider transferring the LUCID system to an auto-stereoscopic display system that would remove the need for any eyewear to view 3D images in CAD applications in the future.

- Besides the four new UIs introduced in this thesis, other new HCI technologies should be investigated in order to provide even better UIs to fully support the conceptual design process. For example, the hand gesture interaction could be investigated and integrated into the LUCID system so as to provide an even more natural two-handed operation paradigm.

- Further research will consider integrating of the new HCIs (currently used for the conceptual design stage) into conventional CAD systems to totally support the whole product design process. This will cover some known topics including design data exchange and management and the new CAD system's structure reconstruction.

New CAD systems are being developed which allow designers to use their existing skills and experience while working in a computer-generated digital environment. The potential of such technologies to allow an intuitive and natural interaction with virtual models has increased the drive towards computer support for the whole product design process. The author believes that the continued exploration of new interaction technologies and their integration into product design applications will result in the future evolution of the next generation of HCIs for CAD systems.

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APPENDIX I

Questionnaire -- The use of virtual reality based interfaces to support computer aided conceptual design process

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Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?
   - ☐ Student
   - ☐ Design Researcher
   - ☐ Design Teacher
   - ☐ Industrial Designer
   - ☐ Engineering Designer
   - ☐ Design Consultant
   - ☐ Design Manager
   - ☐ Other...

2. Have you used any CAD system(s) for your design work?
   - ☐ No
   - ☐ Yes. Please indicate which of the following you have used
     - ☐ Pro/Engineer
     - ☐ UniGraphics
     - ☐ Alias
     - ☐ CATIA
     - ☐ SolidWorks
     - ☐ AutoCAD
     - ☐ ProDesktop
     - ☐ SolidEdge
     - ☐ Other..

3. What do you think of the overall design functions and tools the CAD system provides for your design work? (answer for the system you have used most)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Extremely helpful

   Other comments:

   ....

   ....

4. What do you think of the user interface the CAD system(s) provides for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

   ☐ No

   ☐ Yes

2. Have you used any VR-based input/output devices?

   ☐ No

   ☐ Yes. Please indicate which of the following you have used

   - ☐ 3D Position Trackers
   - ☐ Navigation & Manipulation Interfaces
   - ☐ Gesture Interfaces
   - ☐ 3D Stereoscopic Graphics Displays
   - ☐ 3D Sound Displays
   - ☐ Haptic Feedback
   - ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCIs in the product design process?

   ....

   ....

   ....

   ....

Part C -- Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

2. Have you used any other HCI for your design work?

   ☐ No

   ☐ Yes. Please indicate...

3. What is your expectation for any new HCI to be used in the design process?

   ....

   ....

   ....

   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments:

   ....

   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments:

   ....

   ....

3. Did you find the two-handed operation useful in the LUCID system?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

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Stereoscopic Display

1. Is a stereoscopic display useful in the design process?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

2. Do you think stereoscopic display could provide a more realistic three-dimensional (3D) environment for the design process?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

3. Did you find stereoscopic display useful in the LUCID system?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic interaction useful in the design process?

☐	☐	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

2. Do you think haptic interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find haptic interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

Sound Feedback

1. Is sound feedback useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find sound feedback useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the user interfaces used in the LUCID system for supporting design process?

Strengths...
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Weaknesses...
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Thank you for your assistance in this research.

APPENDIX II

Questionnaire responses

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 1

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

   - ☐ Student
   - ☑ Design Researcher
   - ☐ Design Teacher
   - ☐ Industrial Designer
   - ☐ Engineering Designer
   - ☐ Design Consultant
   - ☐ Design Manager
   - ☐ Other...

2. Have you used any CAD system(s) for your design work?

   - ☐ No
   - ☑ Yes. Please indicate which of the following you have used
     - ☐ Pro/Engineer
     - ☐ UniGraphics
     - ☐ Alias
     - ☐ CATIA
     - ☐ SolidWorks
     - ☑ AutoCAD
     - ☐ ProDesktop
     - ☐ SolidEdge
     - ☐ Other....FreeForm, 3D Studio...

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

   ☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Extremely helpful

   Other comments:

   ....

   ....

4. What do you think of the user interface these CAD system(s) provide for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

   ☐ No

   ☑ Yes

2. Have you used any VR-based input/output devices?

   ☐ No

   ☐ Yes. Please indicate which of the following you have used

   - ☐ 3D Position Trackers
   - ☑ Navigation & Manipulation Interfaces
   - ☐ Gesture Interfaces
   - ☑ 3D Stereoscopic Graphics Displays
   - ☐ 3D Sound Displays
   - ☑ Haptic Feedback
   - ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

   VR technologies could be used to create much natural design environments (digital environment that suits better to designers' needs); more realistic HCI interaction.

   ....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☒ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments:
   One-hand interaction is poor, two-handed interaction needs to be implemented

2. Have you used any other HCI for your design work?

   ☐ No

   ☒ Yes. Please indicate... The Phantom Desktop device

3. What is your expectation for any new HCI to be used in the design process?
   Better mimicking the way designers use modelling tools in non-digital environment

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☒ Strongly agree

   Other comments:

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☒ Strongly agree

   Other comments:

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☒ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

Using two hands at the same time is a good idea. In this way, you won't be loading one hand only. Phantom & Space mouse combination was enjoyable.

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

It's useful and helps seeing / judging things better especially when working with layers. But, it's also tiring to carry goggles on the face for a long time.

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

It could be improved better to feel the surfaces.

....

Three-dimensional (3D) Sound Display

1. Is 3D sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think 3D sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find 3D sound feedback useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:

It's a bit tiring to hear the command completed all the time, this should be optional. I'd like to get realistic (e.g. deforming material) feedback of the functions being performed not a feedback of what I'm doing. Visual feedback is more important.

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths...

Being able to use two hands.
Haptic feedback.
Stereoscopic view.

Weaknesses...

menus could be floating so that can be moved wherever the user wants. When using the Phantom device for example, it's difficult to use icon-menus if the menus are on the same side and closer to the Phantom device, it would help a lot.

Flicking on the screen (when using stereoscopic view) is very tiring.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 2

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

   - ☐ Student
   - ☑ Design Researcher
   - ☐ Design Teacher
   - ☐ Industrial Designer
   - ☐ Engineering Designer
   - ☐ Design Consultant
   - ☐ Design Manager
   - ☐ Other...

2. Have you used any CAD system(s) for your design work?

   - ☐ No
   - ☑ Yes. Please indicate which of the following you have used
     - ☑ Pro/Engineer
     - ☑ UniGraphics
     - ☑ Alias
     - ☐ CATIA
     - ☑ SolidWorks
     - ☑ AutoCAD
     - ☑ ProDesktop
     - ☐ SolidEdge
     - ☑ Other.........Truespace, Magics (RP), Geomagics, Rhino

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☑ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☐ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☑ Haptic Feedback
- ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

Possibly by making modeling operations more intuitive so that it is easier to produce a geometry without having to refer to manuals or a help desk

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:
The interface is generaly quite good, although many functions differ from one system to another which can be confusing when switching back and forth.

2. Have you used any other HCI for your design work?

☐ No

☑ Yes. Please indicate Phantom + Freeform software

3. What is your expectation for any new HCI to be used in the design process?
Cheaper hardware and inclusion within mainstream CAD packages without the need for specialist software (ie Phantom "bolt on's" for Solidworks, ProE, etc)

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:
2 hands are commonly used (Mouse + Keyboard short cuts) and mouse + space ball combination greatly speeds view re-orientations, etc.

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

3. Did you find the two-handed operation useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:
Using the LUCID system it wasn't always clear where the cursor was, but being able to change view with the space mouse and move the selection cursor at the same time was very useful

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

....

....

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:
In a perspective view stereoscopic viewing gives greater depth and removed the need for additional view ports

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:
The Phantom provides feedback from the tip of the tool only. With real physical models haptic feedback relating to form may be recieved simultaneously with both hands and all fingers. Current haptics are like trying to view a painting in sections through a small keyhole.

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:
Being able to feel surfaces with the cursor may be of use when trying to select control points etc

Three-dimensional (3D) Sound Display

1. Is 3D sound display useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:
The build up of sound to express magnitude of force/motion was quite useful

2. Do you think 3D sound feedback could enhance the information exchange in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....

....

3. Did you find 3D sound feedback useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths: There seemed to be a large degree of freedom when creating geometries, which would probably appeal to more visual arts based designers who would find conventional CAD too restrictive.

Weaknesses: It would be nice to experience more haptic feedback from the Phantom when touching surfaces. Being able to follow contours and curves would help the user in locating exactly where the cursor was in 3D space.

Thank you for your assistance in this research.

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Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 3

Department of Design and Technology

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The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Your assistance with this research is much appreciated.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

- [ ] Student
- [ ] Design Researcher
- [x] Design Teacher
- [ ] Industrial Designer
- [ ] Engineering Designer
- [ ] Design Consultant
- [ ] Design Manager
- [ ] Other..

2. Have you used any CAD system(s) for your design work?

- [ ] No
- [x] Yes. Please indicate which
  - [x] Pro/Engineer
  - [ ] UniGraphics
  - [ ] Alias
  - [x] CATIA

- [x] SolidWorks
- [x] AutoCAD
- [ ] ProDesktop
- [ ] SolidEdge
- [ ] Other..

3. What do you think of the overall design functions and tools these CAD systems provide for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☒ 9 ☐ 10

   Poor Satisfactory Extremely helpful

   Other comments:
   Sometimes feature based libraries need to be built when designing families of products

4. What do you think of the interface these CAD system(s) provide for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☒ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:
   ....
   ....

Part B – Virtual Reality (VR) Technology

1. Have you heard about VR technology?

   - [ ] No
   - [x] Yes

2. Have you used any VR-based input/output devices?

   - [ ] No
   - [x] Yes. Please indicate which
     - [ ] 3D Position Trackers
     - [ ] Navigation & Manipulation Interfaces
     - [ ] Gesture Interfaces
     - [ ] 3D Stereoscopic Graphics Displays
     - [ ] 3D Sound Dispalys
     - [x] Haptic Feedback
     - [ ] Other..

3. How do you think of VR-based technologies could be employed to provide better support to the HCI in the product design process?

....
....
....
....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☒ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....
   ....

2. Have you used any other HCI for your design work?

   ☒ No

   ☐ Yes. Please indicate..

3. What is your expectation for new HCI to be used in the design process?

   ......user friendly / accurate......................................
   ....
   ....
   ....

Part D – New Virtual Reality (VR) based Interfaces

Two-handed Operation

1. Is a two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

   Other comments:

   ....
   ....

2. Do you think two-handed operation can provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

Other comments:

....

....

3. Do you find the two-handed operation useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

If there is a tool menu selection, select the tool < shape: o, □, ⊏ size: 1...

- set the increment (depth of sculpting)

- use the haptic device for virtual shaping design

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing display useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing display can provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

Other comments:

....

....

3. Do you find the stereoscopic viewing display useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is a haptic feedback interaction useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☒ Strongly agree

   Other comments:

   ....

   ....

2. Do you think haptic feedback interaction can provide a more intuitive method in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

3. Do you find the haptic feedback interaction useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☒ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces in the LUCID system for supporting design process?

Strengths: – It integrates 3 different devices within one functional design system
– It is completely original piece of work
– Offers flexibility within the design process
– Supports the feature based design

Weaknesses: – Cannot impose any dimensional constraints
– Should be able to export the output – results → to other CAD systems or RP/CNC machine tools
– A specific test part should be found to produce a ca[se] study in order to prove and clearly point out a few advantages of LUCID as compare to ProEngineer, Solid[...]

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 4

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

   - [x] Student
   - [x] Design Researcher
   - [ ] Design Teacher
   - [ ] Industrial Designer
   - [ ] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other..

2. Have you used any CAD system(s) for your design work?

   - [ ] No
   - [x] Yes. Please indicate which of the following you have used
     - [ ] Pro/Engineer
     - [ ] UniGraphics
     - [ ] Alias
     - [ ] CATIA
     - [ ] SolidWorks
     - [x] AutoCAD
     - [x] ProDesktop
     - [x] SolidEdge
     - [ ] Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐1 ☐2 ☑3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10

Poor — Satisfactory — Extremely helpful

Other comments: Most don't allow free 'sketch' type usage, NOT letting designers follow their own design path, having to follow a set system

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐1 ☑2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10

Poor — Satisfactory — Powerful

Other comments: Only used mouse / keyboard desktop screen however

Part B – Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☑ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☑ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☑ Haptic Feedback
- ☐ Other

Only demonstration though!

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

Allow designers the option of these tools allowing them a better representation of 3D space, using these to add to the design process.

- Easy to use, add value to process, aid evaluation,
- comfortable to use, different methods, time saving, more natural use of interaction

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☑ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate..

3. What is your expectation for any new HCI to be used in the design process?

   • Easy to operate, comfortable (Ergonomic) adaptive, ...

   • Non-structured - less Engineer more design / Art / Free form

   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

Buttons can be defined to allow user quick access to functions once get used to system faster control of system / shortcuts,

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☑ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither
- ☑ Agree
- ☐ Strongly agree

Other comments:

Sculpting would be useful

3. Did you find haptic feedback interaction useful in the LUCID system?

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither
- ☑ Agree
- ☐ Strongly agree

Other comments:

Sound Display

1. Is sound display useful in the design process?

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither
- ☐ Agree
- ☑ Strongly agree

Other comments:

instruction / warning useful.

2. Do you think sound feedback could enhance the information exchange in the design process?

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither
- ☑ Agree
- ☐ Strongly agree

Other comments:

3. Did you find stereo sound feedback useful in the LUCID system?

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither
- ☐ Agree
- ☑ Strongly agree

Other comments:

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths. · Effective 3D viewing.

Stereoscopic wireframes - provide accurate representation of 3D shapes

· Auto-change of cursor good, makes easier to use

· Will be an effective design tool - button/menu interface clear.

"

Weaknesses. · Difficult to position where cursor was in 3D space,

· Lighting effects needed in shaded view - Pre

· Allow designers to add more points on form to edit easier,

· Practice of use of this technology is needed.

· Stereoscopics gives a headache after time and haptic device poor wrist posture + hard to use.

· Could use pre-defined views?

Thank you for your assistance in this research.

IDEAS! ⇒

· Instead of using Esc or a create function perhaps using 'C' would be more intuitive.

· Tutorials?

· Icons could be clearer? possibly in 3D?

· 3D menu system?

· Snap to points, grid

· Use more stereoscopic view, quite flat!

· Increase refresh rate / system power to handle more complex ~~sld~~ solids

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 5

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

- ☐ Student
- ☑ Design Researcher
- ☐ Design Teacher
- ☐ Industrial Designer
- ☐ Engineering Designer
- ☐ Design Consultant
- ☐ Design Manager
- ☐ Other..

2. Have you used any CAD system(s) for your design work?

- ☐ No
- ☑ Yes. Please indicate which of the following you have used
  - ☑ Pro/Engineer
  - ☐ UniGraphics
  - ☑ Alias
  - ☐ CATIA
  - ☑ SolidWorks
  - ☑ AutoCAD
  - ☐ ProDesktop
  - ☐ SolidEdge
  - ☐ Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Extremely helpful

   Other comments:

   ....

   ....

4. What do you think of the user interface these CAD system(s) provide for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments:

   ....

   ....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

   ☐ No

   ☑ Yes

2. Have you used any VR-based input/output devices?

   ☐ No

   ☑ Yes. Please indicate which of the following you have used

   - ☐ 3D Position Trackers
   - ☐ Navigation & Manipulation Interfaces
   - ☐ Gesture Interfaces
   - ☐ 3D Stereoscopic Graphics Displays
   - ☐ 3D Sound Displays
   - ☑ Haptic Feedback
   - ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

   ....

   IT WOULD BE NICE TO BE ABLE TO DESIGN WITH OUT BEING CONSTRAINED BY EITHER CAD SYSTEMS OR POOR OPERATING KNOWLEDGE.

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments: MICE ARE OFTEN HARD TO CONTROL & POSITION PRECISELY.

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate ……………………

3. What is your expectation for any new HCI to be used in the design process?

   INTUITIVE TO USE + FAST.

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments: IT WAS HARD TO USE AT FIRST. THERE ARE MANY DIRECTIONS OF TRAVEL – HARD TO REMEMBER.

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments: ……………………

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

THE NONE DOMINANT HAND SHOULD ONLY CONTROL SIMPLE FUNCTIONS - INITIALLY TO GET USED TO THE SYSTEM.

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments: THE VIEW IS NOT THAT DIFFERENT FROM 'NORMAL' EXISTING PACKAGES.

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments: IT CERTAINLY HAS POTENTIAL - ~~YES~~ IT IS A BIT HARD TO KNOW SCALE OF MOVEMENT/POINT LOCATIO[N]

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Three-dimensional (3D) Sound Display

1. Is 3D sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments: IT WAS EASY / CLEAR TO KNOW WHEN A POINT HAD BEEN SELECTED.

2. Do you think 3D sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find 3D sound feedback useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths...LUCID IS A SIMPLE AND FAST PROGRAME, EASY TO LEARN, WITH LOTS OF FEEDBACK.

THE SOUND WAS VERY INFORMATIVE AND REDUCED THE NEED TO CONSTANTLY CLICK TO ENSURE POINT ACTIVATION.

HEAD SET (GLASSES) DID NOT FIT THAT COMFORTABLY OVER MY GLASSES.

Weaknesses...NOT MANY, ONLY THE GLASSES MENTIONED IN THE STRENGTHS !!

ARM ACHED AFTER USING HAPTIC DEVICE BUT THAT COULD HAVE BEEN DUE TO MY INEXPERIENCE.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 6

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

   - [x] Student
   - [x] Design Researcher
   - [ ] Design Teacher
   - [ ] Industrial Designer
   - [ ] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other..

2. Have you used any CAD system(s) for your design work?

   - [ ] No
   - [x] Yes. Please indicate which of the following you have used
     - [x] Pro/Engineer
     - [ ] UniGraphics
     - [ ] Alias
     - [ ] CATIA
     - [x] SolidWorks
     - [ ] AutoCAD
     - [x] ProDesktop
     - [ ] SolidEdge
     - [ ] Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor — Satisfactory — Extremely helpful

Other comments: Generally not good for organic shapes.

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☑ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor — Satisfactory — Powerful

Other comments:

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☑ No

☐ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☐ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☐ Haptic Feedback
- ☐ Other

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

provide different methods of viewing models.

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments: It does the job, but is not very natural for viewing

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate...

3. What is your expectation for any new HCI to be used in the design process?

   ....it should be easy to use + comfortable.

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments: Speeds up modelling

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

It is useful to be able to zoom/pan/rotate with one hand, and use the other hand for working on the model.

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments: The 3D effect does allow a clearer view of the model.

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments: When it worked it was useful - but it was sometimes difficult to find the model in 3D space.

find

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments: Useful for knowing when I was touching the model.

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths. It makes viewing models in 3D more realistic. I especially like the 3D mouse for zooming and rotating. It becomes very intuitive to use.

The sound was useful for knowing when the model was being touched.

It would make using CAD more fun!

It could be a useful way to present design models to users for evaluation.

Weaknesses. Stereoscopic glasses are heavy and uncomfortable. They hurt my ears. I would also worry about the effect of the flickering on my brain. I wouldn't wear them for any length of time.

Although 2-handed operation is useful, it does get uncomfortable after a while - get stiffness in the hands and shoulders.

It was sometimes difficult to pick up points on the curves.

The haptic feedback was not always there, and I found using the 'pen' quite difficult. I think if I used it for a longer period of time it would become easier.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 7

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

- ☑ Student
- ☑ Design Researcher
- ☐ Design Teacher
- ☐ Industrial Designer
- ☐ Engineering Designer
- ☐ Design Consultant
- ☐ Design Manager
- ☐ Other..

2. Have you used any CAD system(s) for your design work?

- ☐ No
- ☑ Yes. Please indicate which of the following you have used
  - ☑ Pro/Engineer
  - ☐ UniGraphics
  - ☑ Alias
  - ☐ CATIA
  - ☑ SolidWorks
  - ☑ AutoCAD
  - ☑ ProDesktop
  - ☐ SolidEdge
  - ☑ Other...Mechanical Desktop...

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☑ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☐ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☑ Haptic Feedback
- ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

.....It allows the user to clearly view the model, and manipulate the model.....

....

....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate..

3. What is your expectation for any new HCI to be used in the design process?

   ...That it would help the designer quickly manipulate and view the model.

   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ...it makes the design process using CAD, a lot quicker

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ....

   ....

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

   • More efficient – it is a lot quicker using two hands, because you can rotate and manipulate the model at the same time
   • Flexible – you can make changes to the model easily from many viewpoints.

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ....

   ....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ....

   ....

3. Did you find stereoscopic viewing useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ....

   ....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments:

   ....

   ....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths - Quick to change the view points and to manipulate the model
- Very easy to visualise the 3D form
- Interface is very clear and easy to pick up

Weaknesses
- It may take time to get used to the new devices, if you had never used them before.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 8

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

   - [x] Student
   - [ ] Design Researcher
   - [ ] Design Teacher
   - [ ] Industrial Designer
   - [ ] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other..

2. Have you used any CAD system(s) for your design work?

   - [ ] No
   - [x] Yes. Please indicate which of the following you have used
     - [x] Pro/Engineer
     - [x] UniGraphics
     - [ ] Alias
     - [ ] CATIA
     - [x] SolidWorks
     - [ ] AutoCAD
     - [x] ProDesktop
     - [ ] SolidEdge
     - [ ] Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☑ No

☑ Yes. Please indicate which of the following you have used

☐ 3D Position Trackers

☐ Navigation & Manipulation Interfaces

☐ Gesture Interfaces

☐ 3D Stereoscopic Graphics Displays

☑ 3D Sound Displays

☐ Haptic Feedback

☐ Other...

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

Better Control of 3D Shapes

Better Viewing of increased Shapes

....

....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☑ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ……………………………………………………………………………………

   ……………………………………………………………………………………

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate……………………………………………………………

3. What is your expectation for any new HCI to be used in the design process?

   To Be Capable of & recieving feedback on Surface models.

   ……………………………………………………………………………………

   ……………………………………………………………………………………

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ……………………………………………………………………………………

   ……………………………………………………………………………………

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ……………………………………………………………………………………

   ……………………………………………………………………………………

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

Greater flexibility in Control and Manipulation.

....

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths: Good Control of 3D Points and Model Control

Weaknesses: Menus Still Awkward and Not user friendly.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 9

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

- [ ] Student
- [ ] Design Researcher
- [x] Design Teacher
- [x] Industrial Designer
- [ ] Engineering Designer
- [ ] Design Consultant
- [ ] Design Manager
- [ ] Other...

2. Have you used any CAD system(s) for your design work?

- [ ] No
- [x] Yes. Please indicate which of the following you have used
    - [ ] Pro/Engineer
    - [ ] UniGraphics
    - [ ] Alias
    - [ ] CATIA
    - [ ] SolidWorks
    - [x] AutoCAD
    - [ ] ProDesktop
    - [ ] SolidEdge
    - [ ] Other...

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B – Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☑ No

☐ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☐ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☐ Haptic Feedback
- ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

....Useful to move around complex assemblies.............

....

....

....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:

   ....

   ....

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate..

3. What is your expectation for any new HCI to be used in the design process?

   I had anticipated greater changes in the nature of the CAD software to exploit the qualities of the new type of interface. For example being able to move shaped tools through a solid controlled by the Haptic device, to create cuts.

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ....

   ....

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

....

....

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☑ Strongly agree

Other comments:

....

Refresh rates need to be higher to reduce flicker.

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☑ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☑ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

Greater degree of hand/eye coordination required.

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [ ] Agree
- [x] Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

Nature of the feedback could be more refined.

Sound Display

1. Is sound display useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

- [ ] Strongly disagree
- [x] Disagree
- [ ] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths... Ability to work quickly and more naturally...

Weaknesses... Strain induced by Haptic interface on unsupported arm over long periods of continuous use.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 10

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?
   - [ ] Student
   - [ ] Design Researcher
   - [ ] Design Teacher
   - [x] Industrial Designer
   - [ ] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other..

2. Have you used any CAD system(s) for your design work?
   - [ ] No
   - [x] Yes. Please indicate which of the following you have used
     - [ ] Pro/Engineer
     - [ ] UniGraphics
     - [ ] Alias
     - [ ] CATIA
     - [ ] SolidWorks
     - [x] AutoCAD
     - [ ] ProDesktop
     - [ ] SolidEdge
     - [ ] Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☑ No

☐ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☐ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☐ Haptic Feedback
- ☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

By reducing the confusion of overlapping lines and details.

....

....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments:
   You can get used to almost anything.

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate ....

3. What is your expectation for any new HCI to be used in the design process?
   I expect it to be more like sculpting.

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

☐	☐	☐	☑	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments:

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

☐	☐	☐	☑	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments:

3. Did you find the two-handed operation useful in the LUCID system?

☐	☐	☑	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

To separate movement of the object from movement of a tool or corser.

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☑ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree	☑ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments: I found I needed to concentrate more in order to place the cursor on a node.

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐ Strongly disagree	☑ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths A small movement of the object make it clear which lines are at the front etc. The dimensional relationships are easier to understand.

Weaknesses I found the haptic device required more attention and more precision than I currently need to use. I also found working with my right hand unsupported difficult. I am sure this would become a significant problem over a long working day.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 11

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

   - ☐ Student
   - ☐ Design Researcher
   - ☑ Design Teacher
   - ☐ Industrial Designer
   - ☐ Engineering Designer
   - ☐ Design Consultant
   - ☐ Design Manager
   - ☐ Other...

2. Have you used any CAD system(s) for your design work?

   - ☐ No
   - ☑ Yes. Please indicate which of the following you have used
     - ☑ Pro/Engineer
     - ☐ UniGraphics
     - ☑ Alias
     - ☐ CATIA
     - ☐ SolidWorks
     - ☑ AutoCAD
     - ☐ ProDesktop
     - ☐ SolidEdge
     - ☐ Other.....IDEAS...

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ 8 ☐ 9 ☐ 10

Poor | Satisfactory | Extremely helpful

Other comments: SOME TEETHING PROBLEMS, BUT HAS GOOD POTENTIAL.

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor | Satisfactory | Powerful

Other comments: GOOD - LIMITED TO CERTAIN FUNCTIONS AT THIS STAGE

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☑ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☑ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☑ 3D Stereoscopic Graphics Displays
- ☑ 3D Sound Displays
- ☑ Haptic Feedback
- ☐ Other.......

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

VISUALISING A MODEL IN 3D IS BETTER THAN ORTHOGRAPHIC VIEWS. HAPTIC FEEDBACK WOULD BE GOOD TO 'FEEL' THE SURFACES, RATHER THAN JUST VISUAL.

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☑ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments: REQUIRES KEYBOARD INPUT TOO. RSI

2. Have you used any other HCI for your design work?

   ☐ No

   ☑ Yes. Please indicate TABLET

3. What is your expectation for any new HCI to be used in the design process?

   MORE INTUITIVE, MORE LIKE WORKING WITH REAL OBJECTS. I.E – SANDING, CUTTING ETC

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☒ Neither ☐ Agree ☑ Strongly agree

   Other comments: Depends on how the designer works in real-life – If they have done real life work & not just brought up on CAD.

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments: SIMULATES REAL LIFE

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....
....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

FASTER
....
....
....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [ ] Agree
- [x] Strongly agree

Other comments:

SEEING A MODEL IN 3D IS MORE TRUE TO LIFE.

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

IF USED WITH HEAD MOUNTED DISPLAYS IF ITS AN IMMERSIVE ENVIRONMENT.

3. Did you find stereoscopic viewing useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [ ] Agree
- [x] Strongly agree

Other comments:

GOOD TO SEE WHERE THE POINTS ARE AS NO SIDE/TOP/FRONT VIEW.

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neither
- [x] Agree
- [ ] Strongly agree

Other comments:

....
....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

TO FIND WHERE THE SKETCHING

PLANES WERE.

Three-dimensional (3D) Sound Display

1. Is 3D sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

IF USED CORRECTLY

....

2. Do you think 3D sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find 3D sound feedback useful in the LUCID system?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

WOMANS VOICE WAS ANNOYING.

SOUND NEEDS TO ADJUST to + ~~or~~ − ~~rather than~~ depending on near or far

quieter / louder

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths......3D VISUALISATION
HAPTIC FEEDBACK
SURFACE CREATION

Weaknesses.....SHADING
MOUSE MOVEMENT

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 12

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

- [ ] Student
- [ ] Design Researcher
- [x] Design Teacher
- [x] Industrial Designer
- [ ] Engineering Designer
- [x] Design Consultant
- [ ] Design Manager
- [ ] Other..

2. Have you used any CAD system(s) for your design work?

- [ ] No
- [x] Yes. Please indicate which of the following you have used
  - [x] Pro/Engineer
  - [ ] UniGraphics
  - [ ] Alias
  - [ ] CATIA
  - [x] SolidWorks
  - [ ] AutoCAD
  - [ ] ProDesktop
  - [ ] SolidEdge
  - [ ] Other..

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☑ No

☐ Yes. Please indicate which of the following you have used

☐ 3D Position Trackers

☐ Navigation & Manipulation Interfaces

☐ Gesture Interfaces

☐ 3D Stereoscopic Graphics Displays

☐ 3D Sound Displays

☐ Haptic Feedback

☐ Other..

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

....

It could replicate 1:1 scale.

....

....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☑ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

   Poor — Satisfactory — Powerful

   Other comments:

   I use a stylus – much better!

2. Have you used any other HCI for your design work?

   ☐ No

   ☑ Yes. Please indicate... See above

3. What is your expectation for any new HCI to be used in the design process?

   I want to feel, physically, the model I'm building.

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☐ Agree ☑ Strongly agree

   Other comments: More closely resembles holding a piece of material with one hand and working it with the other

3. Did you find the two-handed operation useful in the LUCID system?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....
....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

....
....
....
....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....
....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

Linked to a large screen, this could give apreciation of full size models.

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

Locating points in space was difficult

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree	☐ Disagree	☐ Neither	☑ Agree	☐ Strongly agree

Other comments:

....
....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐	☐	☐	☐	☑
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐	☑	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

Sensory feedback was too coarse

....

Sound Display

1. Is sound display useful in the design process?

☐	☐	☐	☑	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐	☐	☐	☑	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐	☑	☐	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

I understood what was happening from the visual display before sound feedback was given

Part E – Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths: • No longer having to work in 2D planes.
• Quicker navigation around the CAD model.

Weaknesses: • Its still an interface: there is a barrier between the designer and the design model.

• Shoulder strain could be a problem if the user needs to elevate the hand/arm for long periods of time

• There is a lot of hardware that takes-up valuable desk space.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 13

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

   - [ ] Student
   - [ ] Design Researcher
   - [ ] Design Teacher
   - [x] Industrial Designer
   - [ ] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other...

2. Have you used any CAD system(s) for your design work?

   - [ ] No
   - [x] Yes. Please indicate which of the following you have used

     - [ ] Pro/Engineer
     - [ ] UniGraphics
     - [ ] Alias
     - [ ]
     - [x] SolidWorks
     - [x] AutoCAD
     - [ ] ProDesktop
     - [ ] SolidEdge

☐

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor | Satisfactory | Extremely helpful

Other comments:

looks cool, when developed, should be great

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor | Satisfactory | Powerful

Other comments:

Great feedback

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No
☑ Yes

2. Have you used any VR-based input/output devices?

☐ No
☑ Yes. Please indicate which of the following you have used

- ☐ 3D Position Trackers
- ☐ Navigation & Manipulation Interfaces
- ☐ Gesture Interfaces
- ☑ 3D Stereoscopic Graphics Displays
- ☐ 3D Sound Displays
- ☐ Haptic Feedback
- ☐

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

make them realistic, and work in all positions

....
....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ 8 ☐ 9 ☐ 1

   Poor Satisfactory Powerful

   Other comments:

   ....
   ....

2. Have you used any other HCI for your design work?

   ☑ No

   ☐ Yes. Please indicate...

3. What is your expectation for any new HCI to be used in the design process?

   ....
   ...good...
   ....
   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

   Other comments: ..

   ....
   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:

   ....
   ....

3. Did you find the two-handed operation useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

....

....

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

Sound Display

1. Is sound display useful in the design process?

Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

.....to many.......comants..

2. Do you think sound feedback could enhance the information exchange in the design process?

Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

.....if.....done.......right..

3. Did you find stereo sound feedback useful in the LUCID system?

Strongly disagree	Disagree	Neither	Agree	Strongly agree

Other comments:

....

....

Part E – Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths...

the ability to move in space

Weaknesses..

needs simplified punchop

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 14

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

- [ ] Student
- [ ] Design Researcher
- [ ] Design Teacher
- [ ] Industrial Designer
- [x] Engineering Designer
- [ ] Design Consultant
- [ ] Design Manager
- [ ] Other........VIRTUAL DESIGN..

2. Have you used any CAD system(s) for your design work?

- [ ] No
- [x] Yes. Please indicate which of the following you have used
  - [x] Pro/Engineer
  - [ ] UniGraphics
  - [ ] Alias
  - [ ]
  - [x] SolidWorks
  - [ ] AutoCAD
  - [ ] ProDesktop
  - [ ] SolidEdge

☐

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments:

....

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☐ Yes. Please indicate which of the following you have used

☐ 3D Position Trackers

☐ Navigation & Manipulation Interfaces

☐ Gesture Interfaces

☑ 3D Stereoscopic Graphics Displays

☐ 3D Sound Displays

☐ Haptic Feedback

☐

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

......HELPING...TO....BETTER.....VISUALIZE....PARTS,...MAKE..
....INTERFACE...MORE.....INTUITIVE...THAN.....MOUSE...........

....
....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☑ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 1

   Poor Satisfactory Powerful

   Other comments:

   ....
   ....

2. Have you used any other HCI for your design work?

   ☐ No

   ☑ Yes. Please indicate......SPACEBALL...

3. What is your expectation for any new HCI to be used in the design process?

   ....
   ....
   ....
   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

   Other comments:

   ....
   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

   Other comments:

   ....
   ....

3. Did you find the two-handed operation useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

....

....

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereo sound feedback useful in the LUCID system?

☐ Strongly disagree ☑ Disagree ☐ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths: VISUALIZATION OF SHAPES BEING PRODUCED.

Weaknesses: DIFFICULT TO MANIPULATE / CONTROLS FOR VIEWING / SPINNING / ZOOMING ETC NEED TO BE ON ONE DEVICE AND SELECTION ICONS NEED TO BE ON OTHER. NOT INTERTWINED AS AT PRESENT.

Thank you for your assistance in this research.

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Loughborough University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 15

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A -- Computer Aided Design (CAD) Systems

1. What is your job function?

   - ☐ Student
   - ☐ Design Researcher
   - ☐ Design Teacher
   - ☐ Industrial Designer
   - ☑ Engineering Designer
   - ☐ Design Consultant
   - ☐ Design Manager
   - ☐ Other...

2. Have you used any CAD system(s) for your design work?

   - ☐ No
   - ☑ Yes. Please indicate which of the following you have used

     - ☑ Pro/Engineer
     - ☐ UniGraphics
     - ☐ Alias
     - ☐
     - ☑ SolidWorks
     - ☑ AutoCAD
     - ☑ ProDesktop
     - ☐ SolidEdge

☐

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☑ 10

   Poor Satisfactory Extremely helpful

   Other comments: Would Almost Stop all work if I COULDNT USE CAD SYSTEM!

4. What do you think of the user interface these CAD system(s) provide for your design work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☑ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments: As I'M USED TO IT

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

   ☐ No

   ☑ Yes

2. Have you used any VR-based input/output devices?

   ☐ No

   ☑ Yes. Please indicate which of the following you have used

   - ☑ 3D Position Trackers
   - ☐ Navigation & Manipulation Interfaces
   - ☐ Gesture Interfaces
   - ☑ 3D Stereoscopic Graphics Displays
   - ☐ 3D Sound Displays
   - ☑ Haptic Feedback
   - ☐

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

   Conveying Ideas + Concepts to Consumers

....
....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☑ 9 ☐ 10

   Poor Satisfactory Powerful

   Other comments:
   ....
   ....

2. Have you used any other HCI for your design work?

   ☐ No
   ☑ Yes. Please indicate Space Mouse / Track Ball

3. What is your expectation for any new HCI to be used in the design process?

   Better than Mouse
   ....
   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:
   ....
   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

   ☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

   Other comments:
   ....
   ....

3. Did you find the two-handed operation useful in the LUCID system?

[ ] Strongly disagree | [x] Disagree | [ ] Neither | [ ] Agree | [ ] Strongly agree

Other comments: 2 Handed fine Mouse / keyboard / Space Mouse / Pen = 4 hands !

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

2 Handed Is how we operate at moment

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

[ ] Strongly disagree | [ ] Disagree | [ ] Neither | [x] Agree | [ ] Strongly agree

Other comments:

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

[ ] Strongly disagree | [ ] Disagree | [ ] Neither | [x] Agree | [ ] Strongly agree

Other comments:

3. Did you find stereoscopic viewing useful in the LUCID system?

[x] Strongly disagree | [ ] Disagree | [ ] Neither | [ ] Agree | [ ] Strongly agree

Other comments: Can't get on with the glasses

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

[ ] Strongly disagree | [ ] Disagree | [x] Neither | [ ] Agree | [ ] Strongly agree

Other comments:

....

....

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

☐ Strongly disagree	☐ Disagree	☑ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

3. Did you find haptic feedback interaction useful in the LUCID system?

☑ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments:

Just Got in the way

Sound Display

1. Is sound display useful in the design process?

☐ Strongly disagree	☑ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments:

....

....

2. Do you think sound feedback could enhance the information exchange in the design process?

☑ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments:

Just Got in the way

3. Did you find stereo sound feedback useful in the LUCID system?

☑ Strongly disagree	☐ Disagree	☐ Neither	☐ Agree	☐ Strongly agree

Other comments:

See above

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths...

Weaknesses...

No freedom for Technical / Engineering Work at present + Complicated to get used to + Expensive

Thank you for your assistance in this research.

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Loughborough
University

Questionnaire

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

Participant 16

Department of Design and Technology

Loughborough University

The Use of Virtual Reality Based Interfaces to Support Computer Aided Conceptual Design Process

This questionnaire is part of a research programme that is investigating the extent to which virtual reality (VR) based technologies are being employed to give better support to the human computer interface (HCI) in the conceptual design process.

Please tick or write a response as appropriate. Any information you provide will be treated as strictly confidential. Your assistance with this research is much appreciated.

Note: Before your software example demonstration operation, please fill in Part A, Part B and Part C first. After the example demonstration operation, please finish the others and return it to me at the address on the cover page.

Part A – Computer Aided Design (CAD) Systems

1. What is your job function?

   - [ ] Student
   - [ ] Design Researcher
   - [ ] Design Teacher
   - [ ] Industrial Designer
   - [x] Engineering Designer
   - [ ] Design Consultant
   - [ ] Design Manager
   - [ ] Other..

2. Have you used any CAD system(s) for your design work?

   - [ ] No
   - [x] Yes. Please indicate which of the following you have used
     - [x] Pro/Engineer
     - [ ] UniGraphics
     - [ ] Alias
     - [ ]
     - [x] SolidWorks
     - [ ] AutoCAD
     - [ ] ProDesktop
     - [ ] SolidEdge

☐

3. What do you think of the overall design functions and tools the CAD system provide for your design work ? (answer for the system you have used most)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Extremely helpful

Other comments:

....

....

4. What do you think of the user interface these CAD system(s) provide for your design work?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☑ 8 ☐ 9 ☐ 10

Poor Satisfactory Powerful

Other comments: 3D support would be good.

....

Part B -- Virtual Reality (VR) Technology

1. Have you heard about VR technology?

☐ No

☑ Yes

2. Have you used any VR-based input/output devices?

☐ No

☐ Yes. Please indicate which of the following you have used

☐ 3D Position Trackers

☐ Navigation & Manipulation Interfaces

☐ Gesture Interfaces

☑ 3D Stereoscopic Graphics Displays

☐ 3D Sound Displays

☐ Haptic Feedback

☐

3. How do you think VR-based technologies could be employed to provide better support to the HCI in the product design process?

WHILE MOST DESIGNERS ARE GOOD AT VISUALISING

2D SCREEN IMAGES, IT WOULD HELP CUSTOMERS

....
....

Part C – Human Computer Interface (HCI)

1. What do you think of the typical mouse-keyboard interface used in most CAD systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ 8 ☐ 9 ☐ 1

   Poor — Satisfactory — Powerful

   Other comments:
   ALLOW INPUT OF NUMBERS OK
   ....

2. Have you used any other HCI for your design work?

   ☐ No

   ☐ Yes. Please indicate..

3. What is your expectation for any new HCI to be used in the design process?
   MUST MAKE YOU WORK QUICKER
   ....
   ....
   ....

Part D – New Virtual Reality (VR) Based Interfaces

Two-handed Operation

1. Is two-handed operation useful in the design process?

☐	☐	☑	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments: I LIKE TO HAVE ONE HAND FREE
   ....

2. Do you think two-handed operation could provide a more natural interaction method for the design process?

☐	☐	☑	☐	☐
Strongly disagree	Disagree	Neither	Agree	Strongly agree

   Other comments:
   ....
   ....

3. Did you find the two-handed operation useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments:

....

....

4. How do you think two-handed operation could be used to make the design process more efficient and flexible?

AS MENTIONED BEFORE, I THINK ONE HAND OPERATION IS BETTER.

....

....

Stereoscopic Viewing Display

1. Is a stereoscopic viewing useful in the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

2. Do you think stereoscopic viewing could provide a more realistic three-dimensional (3D) environment for the design process?

☐ Strongly disagree ☐ Disagree ☐ Neither ☑ Agree ☐ Strongly agree

Other comments:

....

....

3. Did you find stereoscopic viewing useful in the LUCID system?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments: PUT A BIT OF A STRAIN ON THE EYES.

Haptic Feedback Interaction

1. Is haptic feedback interaction useful in the design process?

☐ Strongly disagree ☐ Disagree ☑ Neither ☐ Agree ☐ Strongly agree

Other comments: IF IT WORKS WELL

2. Do you think haptic feedback interaction could provide a more intuitive method in the design process?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

3. Did you find haptic feedback interaction useful in the LUCID system?

- [ ] Strongly disagree
- [ ] Disagree
- [x] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments: DIDN'T WORK THAT WELL

Sound Display

1. Is sound display useful in the design process?

- [ ] Strongly disagree
- [x] Disagree
- [ ] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

2. Do you think sound feedback could enhance the information exchange in the design process?

- [ ] Strongly disagree
- [x] Disagree
- [ ] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments:

3. Did you find stereo sound feedback useful in the LUCID system?

- [ ] Strongly disagree
- [x] Disagree
- [ ] Neither
- [ ] Agree
- [ ] Strongly agree

Other comments: SORRY, I LIKE TO LISTEN TO MUSIC WHILE WORKING

Part E -- Strengths and Weaknesses

What do you consider to be the strengths and weaknesses of the interfaces used in the LUCID system for supporting design process?

Strengths... I THINK A 3D SCREEN COULD WORK VERY WELL WITH A CAD SYSTEM BUT IT MUST NOT GIVE YOU EYE STRAIN

Weaknesses... I CERTAINLY WOULD NOT USE THE SOUND FEEDBACK FEATURE.
THE 3D PEN I FOUND TO BE A BIT OF A STRAIN ON THE WRIST AFTER A WHILE AND I COULD NOT WORK ON IT ALL DAY.

Thank you for your assistance in this research.

APPENDIX III

Publications

Publications resulting from research

1. Ye, J., Campbell, R.I. *et al. An Investigation into the Implementation of Virtual Reality Technologies in Support of Conceptual Design.* Journal of Design Studies. Elsevier Science, 2005 (writing).

2. Ye, J. and Campbell, R.I. *Supporting Conceptual Design With Multiple Virtual Reality Based Interfaces.* International Journal of Human-computer Studies, Elsevier Science, 2005 (submitted).

3. Ye, J. and Campbell, R.I. *A New Virtual Reality Based Conceptual Design System.* Proceedings of the EVEN International Conference on Virtual Engineering Applications and Product Development. Trinity College, Dublin, Ireland. September 4^{th}-5^{th}, 2003. pp. 52-63.

4. Ye, J. and Campbell, R.I. *New CAD Interfaces for the Conceptual Design Process.* Proceedings of the 3rd Annual International Conference on Rapid Product Development. Bloemfontein, South of Africa, November 5^{th}-7^{th}, 2002. pp. 150-162.