Integration of physical and virtual prototyping

DESIGN SCHOOL

INTEGRATION OF PHYSICAL AND VIRTUAL PROTOTYPING

BY

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Abstract

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INTEGRATION OF PHYSICAL AND VIRTUAL PROTOTYPING

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This research was concerned with the integration of physical and virtual prototyping to support user evaluation in the product design process.

The research background, research aim and research objectives which give the overall guide to this research are introduced first. The top-level aim of the research was to explore the ways that physical and virtual prototypes can be simultaneously combined to support industrial designers in testing and modifying their designs. A comprehensive literature review was undertaken into the topics of product design and development, the role of physical and virtual prototype/prototyping and related prototyping integration technologies. A questionnaire survey regarding the applications of prototypes is then presented. The knowledge gained from these was used to define the needs of real time integration of physical and virtual prototyping. A method to quickly transfer the changes in a physical prototype to a virtual prototype has been proposed and developed into an integration system known as the Loughborough University Prototyping Integration System (LUPIS). The feasibility and potential benefits of this system were tested through several user trials. The generic implementation of LUPIS is then discussed and an example of the configuration of this system for a motorcycle is presented. Finally, conclusions about the outcome of the research and suggestions for future work are provided. The main conclusions drawn from the research were:

Real time integration of physical and virtual prototypes/prototyping is an efficient way of helping product design activities, especially in the product evaluation process. LUPIS has presented a new approach to achieve the real time integration. However, more advanced technologies are needed to develop this system and make it more sophisticated.

The main contributions of this research include: i) a deeper understanding of the applications of physical and virtual prototyping (obtained through literature review and questionnaire survey), ii) the needs of real time integration of physical and virtual prototyping has been defined; iii) a wide range of technologies related to prototyping integration have been investigated and analysed, and their limitations are identified; iv) The Loughborough University Prototyping Integration System has been developed and a generic implementation method has been also proposed.

Keywords

Prototype; Physical prototyping; virtual prototyping; integration; product design.

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List of abbreviations

2D	- Two-dimensional
3D	- Three-dimensional
CAD	- Computer-aided design
CAM	- Computer-aided manufacturing
CAVE	- Cave Automatic Virtual Environment
CFD	- Computational fluid dynamics
CNC	- Computer numerical control
FEA	- Finite element analysis
HMI	- Human-motorcycle interaction
HMD	- Head Mounted Display
IGES	- Initial Graphics Exchange Standard
LUPIS	- Loughborough University Prototyping Integration System
NPD	- New product development
NURBS	- non-uniform rational basis spline
PP	- Physical prototyping
RE	- Reverse Engineering
RM	- Rapid Manufacturing
RP	- Rapid prototyping
STL	- Stereolithography tessellation language
VE	- Virtual environment
VP	- Virtual prototyping
VR	- Virtual reality
CE	- Concurrent Engineering

Table of Contents

Figures and tables in the text

Chapter One

Introduction

This chapter introduces the research presented in this thesis. It begins by explaining the research background and introducing the research objectives. 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 to guide the reader through this work.

1.1 Research Background

Prototype is an approximation of the product [Ulrich and Eppinger 1995]. Prototyping is the process of building, modifying and testing prototypes until volume production starts. Within the new product development (NPD) process, prototyping is the pivotal activity that structures innovation, collaboration, and creativity in design [Hartmann et al 2006]. Repeated, efficient, and extensive use of prototypes is a vital activity that can make the difference between the successful and unsuccessful entry of new products into the competitive world market [Zorriassatine et al. 2003]. The different types of prototypes can all be categorised as being either physical prototypes or virtual prototypes.

A physical prototype, as the name suggests, is an object in the real world. It is made with real materials such as wood, clay, foam or metal [Zorriassatine et al. 2003]. The construction and testing of a physical prototype can be called physical prototyping. The methods of physical prototyping can be classified into three types: hand making, mechanical machining and computer aided prototyping. As a conventional prototyping method, physical prototyping still plays a very important role in process and product development. Particularly, it supports a concurrent, time-oriented approach and collaboration in teams composed of people from different functions and backgrounds [Vandevelde et al. 2002]. However, it is a well-known fact, that physical prototyping is a time-consuming and cost-intensive task [Weck & Kuhlen 2000, Zorriasssatine 2003]. For example, compared to the CAD model, it usually takes more time and cost to cut materials from a physical model or to add material to it.

To speak in general terms, a virtual prototype means building the product model in computer using 3D modelling software. The creation and modification of a virtual prototype can be called virtual prototyping. Virtual prototyping is an up-to-date concept in the design and product development cycle. Due to its ability to reduce the design cycle time and cost, virtual prototyping has replaced physical prototyping in many areas and is expected to be used more widely in future [Huang & Chen 1999]. Despite the advantages, a virtual prototype is less preferable compared with a physical prototype in several ways. For example, when testing the ergonomics aspect of a product, most participants still prefer to interact with a physical prototype.

Physical and virtual prototypes both play very important roles from the conceptual design stage to the final prototyping stage. Both of them have advantages and disadvantages in different aspects. However, physical and virtual prototyping should not be seen as competitive but rather complementary technologies [Grimm 2005]. Jain [2005] also claimed that the integration of virtual prototyping and physical prototyping would lead to shorter product development cycles and fewer late-stage errors.

Campbell [2005] initially investigated the research topic “real time integration of virtual and physical prototyping." He suggested that it is valuable to test, modify or verify both virtual and physical prototypes simultaneously. The "real time integration" here means changes to the virtual prototype can reflect any changes that have been made contemporaneously to the physical prototype, and vice versa. It is believed that "real time integration" would improve the traditional use of the two types of prototyping technologies and consequently contribute to the progress of new product development.

1.2 Aim of the Research

The aim of the research is to suggest and develop a tool to simultaneously integrate physical and virtual prototyping. The initial research emphasis was to concentrate on:

i) Investigating how physical and virtual prototyping technologies work and connect with each other,

ii) Identifying methods that could be used to simultaneously convey changes in virtual and physical prototypes to one other and

iii) Testing and evaluating these methods with designers and users to explore their benefits and limitations.

1.3 Research Objectives

The aim of the research was further decomposed into the following objectives:

1. Identify the role of the prototypes and prototyping in product design process.
2. Determine the strengths and weaknesses of PP and VP.
3. Specify the contributions and limitations of PP and VP integration technologies
4. Establish the need of real time integration of PP and VP

5. Develop a system for the integration of PP and VP.

1.4 Research Methodology

In this research, a comprehensive literature review was conducted to investigate the nature of physical and virtual prototyping and prototypes, comparatively study their advantages and disadvantages, investigate the current relevant technologies, and identify the need of real time integration of PP and VP. Through the undertaking of the literature review, the foundation of knowledge in this research area was built and the gap between existing research results and the aim of this research was identified. The outcomes of the literature review showed that although the relevant information and background knowledge are plentiful, research projects that are particularly in this research area are still in their infancy.

In order to further identify the present situation of using physical and virtual prototypes in product design and industry, a questionnaire survey was conducted with product/industrial designers/directors in design companies and consultancies. Based on the results of literature review and questionnaire survey, a deep understanding of the limitations of the current applications of physical and virtual prototypes was identified and the need to develop a method that can achieve real time integration of the two types of prototypes was defined.

Considering the characteristics of physical and virtual prototypes and their advantages in different aspects, a proposed method was developed to test real time integration between them. This method applied infrared sensors as the media to connect the computer aided design (CAD) model and the physical model. The development of this method comprised four stages: 1) planning the conceptual system, 2) pilot trial on the initial system, 3) user evaluation with the developed system, and 4) the proposal for the future development of the system.

User evaluation tests were conducted to measure the method's performance against the evaluation objectives. The disadvantages of the traditional application of physical and virtual prototypes and, the benefits and limitations of the proposed method were gained from the analysis of the user evaluation tests. 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 seven chapters, the content of which is briefly summarised below.

Chapter Two: New Product Development and Product Design

In order to set the background for the later sections of the thesis, this chapter presents a discussion of product development and design. The concepts and process of industrial/product design are reviewed. The varieties of product design activities and theories are also studied.

Chapter Three: Prototypes and Prototyping

This chapter defines prototypes and prototyping, presents the classifications of prototypes and prototyping tools and technologies, analyses the impact of prototyping on product design and development, goes on to define the terms physical prototyping (PP) and virtual prototyping (VP) and then compares the strengths and weakness of the two technologies.

Chapter four: Related research

In this chapter, related research regarding the conversion between and combination of physical and virtual prototypes is presented. It begins by reviewing relevant technologies and goes on to examine their roles in getting users involved in design evaluations. This is followed by a discussion on the necessity to develop a new method of simultaneously integrating physical and virtual prototypes.

Chapter Five: Initial Investigation

As the overall aim of this research was to suggest and develop a tool to integrate PP and VP. The purpose of this initial empirical study was to identify the key problems regarding the application of these two types of prototypes. This chapter begins with a general overview of empirical study as a research methodology and goes on to analyse the results from a pilot trial and a questionnaire study to provide added support to the previous literature review research.

Chapter Six: Development of the proposed PP/VP integration method

Based on the literature review and questionnaire survey, a proposed integration method for PP and VP was introduced in Chapter Five. The trial that followed, with regards to the method, showed its benefits but also exposed its limitations and problems, which indicated further development of this method was needed. This chapter presents an integration system which is named Loughborough University Prototyping Integration System (LUPIS) system. It is based on the proposed method introduced in the previous chapter.

Chapter Seven: Developing a Generic Approach to Prototype Integration

In the early chapters of this thesis, substantial knowledge of the generic process of product design and prototyping has been presented. In the later chapters, a specific prototype integration system called LUPIS was developed and validated through several experiments. In this chapter, the remaining objective of the research is met through the development of a generic method of prototype integration that aims to help product designers working in a wide range of product sectors.

Chapter Eight: Conclusions and suggestions for future work

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

Chapter Two

New Product Development and Product Design

In order to set the background for the later sections of the thesis, this chapter presents a general discussion of product development and design. The concepts and process of industrial/product design are reviewed. The varieties of product design activities and theories are also studied.

2.1 New product development (NPD)

2.1.1 Definitions of products and new product development

Before describing new product development, it is first necessary to consider what is meant by the term ‘product’. The Longman dictionary [1995] defines a product as ‘something useful that is made in factory, grown, or taken from nature’. Ulrich and Eppinger [1995] describe a product as ‘something sold by an enterprise to its customers’. Baker and Hart [2007. P41] have defined a product as ‘the object of the exchange process, the thing which the producer or supplier offers to a potential customer in exchange for something else (e.g. money) which the supplier perceives as being of equivalent or greater value’. Kahn [2001] defined that a product is a particular offering that a company provides to customers. In contrast to services that are intangible, a narrow definition of products is that they are physical and tangible [Murthy et al 2008]. These definitions indicate the basic concept of a product as being something that is made by a supplier and exchanged with a customer for something of equivalent or greater value, typically money. Whereas this exchange may happen quickly and simply, the development of a new product is usually a long-term and complex process.

Simply speaking, “new product” is in contrast to a product that has been on the market for some time. However, the word ‘new’ in NPD can mean a whole spectrum of things from simple adaptation though major re-design to extend life, and ultimately replacement with a completely new product [Inwood and Hammond 1993]. Furthermore, the “newness” of a product could vary from different perspectives and the degree of newness is an indicator of the difference between a new product and the existing one. For example, a change that reduces the production cost might be viewed as a major change from the manufacturer’s perspective but no change at all from the customer’s perspective. From the customer’s perspective, the newness usually deals with improvements in the product attributes or new features that meet new requirements or which result in greater benefits [Murthy et al 2008].

New product development can be defined as ‘a set of activities beginning with the identification of a market opportunity and ending in production’ [Ulrich and Eppinger 1995; SAP 2004]. It involves nearly all the functions of a firm, including marketing, designing and manufacturing [Ulrich & Eppinger 2003]. Otto & Wood [2001] stated that NPD is the entire set of activities required to bring a new concept to a state of market readiness. This set includes everything from the initial product concept, to business analysis, marketing efforts, engineering design activities, manufacturing design plans, and the validation of the product design to conform to these plans. According to the above definitions, NPD covers an entire range of activities for the launch a new product, including marketing, product designing, managing and financing, and so forth.

In today’s industries, new product development is crucial and often referred to as the lifeblood of a company [Annacchino 2003]. Companies must now evolve new products at an increasing rate to enhance their competitive posture or even to survive (ibid). Within NPD, cost, time and customer involvement are three of the most important issues. Companies that are able to effectively develop, produce and introduce new products can become key competitors in markets where variety and time-to-market, besides prices and quality, play an ever-increasing role [Booz et al 1982; Bolwijn et al, 1986; kumpe and Bolwijn, 1994]. Product-based companies that have successful new product development will be able to attain higher revenue and significantly shorter time to market than they would otherwise would [McGrath et al 1992]. Kumar & Phrommathed [2005] also stated that the efficient new product developments, which usually combine both innovation and customer input, will significantly increase the real competitive advantage of firms. However, product development is a risky business. NPD could fail if the development process is not well managed and/or the product does not meet customer requirements [Inwood and Hammond 1993].

In addition, according to the motivation to develop a new product, developments can be characterized into two types: market-pull and technology-push. Market-pull product development is focused on satisfying customer needs and closely parallels the strategy-directed approach to product development, while technology-push product development closely parallels the idea-directed approach to product development, with or without an investigation into its potential [Kahn 2001]. As Kahn [ibid] argued the typical product development organization/function is biased towards one of market-pull or technology-push processes; there is never a true merging of both. The companies that implement a technology-push or innovation strategy are more competitive in the long run while those that follow a customer-responsive or market–pull strategy are more likely to have higher return on investment within a shorter time [Kumar and Phrommathed 2005].

However, combining both innovative and customer-responsive strategies improves the probability of product success when a new product is launched into a market [ibid].

Successful NPD requires many things, such as a feasible new product idea; a team that can design, develop, produce, and deliver the product; and a planned process that is not simply “ad hoc” to assure that this can be done quickly and repeatedly [Rosenau 2000]. The following section will discuss the phases of the new product development process.

2.1.2 The process of new product development

A product development process is the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product [Ulrich & Eppinger 2003]. Although not all successful products come from a planned development process, a structured process of new product development is an important part to improve new product introduction rate and to maximize the benefits from a company’s product portfolio [Stamm 2003]. Kahn [2001] stated that product development processes are similar across companies and industries. Indeed, most product development processes will reflect similar stages. However, diversity in product development processes does exist. Many different models of new product development process with varying numbers of stages have been proposed in the literature [Murthy et al 2008]. Table 1 shows several samples of new product development models.

Model	Phases
Model 1 [Andreasen and Hein 1987]	Recognition of need → Investigation of need → Product principle → Product design → Product preparation → Execution
Model 2 [Pugh 1990]	Market → Specification → Conceptual → design → Detail design → Manufacture
Model 3 [Fox 1993]	Pre-concept → Concept → Design → Demonstration → Production
Model 4 [Roozenburg and Eekels, 1995]	Analysis → Concept → Materialization
Model 5 [Pahl and Beitz 1996]	Clarification of task → Conceptual design → Embodiment design → Detail design
Model 6 [Otto and Wood 2001]	Understand opportunity → Develop concept → Implement concept
Model 7 [Ulrich and Eppinger 2003]	Planning → Concept Development → System-level Design → Detail Design → Testing and refinement → Production Ramp-up
Model 8 [Cooper 2005]	Scoping → Build business case → Development → Testing and validation → Launch
Model 9 [Blanchard 2004]	Conceptual design → Preliminary system → design → Detailed design and development → Construction → Production

Table 1: The new product development models with varying phases

There are some similarities as well as differences between these models. In industry, every organization employs a new product development process at least slightly different from that of every other organization. The diversity of the number and sequence of phases depend on several contexts, such as the type of product, degree of innovation, production process, and so on [Murthy et al 2008]. Here model 6, introduced by Otto and Wood [2001], and model 7, produced by Ulrich and Eppinger [2003], were taken as examples to further study the NPD process in detail and to compare their similarities and differences.

2.1.2.1 NPD Model by Otto and Wood [2001]

Otto and Wood [2001] characterized the NPD process with three phases: understand the opportunity, develop a concept and implement a concept [Otto & Wood 2001]. Each phase encompasses four activities (shown in figure 1). The theory in this characterization can be summarized as follows.

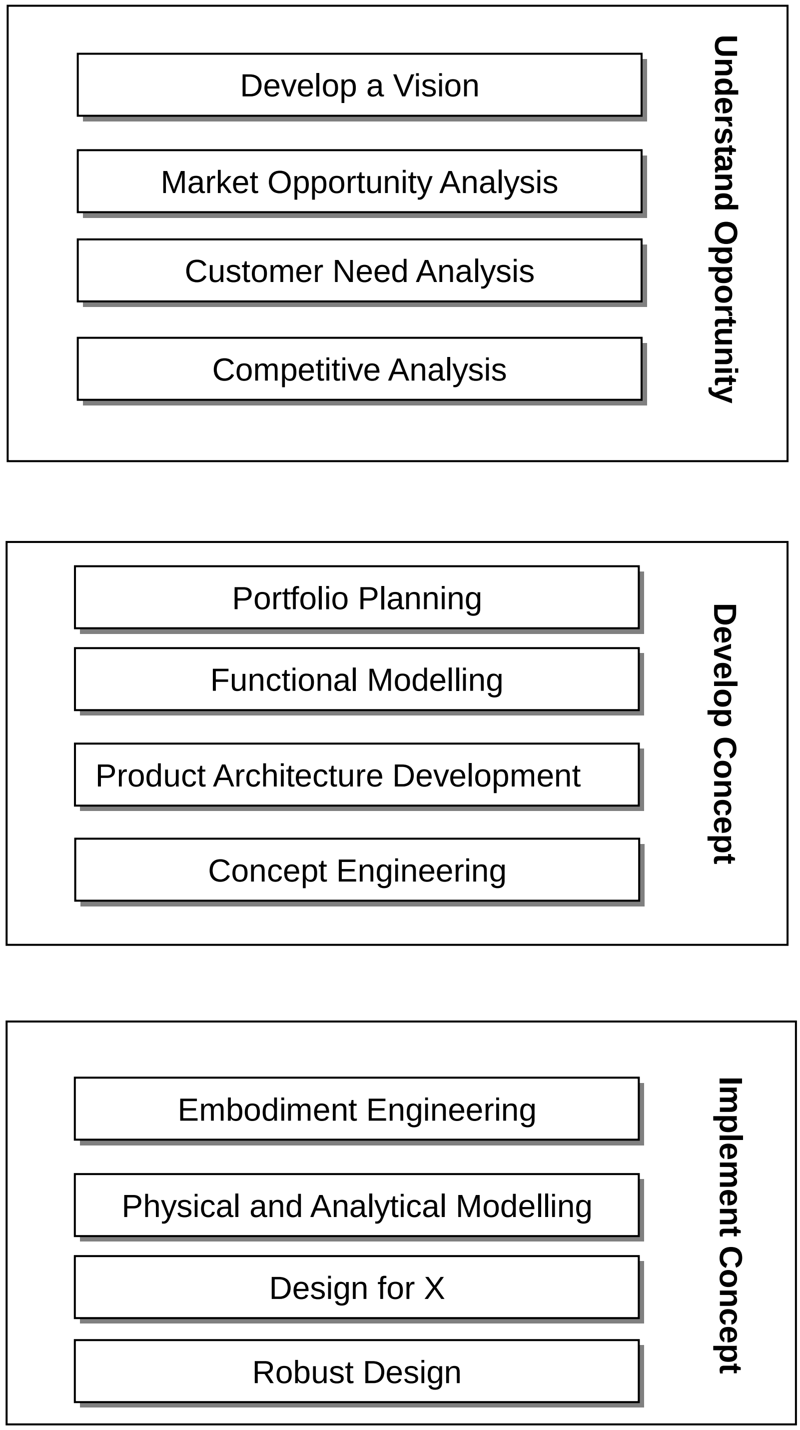

Figure 1: Activities in a typical product development process [Otto & Wood 2001]

As the first step of the front-end phase, as well as being part of a product development process, 'Developing a vision' of a product aims to identify what is difficult with the current product in use; what product people wish to be out there; and what it does not do that people want it to. After the above questions are answered, three analysing activities are conducted, including: market opportunity analysis, customer needs analysis and competitive analysis.

Having clarified all the information about the opportunity, the design team starts to work together to develop the design concept. "A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, analysis of competitive products, and an economic justification of the project" [Ulrich and Eppinger 2003]. Within this phase, portfolio planning is used to create a set of design specifications for the product and to generate concepts to satisfy the customer needs identified in the first phase. In the functional modelling stage, the product functions are established to describe the inputs, outputs, and transformations that must happen for a product to work. Once the functional modelling work has been completed, the development of product architecture may commence. According to Mikkola and Gassmann [2003], product architecture may be defined as "the arrangement of the functional elements of a product into several physical building blocks, including the mapping from functional elements to physical components, and the specification of interfaces among interacting physical components". In this stage, the decisions are made on how the product will physically operate. Based on the work of previous stages, the concept's engineering is developed to implement the functional specification of the product. One thing that needs to be mentioned is that some companies prefer to conduct the concept generation stage prior to the opportunity identification stage. The rationale is that concept generation should not be biased by any preconceived notions of what should be developed [Kahn 2001].

Implementation means putting ideas into practice [Stamm 2003]. At the beginning of the phase of ‘Implementing a concept’, embodiment engineering aims to give form to a chosen concept through specification of components to purchase, parts to manufacture, and a specification for their assembly into the product. The theme of this thesis, i.e. physical and analytical (virtual) modelling is usually allocated to this phase. More discussion regarding these two aspects is presented in sections 3.2, 3.3 and 3.4 of Chapter 3.

According to Blanchard [2004], Design for X is: “an integrated approach where design for reliability, maintainability, human factors, safety, supportability, interoperability, availability, life cycle cost, flexibility, transportability, quality, disposability, environment, and testability are considered throughout the process”. ‘Design for X’ can also mean ‘design for excellence’ and refers to a wide range of approaches applied to meet various engineering and design specifications, where X is any one of these requirements. For example, ‘design for the environment’ is to ensure that a product uses minimal-impact materials and operations; ‘design for manufacturing’ is to ensure the ease of manufacturing. The last stage of new product development, in this model, is robust design, which ensures that the product functions well under various conditions and with different users. Robust design is an engineering methodology for improving productivity during design & development so that high quality products can be produced at low cost [Shyam 2002].

2.1.2.2 NPD Model by Ulrich and Eppinger [2003]

Another typical model of the new product development process was introduced by Ulrich and Eppinger [2003]. Different from Otto and Wood's model containing three main phases, they characterized the NPD process into six sequential phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up (as shown in figure 2). The words on the right column show the outputs from the previous phase. As per Ulrich and Eppinger's theory, these phases are summarized as follows

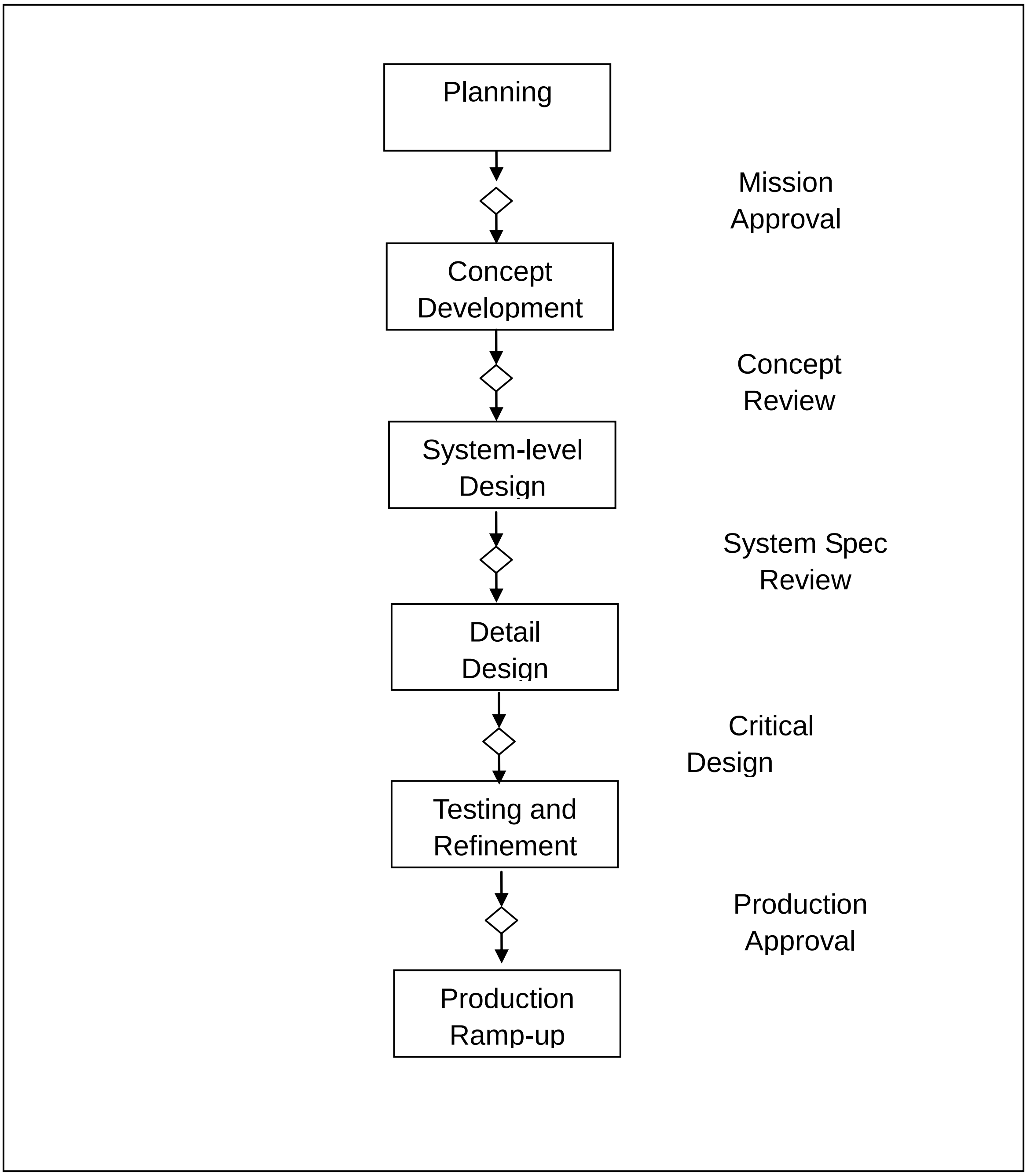

Figure 2: Generic Product Development Process [Ulrich and Eppinger 2003]

As the very first phase, ‘Planning’ begins with corporate strategy and includes assessment of technology developments and market objectives. The output of the planning phase is the approval of the mission for a product development. Although in a different typology system, the activities involved in this planning phase are similar to the ‘understand opportunity’ phase of the first model as created by Otto and Wood

In the ‘Concept development’ phase, a competitive and economic analysis is performed; the customer needs are identified; one or more concepts are selected for further development from several initial ideas; the form, function and features of the product are usually accomplished by a set of specifications. Compared to the model of Otto and Wood, it is found that, in the two models, the authors’ understandings regarding the activities in ‘develop concept’ (or ‘concept development’) are not completely the same. The ‘concept development’ in the second model covers some activities of the first and second phase in Otto and Wood’s model.

In the ‘system-design level’ phase, the product architecture is defined and the product is decomposed into subsystems and components. The output of this phase also includes a geometric layout of the product, a functional specification of each of the product’s subsystems, and a preliminary process flow diagram for the final assembly process. The ‘Detail design’ phase includes the complete specification of the geometry, materials and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased. “In detail design, all properties for each component are defined in detail (e.g. forms, dimensions, tolerances, surface properties, and materials)” [Murthy et al 2008]. The ‘robust design’ takes place in this phase as well and in the ‘Testing and refinement’ phase, preproduction versions of the product – prototypes are constructed and evaluated. Compared the activities involved in these three phases (system-design level, Detail design, Robust) to the activities introduced in ‘Develop Concept’ and ‘Implement Concept’ phases in the previous model, it is found that, although they named the phases differently, quite a few activities are similar, such as product architecture, specifications of geometry, assembly, etc.

In the final phase, ‘production ramp-up’, the product is made using the intended production system. The purpose of the ramp-up is to train the work force and to work out any remaining problems in the production processes. This phase can be seen as the conjunction of the product development and manufacturing process and is not clearly introduced in the previous model. However, in Otto and Wood’s model, the concept of ‘Design for X’ takes some elements into consideration, such as life cycle cost, environment, and so on, which were not emphasized in the Ulrich and Eppinger’s model.

2.1.3 Discussion

Most NPD processes are systematic and sequential. The transition from one phase to another is usually gradual and there is no clear break between adjoining phases. However, there are also some exceptions: the product development process can be haphazard in some firms. Although these haphazard NPD processes also can lead to success, a structured and sequential approach has a better chance of success [Kahn 2001].

The design phase is a subsystem of the new product development process and is concerned with arriving at product characteristics that may provide the desired product attributes determined in the front-end phase [Murthy et al 2008]. Keinonen [2006] also suggested that product design is a subordinate function of production and distribution and must fulfil several requirements, including the degree of detail in the specifications, the internal accuracy of the specifications, the compatibility with production and the accurate timing of the specification delivery. In the following sections, the issues regarding design will be discussed.

2.2 Design

2.2.1 A brief historical review of design and industrial design

Searching the word “design” through Google finds around 1,130,000,000 results. Design is one of the highest expressions of human creativity [Caplan 2005]. It is an ancient and historic activity that can be dated back to early civilizations [Slack 2006]. The Longman dictionary [1995] defines design as a verb: ‘to make a drawing or plan of something that will be made or built; to plan or develop something for a specific purpose’. Consequently, the noun of design means ‘the way that something has been planned and made, including its appearance, how it works etc..’

In fact, the territory of the term ‘design’ is very vast [Lunenfeld 2003] and the meanings of design are many and shift according to the context in which the word is used [Julier 2000]. As Bony [2005] states, the word ‘Design’ is derived from the Latin word ‘designare’, which can mean to mark, trace, represent, draw, indicate, show, designate, signify, place, arrange, settle, or produce something usual. Walker [1989] also argues, ‘design can refer to a process (the act or practice of designing); or to the result of that process (a design, sketch, plan or model); or to the products manufactured with the aid of a design (design goods); or to the look or overall pattern of a product’. Caplan [2005] added that in a wider scope, different forms of design are usually paired in people’s minds with other acknowledged practices, be it fine art, architecture, engineering, cabinet-making, or illustration. The concept could be from the spoon to the city and embraces web sites, interfaces, plastic surgery and other impalpable forms of visual and functional ideas. Bony [2005] summarizes that design is a discipline that sets out to harmonize the human environment, ranging from the design of everyday objects to town planning

The history of design is one of constant evolution. In industry, originally from craft roots, design developed through the division of labour created by mechanisation, which gave birth to the role of the industrial designer [Design Council 2007, Raizman 2003].

The origins of industrial design can be traced back to the Industrial Revolution which began in Great Britain in the mid-18th century. Prior to this, objects were craft-produced, whereby both the conception and the manufacture of an object were the work of a single individual [Charlotte and Fiell 2003]. Industrial design arose from the desire to create a synthesis between form and engineering function and to apply it to industrial objects [Bony 2005]. While both the disciplines of engineering and industrial design are concerned with finding optimum solutions to specific problems, the primary distinguishing characteristic of industrial design is its concern for aesthetics [Charlotte and Fiell 2003].

The term “industrial design” was coined and became a full-fledged discipline in the early 20th century to describe the role performed by an industrial artisan for the design of mass-produced goods. Since then, design was integrated into industrial methods of production [IDSA 2006, Charlotte and Fiell 2003]. The appearance of the professional industrial designer, beginning in the later 1920s and 1930s, was ‘primarily a product of manufacturers’ interest in stimulating consumption through an appeal to novelty and fantasy in a more competitive economic climate’ [Raizman 2003].

The history of industrial design also defines it as a cross disciplinary activity. As Bony [2005] suggested, the history of design touches on many areas: aesthetics, sociology and politics; technology and materials; and commerce and the production-consumption system. Walker [1989] also stated design history has close links with other disciplines such as anthropology, archaeology (especially industrial archaeology) and sociology. As a cross disciplinary activity, the definitions of industrial design are still diverse nowadays.

2.2.2 What is industrial design

As a profession, design is recognized as a pursuit which requires specific education and training and could thus meet certain expected standards of knowledge, intellect and skill [Julier 2000]. Consequentially, industrial designers are, by training and inclination, especially capable of working with the visual aspects of a design problem. They can examine the engineering specifications and details of the working of an automatic washing machine, and provide a design for its external cover and its ergonomics [Lindbeck 1995].

However, there are too many definitions of industrial design to narrow it down to a definitive one [Lunenfeld 2003].The Industrial Designers Society of America [IDSA 2010] defines industrial design (ID) as the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer.' It links knowledge about technology and visual arts with knowledge about people. In addition, it requires a thorough understanding of physical sciences, engineering principles, ergonomics, aesthetics and industrial materials and processes [IDSA 2006]. However, It is important to remember that industrial design should never be considered as a precise science [bytestart 2010] since the problems encountered in industrial design are usually amenable to many solutions and there will never be just one “correct” design solution [Otto and Wood 2001].

In addition, the World Intellectual Protection Organization [WIPO 2011] defines industrial design in the following way. ‘An industrial design constitutes the ornamental or aesthetic aspect of an article. The design may consist of three-dimensional features, such as the shape or surface of an article, or of two-dimensional features, such as patterns, lines or color.’ WIPO also emphasizes that, to be protected under most national laws, an industrial design must be non-functional. This means that an industrial design is primarily of an aesthetic nature and any technical features of the article to which it is applied are not protected. Ulrich and Eppinger [1995] also state that industrial designers focus their attention upon the form and user interaction of products. This would seem to be at odds with the IDSA definition, showing that there is no universally accepted definition of industrial design.

Moreover, similar to the “newness” issue of new product development, the level of “creativeness” involved in a design can lead to a means of classification of industrial design. To indicate the extent of the effort required, Otto and Wood [2001] classified design into four categories as well, which are: original design, adaptive design, variant design or redesign, as follows:

1, Original design (or inventing) involves elaborating original (new/novel) solutions for a given task.

2, Adaptive design involves adapting a known system to a changed task or evolving a significant subsystem of a current product.

3, Variant design involves varying the parameters of certain aspects of a product to develop a new and more robust design.

4, Redesign could mean any one of the above and implies that a product already exists that is perceived to fall short in some criteria and a new solution is needed

In addition, to avoid possible confusion, the difference between 'creativity' and 'innovation' needs to be briefly discussed. As Stamm [2003] stated, creativity is an essential building block for innovation. Innovation equals creativity plus implementation. Creativity alone, to come up with ideas, is not enough. For example, EMI invented the x-ray scanner, but General Electric made a commercial success of it [ibid].

2.2.3 The concepts of industrial design and product design

There has been a wide debate over the differences between two similar concepts: 'product design' and 'industrial design'.

In practice, these two terms are usually interchangeable. For example, the company Industrial Design Consultancy [IDC 2011] describes itself as 'an international product design and development consultancy'; while Slack [2006] defined product design as an ambiguous term that blurs the boundaries between specialist fields of lighting, furniture, graphic, fashion, and industrial design. In addition, the UK's official graduate career website Prospects [2009] directly introduces a job titled as 'industrial/product design', and included the description 'an industrial/product designer employs a range of creative design, craft and engineering skills and processes to design and shape products for a variety of applications.' The Design Institute of Australia [2010] also states that industrial designers are also known as product designers.

Therefore, it can be concluded that the terms industrial design and product design are largely interchangeable. However, to maintain consistency and avoid confusion in this thesis, product design is taken as an all-inclusive term. The term ‘product design’ will be used throughout and it should be recognised that this includes all the activities of ‘industrial design’.

2.2.4 Product design process

As mentioned in the early section, design is an important part of new product development (NPD). Otto and Wood [2001] stated that a product design process is the set of technical activities within a product development process that work to meet the marketing and business case vision. The main difference between product design process and new product development process, as per Otto and Wood’s [2001] theory, is that, the design process does not necessarily include all of the business and financial management activities of product development nor the extensive marketing and distribution development activities.

In general, product design is the process of converting information that characterizes the needs and requirements for a product into knowledge about that product and its implied process [Magrab 1997]. A similar opinion is provided by Stamm [2003] who suggested that design is the conscious decision-making process by which information is transformed into an outcome. This is also approved of by Hudson [2010] who stated that product design is the process by which the needs of the customer or marketplace are transformed into the product specifying these needs. In addition, some researchers suggested the design process is a form of problem-solving where the means to reach the ends are sought intentionally [Roozenburg and Eekels 1995]. However, some other researchers emphasized that product design is a creative and inventive process [Charlotte and Fiell 2003]. The designers do not just meet the needs of customers but also create needs for them. As kahn [2001] stated, customers can have trouble articulating innovative or next-generation products. In addition, according to Kelley's opinion [2001], the customer can suggest the flavours that he likes, but it is not his job or even within his ability to create new flavours.

In practice, the process of design is extremely complex and is subject to many different influences and factors. Not least of these are the constraints imposed by the social, economic, political, cultural, organizational, and commercial contexts within which new products are developed, and the character, thinking and creative abilities of the individual designers or teams of designers, aligned specialists and manufacturers involved in their realization [Charlotte and Fiell 2003]. In addition, design is a team effort consisting of experts from many areas, especially for a large project. For example, no one person knows the totality of a Boeing 747 [Dormer 1991]. The complexity of design process is also reflected by its iterative character. Therefore, in order to achieve the synthesis of these factors and optimize the cooperation of all the members in a design team, the study of the process of design is crucial. The direction and stages of the design process are usually represented by a design model [Hollins and Hollins 1991]. As Twiss [1987] argues, decisions will be better if they are made with an understanding of the processes at work and within a 'conceptual framework'. This conceptual framework is referred to as the Design Model.

At the simplest level, the product design process may be classified into three traditional stages: specification development, conceptual design and embodiment design [Ehrlenspiel 2003]. However, similar to the NPD models, there are various product design models in practice. Within these types of design models from researchers, the vast majority of them still have similar core stages [Hollins and Hollins 1991]. In the following sub-sections, several Design Models devised by scholars are reviewed and analysed.

2.2.4.1 Model one [Garratt 1991]

This model is characterised by a 'flow chart' illustrating a design process, which was developed by Garratt [1991]. As shown in figure 3, the large arrows show how the design progresses from one stage to the next. The side arrows show that the design process is not straightforward and that designers often need to re-think an earlier stage. The purpose of this flow chart is to demonstrate the stages in design process for the students studying design and technology at school.

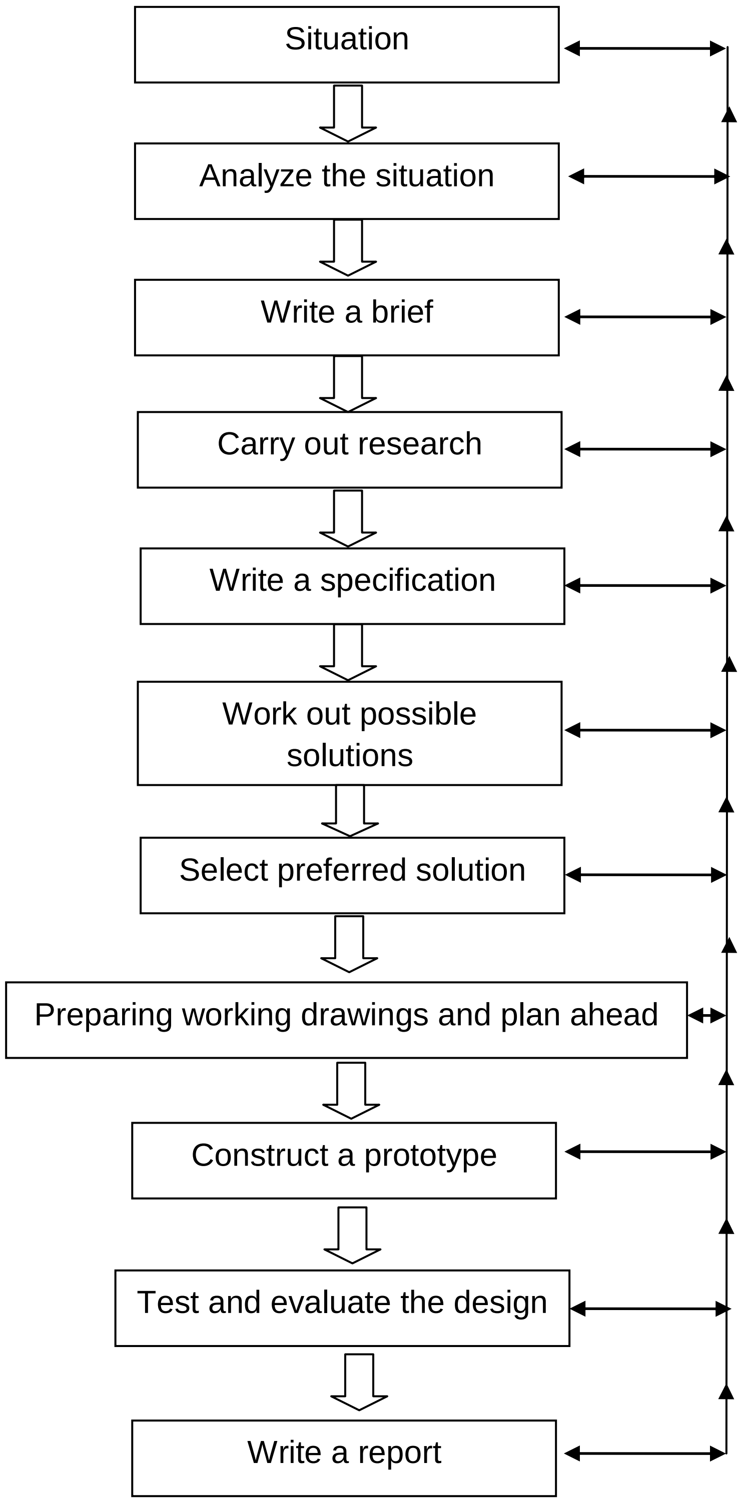

Figure 3: The design process flow chart [Garratt 1991]

According to the Garratt's theory, in the first stage of 'Situation', the designers need to identify practical problems in life's situations. In the second stage, the designers need to analyse the situation through interview, questionnaire, observation, and so on. Based on this analysis, a 'brief' is written in the following stage. The brief is a short statement describing the problem to be solved and it must not be so detailed that the designer does not have the freedom to be creative.

In the 'Research' stage, the designer needs to seek out information in order to answer the questions as follows: 1, What is the intended market for the design; 2, What is the practical function (or functions) of the design; 3, What materials are suitable for the design; 4, What construction methods are appropriate to the design; 5, What are the likely social and environmental effects of the design.

Based on the work of the previous stages, a 'specification' should then be produced. Different from the 'brief' in the third stage, a specification is a detailed description of the problem to be solved.

In the following two stages, 'work out possible solutions' and 'select preferred solution', the designer needs to generate solutions for the problems identified previously and chose the best one to meet the requirements listed in the specification stage. It needs to be mentioned here that the usage of quick hand drawing during this stage is preferable to a more time-consuming computer rendering to develop ideas and communicate with other students, clients or teachers [Essen and Steur 2009]

In the next three stages, the designer must produce a detailed drawing containing all the information needed to allow the design to be made, to construct a prototype and to test it to check that the product satisfies the specification. The purpose of the report in the final stage is to provide the teacher and examiner with evidence of the designer's ability to analyse, design, plan and carry out practical work, to evaluate and to communicate.

2.2.4.2 Model two [Lindbeck 1995]

Lindbeck [1995] created a five-stage product design process, as shown in figure 4. Similar to the first model, the arrows in this chart also show the iterations between different stages. A special mention should be given to the third stage 'Hypothesize'. This is the concept-development stage, where intuition and technical experience merge to produce a range of possible problem solutions. As per Lindbeck's theory, this is the core stage of the design process, where potential configurations emerge and are evaluated. In addition, because this model is developed in the context of industry, there are some different concerns involved in the design stages compared to the first model. For example, when collecting data in the second stage, the design team must know the industry leaders and competitors in the market.

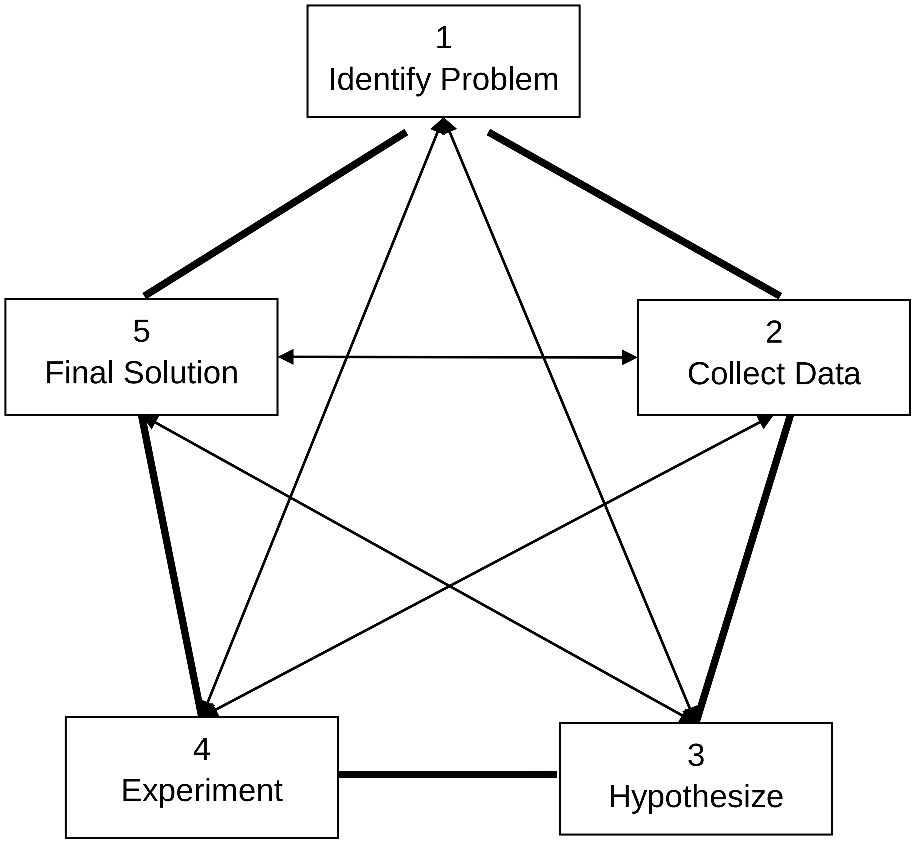

Figure 4: Product design process serves as a guide to creative design activities [Lindbeck 1995]

2.2.4.3 Model three [French 1999]

The third model is proposed by French [1999], as shown in figure 5. He emphasized that since design is a field where boundaries are imprecise and interactions are many, so any expert could produce a design process diagram which is different from others. However, every single process could be seen as being valid.

Similarly, his process also starts from need identification and indicates the feedbacks and iterations between stages. In addition, the stage of

‘Conceptual design’ is similar to the ‘Hypothesize’ of the second model, which is also emphasized by French as being the core of the design process.

A big difference from the previous two models is that he did not put ‘evaluation’ (or experiment) in this model, because he believed it should be going on continuously in all the rectangles. Furthermore, in the ‘Embodiment of schemes’ stage, the schemes are worked up in greater detail, and if there is more than one, a final choice between them is made.

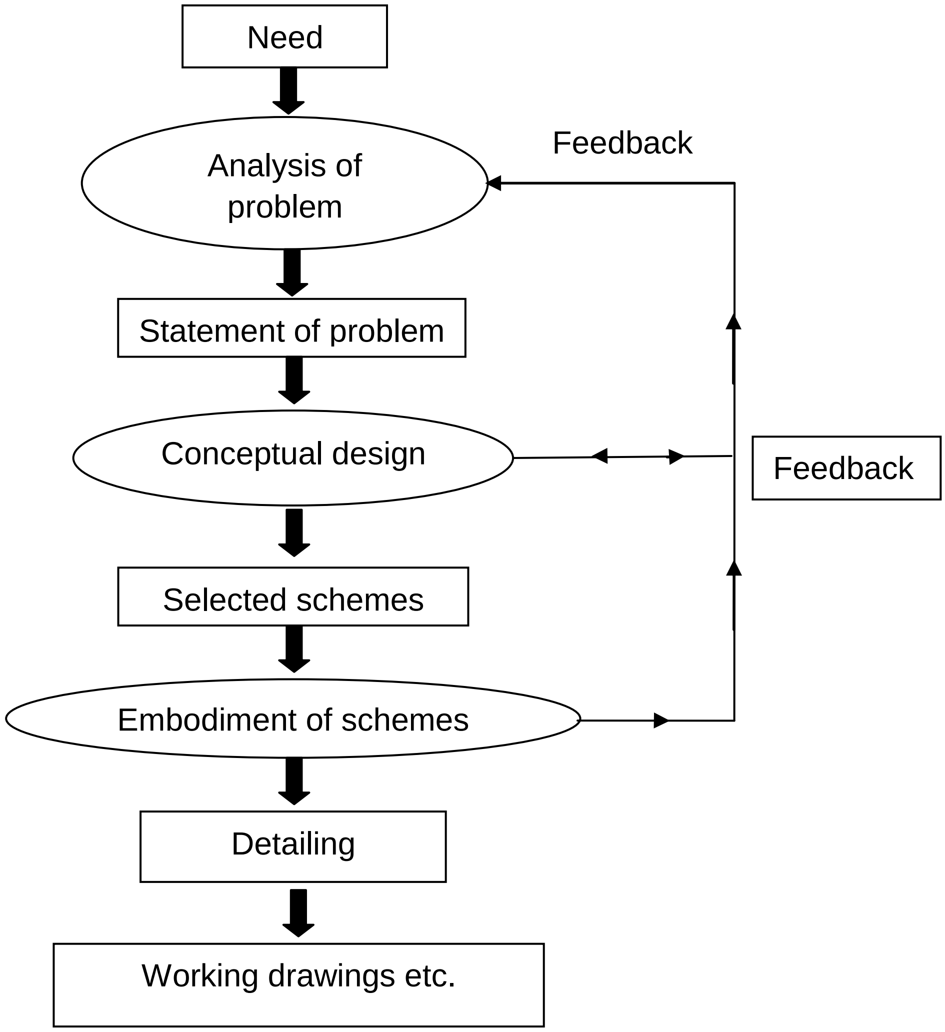

Figure 5: Product design process [French 1999]

2.2.4.4 Model Four [Pugh 1990]

The fourth model was created by Pugh [1990]. Firstly, he developed a model called the 'design core' (as shown in figure 6) to represent the main design flow. However, as per his theory, in order to enable design to be practised effectively and efficiently, the technologies and techniques that related to the design core should be involved in a planned and organized way. Therefore, he expanded the design core model and made a 'total design activity model'. Through this model, he introduced the concept of 'Total design'. He defined total design to be the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy that need – an activity that encompasses product, process, people and organization.

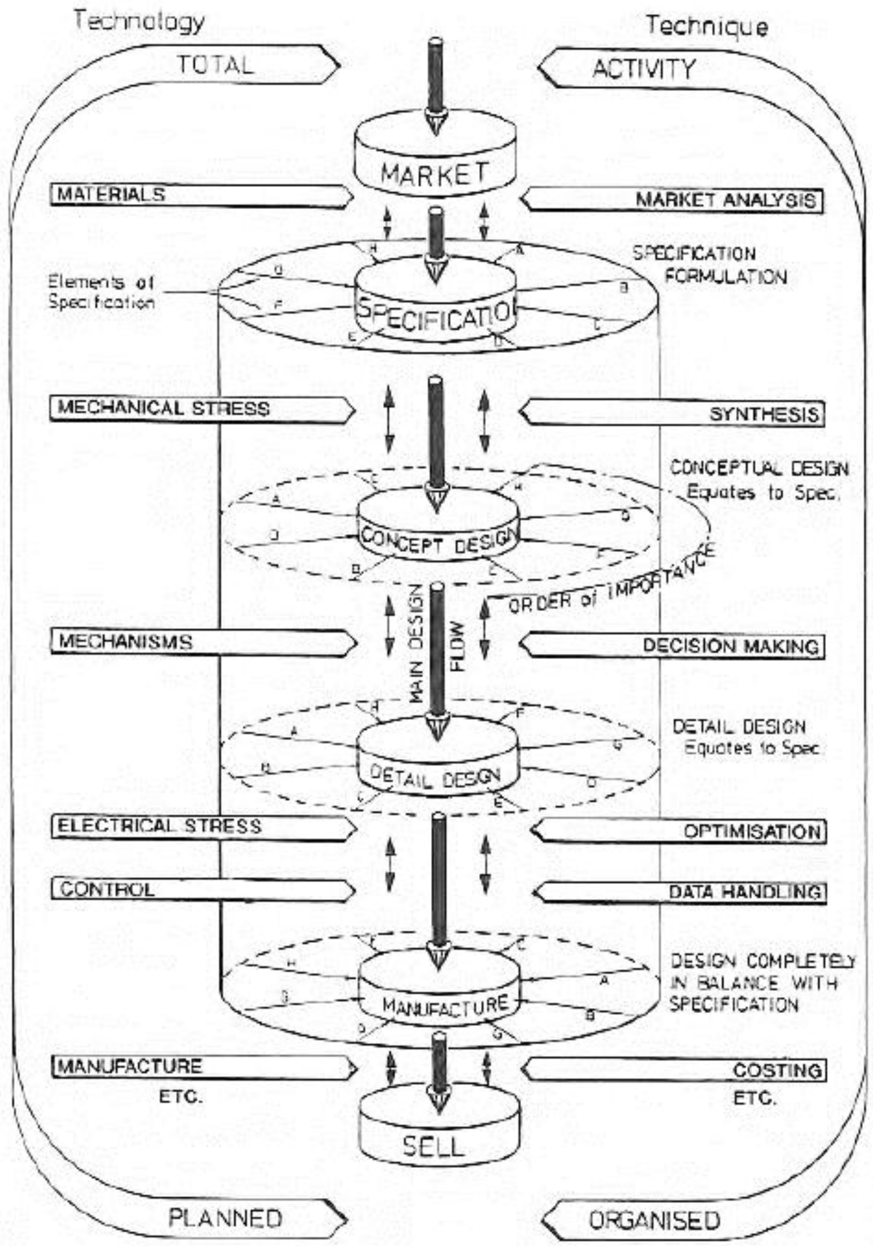

Figure 6: The Total Design activity model by Pugh [1990]

As per his theory, industry is concerned with total design. Engineering work involved in product design is paramount to the whole design process. In addition, according to his theory, because the product design specification (PDS) places boundaries on the subsequent designs, it acts as the control for the total design activity. This is also approved by Keinonen [2006], who suggested that product design must fulfil several requirements, including the degree of detail in the specifications, the internal accuracy of the specifications, and compatibility with the accurate timing of the specification delivery. Furthermore, the double-headed arrows in the total design model show that iterations occur in the design process, which again argues that iteration is inevitable in design process.

2.2.5 Discussion on the design process

The four design process models above have both differences and similarities between them. Some models were created in the educational environment and others were produced in the industrial context. Although the end of these design process models is quite debatable (some end with a report and others end with a working drawing or selling, etc.), the starting point of the different models are quite similar, i.e. the identification of needs. Another common characteristic seen here is the iterations between stages of the design process, even though these iterations should be minimized as stated by Pugh [1990].

2.2.6 The characteristics of product design

Compared with other disciplines and professions, such as science, engineering, fine art, etc., product design has some typical characteristics. Based on a review of previous research, some of these characteristics include, but are not limited to, the following:

1. Product design is an activity that adds value to products

In free and global market economies, product design plays an important role for companies, even countries, in adding value to their products and hence improving their competitive edge. As Stoll [1999] argued, excellence in product design is crucial to the survival of manufacturing enterprises in today's highly competitive global economy. Mitchell and Oakley [1987] also stated that the 'added value' of design is a vital factor in the economic success of businesses and nations

In addition, the more product alternatives that firms provide in the marketplace, the more likely they are to be financially successful [Kumar and Phrommathed 2005]. Design is the vehicle for product change and the more products change, the more design will be needed [Baxter 1995]. Slack [2006] also stated that a carefully designed and marketed product can bring iconic status to a company and it can also offer a unique stance in a highly competitive world.

Furthermore, the benefits of using product design include increased product appeal and greater customer satisfaction through additional or better features, strong brand identify, and product differentiation. These benefits usually translate into a price premium and/or increased market share [Ulrich and Eppinger 1995]. Peter Dormer [1993] also noted that design has two separate but related functions: it can be used strategically by a corporation to help plan its manufacturing and shape its marketing, and it can have a more obvious role in making individual products attractive to consumers.

2. Product design is a creative and innovative and activity

Undoubtedly, creativity and innovation are key to product design. This has been reflected in the previous definitions of design and product design. As Dyson [1999] stated, good design is about looking at everyday things with new eyes and working out how they can be made better. Keinonen [2006] also argued that the development of products with new solutions that challenge the entire essence of the product is a key means of achieving a competitive advantage. Weak market acceptance of new products can result if the products are not distinct or innovative enough to capture customers' attention or if their features are not attractive [Brand 1998].

3. Product design is a cross disciplinary activity

This characteristic has been influenced by the root and history of design. As Bony [2005] stated, the history of design touches on many areas: aesthetics, sociology and politics; technology and materials; and commerce and the production-consumption system. Walker [1989] also stated that design history has close links with other disciplines such as anthropology, archaeology (especially industrial archaeology) and sociology. Moreover, the early product designers also came from other disciplines. For example, early European product designers were architects and engineers, while most product designers in America were actually theatre designers and artist-illustrators [Ulrich and Eppinger 2004].

4. Product design is neither a precise science nor a fine art

Even though product design touches many areas, it should never be considered as a precise science [bytestart 2010], nor a fine art. However, as Keinonen [2006] has argued, research and technological development create the foundations for product opportunities, but do not identify them. In order to find and implement these opportunities, design is needed. In addition, product designers do not have as much freedom as a fine artist in creating objects and, as a profession, design is recognized as a pursuit which requires specific education and training and could thus meet certain expected standards of knowledge, intellect and skill [Julier 2000]. Therefore, some people consider product design as a kind of applied art, in contrast to fine art [Raizman 2003].

5. Product design is an art of "trade-off"

Product design involves many factors, such as development time, cost, aesthetics, ergonomics, functions, and so on. Therefore, product designers must make a trade-off between these factors to achieve an optimized design. As Pugh [1990] stated, a product is made up of the many technological and non-technological components that impinge on the product design, such as, ergonomics, shape, form, texture and colour. Unless these are in balance, the product may fail in the market place.

For example, as mentioned before, the more product alternatives firms provide to the marketplace, the more likely they are to be financially successful [Kumar and Phrommathed 2005]. However, Product design can require major investment and can lead to significant financial implications in the event of a solution being unsuccessful. Risks can be managed by further developing and testing new solutions, but the tight schedules of product design rarely allow for the examination of radically new proposals.

In addition, as Lindbeck [1995] suggested, functional sufficiency is no guarantee of good or appropriate design. A product may be perfectly adequate from the functional standpoint, but fail to be appealing to the senses. However, he also added that designers can be guilty of allowing aesthetics to interfere with function.

Therefore, product design is a process concerned with the synthesis of such instrumental factors as engineering, technology, materials and aesthetics into machine-producible solutions that balance all user needs and desires within technical and social constraints [Charlotte and Fiell 2003]. As Doermer [1991] also indicated, the product designer can be seen as a broker of ideas and values, a middle personage between the manufacturers, engineers and applied scientists on the one hand, and the consumer on the other. Products need to address excellent technology, as well as cultural and emotional values, leading to a more balanced 'joy-to-stuff' ratio [Hecht and Colin 2005].

6. Product design is an iterative process

Upon analysis of the product design process models above, it can be seen that, product design is an iterative process. The design phase involves running many design activities in parallel, and many product characteristics need to be considered simultaneously. Decisions made regarding one product characteristic may have implications for other characteristics, and changes in one component may require changes in other components. Thus, the design phase is strongly iterative. Iterations in the design process are inevitable and will cause significant time and cost increases. Therefore, it is necessary for the designer to do proper research in order to minimise the numbers of iterations and/or improve the speed of iterations.

2.3 Summary

In this Chapter, the new product development and product design processes were briefly reviewed. It is seen that product design plays an integral part in the lives of many people, surrounding them at home and in the office

[Raizman 2003]. Not only has it come to be regarded as crucial in economic terms, but also as a means of social control and harmony [Walker 1989].

However, on the other hand, product design is a high risk task. Two out of every three products put on the market are failures and do not bring in any profit [Hollins and Hollins 1987]. This might be caused by wrong identification of user/market need, or over investment in time and money on the development of a new product. As one of the key stages in design, prototype development is a well-recognised need within NPD [Campbell 2004], not only because much time and cost are spent on prototyping, but also because of its significant role in improving customer input. As the vehicles of communication, prototypes provide all team members with a tangible means with which to validate the product before it goes into production [Slack 2006]. For this reason, more comprehensive research on prototypes and prototyping is discussed in sections 3.1 of Chapter 3.

Chapter Three

Prototypes and Prototyping

This chapter defines prototypes and prototyping, presents the classifications of prototypes and prototyping tools and technologies, analyses the impact of prototyping on product design and development, goes on to define the terms physical prototype and virtual prototype and then compares the strengths and weakness of the two technologies.

3.1 A brief review of prototypes and prototyping

3.1.1 Concepts and classifications

‘Prototype’ is a wide ranging concept and has specific meanings in different domains, such as computing science, metrology and pathology, etc. In product development, there are two other similar concepts to ‘prototype’: ‘model’ and ‘mock-up’. To avoid confusion, it is necessary to distinguish them in the beginning of this chapter.

In Longman dictionary [1997], ‘model’ refers to ‘a small copy of a building, vehicle, machine etc. ’, while ‘mock-up’ is described as ‘a full-size model of something that is going to be made or built’. The ‘prototype’ is defined as ‘the first form of a new design of a car, machine, etc.’. In addition, Ulrich and Eppinger [1995, p219] defined prototype as “an approximation of the product along one or more dimensions of interest”. From the above definitions, it is found that, a ‘model’ is usually smaller than the original while ‘mock-up’ is a full-scale representation. Compared to the other two concepts, the concept of ‘prototype’ covers a wider range and has no limitations regarding its size: full-or limited-scale models. Bond [1996] also stated that the term prototype is all embracing. It varies from simple cardboard and drawing pin models to prototypes made with engineering precision and almost indistinguishable from the intended final product. Furthermore, Ulrich and Eppinger [2003] and Rooden [1999] even suggested that rough sketches should also be viewed as prototypes. Therefore, in this research, prototype is taken as an all-inclusive term. However, each of these three synonyms, prototypes, models and mock-ups, might be used depending on their context in this thesis.

In addition, although dictionaries define prototype as a noun only, the word could also be used as a verb [Ulrich and Eppinger 2003]. Based on the definitions of prototypes, prototyping refers to the activities and process of creating and developing prototypes [Ulrich and Eppinger 2003, Lidwell et al 2010, p194]. Therefore, prototype and prototyping are two concepts that always relate to each other and should not be split.

The purpose of building a prototype (i.e. prototyping) is usually to embody design hypotheses, test the function and feel of the new design and elicit market feedback prior to production of a product [Ulrich and Eppinger 1995, p232, Schrage 1996, Hartmann et al 2006]. For example, industrial designers use prototypes to develop the look and feel of the product (including aesthetics and semantic product statement, ergonomics studies, etc.), electrical engineers use prototypes to validate the variety of states that systems can achieve and change, and mechanical engineers use prototypes to develop the physical behaviour of a product [Otto and Wood 2001, p 845].

During the design and development of a new product, different classes of prototypes will be built sequentially to meet different testing tasks. As Schrage [1996] stated, not all prototypes are the same, either in how they are built, or in the role they play in the design process. Several examples of prototype classifications are presented as follows:

First example

Classes	Description
Proof-of-concept models	which are used to answer specific questions of feasibility about a product
Industrial design prototypes	which demonstrate the look and feel of the product
Design of experiments (DOE) experimental prototypes	which are focused physical models where empirical data is sought to parameterize, lay out, or shape aspects of the product
Alpha prototype	which is constructed to answer questions regarding overall layout of the actual product, including materials and geometry
Beta prototypes	which are the first full-scale functional prototypes of a product, constructed from the actual materials as the final product
Preproduction prototype	which is the final class of physical models to perform a final part production and assembly assessment using the actual production tooling

Table 2: Prototype classifications created by Otto and Wood [2001, p839-845]

Second example

Classes	description
Early “proof-of-concept” models	which help the development team to demonstrate feasibility
“Form-only” models	which can be shown to customers to evaluate ergonomics and style
Spreadsheet models and experimental test models	which can be used to set design parameters for robust performance

Table 3: Prototype classifications created by Ulrich and Eppinger [2003]

Third example

Classes	description
Crude model	enables you to get a better feel for the basic premise of your invention
Working prototype	allows users to try out some or all of the features of the invention
Final prototype	a model that looks and functions almost like a manufactured product

Table 4: Prototype classifications created by Invention-city [2007]

Forth example

Classes	description
Concept prototype	which is useful for exploring preliminary design ideas quickly and inexpensively
Throwaway prototype	which is useful for collecting information about the functionality and performance of certain aspects of a system
Evolutionary prototype	which is useful when many design specifications are uncertain or changing

Table 5: Prototype classifications created by Lidwell et al [2010]

Besides the above methods of classification, all prototypes can also be generally categorized into physical prototypes as opposed to virtual prototypes [Stoll 1999, p131]. A physical prototype refers to a model made from real materials and substances, while a virtual prototype basically means a model created in computer. The research presented in this thesis is conducted based on this classification and aims to explore the characteristics of physical prototypes and virtual prototypes and the relationship between them.

3.1.2 The role of prototype/prototyping in product design process

Prototypes and prototyping play an important role in product design and development. They help designers to identify problems and aid communication between experts from different functional departments. However, improper use of prototypes might cause a waste of time and materials, hence delaying product development and increasing cost.

3.1.2.1 The benefits of prototypes/prototyping

Prototyping is the pivotal activity that structures innovation, collaboration, and creativity in design [Hartmann et al 2006]. Schrage [1996] stated that companies that want to build better products must learn how to build better prototypes. In the product development process, prototypes play a key role at almost every stage, from early concept development until preproduction [Stoll 1999, p131], and every aspect of the product must be considered and approved by the designer and client with prototyping [Slack 2006]. The importance of prototypes are mainly reflected in testing the feasibility of a product design concept, enhancing user involvement and communication between clients, managers, manufacturers and experts of design team that from different departments.

Prototypes can also act as a medium for managing risks [Schrage 1996], and are extremely important tools for improving the quality of design decisions [Stoll 1999]. In the early conceptual development stage of a product design, prototyping is usually used to test the feasibility of design, uncover unpredicted phenomena, catch design flaws and change directions [Otto and Wood 2001, Medero 2007]. Rosenau [2000] also stated that testing of prototypes is an effective means to reduce surprises and any design changes subsequently required. This could avoid unnecessary investment, including cost and time, before the details are defined to the point where appearance, accuracy and precision are important [Stoll 1999].

The importance of user involvement for the success of product development has been mentioned previously. Because prototypes can give potential customers and users hands-on experience with the product, including aesthetics and ergonomics, etc. [Rouse 1991], the user involvement must be enhanced by users' trialling with prototypes of the intended product [Rooden

1999]. Schrage [1996] also suggested that in customer-centred design, the customer must have the opportunity to see and try the prototypes as they evolve. Therefore, prototypes play important roles in facilitating user involvement. In addition, in a product development team, the members from different areas (design, engineering, management, etc.) need to work together. Prototypes can act as communication and demonstration tool to show them the accomplishment of project goals and milestones and obtain feedback from suppliers, vendors, and management [Otto and Wood 2001].

3.1.2.2 The risks of prototypes/prototyping

Prototypes have shown their significant impact on the design process. However, as Otto and Wood [2001] advised, model validation is important but often expensive and time consuming [Otto and Wood 2001, p661]. Improper use of prototypes will cause a waste of money and time, delay the launch of the product to market, hence reducing the competitive edge of companies. The main questions that should be answered are: 1, when should a prototype be built? And 2, how realistic a prototype should it be?

Baxter [1995] suggested that prototypes should be built only when it is essential. He explained that prototyping is a time consuming activity and inevitably diverts effort from other activities. He emphasized that the designers should avoid “just building a prototype” without carefully investigating and planning. In contrast, Instead of producing prototypes when design teams think that doing so is appropriate, some time-sensitive organizations are now supporting the philosophy of “just build it” in developing prototypes [Schrage 1996]. Their theory is to get information as soon as possible through building and testing simple prototypes or mock ups in the product development process. Even if the prototype fails, they learn from the failure, rather than carefully planning for a long time [Stoll 1999, p134]. However, the choice of the above theory will depend on the particular context. If the prototype is going to be complex and costly, the first theory should be more suitable to avoid waste; if the prototype is just an initial mock up, the latter theory should be more preferable.

According to the study of the classifications of prototypes, the degree of realism of prototypes varies. It could be a very rough mock up or a preproduction prototype that is essentially the same as the final product. However, the company and designers do not have infinite time or money to build a perfect prototype [Otto and Wood 2001]. How realistic a model should be depends on many different factors, chief among them are the purpose of the model, choice of materials, and the amount of time available [Lucci and Orlandini 1990]. For example, in the early stage of product design, a quick hand sketch is preferable to a more time-consuming computer rendering to develop ideas and communicate with other students, clients or teachers [Essen and Steur 2009]. In addition, as the model is a medium for the designer, not the goal, the energy required for building models should, therefore, be minimal [Lucci and Orlandini 1990]. This is also supported by Baxter [1995], who suggested that the prototypes should be kept as simple and inexpensive as possible during the early stages of the design process and that prototypes should only be developed to the minimum degree of complexity and sophistication required to obtain the answers that are needed.

3.2 Physical Prototypes and Physical Prototyping

The above analysis presented a general overview of prototypes and prototyping. However, in recent decades, two radically different types of prototypes, physical and virtual, have shown their own features in product development. In this section, research on physical prototypes and prototyping will be presented.

3.2.1 Definitions and classifications

A physical prototype, as the name suggests, is an object in the real world. It is a tangible artefact [Ulrich and Eppinger 2003], and made with miscellaneous materials such as wood, clay, foam, metal, plastic or even paper [Zorriassatine 2003, Medero 2007]. Wallentin [1999] defined physical prototypes as hardware models created to approximate the product and for testing and experimentation. Otto and Wood [2001, p 838] stated that “a physical prototype is an object (or set of objects) that is fabricated from a variety of materials to approximate an aspect(s) of how a product concept performs”.

The classifications of physical prototypes correspond to the classifications of general prototypes mentioned in section 3.1.1. However, they also can be classified from another point of view. Zorriassatine et al [2003] classified physical prototypes into three main groups according to the possible nature of physical change used to create them. They are traditional prototypes (material removal), rapid prototypes (material addition) and hybrid prototypes (both material removal and addition). This classification refers to the main possible physical changes to a prototype – material removal and addition. However, other changes might also be made to a prototype, for instance, part motion. When a part of a prototype is moved to a different position without material removal or addition, the performance or the whole structure of the prototype can be changed as well. Therefore, the third classification of prototype should actually be material deformation. This concurs with [Vandevelde et al. 2001] who stated that the process of physical prototyping is based on material deformation, removal or addition. This is significant to the research on integration between physical prototyping and virtual prototyping, since it concerns the conversion of changes between the virtual and physical prototypes.

The construction and testing of a physical prototype is called physical prototyping. Within the new product development process, physical prototyping is a design method to help designers solve any unanticipated problems with creative ideas [Design-Council 2007].

3.2.2 Methods of physical prototyping

Physical prototyping technologies range from simple models made with common hardware and simple materials to precision prototypes made with specialized processes and advanced materials [Otto and Wood 2001]. These technologies are extensive, from traditional hand crafting to advanced computer-controlled prototyping.

According to the tools involved, the methods of physical prototyping can be classified into three types: hand making, mechanical machining and computer aided prototyping. To achieve the final physical prototype, these approaches might be employed individually or in combination.

Hand making is the most traditional and is probably the most flexible way to create prototypes. People could use any hand tool, even just their hands, to create a prototype. These tools might be hammer, carving or sculpting knives, screwdriver, scrapers, etc. (see figure 7 and figure 8).   Furthermore, the material adopted also varies, such as clay, plastic, wood, metal, foam and so on.

Figure 7: Handmade prototyping tasks and tools [Bordegoni 2006]

Figure 8: A set of clay tools [Sculpturetools 2007]

Clay models can play an important role in some product development processes. They allow the designers to develop and experiment with the form of their design freely (see figure 9). However, this freedom of form development is rarely matched by computer tools (Car-design-online 2011). In practice, the designers could create a small-scale clay model (see figure 10) for initial test in the earlier stages and then build a full-scale prototype (see figure 11) for detailed experiment and presentation in later phases.

Figure 9: Freely creating a clay model [car design online 2011]

Figure 10: The small scale clay model of a car design [car design online 2011]

Figure 11: The full-scale clay model of a car design [car design online 2011]

A typical type of plastic used in prototyping is Acrylonitrile Butadiene Styrene (ABS). ABS plastic has a good balance of properties. Because of the toughness, strength, temperature resistance coupled with its ease of moulding and high quality surface finish, ABS has a very wide range of applications in modelling [British Plastics Federation 2011]. Figure 12 shows some models made from ABS plastic. To create ABS models, the designers usually need to create some wood models by hand (sometimes with the help of mechanical machines) and then put them with ABS sheet into a vacuum forming machine (see figure 13) to obtain the ABS model. Although vacuum forming is applied, the stage of hand making is still the main part in the process of creating an ABS model.

Figure 12: Some ABS plastic models [Build-stuff 2007]

Figure 13: Vacuum forming machine [cn-brother 2007]

Hand making gives designers plenty of freedom to develop the models, however, the quality and accuracy of hand-made prototypes might be the weakest aspect with this prototyping approach, since it is entirely dependent upon the skill level of the individual model-maker.

Mechanical machining is an activity using a combination of manual and machining skills to operate devices such as drilling, turning or milling machines [Zorriassaitine 2003] (see figure 14). These machines are used for the complex shaping of metal and other solid materials. Figure 15 shows a technician operating a milling machine to create a part. Although still influenced by the skills of the machinist, mechanical machining has made big progress in improving the efficiency and quality of prototyping.

		
drilling machine [gatha 2007]	turning machine [sjmcs 2007]	milling machine [germer-online 2007]

Figure 14: Mechanical modelling machines

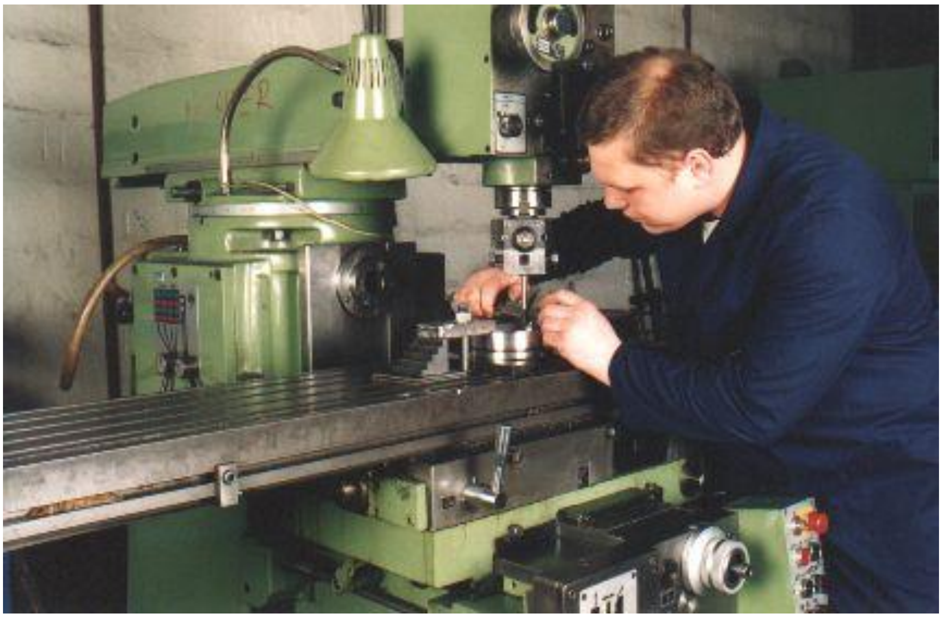

Figure 15: Operating a milling machine to create a part [metalko 2007]

Thanks to the development of computer technology, computer aided prototyping is widely used by today's manufacturers. Two typical computer aided prototyping technologies are computer numeric control (CNC) (see figure 16 and figure 17) and rapid prototyping (RP) (see figure 18). These technologies can be used to create physical prototypes with high surface quality (see figure 19) and/or a complex shape (see figure 20). Both of them are based on computer technology that converts a virtual prototype (CAD model) into a physical prototype. One major difference between them is that CNC is a process of material removal whilst RP is a process of material addition. In addition, although these two technologies are process of physical prototyping, they first require a virtual prototype to be developed.

Figure 16: A computer numeric control (CNC) machine [ultra-form 2007]

Figure 17: A CNC machine is working to create a metal part [Klaus 2007]

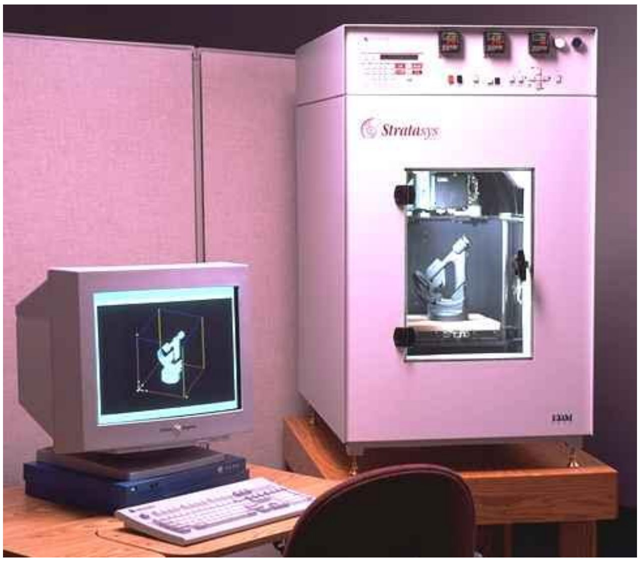

Figure 18: A FDM (fused deposition modelling) Rapid prototyping machine [Egr.msu 2007]

Figure 19: A model with high surface quality created by CNC machining [product design forums 2005]

Figure 20: A model with complex shape created by Rapid Prototyping [Fraunhofer 2007]

In practice, designers normally do not use only one modelling method to achieve the final prototype, but apply various methods in different phrases. For example, they might use hand held tools or milling machines to create a wood model, and then use it to create an ABS model with the help of vacuum forming. In addition, a prototype created by rapid prototyping usually needs hand working to obtain a satisfactory surface quality.

3.3 Virtual Prototypes and Virtual Prototyping

In order to reduce costs and development time, companies are increasingly turning to virtual prototyping methods during the early phases of design development. Such methods can range from sketches and renderings to detailed 3D computer models of potential designs. Visual representations are supplemented by physical models made using rapid prototyping equipment or traditional model-making skills [Design Council 2007].

3.3.1 Definitions and classification

The literature review shows that compared to the high level of agreement found for physical prototyping, the definitions of virtual prototypes and prototyping are more various and arguable. Therefore, it is necessary to be clear about what virtual prototyping is.

Chua et al. [1999] from Nanyang Technological University said that virtual prototyping (VP) is the analysis and simulation carried out on a fully developed computer model, therefore performing the same tests as those on the physical prototypes. This definition indicates that a virtual model can replace a physical prototype for analyzing and testing tasks.

According to Gowda et al. from Michigan State University [1999], virtual prototyping (VP) is a kind of technology, which involves the use of Virtual Reality (VR), and other computer technologies to create digital prototypes. This definition has just categorized VP as a tool to "create" a prototype, but has not mentioned if VP could be used in other activities, such as "modifying", "analysing" or "testing" the prototype. Song et al. from University of Pennsylvania [1999] claims that: "by virtual prototyping, we refer to the process of simulating the user, the product, and their combined interaction in software through the different stages of product design, and the quantitative performance analysis of the product". In this definition, the user, the product and their interaction are essential components of VP. In addition, this definition puts virtual prototyping technology in the product design context and states its value in analysing a product design.

All the above definitions have their own focused respects while still failing to identify some elements of the nature of virtual prototyping. Based on the

analysis of several versions of VP definition, Gary Wang [2002] from the University of Manitoba defined virtual prototyping as below:
“A virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analysed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP).”

Compared to others, this definition is relatively comprehensive and detailed. It states different functions of VP in different phases of the product development process. In addition, the definition of VP is given based on the definition of a virtual prototype, which defines the relationship between virtual prototypes and virtual prototyping. It is to be noted that the acronym VP stands for virtual prototyping and not for the virtual prototype [Wang 2002]. In this report, the phrases “virtual prototype” and “virtual prototyping” are used frequently, therefore it is necessary to differentiate the two concepts.

In terms of the classification of virtual prototypes, Tseng et al [1998] classified them into two types, i.e. immersive virtual prototypes and analytical virtual prototypes. However, literally from those definitions, a virtual prototype is a general concept. In a different context, it might have many synonyms (see figure 21). Similarly, as the construction and testing process for a virtual prototype, virtual prototyping might mean various particular technologies or activities. It might mean the use of a sort of software package, such as Pro/Engineer, 3D solid, Alias studio, etc.; or the use of an analysing and testing system, such as Computer Fluid Dynamics (CFD) or Finite Element Analysis (FEA). In practice, virtual prototyping might act as creating, building, modifying, or analysing a virtual prototype.

Synonyms of virtual prototype
Digital prototype
Digital mock up
Digital model
CAD model
Geometric model
Computer model
Analytical prototype/model
3D model

Figure 21: Some synonyms of virtual prototype

3.3.2 Methods of virtual prototyping

According to the definition, virtual prototyping is the process of constructing and testing virtual prototypes. Therefore, the study of the methods of virtual prototyping should be classified to two parts, e.g. the methods of constructing and the methods of testing virtual prototypes.

The construction of virtual prototypes is usually achieved through 3D modelling software. The software packages that are popularly used in industrial design are Rhino, Pro/Engineer, Alias Studio, 3D SolidWorks (see figure 22), and so on. However, these packages usually have different advantages in modelling. For example, Pro/Engineer is beneficial in modelling 3D solids (see figure 23) while Alias Studio is good at building 3D surface models (see figure 24). In the manufacturing industry, 3D modelling software has been widely used in designing products, including aeroplanes.

For example, the “Boeing 777” was Boeing’s first aircraft to be completely designed using a CAD framework for every single part and a total of 350 million parts were built [Andreas et al 2004] (see figure 25).

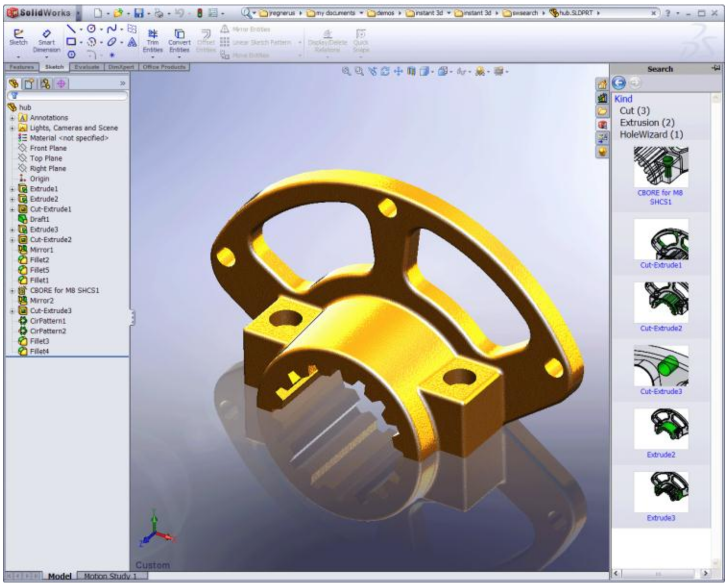

Figure 22: A model built and rendered by SolidWorks [solidworks 2006]

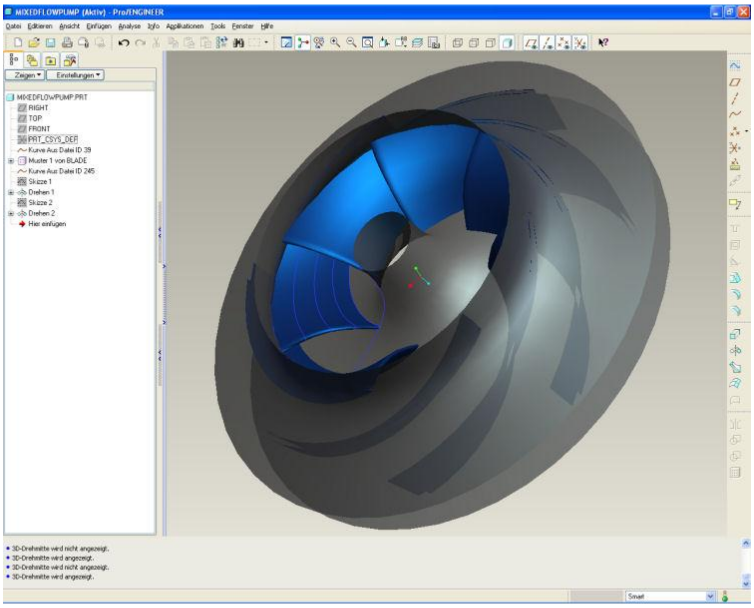

Figure 23: A solid prototype built with Pro/Engineer [cfturbo 2007]

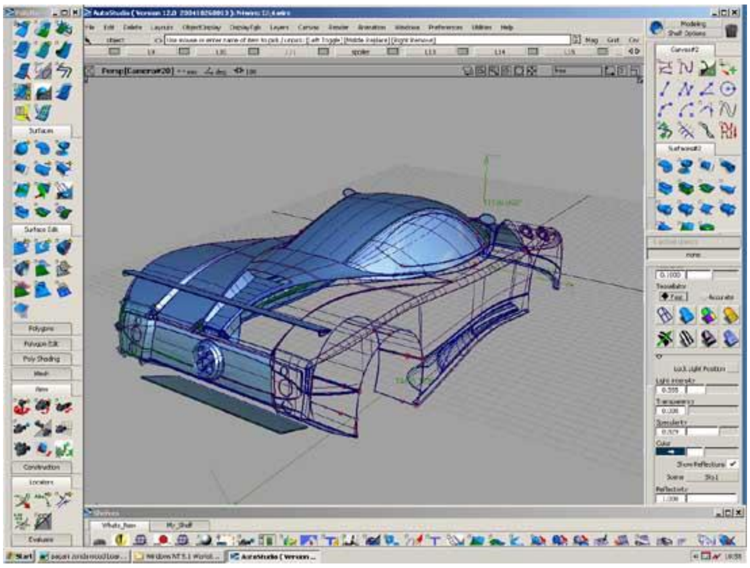

Figure 24: A surface model is being created with Alias studio [Diseno-art 2007]

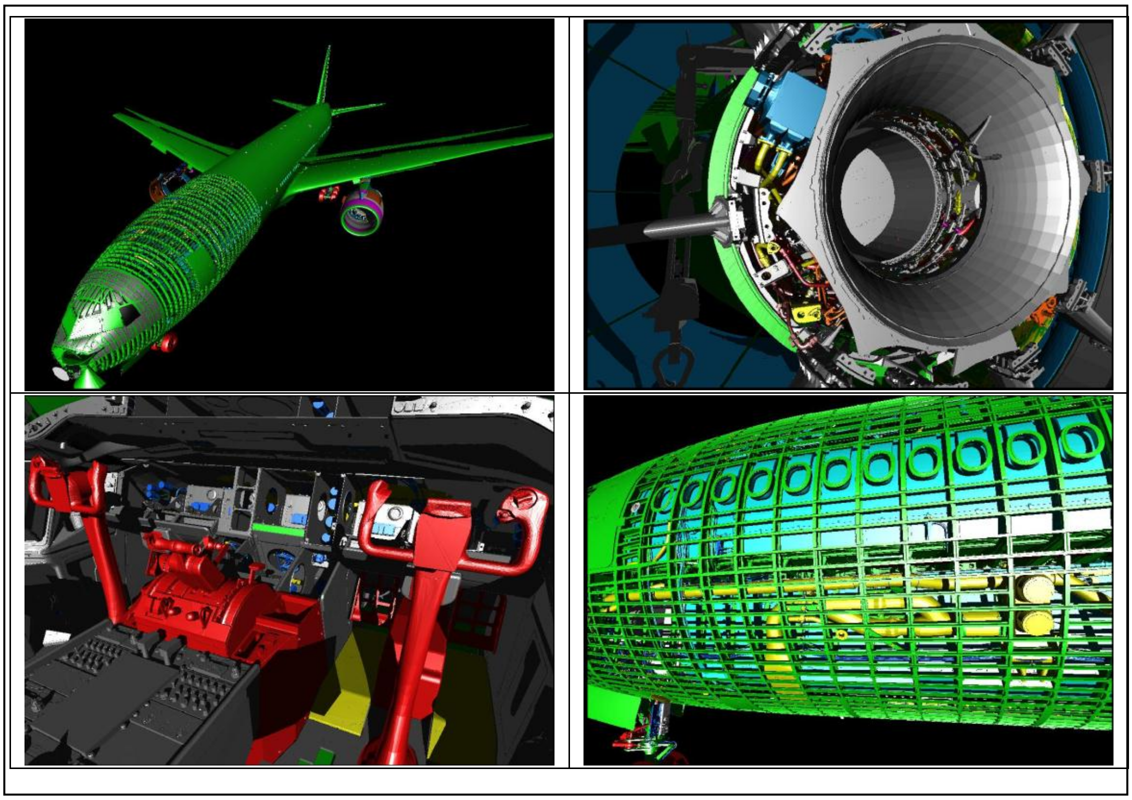

Figure 25: The CAD model of Boeing 777 [Andreas et al 2004]

In addition to using the above modelling software to build a virtual prototype in the computer, there is other approach to obtaining a geometric prototype, which is called reverse engineering (RE). RE is the process of extracting design information from an existing part, for which such information is unavailable or mislaid [Jamshidi 2006]. It enables people to rebuild a geometric digital model through contact or non-contact scanning of the existing product. Figure 26 shows a person using non-contact scanning equipment to scan the interior of a car and obtain a geometric model.

Figure 26: The use of 3D scanning in creating a virtual prototype [T&P 2007]

Besides the ability to build a 3D virtual model, most 3D modelling software has functions for testing and analysing virtual prototypes. For example, Pro/Engineer has a feature called “model analysis” that lets users perform three different types of model evaluation: behavioural modelling, model checking, and design editing. In addition, there are other technologies used in industry for testing and analysing virtual prototypes, such as computational fluid dynamics (CFD) and finite element analysis (FEA). CFD is used to predict what will happen, when fluids flow, often with the complication of simultaneous flow of heat, mass transfer, mechanical movement, and so on [Cham 2007]. Figure 27 shows the model of an F-18 plane being evaluated with CFD technology. FEA consists of a computer model of a material or design that is stressed and analysed for specific results. It can be applied to analyse multiple properties of the model, such as stress (see figure 28), thermal, gravity, and centrifugal static loads [Sv.vt 2011].

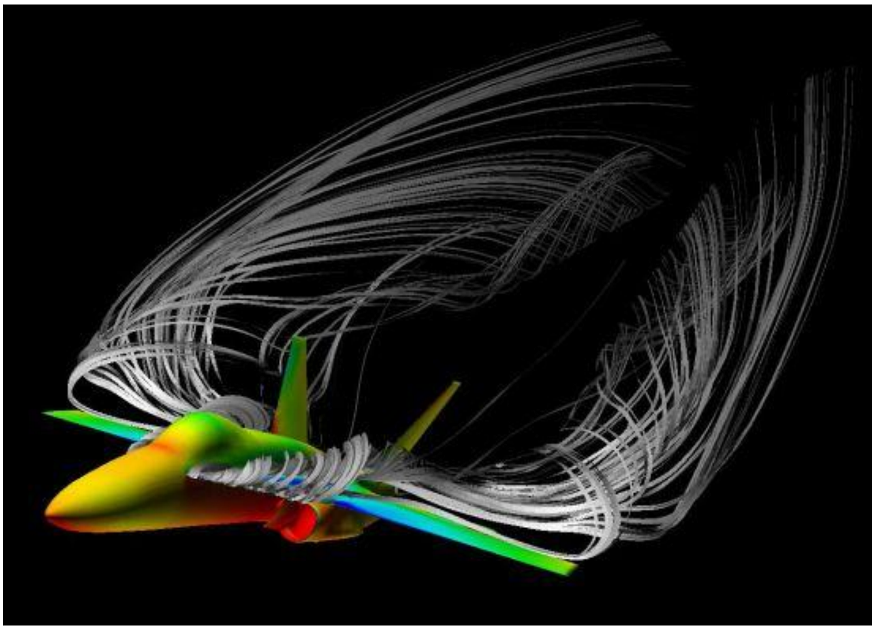

Figure 27: The evaluation of F-18 with CFD technology [Aerospaceweb 2011]

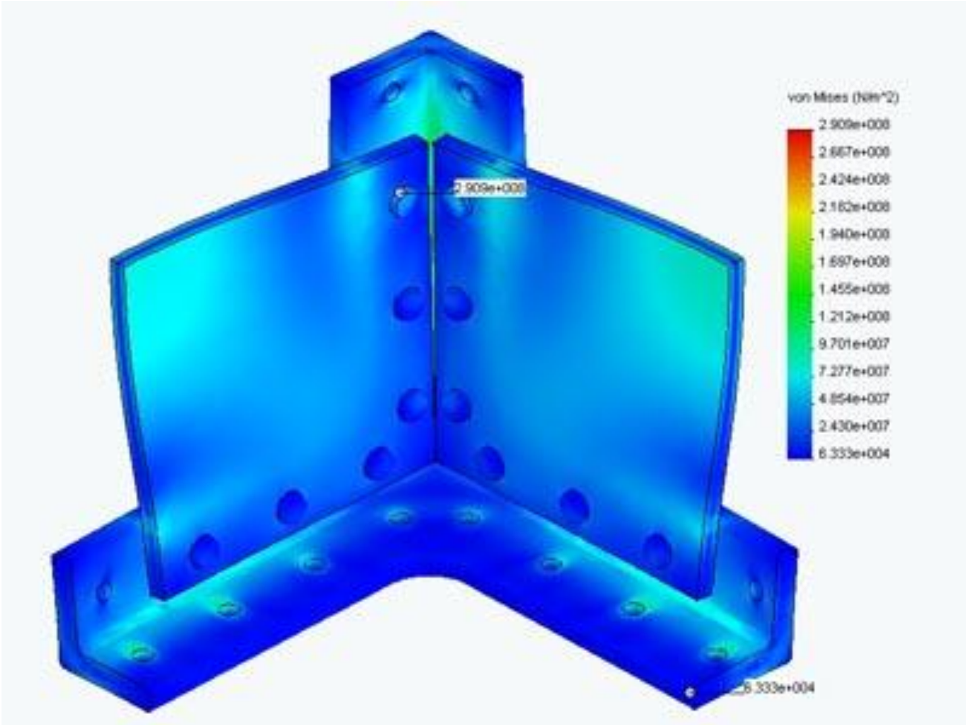

Figure 28: The stress analysis of a model with FEA [Myoops 2005]

In addition, based on the modelling objectives and purposes, Zorriassatine et al [2002] identified five broad classes of virtual prototyping methods. These classes consist of prototypes for:

- Visualization
- Fit and interference of mechanical assemblies
- Testing and verification of functions and performance
- Evaluation of manufacturing and assembly operation
- Human factor analysis

3.4 Physical Prototyping versus Virtual Prototyping

This section presents a comparative study of the two types of prototyping technologies with respect to their relevance in the product development process. This study investigates and analyses the advantages and disadvantages of both technologies in various aspects. The aim of this is to demonstrate the need for combining their strengths in the NPD process.

The success of every product development effort is measured by three criteria: adherence to the schedule, adherence to the budget and adherence to the design requirement [Jennings & Bourne 2001]. Therefore, the comparative study of PP and VP is mainly about checking which one is advantageous in matching these criteria.

3.4.1 Advantages of physical prototyping and disadvantages of virtual prototyping

Physical prototyping technologies have a long history in contributing to design and manufacture. Figure 29 shows the use of physical prototypes in the product development process. Today, although virtual prototyping has replaced physical prototyping in many aspects, physical prototyping is still beneficial and irreplaceable in some circumstances.

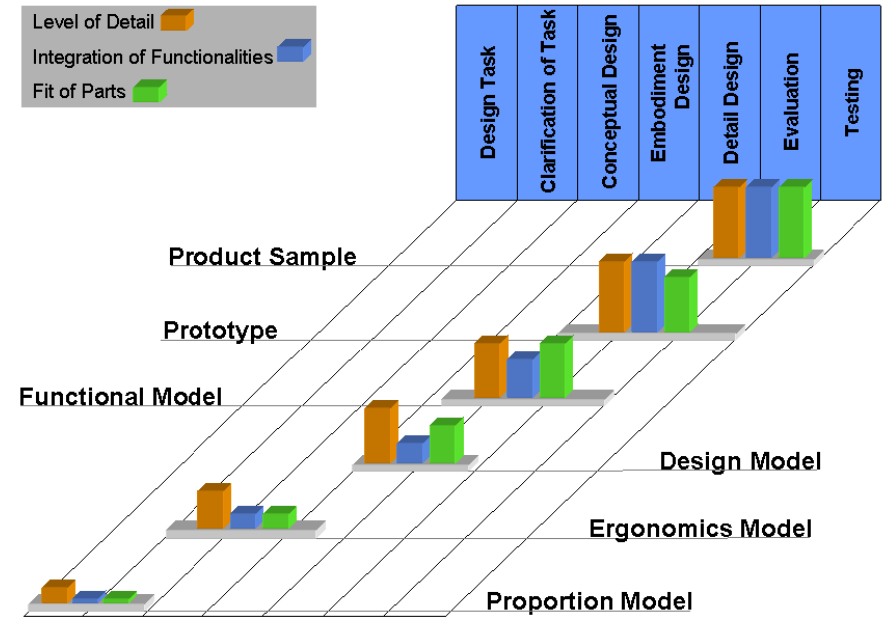

Figure 29: Use of physical models in the product development process [Anderl 2006]

Firstly, physical prototypes are advantageous in facilitating communication. Vandevelde et al [2002] stated that because physical prototypes carry their information in an accessible and universal way, they help make some aspects of the design more transparent, and avoid misunderstandings. Chua [1999] also claimed that as a true three dimensional real-world object, a physical prototype is able to give the designer a sense of size estimation. The judgement of a virtual object can be erroneous because parts are often automatically sized to fit the viewing window. In addition, tactile representation, which is one of the unique characters of physical prototypes, makes a product or prototype much easier to understand than just a visual simulation of a product. Anderl [2006] stated that human perception of objects prefers physical objects, because of natural sensation. Therefore physical presentations are given a higher priority by the designer. Furthermore, Wallentin [1999] suggested that making a physical prototype forms a good opportunity to make team members get together and discuss the project.

Secondly, physical prototyping is more beneficial than virtual prototyping in some product evaluations, such as physics and ergonomic issues of a product. As a simulation of a real object, a virtual prototype usually hides many aspects of how a product will actually perform, for example, the flexibility of the material used on a prototype. To well understand the physics of a product, a physical prototype would be preferable [Otto and Wood 2001, p836]. In addition, compared to virtual prototypes, physical prototypes are tangible. Therefore, it is more advantageous in testing ergonomics with users. As Otto and Wood [2001, p836] suggested, physical prototype construction and analysis is a critical aspect of product realization when ergonomic effects are to be demonstrated. Grimm [2005] also claimed that without vast improvement in haptic devices, the virtual prototype will be a poor predictor of the fit of a pistol grip or the balance of a handheld power tool. In the evaluation of products, customers often judge the quality of a product by its feel, the sound of a door closing or the texture of its finish. These are the things that virtual prototypes do not convey.

In addition, although it seems to be universally accepted that virtual prototyping has a better performance in respect of time and cost, there are still some cases where physical prototyping is more efficient. The reasons are that virtual prototyping requires costly hardware and associated software and the learning time is relatively long. In general, in modelling and testing of a product with a simple structure, physical prototyping is the preferred solution. Jennings and Bourne [2001] stated that for less complex, lower liability products or systems that can be prototyped reasonably, the correct path is physical prototyping.

Overall, physical prototypes and prototyping would be the preferred solutions in many designing and evaluating activities. Proclamations that virtual prototyping will completely replace physical prototyping are unlikely to be realised, at least in our lifetime [Grimm 2005].

3.4.2 Advantages of virtual prototyping and disadvantages of physical prototyping

The importance of virtual prototyping is associated with current trends in the process of new product development. In today's process of product design, production scheduling and management, marketing and customer assistance are being performed increasingly with the aid of IT tools, as well as most product data being digitally stored and managed. In this context, the roles of virtual prototyping and simulation technologies are becoming more and more important [Colombo and Gugini 2005].

One of the main reasons that designers and manufacturers use virtual prototyping widely is its significant contribution in reducing product development cycle times and cost. As Lin et al [(2005] argued, as demand for fast-to-market and cost-reduction mounts, virtual prototyping becomes increasingly important in meeting the timing and performance goals. Especially for early concept models, where changes are fast and frequent, virtual prototyping may be the most practical and efficient [Grimm 2005]. In contrast, it is a well-known fact, that physical prototyping is a time-consuming and cost-intensive task [Weck & Kuhlen 2000, Zorriasssatine 2003].

The capabilities of virtual prototyping in time and cost reduction are related to characteristics that physical prototyping does not have. Product development is an iterative process in which prototypes need to be built, modified and rebuilt numerous times. In this regard, virtual prototyping provides a very quick iterative design process [Chua et al 1999]. Changes to the virtual prototype, which is with a digital format, are usually simple tasks. Operators just need to edit the CAD model in a short time and generate a new FEA mesh or CFD grid. This can be done at relatively little extra cost. However, iterative changes to physical prototypes often take a much longer time and would increase the cost in material and tools.

In addition to the strengths of time and cost reduction, virtual prototyping is also advantageous in many other domains. For example, virtual prototyping has shown great strengths in analysing complex stress, thermal properties, fluid flow, etc., using numerical techniques such as finite element analysis [Stoll 1999, Zorriassatine et al. 2003]. Furthermore, virtual prototyping is very useful when the designers are geographically distributed, since the prototypes can be shared over the internet for synchronous evaluation and design sessions [Halttunen & Tuikka 2000].

Overall, virtual prototyping will enable designers to fully develop their creations and work out the design details prior to moving forward with developing a physical prototype or filing for patent protection [Invention-home 2006]. Although the cost of software and associated hardware is high and the learning time to employ them is long, it is widely accepted that virtual prototyping is a more cost-effective and fast-to-market approach than physical prototyping, from the perspective of the whole product development cycle.

3.5 Summary

After this comparative study of physical and virtual prototyping, it is apparent that in the product development process, there are some situations where physical prototyping is more beneficial, while in many other situations, virtual prototyping is to be preferred. Figure 30 shows a checklist of criteria to indicate whether virtual or physical prototyping is more desirable.

	Virtual prototyping	Physical prototyping
cost	√	
time	√	
Ability of iteration	√	
Evaluation of ergonomics		√
Aesthetics	√	
tactility		√
Dynamic analysis	√	
Complex product	√	
Product with simple structure		√
Function test		√
User communication		√

Figure 30: Checklist of situations where either virtual or physical prototyping is more suitable

A physical prototype usually allows human beings' sensory evaluation of a product, such as form, tactile feel, softness, and so on. Product ergonomics are also an increasing concern. Virtual prototyping applications will be those where physical prototyping is impractical, impossible or inefficient [Grimm 2005].The two types of technologies are not strictly competitive, with the strengths and advantages of one technology addressing the weakness and limitations of the other. Physical and virtual prototyping are valuable techniques that can join together to form a powerful tool for rapid development of complex products [Campbell et al 2004]. In the future, industry leaders will have both technologies providing the ability to select the best for the task at hand [Grimm 2005] or to combine their strengths together. This need for combined use leads to a discussion on the integration of physical and virtual prototyping, which is the topic of the next chapter.

Chapter Four

Related research

In this chapter, related research regarding the conversion between and combination of physical and virtual prototypes is presented. It begins by reviewing relevant technologies and goes on to examine their roles in getting users involved in design evaluations. This is followed by a discussion on the necessity to develop a new method of simultaneously integrating physical and virtual prototypes.

4.1 Overview of current integration technologies

As stated in the section 3.4 of previous chapter, physical and virtual prototyping have their own advantages and disadvantages in either user evaluation or through saving cost and time. To optimize the application of these two types of prototyping technologies, a vital need is to integrate them. As Jain [2005] stated, the integration of physical and virtual prototypes would yield shorter development cycles, fewer late-stage errors, and a higher return on intellectual property such as design, simulation, and testing data. For example, since virtual prototyping can provide high accuracy in dimensions, while physical prototype is good for ergonomics evaluation, the designer could build a CAD model first, and then use Rapid Prototyping to produce a physical prototype for ergonomic testing and development.

According to Longman dictionary [1995], integration means “the combining of two or more things so that they work together effectively”. In fact, the idea of the integration of physical and virtual prototypes is not new and various means of integration have been widely applied. In a broad sense, when the physical model and the 3D CAD model of a product are shown to the users or clients at the same time, the physical and virtual prototypes have been used in an integrated way. In addition, when a physical prototype is built based on a virtual one or a virtual one is made using data taken from a physical one, then physical and virtual prototyping are also being integrated.

In this section, the investigation will focus on the current technologies related to the integration of virtual prototyping and physical prototyping. These technologies refer to either conversion from virtual prototyping to physical prototyping, such as Computerised Numerical Control (CNC) machining, Rapid Prototyping (RP), etc.; or the opposite, such as Reverse Engineering (RE) technologies. In addition, some researchers are developing and have developed some methods to convert between physical and virtual in a bidirectional manner, to some extent, i.e. changes to the physical prototype can physically give feedback to the user or cause a change to the virtual prototype, and vice versa. For example, haptic technology and parametric prototypes, which will be discussed in the section 4.4 of this chapter.

Prototype integration technologies (such as CNC, RP and RE) have made use of advances in both computer hardware and software. Such combinations have enhanced significantly the prototyping stages in product development, hence proving the necessity of integrating PP and VP. However, as most of these technologies were developed within the context of engineering needs, the problems faced by industrial designers when applying them are inevitable. In addition, they also have shown some problems such as being time consuming and expensive in terms of equipment and materials. Throughout the study of these technologies, the aim was to build up a working knowledge about data transfer between physical and virtual prototyping methods. In addition, as mentioned in section 2.2 of chapter two, user involvement is important to today's industrial designer and is one main concern of this research. Therefore, within the context of industrial design, it is necessary to analyse and evaluate to what extent the integration of PP and VP provided by these technologies has influenced and improved user involvement. The outcome of these studies will help to propose a new method to combine physical and virtual prototypes/prototyping.

4.2 Conversion from virtual prototype to physical prototype

Traditionally, physical prototypes have been made by hand crafting or by manual mechanical machining as described in subsection 3.2.2 of Chapter three. Thanks to developments in both software and hardware and within manufacturing engineering, it is now possible to produce a physical prototype based directly on a virtual prototype. This brings about one way integration of the two types of prototypes. Two typical technologies in converting virtual prototype to physical prototype are CNC machining and Rapid Prototyping.

According to Gibbs [1984], "numerical control (NC) is the term used to describe the control of machine movements and various other functions by instructions expressed as a series of numbers and initiated via an electronic control system". Computerised numerical control is the term used when the control system includes a programmable computer. Typically, CNC machining It is a process of removing material from a solid block of metal, plastic or wood to obtain a finished part or physical prototype. In the application of CNC machining, the programmer must deal with every feature in a part, and this can add significant time and cost to the product development process [Wohlers & Grimm 2003].

In contrast to the material removal process of CNC machining, Rapid Prototyping is a process of material deposition [Grote et al 2001]. Although a relatively recent technology, RP has its roots in topography and photosculpture technologies from the nineteenth century [Prinz 1997]. It is the automatic construction of physical objects directly from CAD data, normally achieved by depositing material in a layer-wise manner. Within the RP process, the part is first created as a 3-D computer model and then sliced into 2-D layers and consecutively fabricated from the first layer to the last, using control schemes to direct the shaping of each layer. Once one layer is created, another layer of material is added, and the entire process is repeated until the completion of the whole part [Otto and Wood 2001, p854]. RP is also referred to as solid freeform fabrication, desktop manufacturing or layer manufacturing technology [Zorriassatine et al 2003]. Currently, there are various commercial RP systems available in the market, such as stereolithography apparatus (SLA), fused deposition modelling (FDM), selective laser sintering (SLS) and 3D printing (3DP) [Ramanath and Chua 2006].

Rapid prototyping allows designers to produce a complex and high quality physical prototype to verify their design [Rouse 1991, Ramanath & Chua 2006]. The relative accuracy of prototypes made by RP (in comparison to hand-made models) can reduce risk in the product development process [Mueller 1999]. Compared to CNC machining, RP can produce physical prototypes with more complicated shapes such as convoluted shapes or parts that are nested within other parts [Efunda 2010]. RP is well known for shortening the product design and development process [Chua 1999] but there are still some pre-processing steps that need to be taken before a model can be built. Data transfer into an RP machine is normally by means of an STL (Stereolithography tessellation language) file. The original CAD model must be converted to the STL format for a specialized computer program within the RP machine to analyze and process into the slices used to build the RP model. Both the conversion to STL and the subsequent slicing procedure can lead to some deviation from the original CAD geometry.

CNC machining is a material removal process while RP is a material addition process. In addition, researchers have been investigating another prototyping strategy called “hybrid prototyping”, which use can produce a part through both material removal and addition within the same system. One technology developed based on hybrid prototyping theory is called Shape Deposition Manufacturing (SDM), which is a freeform fabrication process combining material deposition with material removal processes [Amon et al 1998]. Material addition is used to lay down bulk geometry quickly whilst the material removal is used to produce precise geometric features. Therefore, hybrid prototyping systems can provide better accuracy than normal rapid prototyping systems [Zorriassatine et al 2003] and can save prototyping time and cost [Thefreelibary.com 2010].

Compared to conventional hand making and manually controlled machining approaches, CNC machining, rapid prototyping and hybrid prototyping have made significant progress in combining virtual prototyping and physical prototyping technologies. In addition, with the use of computer control, the physical prototype produced with these technologies can faithfully reproduce the VP from which it was built, in terms of appearance, scale and dimension, which allows designers, engineers (and users) to quickly visualize and react to part designs [Stoll 1999]. In contrast, to achieve this level of reproduction by hand crafting would be much more difficult. Faithfulness of reproduction is very significant when testing prototypes with users. For example, if the physical prototype does not look like the virtual prototype, it will be difficult for the designer to present them together to the users, as in their mind, the physical and virtual prototype might present different products rather than the same one.

However, product design is an iterative process and the prototyping is no exception. The first physical prototype produced by CNC and RP is usually not the last one. With CNC machining, RP and hybrid prototyping technologies, the processes of virtual prototyping and physical prototyping still occur at different times. A virtual model must be completed before it can be used within the process of CNC or RP to generate a physical part. The physical prototype will then be used for testing with users and any design problems will be identified. Based on these problems, the virtual prototype needs to be modified and be made ready for the next prototyping stage. This iterative cycle can happen several times, with a time delay is incurred during each conversion. In another words, the virtual and physical prototyping processes are not synchronized. There are some problems within this cycle of conversion. Firstly, each time the cycle is repeated, it will add to the product development time, hence increasing costs and potentially delaying the time-to-market. Secondly, because the user cannot see the changes to the prototypes immediately, they will have to come back again and re-evaluate the newly updated prototypes, which will increase the difficulty of user-evaluation experiments. Thirdly, the designers need to modify the virtual prototype according to the changes identified through the evaluation of the physical prototype. Since it is difficult to capture these changes precisely and because the 3D modeling skills of designers are variable, this modification process will not be seamless. If the changes from the physical prototype are not well reflected in the virtual one, the new physical prototype produced from the modified virtual one will still not reflect the user's requirements.

4.3 Conversion from physical prototype to virtual prototype

A method that converts a physical object to a virtual prototype is often known as Reverse Engineering (RE). The purpose of RE is to obtain a CAD model from an existing product for further evaluation and development [Kruth et al 1997, Lee 2000, Chen 2005]. The role of RE in industry generally consists of the following stages: 1, Analysis of the product; 2, Generation of an intermediate level product description; 3, Human analysis of the product description to produce a specification; 4, Generation of a new product using the specification [Musker 1998] (see figure 31).

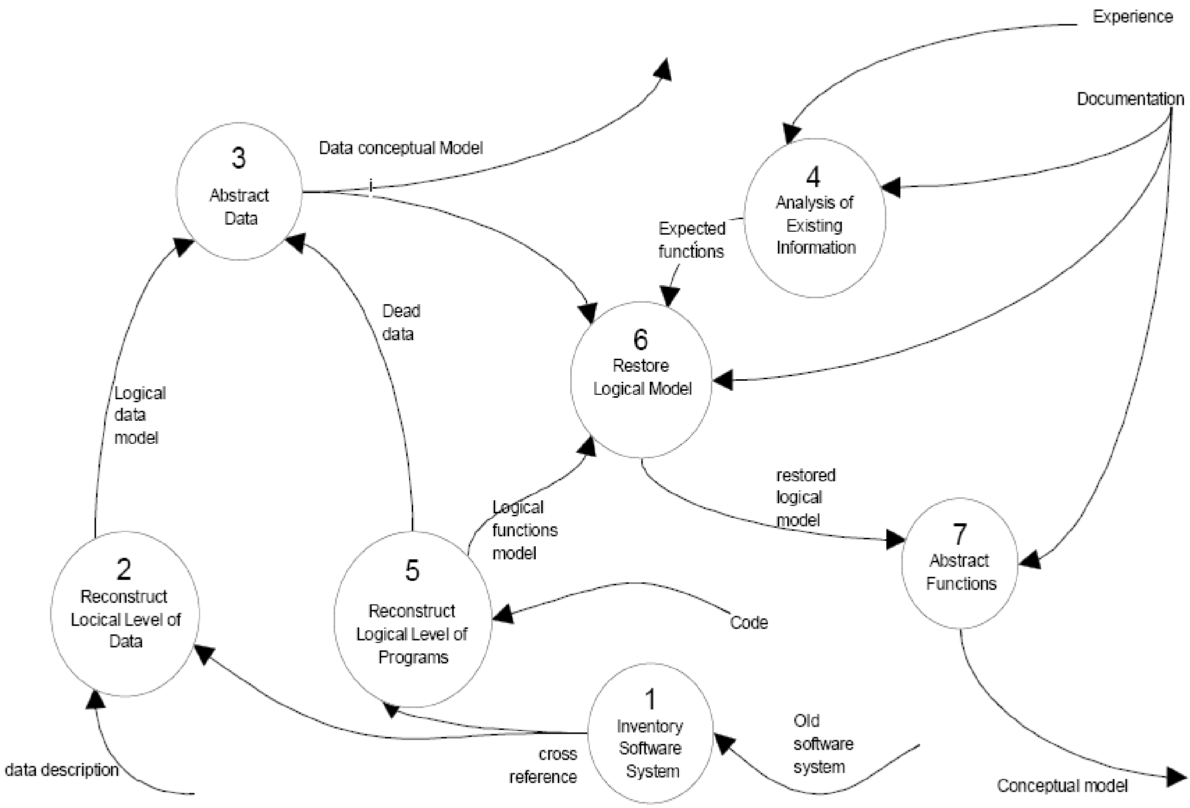

Figure 31: A process model of reverse engineering [Abbattista et al. 1994]

The operation of RE is divided into three parts: measuring of the part (to create 3D point data) modelling (creating surfaces from the measured data) and finally further CAD processing [Kruth et al 1997]. To obtain a digital model of a physical product, various scanning systems could be employed, such as a Coordinate Measurement Machine (CMM) (see figure 32) or a 3D Laser Scanner (LS) (see figure 33). These machines can be used to measure the existing physical object and represent the measured data as a data "point cloud". The point cloud usually lacks topological information and often needs to be processed within a specialised 3D software package to develop a more usable format for CAD, CAM or CAE applications. There are various 3D software packages in the current market such as, Geomagics, DezignWorks, Imageware, PolyWorks, Rapidform, etc. Figure 34 shows an example of applying reverse engineering to convert a physical object to a CAD model.

Figure 32: Brown and Sharpe's DCC GAGE Coordinate Measurement Machine [metrologyworld 2011]

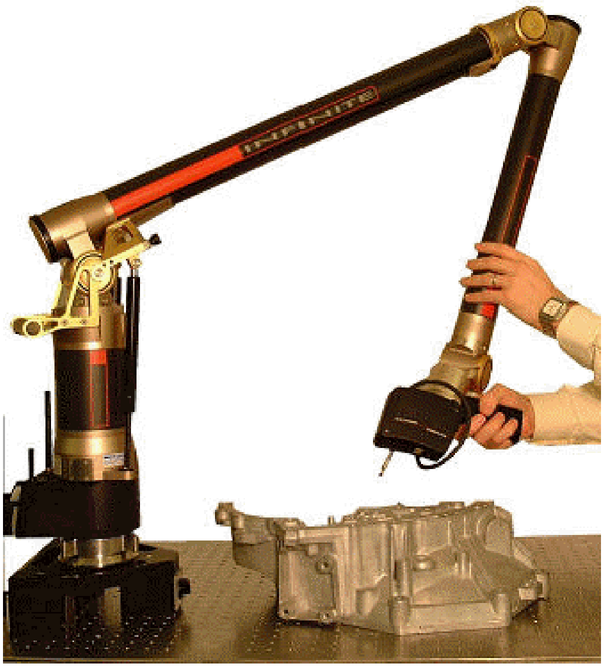

Figure 33: A type of portable 3D laser scanner [Nvision3d 2007]

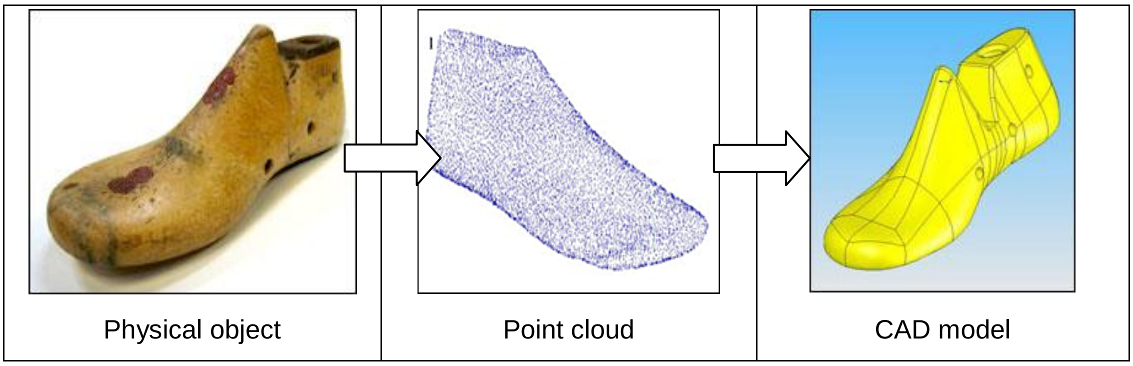

Figure 34: The process of converting a physical object to CAD model with reverse engineering [Gaspardo 2007]

In addition, CMMs integrated with a LS probe are now available in industry [Jamshidi et al 2006]. These systems are used to scan the surface of a product in contact or non-contact way to obtain the point data cloud. The processed point cloud can tehn be exported to CAD modelling platforms, such as Pro/Engineer, SolidWorks, in an STL or IGES (initial Graphics Exchange Standard) format and used to create CAD models. If needed, these CAD models can be converted to physical prototypes through CNC machining or RP.

RE achieves the conversion from a physical prototype to a virtual prototype, while CNC/RP can do the opposite task. When using these technologies, a two-way conversion loop between physical and virtual prototype exists (see figure 35).

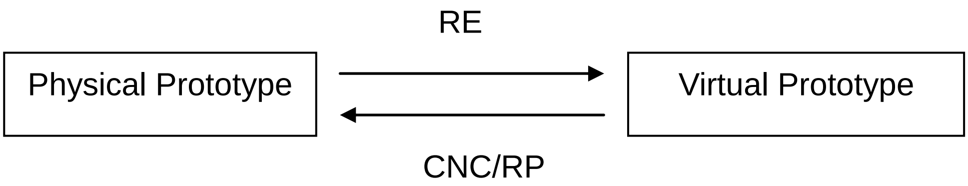

Figure 35: Two way conversion between physical and virtual prototype

Ideally, if the conversion between physical and virtual prototype could be made quickly, it would be very helpful in getting the user involved in testing a product design. For example, when testing the ergonomics aspects of an office chair, the designer could adjust the dimensions of the physical chair according to the feedback from the user. RE would then convert the modified physical prototype into a virtual prototype and CNC or RP could convert the virtual prototype to a new physical prototype for the user to test again. If this scenario could be achieved, the time for user-evaluation will be significantly shortened. However, both RE and CNC/RP are currently very time consuming making this scenario impossible.

4.4 Other related technologies

In this section, three other technologies and devices with a potential for integrating physical prototypes and virtual prototypes will be described briefly. They are haptic technology, parametric prototyping and the WebShaman Digiloop system. All of these technologies and devices provide some kind of approach for bridging between the virtual environment and the physical world. The investigation of these approaches will be helpful for further development in integrating virtual and physical prototyping.

4.4.1 Haptic technology (an intuitive touch-based modelling tool)

The simulation of tactile sensation is usually a difficult task for normal virtual prototyping technologies. However, haptic technology can solve this problem, to some extent. Through haptic devices, users are allowed to experience a sensation of touch and force feedback when they interact with virtual material sin virtual environments [Bordegoni et al. 2006]. Figure 36 shows an example of a haptic system.

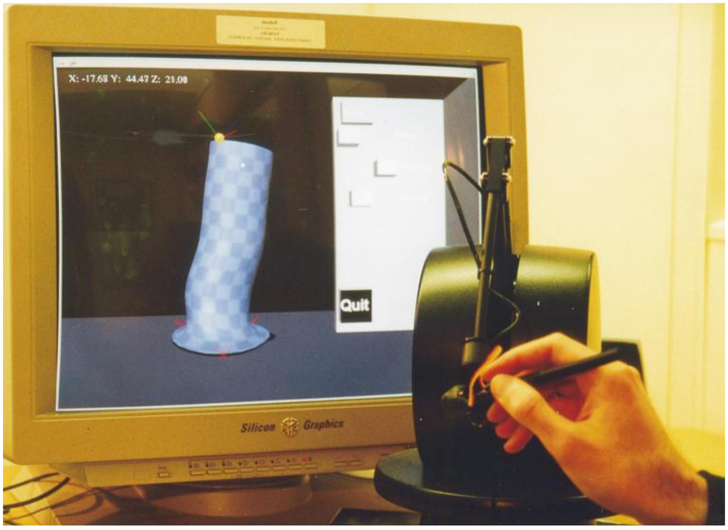

Figure 36: Haptic system [IX et al 2001]

Haptic devices can be subdivided into force feedback devices and tactile devices [Bordegoni 2006]. With these devices, users can “touch” and model a virtual object in a virtual environment that is similar to a natural setting. This device does not only help designers but also can help with user evaluation. For example, the users can “touch” the design and see how it looks. They can give feedback to the designer to change the geometry of the design and then the users can evaluate the updated design immediately (if the changes are not complex). Strictly speaking, haptic technology is not a way of combining the physical and virtual prototype, because there is only a virtual prototype and no physical prototype. However, the main advantage of this technology is that it combines the flexibility and efficiency of virtual prototyping with the tactile sensation which usually only a physical prototype can provide [Chen 2005]. Compared to CNC or RP, haptic devices will help reduce the time and cost of prototyping because there is no need to produce a new physical prototype to evaluate the tactile aspects of the updated design.

Inspired by this technology, the author proposes a system that integrates virtual and physical prototyping. This system will combine haptic technology with a robotic arm. The end of the arm will be equipped with a sculpting tool and a sensor that can be used to measure the coordinate dimensions of a physical part. The method is similar in some ways to tele-presence surgery where a surgeon operates the surgical tools remotely. The principle of this method can be simply described as follows:

On one side, the designer operates the haptic system to create a virtual model; on the other side, the robotic arm follows the movement of the virtual tool to sculpt a block of clay thus creating a physical model. This is the process from virtual to physical prototypes. For physical to virtual prototypes conversion, after the created physical prototype has been evaluated and modified; the sensor in the end of the robotic arm will obtain the coordinate dimensions of the modified physical model and export this data to the haptic system to upgrade the virtual prototype.

Although this proposal is in its infancy and needs much more knowledge to support it, it might provide a potential approach to develop the real-time conversion between virtual and physical prototype in a bidirectional way. This issue will be addressed again, later in the thesis.

4.4.2 Parametric prototyping

A detailed description of this technology can be seen in the article "Advanced prototyping with parametric prototypes" presented by Anderl et al [2006]. Just a summary is given here. Anderl defined the parametric prototype as "the set of a physical mock-up and a virtual model which are linked by an interface." This prototyping technology takes the form of a physical prototype, which has been divided into several parts. Every separate physical part links with a corresponding virtual part in a personal computer through a hardware interface. The changes to the virtual part can be converted to the corresponding physical one through electrical, mechanical and control components. The changes to the physical part can be converted to the corresponding virtual part through outputting data to the computer. The reason for developing this technology is based on the reality that in a new car development process, virtual and physical prototypes will be converted iteratively to each other which will take too much time. Figure 37 shows the interaction of the virtual model and the physical parametric prototype.

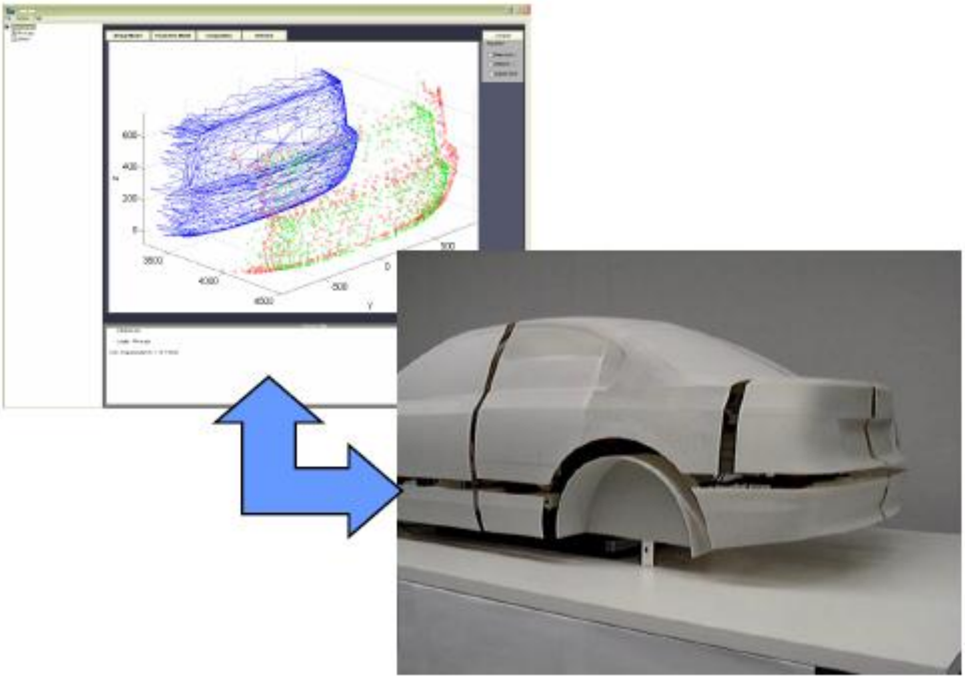

Figure 37: Virtual model with physical parametric prototype [Anderl 2006]

Compared to other integration technologies, the most important advantage of this technology is its achievement of bi-directional conversion [Anderl et al 2006]. However, the purpose of this system is limited to evaluating and developing the preliminary outer-shape styling of car design in the concept phases of the product development process. Other elements which are usually also important to user evaluation, such as ergonomics, the colour and material, are not well considered in this research. Moreover, within this system, a specific Graphical User Interface was programmed and developed by the researchers. As this interface is specific for the car industry and not familiar to industrial design students and industrial designers in other domains, plus the cost of the system, it will be difficult for it become a flexible tool for most industrial designers in various design situations.

4.4.3 WebShaman Digiloop system

The detailed introduction of this system can be seen in the article "Augmenting virtual prototyping with physical objects" [Halttunen & Tuikka 2000]. Compared to the 'Parametric Prototype' system discussed above, this system tackled the integration of physical prototypes and virtual prototypes from another point view. In developing this system, the authors realized that some attributes of a product concept can only be represented by physical prototypes, such as dimensions, weight and surface texture, and therefore, there is a need to integrate the physical prototype with the virtual prototype. This system consists of a flat panel display, a data glove (virtual technologies Cyberglove) and a position tracking sensor (see Figure 38). The system is limited to evaluating hand-held prototypes. Behind the screen, the users hold the physical prototype to test the weight, surface texture, etc. At the same time, on the screen, the user can see the prototype in a virtual environment. The data glove and the tracking sensor bridge the link between virtual and physical prototypes.

Figure 38: WebShaman Digiloop system [Halttunen & Tuikka 2000]

This system enables the users to evaluate a hand-held product concept in both the virtual and physical worlds, simultaneously. With system, the user can not only feel the dimensions, material and weight of the product, but also can see the simulated environment to which the product belongs through the computer screen. Although the authors did not mention it in their article, it is not difficult to imagine that the virtual prototype would be able to present different colours to the users for evaluation. However, there are still some limitations with this system. As the authors stated, the user's head must remain relatively still because the system cannot simulate the viewing angle of the physical mock up according to the head position. In addition, the system can only be used with button-type controls in the prototypes. Other possible components, such as sliders, rollers, or covers cannot be experimented with in this system.

4.5 Chapter Summary

From the discussion presented in the previous chapters, it was found that in the product development process, both physical and virtual prototypes have their benefits and limitations and that conversion between them is iterative in nature. To make the best use of both physical and virtual prototypes, it is vital to integrate or combine these two types of prototypes in some way. In addition, to shorten the time of the iterative conversion between physical and virtual prototypes, developments in both software and hardware are needed. In this chapter, the technologies that related to the integration and conversion between physical and virtual prototypes were studied.

The findings through this study can be summarized as follows:

- There are various technologies related to the integration of virtual and physical prototyping.
- These technologies have different emphases, some are concerned with the conversion from physical to virtual prototype, some concern the conversion from PP to VP and others concern bidirectional conversion.
- These technologies can represent different types of changes made to physical and virtual prototypes. Some can represent material subtraction, such as CNC; some can represent material addition, such as RP; others can represent component movement, such as parametric prototyping.
- Some of these technologies have contributed significantly to the product development process, such as CNC, RP, RE, etc. Others have shown their potential value in this area, such as hybrid prototyping, parametric prototyping, etc., but are yet to be used widely.
- The data transfer that bridges physical and virtual prototypes is usually achieved through the STL file format or some other neutral format. Digital sensors can be used to track the motion of a physical prototype and transfer the data to computer to drive the changes to a virtual prototype, for example within the parametric prototyping and WebShaman Digiloop systems.
- Some researchers have shown a trend for combining some of these technologies to make further developments in the integration of virtual and physical prototype. For example, hybrid prototyping is way of combining CNC and RP.
- User involvement has been addressed by some researchers when developing their technologies, such as the parametric prototyping and WebShaman Digiloop systems.

The discussion in this chapter has outlined the current situation of integrating or combining physical and virtual prototype. The methods presented all have different applications and areas of focus, and have shown their benefits within specific industrial domains. However, they still have some limitations. For example, the processes of CNC, RP and RE are still very time-consuming and costly. This is in conflict with the requirement that physical and virtual prototype should be converted quickly. In addition, specialised software is usually needed to support these technologies or systems. This could limit their application by industrial designers. Furthermore, although user’s factors have been mentioned by some researchers when developing their technologies, obviously, the user involvement needs to be addressed further. Therefore, it is necessary to develop other possible ways to solve these problems. Information obtained through literature review has now laid the basic foundations for the research in this thesis. To gain a further understanding of the current situation in the application of physical and virtual prototype, first hand data is needed. This will be the focus of Chapter Five.

Chapter Five

Initial Investigation

As the overall aim of this research was to suggest and develop a tool to integrate PP and VP. The purpose of this initial empirical study was to identify the key problems regarding the application of these two types of prototypes. This chapter begins with a general overview of empirical study as a research methodology and goes on to analyse the results from a pilot trial and a questionnaire study to provide added support to the previous literature review research.

5.1 Empirical Research

Empirical research is kind of research method involving the collection of new data [Rose 1982]. It can be divided into two categories:

- Quantitative research methods: such methods collect numerical data (data in the form of numbers) and analyse it using statistical methods.

- Qualitative research methods: such methods collect qualitative data drawn from observations, interviews and documentary evidence, and analyse it using qualitative data analysis methods [Moody 2002]

Compared to the literature review, empirical research methods could provide first-hand information from the real context. This information could be used to support or challenge the knowledge found through the literature review. In addition, empirical means can be used to test the research hypothesis developed by the researcher [experiment-resources.com 2011]

In the initial empirical research, the quantitative research method was applied in the format of questionnaire survey, including the design and delivery of 102 questionnaires and, the analysis of the feedback. The qualitative research method used was in the format of a pilot study, comprising the design of the proposed integration method, the trial of the method, observations and interviews.

5.2 Questionnaire survey

5.2.1The purpose of the survey

The aim of this survey was threefold. Firstly, to assess each interviewee's views as a product/industrial designer when comparing the use of virtual and physical prototyping in the product development process; secondly, to investigate the current situation regarding applications that integrate them; thirdly, to see if there is any requirement for them to be more closely integrated.

5.2.2 The survey strategy

Before the survey started, a questionnaire was designed (see Appendix I). The questionnaire consisted of three main catalogues: background, respondent's personal details and main questions. The "background" gave the respondents an overview about the research and the purpose of the survey. The questions were in the format of "open-ended questions", since the answers might cover a wide range and were difficult to be predicted. In order to avoid the questionnaire taking too much of the participants' time, only 12 concise questions were designed.

Ethical conduct was taken into account during the investigations. A cover letter was sent along with the questionnaire. The participants were told their information would be kept confidential and their answers would be only used for research purposes in Loughborough University. Each cover letter had the interviewee's name as the greeting, for example, Dear James, Dear John, etc.

It was decided to print the questionnaires and post them, instead of simply emailing them. Although sending by traditional mail would cost money and take longer, the reason for this was safety and in the hope that participants would take the survey more seriously. If sent by email, the participants might be worried about a virus infecting their system and may not even open it because it was from a stranger and had an attachment. The worse possible situation would be that the email might be classified as spam by the respondent's email system.

This survey was undertaken from the middle of April 2007 to the end of July 2007, lasting around four months. The targeted participants were designers and engineers working in companies, consultancies or institutions that have courses in industrial design or product design and manufacture. The reason for selecting engineers as well as designers was that interviewees from different occupations could look at the same questions from different perspectives, which can give the researcher a wider range of information. However, because the focus of the research is regarding industrial design, designers made up the majority in the participants. Table 6 shows the breakdown of the respondents' occupations. In total 102 companies, consultancies and institutions were selected. The contact information of the participants was mainly from the public websites of their organizations. In order to get a large variation of views, only one person was selected from each organization. Therefore, 102 questionnaires in total were sent.

Occupation	Number of interviewees
Designer	4
Director	3
Development director	1
Design director	1
Management director	2
Senior engineer	1
Product designer	2
Industrial designer	1
Design consultant	1

Table 6: Breakdown of the respondents' occupation

Unfortunately, only 16 valid questionnaires were returned, giving a percentage response rate of 15.7%. The reasons causing the low feedback rate could be as follows:

- The questionnaire was sent by mail. The interviewees had to fill it by hand and send it back. This process might be seen as overly time consuming.
- Some interviewees were not interested in the questions in the survey

This feedback rate was relatively low. However, knowing this rate was useful for future questionnaire surveys. For instance, in a similar situation, if 35 returns are required, then around 200 questionnaires should be sent. On the other hand, some efforts should be made to improve the rate, such as making the questionnaire easier to complete, reminding the interviewees through telephone, using an online questionnaire survey, etc.

5.2.3 The survey findings

To make the list of questions consistent and logical, question 1 to question 4 were about virtual prototypes and prototyping; while question 5 to question 8 were about physical prototypes and prototyping. Then followed questions 9, 10 and 11 asking about the integration of PP and VP. At the end of the questionnaire a section was added to allow the respondents to expand on any ideas brought up during the earlier questions. All of the questions are in open format. However, in order to find the difference between physical and virtual prototype, the analysis process used a comparative approach, i.e. comparing the answers to the similar questions about physical and virtual prototype. The following paragraphs will show the results of these comparative studies and analysis.

First Comparison:

Q 1) What type(s) of virtual prototyping do you use?

Q 2) What types of products have you used virtual prototyping for?

Q 5) What type(s) of physical prototyping do you use?

Q 6) What types of products have you used physical prototyping for?

Table 7 shows the types of virtual prototyping tools used and the products they are used for; table 8 shows the same for physical prototyping. As the companies participating in this survey does different businesses, their answers are quite various and difficult to categorize them. Therefore, the answers of each participant are just listed as follows and analysed together after that.

Virtual prototyping		
The respondents	**The types of virtual prototyping**	**The types of product that virtual prototyping are used for**
No.1	3D solid modelling	Medium, small electronic products
No.2	Only used once, for thermal analysis	Temperature controlled retail window furniture
No.3	Solidworks, Pro/Engineer, Cosmos Works FEA, Moldflow analysis	Medical devices, transport products, consumer products
No.4	CAD generated image and animation	All types of medical consumer
No.5	Solidworks	Product of : Homecare, prestige, Mother-baby, DIY
No.6	Solidworks, Photoworks	Injection moulding/ Fabrication/extrusion/ceramics
No.7	3D CAD, photoreal renders, FEA	Plastic, metal, consumer goods
No.8	Photorealistic Rendering, FEA	Pressure test equipment, consumer goods
No.9	Solid works, Cosmos Designer	Medical devices, technical packing, telecoms and electronic products and enclosures
No.10	Solidworks; Cosmos FEA	A small snap fit widget
No.11	Solidworks	Consumer/LAB/industrial/
No.12	Renderings, Animated 3D PDF, FEA, SLA	Medical instruments, furniture parts
No.13	Solid Modelling, Finite Element Analysis	Composite vessels, pressure vessels, turbine blades, rollercoaster.
No.14	None	None
No.15	CAD, Pro/Engineer, Alias	Various manufacturing products
No.16	3D CAD	(Not provided)

Table 7: Virtual prototyping tools and the products they are used for

Physical Prototyping		
Respondents	**Types of physical prototyping**	**The types of product that physical prototyping are used for**
No.1	Mostly Rapid prototyping	Small/medium electronic based products
No.2	Handmade models and rapid prototyping	Interactive retail display units
No.3	3D printing; SLA; SLS; Vacuum castings	Medical devise, transport projects, consumer products
No.4	Rapid prototyping, CNC	Medical consumer
No.5	Foam models, CNC machining, SLA/SLS/FDM, Rapid tooling	Appearance models for consumer testing
No.6	Traditional modelling; 3D printing	Ceramics, audio equipment, house wares.
No.7	Rapid prototyping	Plastic, metal, consumer goods (same to the virtual prototyping)
No.8	Block models, appearance models	Pressure test equipment, consumer goods
No.9	SLA, foam models, CNC	Medical device, technical packing, telecom electronic product (same to the virtual prototyping)
No.10	SLA, FDM, SLS, 3D print, vacuum casting, model board	Everything we ever do
No.11	SLA, Casting, Sheet metal	Same to virtual prototyping
No.12	SLA, Machined parts, FDM	Medical devices
No.13	Prototype manufacture of structural turbine blades	Nor provided
No.14	Handmade, CNC, SLS, SLA, VAC casting, soft tooling	Everything from toys to power tools
No.15	All	All
No.16	Model making, Rapid prototyping	For proof of concept

Table 8: Physical prototyping methods and the products they are used for

Table 7 shows that various virtual prototyping tools have been popularly used for a wide range of products, from small electronic products to transportation; from medical devices to furniture, etc. The types of software packages that have been employed might depend on the projects or particular products the respondents worked on. The software packages used for 3D modelling were Solid Works, Pro/Engineer, Rhino, CAD, etc.

The above information regarding the types of software package would be helpful for the research development presented in this thesis. As discussed in section 4.4 of chapter 4, although some systems, such as parametric prototyping and WebShaman Digiloop, have improved the integration of VP and PP to some extent, they both have problems in being compatible with the software packages used by designers. If there is a new system or method that can integrate VP and PP as well as being compatible with these 3D modelling software packages used by designers, it could provide more help for product designers in their design activities.

The table 8 shows that various physical prototyping approaches, ranging from traditional hand-made modelling to Rapid Prototyping, are used in a wide range of product design and manufacturing applications, from small sized electronic products to larger products, such as transportation. In addition, some respondents stated that they often used physical prototyping and virtual prototyping for the same product in different phases of the product development process. This implies that there are some stages of the product development process where physical prototyping might be more suitable, while in others virtual prototyping is preferred. These results supported the findings from the previous literature review, i.e. both PP and VP play important roles in product development and that physical prototypes have not been totally replaced by virtual prototypes.

Second comparison:

Q 3) What are the main benefits of using virtual prototyping compared with physical prototyping?

Q 4) What problems/limitations have you encountered when using virtual prototyping?

Q 7) What are the main benefits of using physical prototyping compared with virtual prototyping?

Q 8) What problems/limitations have you encountered when using physical prototyping?

The next group of questions was designed to explore the benefits and limitations of VP and PP. Table 9 shows the answers for VP, and Table 10 shows the answers for PP.

Virtual prototyping		
Respondent	Benefits	Limitations
No.1	Integral part of design process; Good for evaluating compete packages	Sometimes time consuming for design result
No.2	Able to simulate various temperature conditions for a variety of size modules to achieve optimum performance	No problem encountered
No.3	Less investment cost; Prototypes can be tested without large costs incurred	Models are not as good as the assumptions used
No.4	Cost	Limitations in ergonomics and scale
No.5	Cost – confidence check before tooling – easy to amend in real time	It is virtual, it can only be used theoretically
No.6	Time to amend; flexibility	Physicality; Ergonomics; tactility
No.7	Cost; Time	Lack of feedback, ergonomics testing, functional testing.
No.8	Impresses clients, can proceed with high level of confidence.	Clients do not always understand the form/scale
No.9	Speed; Cost; Flexibility (ability to change)	It's not real – need to back up with real models and testing.
No.10	Speed; Cost	It's never spot on, cannot be relied on
No.11	Can be quicker; Cheaper	Physical access; Feel of parts or assembly
No.12	Speed; Transferability	FEA is only comparative ; People like to touch/see -

		ergonomics
No.13	Definition of stress fields; Design optimisation; Complex surface accuracy of definition; Reduction of physical interferences; Mass optimisation; Shock analysis; Marketing aid.	Scale too small to physically appreciate; actual size/feel touch.
No.14	Not sure	No experience in this
No.15	Less cost; easy to review in context.	Different to gain full appreciation of product; size; tactile; subtle form.
No.16	Cost and Speed	Lack of tactile feedback; manipulation is not so easy

Table 9: The benefits and limitations of virtual prototyping

Physical prototyping		
Respondents	**Benefits**	**Limitations**
No.1	Tactile-hold it, see it, feel it	Tech-file transfer limitation of materials, not real mouldings
No.2	Physical interaction with application / product	Can be costly to produce
No.3	More tangible, good for communication, mechanical testing , usability testing	Lead time, costs
No.4	Ergonomics and mechanics, overall feel	Cost, material limitations
No.5	Hands on testing, evaluation of form. “nothing like the real one”	Difficult to make amends, replicate production materials
No.6	Assembly, real life construction issues, ergonomics	Material limitations
No.7	Testing, good for presentations	Tooling, Rapid Prototyping in correct material
No.8	Successful communication of ergonomic design	Block models are often dismissed because they do not look good
No.9	More convincing – can find unexpected problems	Making parts in same material as production part
No.10	You can hold it in your hands,	It can be a time consuming and costly affair
No.11	Greater client confidence	Not provided
No.12	Touch, scale, function	Time to produce/transit

No.13	Always physical structural testing needed for design code and actual fitting testing	Cost and time
No.14	You achieve real results	None if you use time limit process
No.15	Human interaction, appreciation of product in its environment	Strength of part, cost
No.16	More pleasant to work with physical object	Time taken and cost

Table 10: The benefits and limitations of physical prototyping

Tables 9 and 10 indicate the respondents' attitude to virtual and physical prototyping technologies. As user evaluation is one main concern for this research, the information from this aspect that was gained from the responses was particularly important. The results showed that most respondents have experienced both benefits and limitations for both types of technologies. In summary, compared to virtual prototyping, physical prototyping was seen as being more beneficial in user evaluations in the following respects:

- Communication
- Ergonomic evaluation
- Tactility
- Usability test
- Function test

Compared to physical prototyping, virtual prototyping was not seen as being preferable for user evaluation. However, it was seen as being more advantageous in the following respects:

- Accuracy
- Lead time
- Cost
- Ease of modification

The answers from respondents were consistent with the findings of the previous literature review. Understanding the benefits and limitations will help to achieve the aim of this research, i.e. integrating PP and VP in the most beneficial way.

Integration of PP and VP

Q 10) In what situations (if any) has it been desirable for you to use virtual prototyping and physical prototyping simultaneously/in real-time?

Q 11) Have you been able to accomplish this and, if so, how?

Question 10 and 11 were about the situations in which the simultaneous use of virtual and physical prototyping has been desirable and how has this been accomplished. As stated earlier, quick conversion between physical and virtual prototype is significant for shortening product development lead time. CNC, RP and RE can convert between physical and virtual prototype, but usually take several days to accomplish the conversion process. Parametric prototyping and WebShaman Digiloop systems have achieved instant conversion between physical and virtual prototype but still have some limitations. These two questions were designed in the hope of finding out if designers really desire the quick conversion between these two prototypes and if they have other ways of doing so besides the methods found from the previous literature review.

The answers showed that about half of the respondents had never seen the need for simultaneous use of the two types of prototyping technologies. Most of these suggested that virtual and physical prototyping were usually used sequentially and in different stages of product developments. However, the other half of the respondents said they had either already experienced or else realised the necessity of real time integration. There are two main categories for the situations where they used or wanted to use virtual and physical prototyping together:

- Presentation: presenting CAD models and physical prototypes simultaneously to the clients.
- Testing: using FEA and physical prototyping in parallel to test strength and other characteristics.

After analyzing the answers from the two different halves, two findings were identified:

1. There are some situations where either virtual or physical prototyping can match the design or test requirements independently, and using them together in real-time might not be necessary.
2. The simultaneous use of the two types of technologies is necessary in some situations but is only being done in a simple way. Although they have been synchronously used for presentation and testing, the simultaneous conversion of changes from one to the other has not been accomplished.

5.2.4 Summary of the questionnaire survey

Although the response rate was low, and must be taken into consideration, the valid responses given still helped significantly in the development of this research. The findings of the questionnaire survey supported the results obtained from the previous literature review, i.e. that physical and virtual prototyping will not replace each other since each of them has its own benefits and limitations. In addition, some consultancies and designers have recognized the need for simultaneous use of the two types of technologies. However, the actual simultaneous use of them was only done in a simple way. There was no existing system being used by any of the designers or engineers to synchronously convert changes between physical and virtual prototypes.

In addition, the survey provided evidence of which 3D modelling software packages were being used commonly by industrial designers. This should be taken into consideration when developing a new system or method to integrate PP and VP, i.e. the system should be compatible with these software packages, so it can be applied within designers' usual design and testing activities. Furthermore, the responses have shown that prototypes, especially physical prototypes, play an important role in user evaluations. The respondents from different consultancies repeatedly mentioned the benefits of physical prototype in testing ergonomic issues of product design. Therefore, this advantage of using physical prototypes should also be emphasised and embedded into any future integration system.

5.3 Initial Pilot Study

Through the literature review and questionnaire survey, basic knowledge about the characteristics of both physical and virtual prototype was gained and the need for integrating them was also demonstrated. The limitations of the current integration technologies and the current methods of applying physical and virtual prototype in design consultancies show the requirements for a new system to integrate them with each other in a better way.

Having considered all the information collected from the previous research, a conceptual method for integrating virtual and physical prototyping was hypothesized by the researcher to enable further study of the integration of PP and VP. To test the method, the experimental research method was applied. According to James [1997], experimental research enables the researcher to test his hypothesis. To achieve this, the researcher attempted to determine or predict what may occur and conduct the experiment within the conceptual framework. However, since this method had just been proposed and many issues could not be predicted, the experiment was conducted as a "pilot study" to find out any problems regarding both the method and the experimental activity. In the following sections of this chapter, the proposed method and the pilot trial will be introduced.

5.3.1 Introduction of the proposed method

The proposed method can be simply described as simultaneously using a CAD model of a chair created within Pro/Engineer to test the design aesthetics and a corresponding physical mock-up to evaluate the design ergonomics aspects and quickly modifying both types of models. The reason to choose chair as the platform to test the method were as such: first, design a chair requires the concern on ergonomics which physical prototype has strength to test for; second, the aesthetic aspect is also important for an appealing chair and this aspect could be tested through virtual prototype. Design aesthetics are the combination of a number of different elements, such as form, colour and proportion, etc. [Niku 2009]. The aesthetics in this case were the shape of the chair while the ergonomics included the seat height, seat angle and backrest angle of a chair. The user was asked to test the height, backrest angle and seat angle of a physical chair mock up; the designer read the values of the user's preferred height and angles and then input them into the chair CAD model to quickly update it. The updated CAD model would be presented to the user immediately to let him/her evaluate the appearance. The designer could adjust the CAD model again according to the user's evaluation results. The physical mock up would then be adjusted again according to the new data shown in the CAD model. This two-way loop could be repeated several times within a short period of time until the user was happy on both the ergonomics of the physical mock-up and the appearance shown by the CAD model. The method was proposed based on the theory evolving from the literature review and questionnaire survey that a physical prototype is more advantageous in evaluating ergonomics while a virtual prototype is more beneficial in testing aesthetics.

Initially, a suitable chair had to be chosen for use in the trials. The assumption was made that a rigid chair had been designed and needed to be tested and possibly modified. The reason for choosing a rigid chair were: firstly, the structure of the chair was relatively simple, which is suitable for an initial pilot study; secondly, aesthetics and ergonomics are two elements needed to be considered in chair design; and thirdly, compared to an adjustable office chair, the ergonomic elements of a rigid chair need to be defined more carefully, since it cannot be adjusted to suit different people. As this was prepared as a pilot study, only the backrest angle, seat angle and seat height of the chair were going to be tested.

To apply this proposed method, two prototypes were needed to be prepared in advance. One was the CAD model and the other is the physical mock-up. The CAD model was built with Pro/Engineer. There were two reasons for choosing Pro/Engineer as the modelling tool. Firstly, according to the questionnaire survey, Pro/Engineer is one of the commonly-used 3D modelling software packages for industrial designers in design consultancies, and compatibility with commonly used software packages is one requirement for the integration system, as mentioned before. Secondly, Pro/Engineer was one of the software packages that the author of this thesis was familiar with. However, as Pro/Engineer is considered as a software package focusing on solid modelling instead of surface modelling, trying Pro/Engineer alone for the proposed method would not necessarily indicate its general suitability.

Therefore, it was decided that the Rhino 3D modelling software package should be used in the experiments for the next stage of the trials, which will be described in subsection 6.2.2 of Chapter Six.

A typical office chair was used as the physical mock-up of the chair design (as shown in figure 39). Although the product design under consideration was a rigid chair, the physical mock-up needed to be adjustable in seat height, seat angle and backrest angle. There were two reasons for selecting an adjustable office chair. Firstly, based on the previous research, in the design process, physical prototyping was seen to be an iterative cycle between modifications and evaluations. Therefore, using an adjustable physical prototype in evaluation situations would save time and cost since it would negate the need for several prototype versions to be created. Secondly, as this was the first pilot trial, in order to save time and cost, the researcher and supervisor decided to use a readily available chair instead of building a new chair mock up. For the later trials, it was decided that a completely new physical mock up would be built, which will be described in sections 6.2.1and 6.3 of Chapter Six.

Figure 39: The physical mock-up

5.3.2 Building the CAD model

According to Baxter's study [1995], during the early stages of trials, the physical prototype should be kept as simple and inexpensive as possible. Therefore, the physical mock-up was an existing chair which had enough adjustability to obtain the answers and did not need much further effort to be spent on it. However, as this proposed method was addressing the integration of VP and PP, the virtual prototype must be designed to make it able to communicate with the physical prototype to some extent. Therefore, there were several aspects that needed to be considered when creating the 3D CAD model of a chair (virtual prototype). These considerations are described as follows:

Firstly, the CAD model should clearly show some characteristics regarding aesthetics to emphasize the benefits of virtual prototype in user evaluation, i.e. virtual prototype has more advantages in evaluating the design aesthetics compared to physical prototype according to the previous literature review and questionnaire survey.

Secondly, the shape of the model should be easily modified. As the proposal suggested, the users would be asked to adjust the physical chair mock-up to meet their own ergonomics requirements. When the physical mock-up was adjusted, the designer must be able to modify the CAD model quickly, so that the user could evaluate the appearance of the updated CAD model immediately. Otherwise, the significance of integration could not be represented and the limitations identified with CNC, RP and RE would remain, i.e. there is an unacceptable delay in the update to the physical or virtual prototype.

To meet these considerations, the researcher spent much time in building several different CAD models using various features of Pro/Engineer. However, most of these models could not meet the requirements of the proposal. The main difficulty was the adjustability of the CAD model, i.e. how to quickly modify the shape of the chair model while keeping the shape changing smooth. After analysing the failures of these models and applying some specific features and set-ups, a CAD model was built eventually that met the above considerations to a reasonable extent. With this model, the three elements, backrest angle, seat angle and seat height, could be adjusted quickly. The detailed process of building the CAD model is presented in the following subsection.

5.3.2.1 The process of building an adjustable CAD model with Pro/Engineer

This process consists of four main steps as follows:

1. A single freeform line, with active points A,B,C,O,E,F, was firstly created with the "spline curve" feature (see Figure 40); This line was then split at point O. Point A, B, C and O are active points to control the shape of the backrest while point E,F and O are the active points to control the shape of the seat. With this set-up, line ABCO and EFO could keep tangent at point O. Angle α between the line OA and horizontal line was defined as the backrest angle; the angle β between line OE and horizontal line was defined as the seat angle. As line ABCO and EFO has been constraint as tangent at point O, when angle α and β were given different values separately, and the whole line of ABCOEF can still keep consistent in curvature.

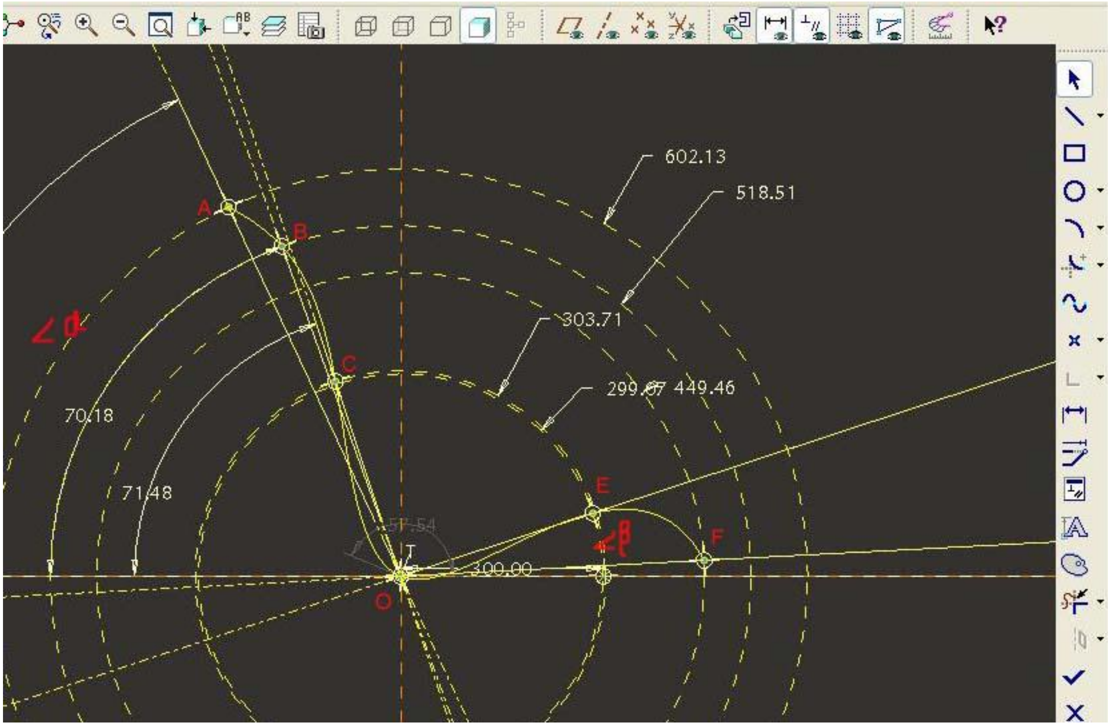

Figure 40: Building the line of the model

2. To make sure the shape of the chair change smoothly when the different values of the angles are input, reference circles were applied to constrain the point A, B, C, D, E and F and all these points would only move on these circles. In addition, to make the value of the angle able to drive the movements of all the relevant points, a feature of Pro/Engineer, called “relations”, was applied (see Figure 41). With these relations, the relevant points could move together at a present angle when the angle α and β were changed. For example, when angle α changed five degrees, point E and F could automatically move five degrees.

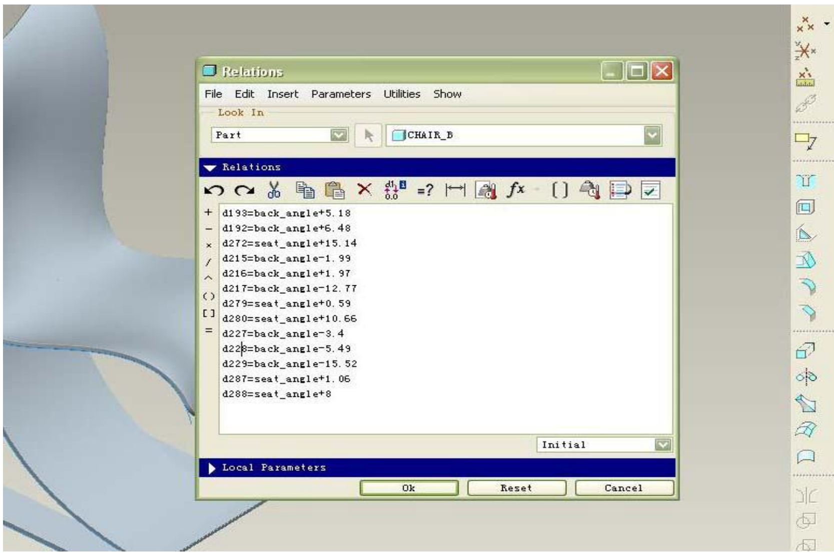

Figure 41: The feature of “relations” in Pro/Engineer

3. With the same method, several lines were created. After applying the feature “Boundary blend tool” and other normal modelling features, such as extrude, cut, round etc., a virtual chair model was created (see Figure 42).

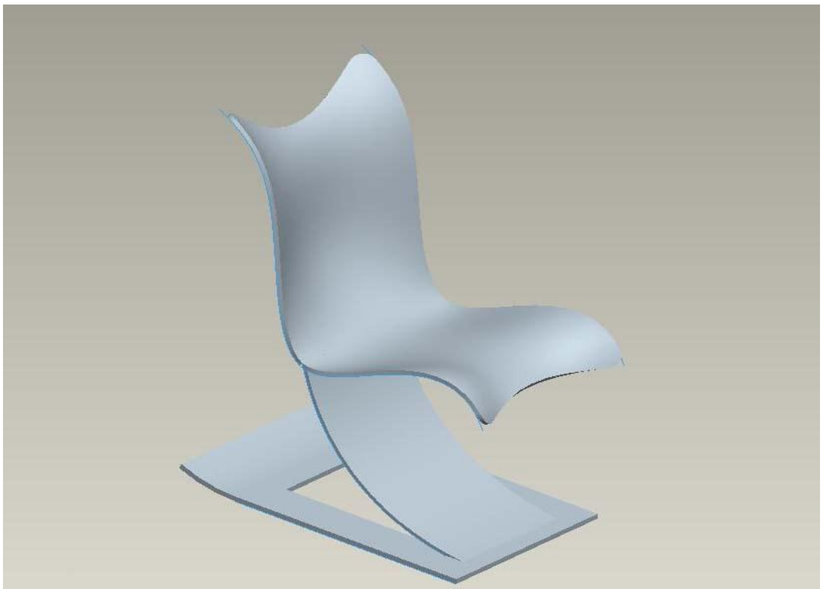

Figure 42: The CAD model of the chair

4. The three elements (backrest angle, seat angle and seat height) were imported to the “family table” (see Figure 43). The designer got feedbacks regarding the data of angles and height and input the data to this table, the system would generate a new CAD model immediately.

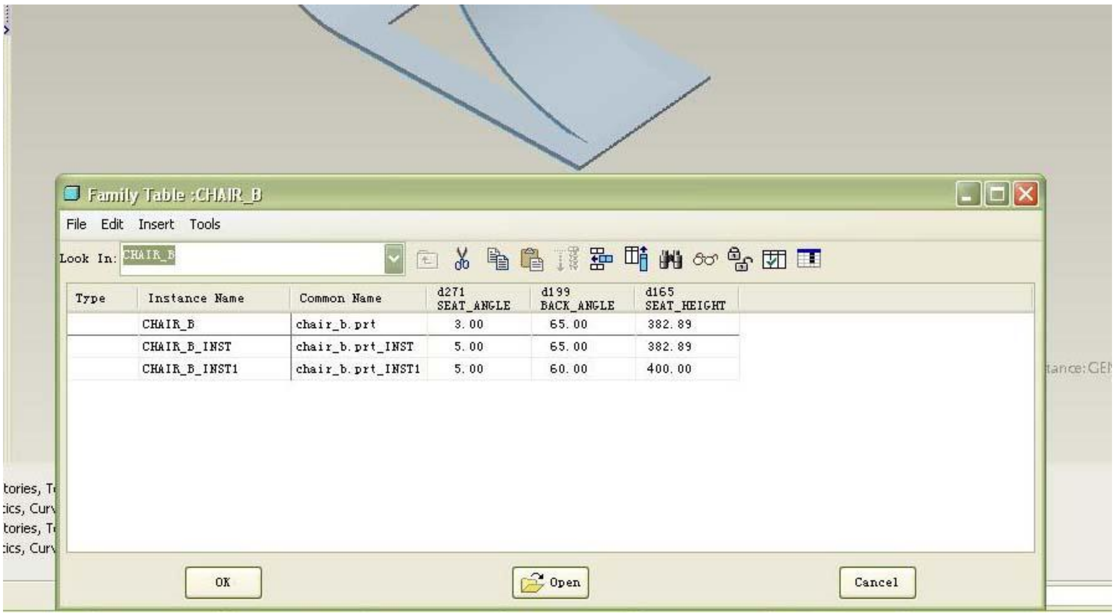

Figure 43: The feature of “family table” in Pro/Engineer

5.3.3 Trial Process

When the physical mock up and CAD model were ready, a pilot trial was conducted. The purpose of the pilot study was to check if the proposed method could help designers improve the evaluation of their design and to address the problems associated with this method, in order to prepare for the more complex and detailed experiments that would be conducted later.

There were five groups of people involved in this trial. In each group, the author acted as a “director”, one participant acted as a “designer” and the other participant acted as a “user”. The participants that acted as “designer” were all PhD researchers from The Design and Technology Department of Loughborough University (now part of Loughborough Design School). As “director”, the author told the designer and user how to operate the mock up and the CAD model and gave necessary explanations about the process. The CAD model was used to test the aesthetics and the physical mock-up was used to test three ergonomic elements: the seat height, the seat angle and the backrest angle.

For each group, the trial process followed five steps:

1. The designer asked the user to try the physical mock-up of the chair and collected a group of data of the three evaluated elements (the values of the three elements were measured with a ruler and goniometer).

2. The designer input the groups of data to the “parameter table” associated with the CAD model and the CAD model was updated immediately.

3. The designer displayed the changed model to the user using a projector, as shown in Figure 44) to obtain feedback about the aesthetics of the design and to modified it again according to the user’s preference. The impact of these modifications on the three adjustable elements was noted.

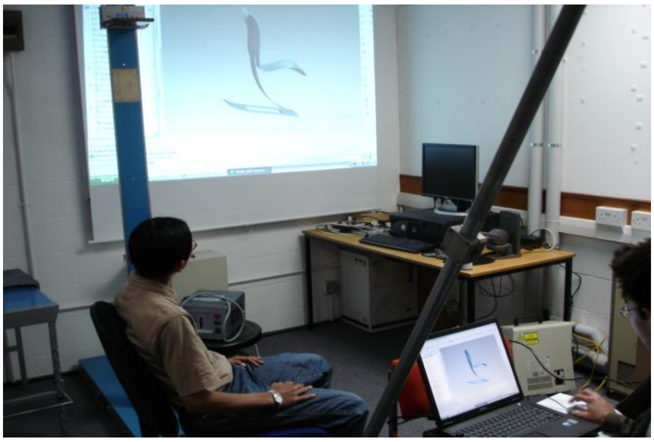

Figure 44: The evaluation of the chair with both virtual and physical models

3. The user modified the physical mock up according to the dimensions of the modified CAD model. Taking the backrest angle of the chair for example, figure 45 shows the corresponding changes in both the physical and virtual chair models. When the backrest angle of the physical mock-up was adjusted to position 1, 2 or 3, the angle of the CAD model was changed correspondingly. When the CAD model was moved to a new position, the physical mock-up was changed to the corresponding position, as well.

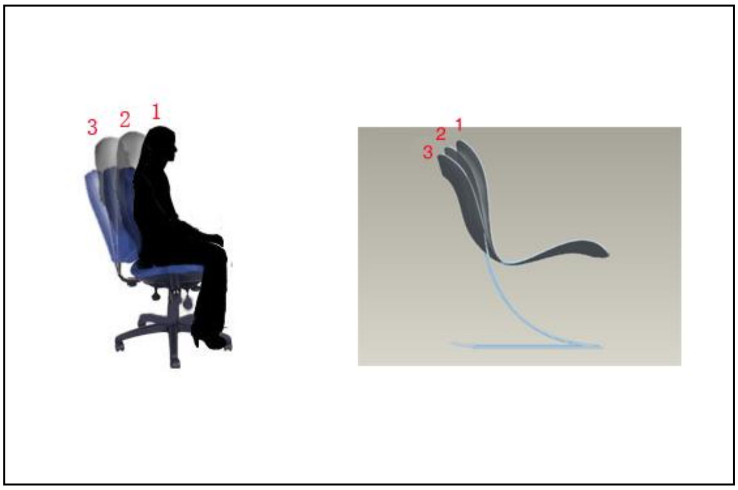

Figure 45: The corresponding changes of physical and virtual chair models

4. The above four steps were repeated several times until the user was happy with both the aesthetics and the ergonomics of the chair design, as indicated in figure 46.

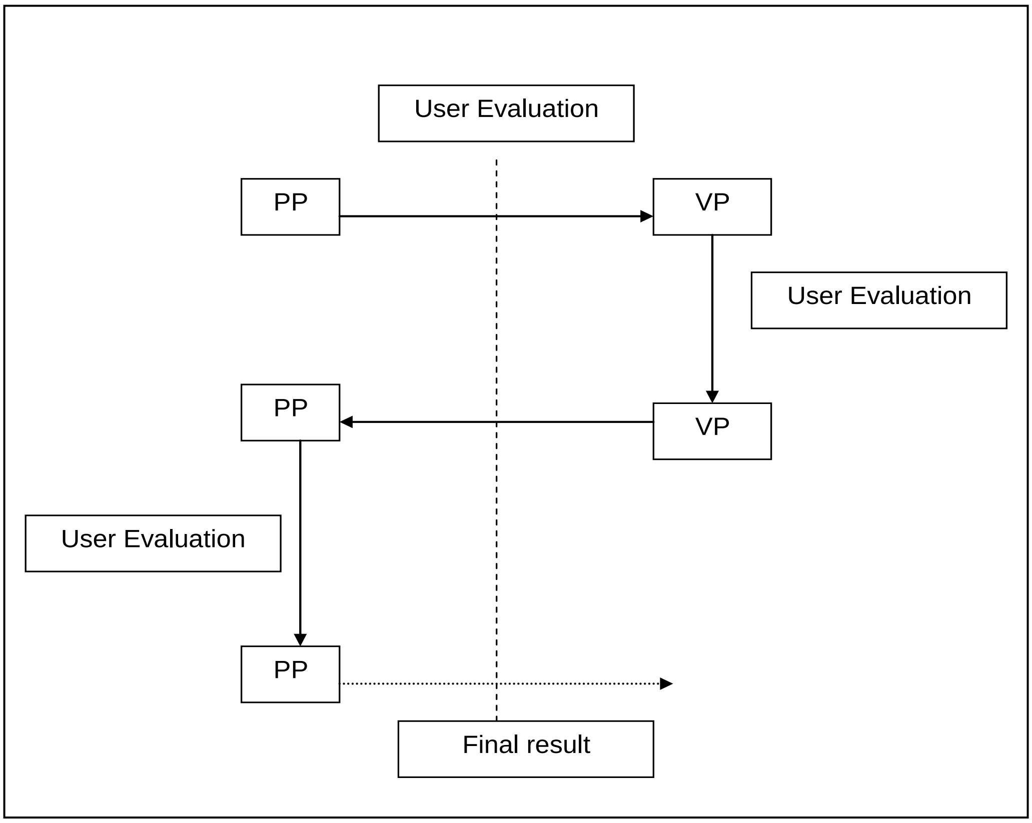

Figure 46: The procedure of the evaluation

5.3.4 Questionnaire for the trial

After the trial, the participants who acted as 'designers', were asked to complete a questionnaire (shown in Appendix II). Because this was the first trial for a proposed idea and its aim was to test its feasibility and get suggestions from the researchers' professional perspective, the participants acted as 'users' were not asked to do questionnaire in this stage.

The questionnaire had a mixture of both open and closed questions, starting with the designer's basic background in physical and virtual prototyping to several questions regarding this trial and the proposed integration method. A summary of the responses received is given below.

Q1) Have you ever used Pro/Engineer in designing activity?

This was a mixture of open and close question. If the answer was no, the participant was asked to state what kind of 3D software package they used. This question was included to evaluate whether the designer would give different feedback to this trial when they had or did not have experience with Pro/Engineer. It was expected that if the designer had no knowledge on Pro/Engineer, they might feel that it was more difficult to operate this method. The answers showed that there were two participants who had used Pro/Engineer for designing activities and the remaining three had never used it before, instead using SolidWorks and a 2D software package. These answers were used as references to evaluate the responses of the latter questions.

Q2) Have you ever built a physical mock-up to test your design?

This was a closed question. The participants' answer was used as reference for the evaluation of the answers of the rest questions. It was supposed that if the designers had no experience in physical prototyping, they might feel this proposed method was less desirable, compared to the designers that had this kind of experience. The answers showed that three participants had built physical mock ups while the other two never did it before.

Q3) Do you think this method (combination of CAD model and Physical mock-up) is helpful in reducing testing cycle time?

This question was included to evaluate whether this method could reduce testing cycle time compared to the traditional prototype testing process where physical and virtual prototype were tested separately. This was a closed tick-box question, where participants were asked to select only one response from the following: very much, a little, not at all and disadvantageous. Four participants selected 'very much' while only one selected 'a little'. The feedback from the participants further indicated the potential benefits of integrating PP and VP in reducing testing time, which had also been found in the previous literature review and questionnaire survey. Within the four participants who chose 'very much', three of them never used Pro/Engineer and two of them never built a physical prototype. The one who chose option 'a little' had previously used Pro/Engineer and had built a physical mock up. In general, all these answers were positive and the experience with the Pro/Engineer and physical mock up did not show significant influence to the participants' opinions.

Q4) Do you think this method is helpful in modifying your design quickly?

This was another closed question, offering a choice of: very much, a little, not at all and disadvantageous. Seemingly, Q4 is similar to Q3. However, they were explained by the author to the participants that, Q3 focused on the theory of the combination of physical and virtual prototype, while Q4 emphasized the technical set-up of the physical mock up and CAD model regardless of their combination. As a 'Design' is usually represented by a physical prototype or virtual prototype or both, this question was included to evaluate if both the physical mock up and the CAD model could be technically updated quickly. The answers showed that four participants chose 'very much' and one participant wrote down his own idea: fairly quickly. The results suggested that the set-up regarding the changing of the physical mock-up and the CAD model were acceptable to the participants. Since there was not much effort in changing the physical mock up, the results particularly proved that the way of changing the CAD model met the pre-trial considerations. The participants' experience with Pro/Engineer and physical mock up did not clearly show its influence to their answers as well.

Q5) In summary, how do you think of this method for testing a design?

This was a closed question as well, offering a choice of: not necessary, just ok, helpful and very helpful. Three participants chose ‘very helpful’ and the other two chose ‘helpful’. These results suggested this method was generally approved by the participants. Although the set-up of the prototypes and trial was very initial and rough, the positive feedback from the “designer” participants showed that the direction of the experimental research was right and worthy of further development. Again, the participants’ experience with Pro/Engineer and physical mock up did not clearly show its influence to their feedbacks.

Q6) Do you have any other comments or advice about this method?

This was an open ended question allowing participants to respond as they wished. This question was included to collect the comments and suggestions about the trial and method. These comments are listed and analysed below:

1. “This is an excellent way testing a product concept prior to full-scale prototyping. By combining virtual prototype and physical model, designers are able to get feedback and to input this to make changes instantly.” This participant agreed with the advantage of integration of physical and virtual prototype in testing product design.
2. “If it integrates other vectors such as: texture, feeling, etc., it will be great!” These vectors are easier to test with physical prototypes but difficult for virtual prototypes to simulate. In this pilot trial, these vectors were too complex to achieve. However, as haptic technologies have contributed to simulating the tangible feedback from CAD models, therefore, it is potential to be embodied to the integration system.

5.3.5 Summary of the trial

The responses of the participants in this trial have shown that this proposed method was feasible and useful. This result also supported the findings from the literature review and the questionnaire survey. However, as a pilot study, this trial was only designed to explain how the proposed method would work, the physical mock up and the CAD model has not been really connected together.

5.4 Chapter summary

After the literature review in previous chapters, foundational knowledge in this research area had been acquired. To obtain primary data for this research, a questionnaire study and an initial pilot trial were conducted. The questionnaire study was designed to investigate the current situation of applying PP and VP in design consultancies and the need for integrating PP and VP. Although the response rate was low, the valid opinions held by designers and engineers demonstrated that physical and virtual prototypes are complementary to, rather than competitive with, one another. In addition, the responses showed that the simultaneous integration of PP and VP is needed but still in its infancy.

Based on the studies of literature and the questionnaire survey, a method for the integration of PP and VP was proposed and a pilot trial of this method was conducted. The method used a 3D CAD modelling software package that is commonly used by industrial designers. From the results of the trial and subsequent participant feedback, it was clear that the synchronous integration of PP and VP would be helpful for user evaluations. The next step was to develop this method and make it more operational and sophisticated. This will be discussed in the next chapter.

Chapter Six

Development of the proposed PP/VP integration method

Based on the literature review and questionnaire survey, a proposed integration method for PP and VP was introduced in Chapter Five. The trial that followed, with regards to the method, showed its benefits but also exposed its limitations and problems, which indicated a further development of this method was needed. This chapter presents an integration system which is named Loughborough University Prototyping Integration System (LUPIS). It is based on the proposed method introduced in the previous chapter.

6.1 Overview of LUPIS

LUPIS is a conceptual design for a system that facilitates a new way for integrating physical and virtual prototyping. This system design was developed based on the findings of the proposed method introduced in Chapter Five. In contrast to the proposed method, where the connection between physical and virtual prototype was just assumed, a realistic and simultaneous connection between them was actually achieved in this system.

In order to keep the experimental research consistent, it was decided that the 'Chair Design' should still be used as a platform for the integration system. Therefore, there were still three main components in this system: the physical mock-up of the chair, the 3D CAD model of the chair and the device that connects them. In addition, one thing must be emphasized to avoid confusion, that is, the system was developed to test the method of integrating PP and VP; the chair was only used as a platform to test this method and was not part of the system. The system was supposed to be applicable to many other kinds of products, such as tables, cars, kitchen appliances, etc. There were two stages of trials for the system. In the first stage, relatively rough prototypes were built to initially test the performance of the system. After obtaining participant feedback about this system, an upgraded version was built and another more detailed trial was conducted. The following sections will describe the process of building the systems and undertaking the trials.

6.2 The first stage trial

6.2.1 Building the physical mock up

The author considered building a completely new chair with adjustable components. However, it would be much more costly and time consuming and not necessary for these early stage trials. Therefore, after discussing with the author's supervisor, this idea was given up. Similar to the mock up used in the previous trial, most components of the mock up were built using off-the-shelf materials. This followed the prototyping principles suggested by Baxter [1995], i.e. only developing prototypes to a minimum degree of complexity and keeping the prototypes simple and inexpensive.

This mock up (as shown in figure 47) consisted of two main parts: a car chair (as shown in figure 48) and a base (as shown in figure 49) which was used to support the chair.

	
Front View	Side View

Figure 47: Physical mock up construction

Figure 48: The car chair

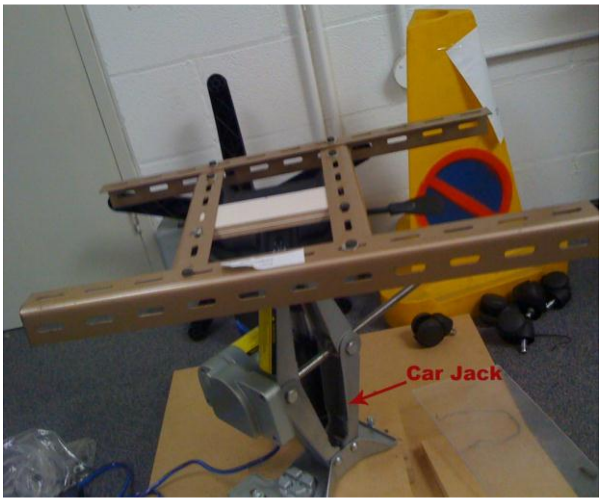

Figure 49: The base with car jack

In the previous trial, three adjustable elements of the chair were tested: backrest angle, seat angle and seat height. In this set up, it was decided that only the backrest angle and seat height were needed as testing elements. The reason for this was the chair mock up itself was not a part of the system and was only used as a platform to test the system. Therefore, the number of testing elements should be kept as few as possible to shorten the testing process and save cost.

Instead of using an office chair, this time a car seat was borrowed to act as a physical mock up. The advantage of the car seat was it had an electrical motor to control the movement of the backrest angle. After connecting to an AC power source through an AC adapter, the backrest angle of the chair could be adjusted by pressing a switch (as shown in figure 50). In this way, the backrest angle could move smoothly, hence improving its stability and the ease of operation.

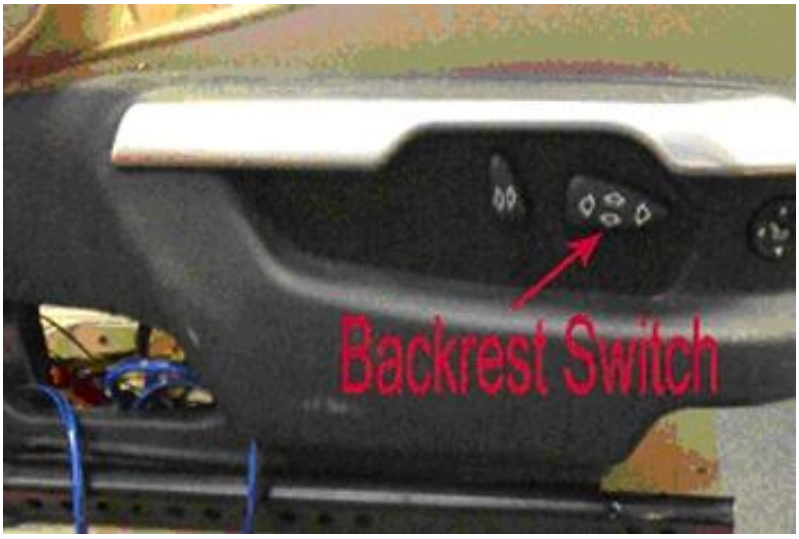

Figure 50: The switch of the car chair

Another issue for the physical mock-up was the adjustment of the seat height. For the previous trial, the seat height of the mock up was adjusted manually by the user and the size of the height changes was difficult to control. Therefore, this time, an electrically operated car jack was applied to support the adjustment of the seat height (as shown in figure 51). The car jack was also connected to an AC power source through an AC adapter. The user could operate the switch of the car jack to lift and chair up and down. As the maximum capacity of the car jack was 1,000 kilograms, it was able to lift the chair up and down smoothly, even when a person was sitting on it. The base structure was built with L-section steel rods and had two telescopic supports. One support was circular in section and was removed from a broken office chair. The other one was built with two square-section steel tubes by inserting a thinner one inside a thicker one, as shown in figure 52, the thicker tube was welded to a piece of L-section steel in the base. These components were assembled mainly with screws. This was due to the consideration of sustainability, because they could be easily disassembled after the trials in order to reuse the materials.

This mock-up was still quite rough but much more stable and automatic compared to the previous one and was deemed well enough for this stage of testing.

Figure 51: Electrical car jack

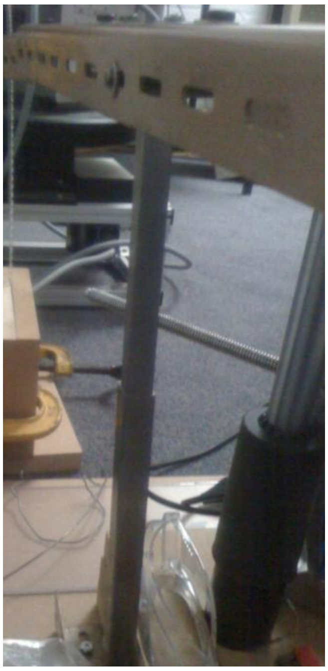

Figure 52: Supportive bar

6.2.2 Building the virtual prototype

This time, the Rhinoceros (Rhino) 3D modelling software package was applied. There were two reasons for choosing this package. Firstly, according to the questionnaire survey, Rhino was a 3D modeller commonly used by industrial designers. Secondly, different from Pro/Engineer which is a parametric, feature-based solid modelling software package (ptc.com 2010), Rhino is a non-uniform rational basis spline (NURBS) – based surface modelling software package. If the virtual prototype built with Rhino could also be adjusted in a quick manner as Pro/Engineer, it will be convincing to some extent that both surface and solid modelling software packages could be used for the prototyping integration.

Similar to the previous trial, the CAD model would be adjusted following the changes made to the physical mock up. Therefore, the main challenge when building the CAD model was to make it able to be modified quickly and easily.

When building the CAD model in Pro/Engineer, the author tried many methods and features and finally found a workable way. This happened again when using Rhino to build the CAD model. It was not difficult to build a chair model within Rhino. However, it needed some additional efforts to build a CAD model that could be easily adjusted in terms of its shape. After building several models that did not match the requirement, a feature called ‘control points’ was applied and a model that could be quickly adjusted was built (see the screen shot in figure 53)

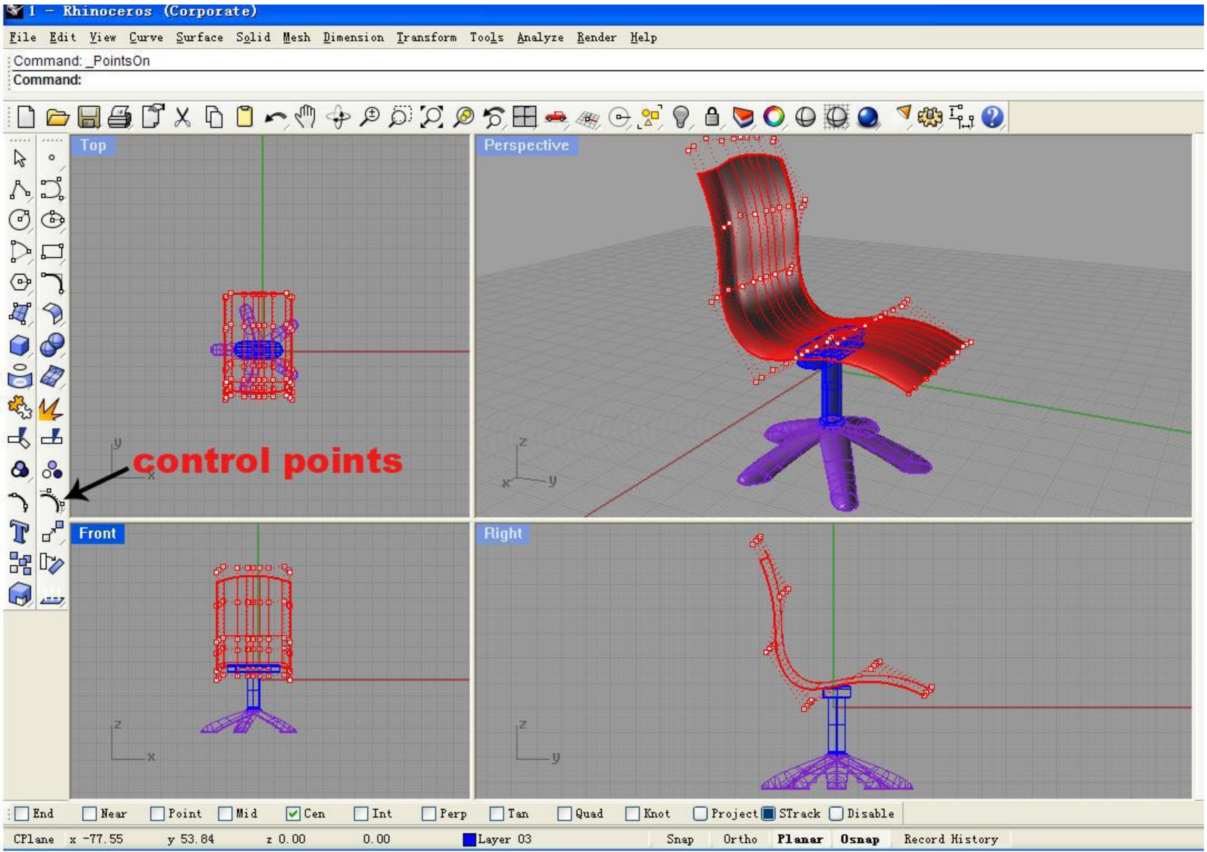

Figure 53: The CAD model built with Control Point Curves

The surfaces of chair seat and backrest were built through the Rhino feature ‘Control Point Curve’. As the name suggested, these curves were controlled through the ‘control points’. These points could be shown or hidden. When these points were shown, they could be selected by cursors to activate them. After that, they could be dragged to the wanted position. As shown in the right view of the model (see figure 54), the backrest could be adjusted from position A to position B by dragging a number of points together. With a similar operation, the seat height could also be adjusted. Compared to the model created in Pro/Engineer, this model was easier to adjust. However, because it was modified by dragging control points to an approximate position rather than by typing a specific value, the accuracy was relatively poor.

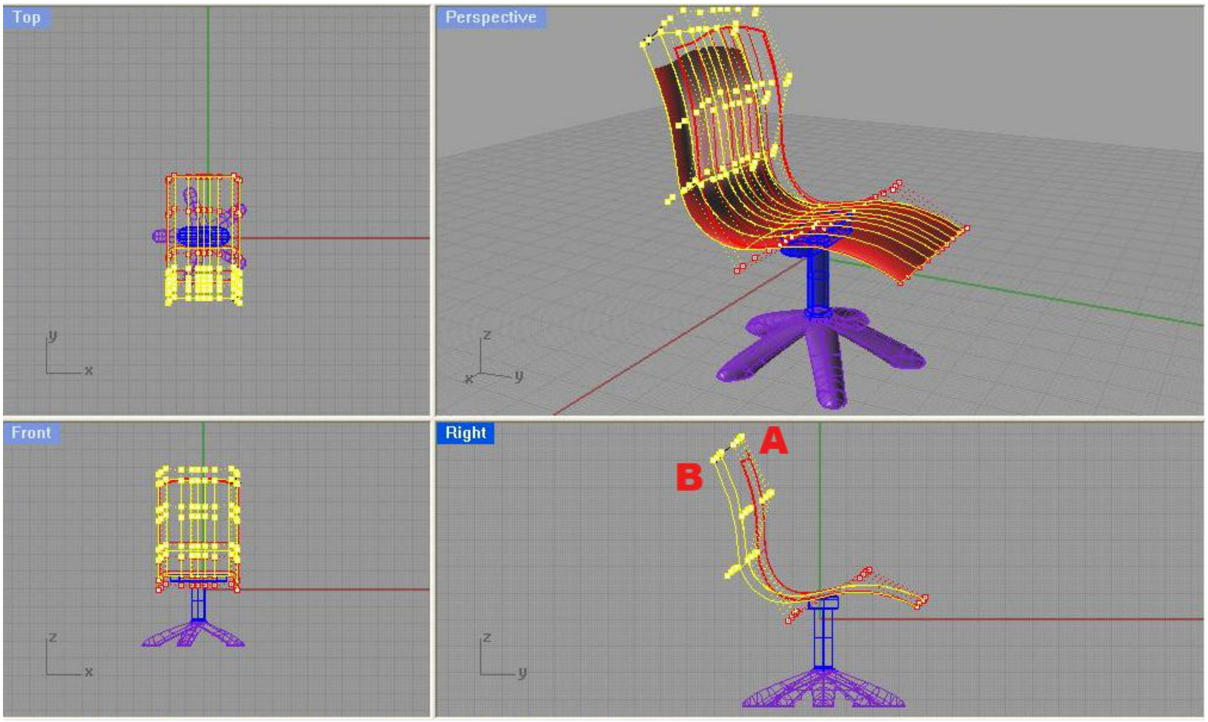

Figure 54: The backrest of the chair model being adjusted from A to B

6.2.3 Connection between the physical mock up and the CAD model

6.2.3.1 Related technologies

One issue that had not been fully solved in the previous trial was the data transfer between the physical mock up and the CAD model. Some technologies relating to the conversion between physical and virtual prototype have been discussed in section 4.4 of Chapter Four, such as CNC machining, RP, RE, Parametric Prototypes, etc. There are two main limitations among these technologies. Firstly, these conversions are not synchronous. For example, to convert virtual to physical prototype by CNC machining or Rapid Prototyping, it will usually take hours or days to finish. To convert physical to virtual prototype by Reverse Engineering, it will take minutes or hours to complete the 3D scanning and require even more effort to process the point cloud to a workable CAD model. Therefore, these technologies can only be considered as static conversions, e.g. one static model is converted to another type of static model, and the dynamic changes to one cannot be represented in the other.

Secondly, although some researchers have developed systems that can achieve dynamic conversion between physical and virtual prototype, the complication of hardware and the specifications of software might limit its usage within industrial design. Take Parametric Prototyping system for instance, the virtual prototype is still in point cloud form and cannot be directly modelled with the commonly used 3D modelling software packages. These two main limitations could constrain the user involvement, increase cost and delay the product development process. Therefore, it was decided that the new system should be able to simultaneously exchange data between physical and virtual prototype and, it should be compatible to most common 3D modelling software packages used by industrial designers.

To combine physical and virtual prototypes, a possible example was to embed sensors in physical prototypes to provide feedback to a computer [Otto and Wood 2001, p611]. The questions here were what kind of sensor is suitable for this research and how to apply it. Therefore, a study was conducted in order to find an appropriate type of sensor for this system.

The Longman dictionary defines sensor as ‘a piece of equipment used for discovering the presence of light, heat, sound, etc.’ [Longman 1995, p1298].

In fact, besides the issues mentioned in this definition, different sensors can be applied to measure many other physical elements, such as pressure, radio waves, moisture, etc. For the specific requirements of LUPIS, the sensors should be able to detect the movement of the seat and backrest of the physical mock up and transfer the signal to a computer to drive the changes to the virtual model.

The technologies that use sensors to detect the motion of an object and translate it into a digital signal are usually referred to as motion capture [Menache 2000]. A typical example of applying motion capture technology is in the film making process, as seen in figure 55. A series of sensors are attached to the body of the actor/actress to record his/her movement. The signals of the movement are then sent to a computer and used to animate a virtual model. Another application of motion capture is in medical area. Researchers use motion capture technology to do biomechanical analysis in order to study the patients' body movement in order to improve their rehabilitation. As shown in figure 56, a polio survivor was involved in determining the implications of a shoulder dysfunction. Motion capture sensors were set up for data collection and the data was analysed within the Motion Lab System.

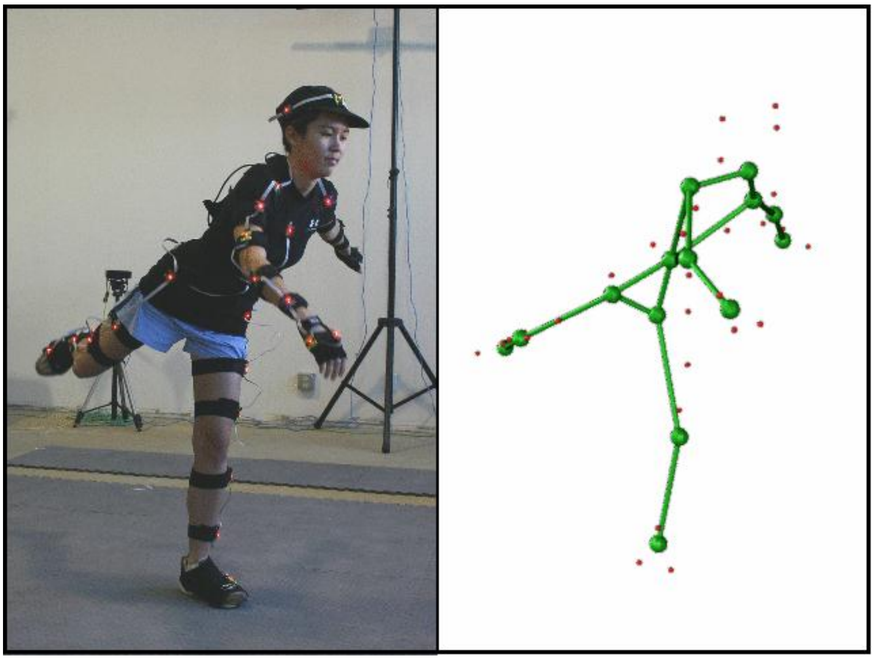

Figure 55: Motion capture technology in film making [motioncapture.com 2010]

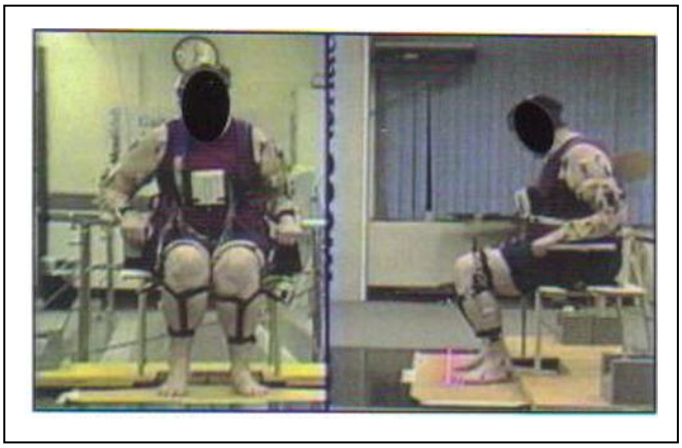

Figure 56: Patient set-up for data collection [Esquenazi and Klein 2005]

These technologies can provide real time integration between a physical object and a virtual model with high accuracy. However, the set up and data collection usually need specific hardware and software, which are very different from those employed by industrial designers and much more expensive. Therefore, it would be impossible for the researcher to transplant these technologies into the current proposal for a PP/VP integration system. However, their use in this area is worthy of future consideration

6.2.3.2 Computer mouse

The main problem with the above technologies was still their compatibility with the 3D modelling software packages generally used by industrial designers. Because it would be difficult to anticipate what particular software package the industrial designer could use, the sensor must be compatible with as many types of 3D modelling software packages as possible. For this reason, a widely used input device was needed that contained one or more movement sensors. After some deliberation, the choice was made to use a standard computer mouse. When a computer mouse moves in a physical environment, the screen cursor will move simultaneously on the computer display which is, in effect, a virtual environment. In addition, the motion of the cursor is also the main means for creating and modifying a CAD model. Therefore, a computer mouse offered the potential to integrate the physical prototype and virtual prototype for the proposed system.

There are two typical types of computer mice on the current market: mechanical and optical. Figure 57 shows the interior structure of a mechanical mouse. The main components include a ball (1), two chopper discs (2) and two pairs of infrared LED and light sensors (3). The turning of the ball causes the two optical encoding disks to revolve. When the discs are revolving, the infrared LED's shine through the disc slots and the sensors "count" light pulses to convert the rotation to X (right-left) and Y (upward-downward) motion of the cursor on the screen. Therefore, the speed of the cursor movement depends on the speed of the mouse moving and the density of the slots. When other settings remain the same, the denser the slots are, the more quickly the cursor will move. Figure 58 shows the interior structure of an optical mouse. The main components are (1) LED, (2) Lens, (3) Controller and (4) Optical mouse sensor. The optical mouse works by using an optoelectronic sensor to take successive images of the surface where the mouse moves on. Through the image-processing chips in the mouse itself, the movement of the mouse will be translated to the motion of the cursor in the computer screen.

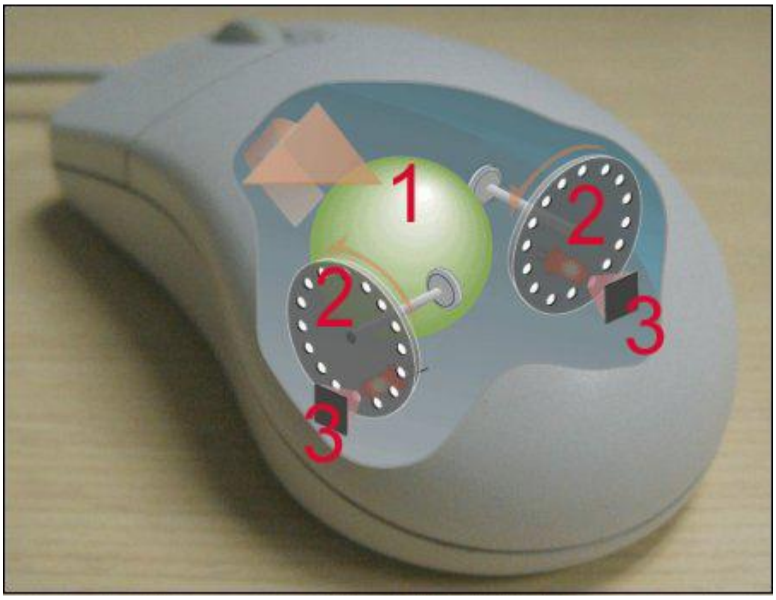

Figure 57: The main device and structure of the mechanical mouse [mousearena 2011]

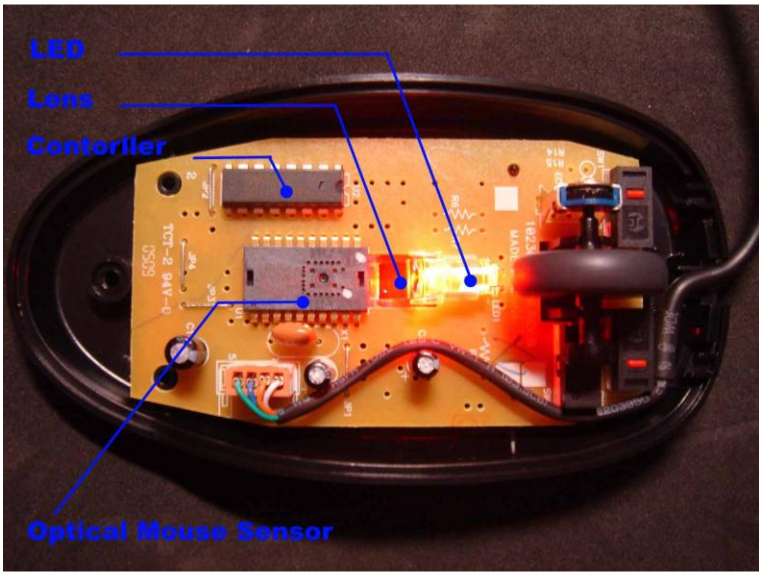

Figure 58: The interior structure of the optical mouse [mousearena 2010]

After studying the computer mouse, an idea was created to make use of the sensors of the computer mouse and attach them to the physical mock up to detect the changes of the seat height and backrest angle. Compared to the optical mouse, the sensors in the mechanical mouse are easier to disassemble and reconfigure. In addition, it was possible to make two new chopper sticks to replace the original chopper disks of the mechanical mouse and further control the speed of the cursor movement. Therefore, it was decided to adopt the mechanical mouse and use its internals as the media to connect the physical and virtual prototype in LUPIS.

Following the working principle of the mechanical mouse, the author made two new chopper elements to replace the original encoding disks. Although one element was made from transparent plastic, the penetration of the infrared rays is quite weak, so the visible clarity and the thickness of the board do not influence the performance of the system. One element was attached to the back of the chair to detect the changes of the seat height, whilst the other was attached to one side of the chair to track the change of the backrest angle (see figure 59). In addition, the LED lights and the sensors were removed from the main board of the computer mouse, mounted on the physical prototype and then reconnected to the board using wires (see figure 60). This allowed the sensors to be located at the appropriate positions. When the seat was adjusted up and down, or the backrest was moved backward and forward, these two encoding elements would follow their movements, hence causing light pulses to the sensors located on their sides. The main board of the computer mouse was connected to the computer through a USB cable. With this set up, the movement of the chair caused the motion of the cursor on the screen. As the computer is compatible with two or more mice at the same time, the user could use another ordinary mouse to control the cursor as well. For example, for the CAD model built in Rhino, the designer could just do the normal operations to select the active control points and hold the left button of the normal computer mouse. Then, rather than moving the mouse, the designer will ask the user to adjust the seat height or backrest angle of the chair. The movements of these elements would cause the movement of the cursor and drag the active points to a new position, hence changing the shape of the virtual chair model.

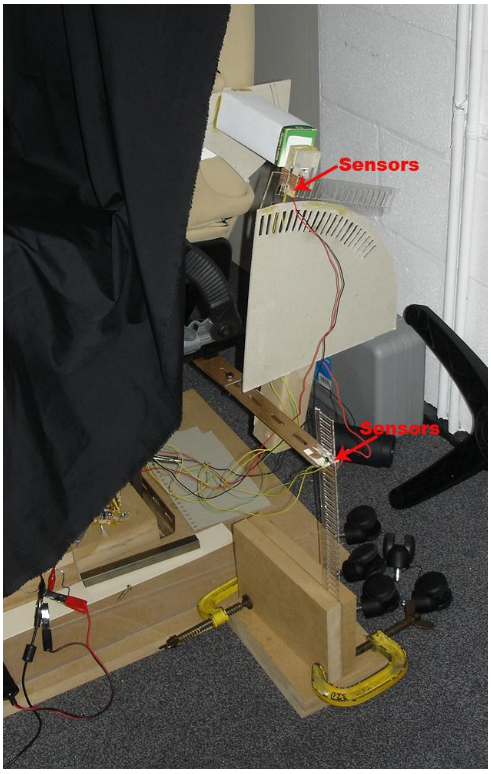

Figure 59: Two chopper elements

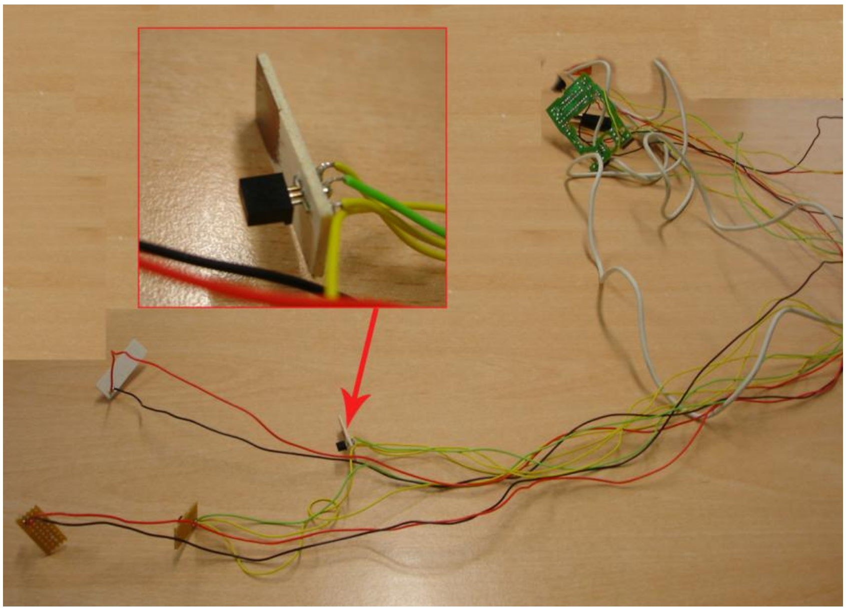

Figure 60: Rebuilt sensors of computer mouse

6.2.4 The assembly of the system

After the physical mock up, the CAD model and the connection device between them were individually prepared, they were assembled together. Figure 61 illustrates how the objects involved in this system were connected with each other. The two sensors of the mechanical computer mouse were connected to the physical model. The horizontal sensor tracked the movement of the backrest in the horizontal direction, while the vertical one tracked the height changes of the chair's seat. The movements of the physical model were transferred to the computer via the refitted computer mouse and drove the movement of the cursor. The movement of the cursor modified the shape of the existing virtual model. When the user used the switches to change the dimensions of the seat height and backrest angle, the CAD model of the virtual chair was also changed. In addition, a projector was used to project the image of the CAD model on a wall. In this way, the virtual chair would be shown at the same size as the real chair and it would be convenient for both the designer and user to see the changes of the CAD model simultaneously.

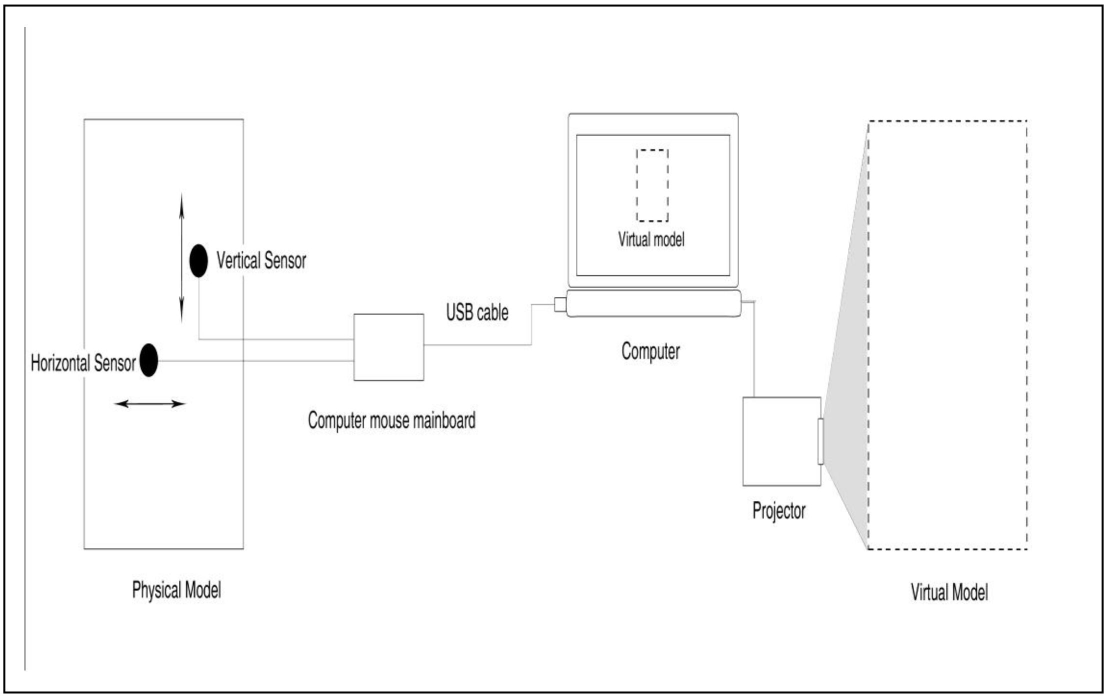

Figure 61: Overview of settings of the system

When all the components were connected to each other, the system needed to be pre-tested before it could be used for the trial. The reasons for this are explained as follows:

Since the X and Y movement of the cursor was produced through the sensors gathering light pulses, the more frequently the pulses occurred, the faster the movement of the on-screen cursor. Therefore, the arrangement of the holes on the encoding elements dictated the match between the physical and virtual prototype. For example, if other factors remained constant, large holes with a sparse arrangement, would cause the cursor to move slowly. In addition, the larger and sparser the holes are, the lower the accuracy of the match between the physical and virtual prototype. This is because the resolution of the system would be lower and movements could only be tracked to the nearest hole, giving a significant “rounding error”. Great care was needed to ensure that the correct arrangement of slots matched-up with the mouse movement on the screen within the Rhino software.

Another issue that could influence the accuracy of the match between the physical and the virtual prototype is the zoom ratio of the CAD model. For example, when the cursor moves a specific distance on the computer screen, for a larger zoom ratio, it can drive a smaller movement of the CAD model; while for a smaller zoom ratio, it can cause greater changes to the CAD model. The designer should calibrate the zoom ratio according to the cursor speed.

Overall, the factors that influenced the match between the physical and virtual prototype were: 1. the speed of the cursor, which could be influenced by the arrangement of the holes on the encoding elements and, the computer set up of the mouse. 2. The zoom ratio of the CAD model.

Therefore, both of the above factors had to be properly set up to make sure that the physical and virtual prototype were matched properly, i.e. when the physical mock up moved through a certain distance in the physical environment, the virtual model would change by the same distance in the virtual environment.

6.2.5 The trial

6.2.5.1 The testing procedure

When the system was competed, a preliminary trial was conducted. The main purpose of this trial was to test the reliability of this integration system, find the technical problems and prepare for more formal trials in the future. Four groups of participants took part into the trial. It was hoped that all the participants that were involved in the previous trial could do this trial also, so they could make a clear comparison. However, it was found that it was impossible as some of them had left the country or were not available during the testing time.

Similar to the previous trial, in each group, one participant acted as a user and the other acted as an industrial designer (as shown in figure 62) and the author acted as an observer in this process. All of the ‘designers’ were students or academics from the industrial/product design area whereas the ‘users’ had no design background.

Firstly, the designer moved the cursor to the correct position on the screen and held the left button of the computer mouse to snap to the CAD model. Then the user sat on the chair and adjusted the seat height and the backrest angle respectively. Through the connection of the reconfigured computer mouse device, the cursor in the computer display was moved according to the movement of the physical chair and drove the changes to the CAD model. When the user was happy with the dimensions of the seat height or backrest angle, the designer released the left button of the computer mouse and a CAD model with new shape and dimensions was achieved. After that, the designer applied different textures or colours to the CAD model and showed them to the user through the projected images and asked the user to pick their favourites. Through this testing process, the designer could quickly collect the user’s feedback in regard to the dimensions and colours of the chair and use them as a reference to develop the product in the aspects of ergonomics and aesthetics.

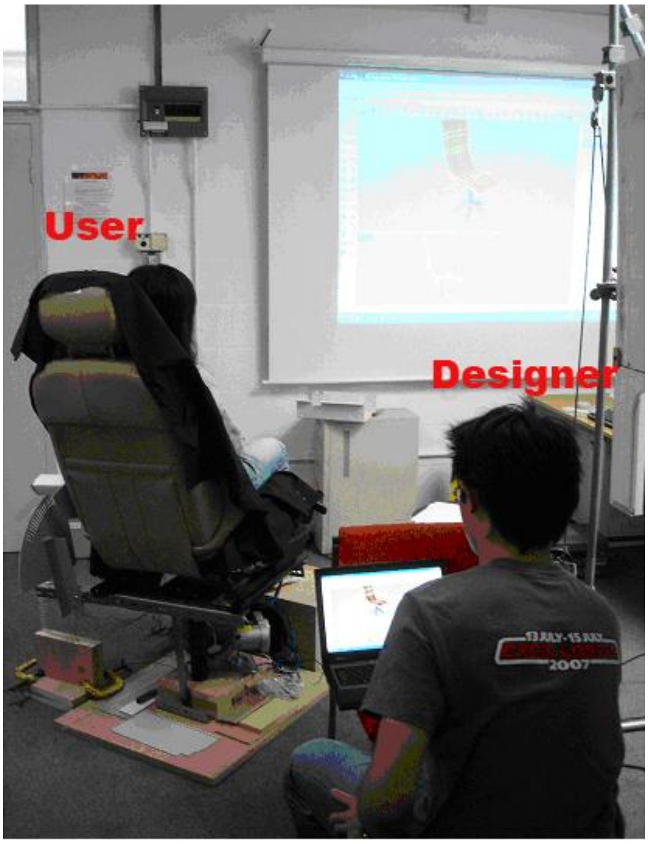

Figure 62: A pair of participants testing the system

6.2.5.2 Questionnaire following the trial

Two questionnaires were designed to investigate the opinions of the participants on the trial of this conceptual system. One questionnaire (see Appendix III) was designed for the 'designer' and the other (see Appendix IV) was designed for the 'user'.

Outcomes of the questionnaire to the 'designers'

There were two sections in this questionnaire. The first section was a background knowledge survey on several aspects including 3D modelling software, prototypes and prototyping. The second section contained several questions regarding the trial and the system. The questionnaire had a mixture of both open and closed questions.

As the CAD model used in this system was built with Rhino, the participants' knowledge with this and other CAD software was first surveyed in the questionnaire. Figure 63 shows the number of participants experienced with each of several 3D modelling software packages. The result indicated the diversity of 3D software that designers are familiar with.

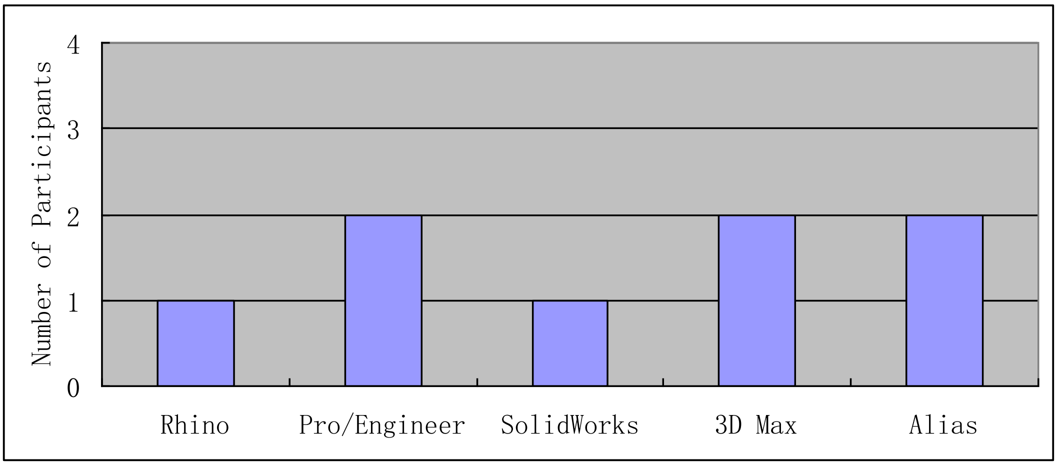

Figure 63: Participants' experience with CAD modelling software

The second question in this section was designed to investigate the participants' experience with physical prototyping. All the 'designers' replied that they had previously built a physical prototype to test their designs. In addition, to the following question "what aspects have you tested with the prototype', all the participants chose all the given answers which were Ergonomics, Functionality and Aesthetics. Even though they were asked to give their open answers to this question as well, none of them did this. However, the results showed that ergonomics and aesthetics were two common aspects that were evaluated with physical prototypes. Therefore, it was rational to evaluate these two aspects with this integration system.

Along with the second question, the participants were asked if they had previously built a virtual prototype as well as a physical prototype for the same design. All the participants answered ‘Yes’. This indicated that for a particular design, designers usually need to build both a physical and a virtual prototype, rather than just build one format of prototype. However, when they were asked whether they used these two types of prototype simultaneously to test their design, all the answers were ‘No’, which showed that simultaneous use of physical and virtual prototypes is not commonly used.

The second section of this questionnaire aimed to evaluate the participants’ satisfaction with this integration system. The first three questions were answered on a five point Likert scale where 1 was the most negative response and 5 the most positive. Each question was followed by a space on the questionnaire where participants could give an explanation for their answer.

In order to apply this system, the CAD model was built in a particular way. Therefore, it was necessary to know if this type of CAD model was compatible with easy use of this system.

The first question in this section was “How do you feel about the ease of operation of the CAD model?” Figure 64 shows the spread of the responses.

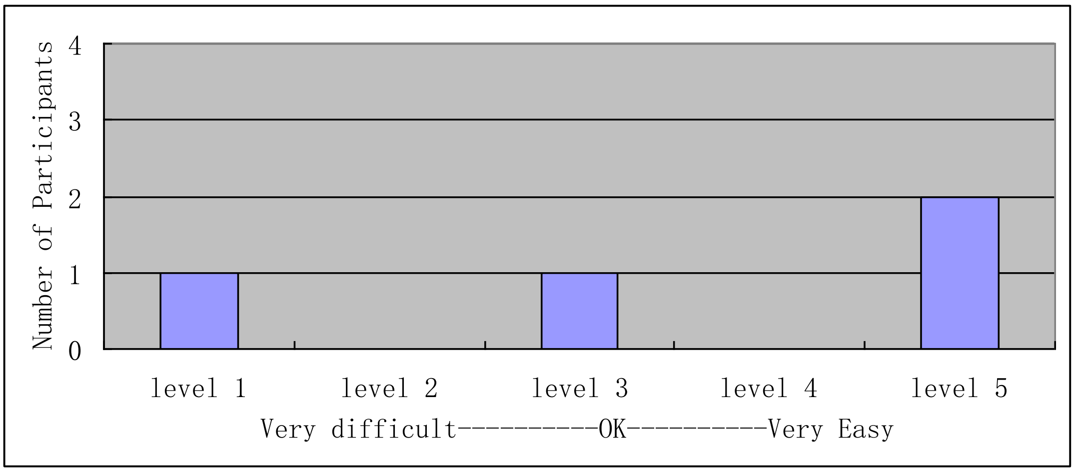

Figure 64: Satisfaction with the ease of the operation of the CAD model

According to the responses, an average of 3.5 was obtained on a scale of 1 to 5. The score was mainly dragged down by the participant who chose level one. In the following space, this participant stated “Not a real link to the activity. CAD model did not follow the real motion (of the physical model)”. This could have been caused by the unstable structure of the physical model. When the ‘user’ was operating the physical model, especially when the seat was lifted up and down, it shook and did not move smoothly. This resulted in the sensor not catching the movement of the encoding disk properly and consequently, the cursor in the display did not move accordingly. This showed that further development of the physical model was needed.

The second question in this section was “What do you think about the process of the trial”. This question was designed to evaluate the ease of the application of the system. Figure 65 shows the result that an average value of 4 was obtained on a scale of 1 to 5. This value indicated that the participants were generally satisfied with the process of the trial. There might be two reasons for this result. On the one hand, the trial was set up properly and the physical and virtual model was easy to operate. On the other hand, the task for this trial was relatively simple, since only two elements (backrest angle and the seat height of the chair) were tested.

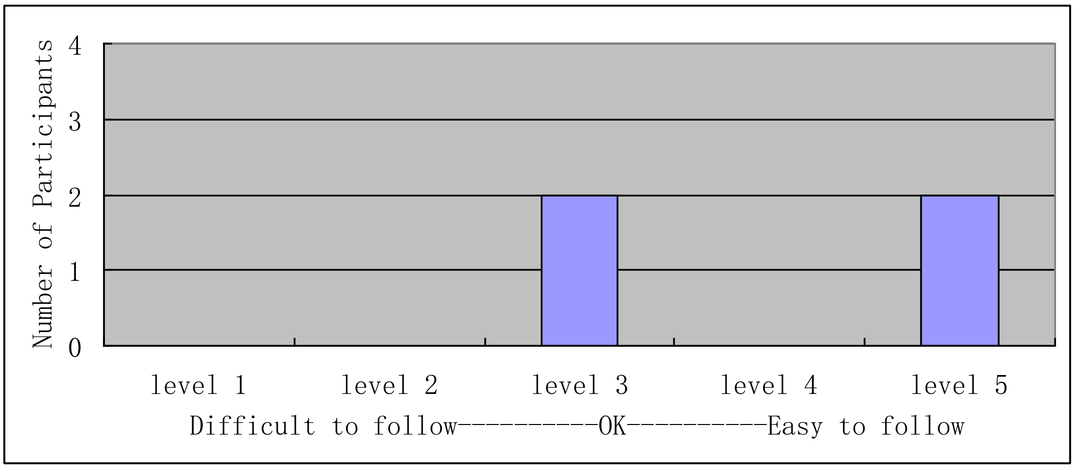

Figure 65: Satisfaction with the process of the trial

The third question was designed to evaluate the efficiency of the system in testing the chair design. As identified in previous research, prototype testing is an iterative process and usually takes a long time, causing delays to the launch of the product to the market. Therefore, one aim of the proposed system was to reduce the testing time. Figure 66 shows the result that an average of 3.75 was obtained on a scale of 1 to 5 for the efficiency of the system. The participants commented that: i) can envisage few applications where the product can be modified live, ii) it made the changes immediately which make it very useful. I would have said very much but the height alteration was not as good as the back. This result indicated that the system was helpful in reducing the testing time. However, as the structure of the physical mock-up was not robust enough, the match between the physical mock up and the CAD model was not very steady, which influenced the trial to some extent.

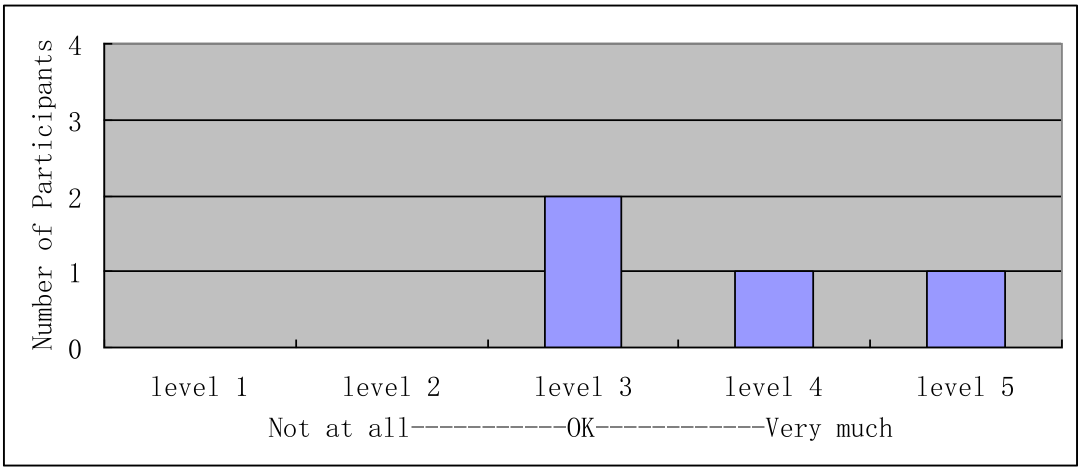

Figure 66: Satisfaction with the effectiveness of the proposed system

The fourth question was designed to evaluate if this system could help in user involvement. The question was: Do you think this method is a valuable way of getting users more involved in the design activity? This required a mix of closed and open responses. The participants were asked to answer ‘Yes’ or ‘No’ and then gave their reasons. All the participants chose ‘Yes’ to this question and commented that: i) user can see the changes needed in the design and take a better feel and look at the final design; ii) interaction in the design process; iii) the potential customer/user can have an early feel of how they want their product to be. One participant chose ‘Yes’ but did not give any reasons.

At the end of the questionnaire, the participants were asked to give any other comments regarding this system and trial. The participants commented that i) it was most useful for the designers; ii) it would be good to know the amount of time and work needed to build the CAD models; iii) an excellent way to simultaneously test the properties of both physical and virtual mock ups. It allows instantaneous visual changes to be seen.

Outcomes of the questionnaire to the 'users'

The first question was "How do you feel about operating the physical chair prototype?"

Figure 67 shows the result that an average of 4 was obtained on a scale of 1 to 5.

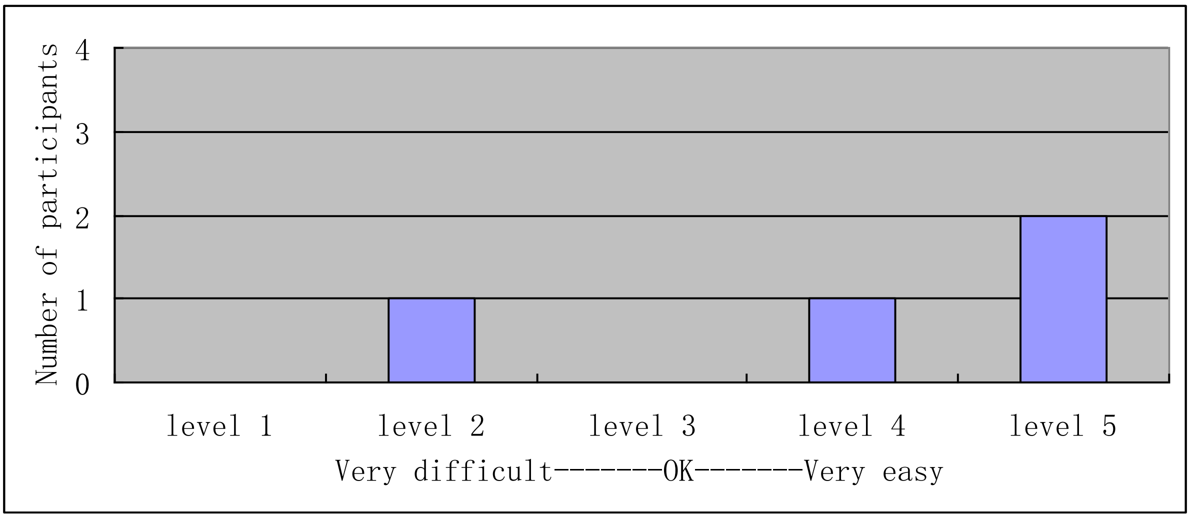

Figure 67: Ease of operating the physical chair prototype

The results showed that the participants were mostly satisfied with the operation of the physical prototype. However, as the structure of the prototype was not robust enough, sometimes it shook quite a lot and this influenced some participants' operations.

The second question was "How do you feel about the visibility of the CAD model?" Figure 68 shows the spread of the responds.

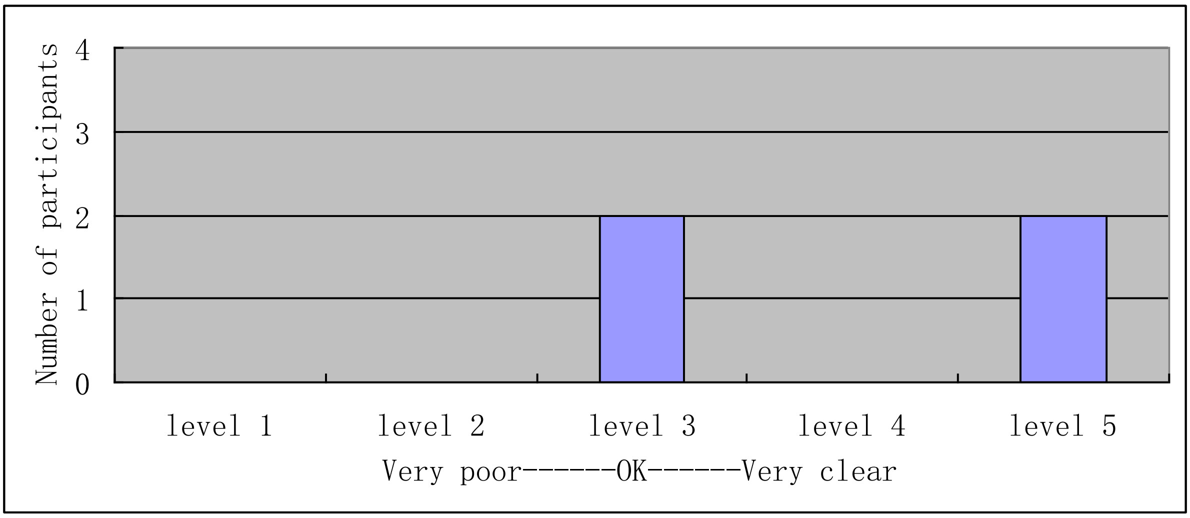

Figure 68: The visibility of the CAD model

The results showed that half of the participants were quite satisfied with the visibility of the CAD model, while another two were neither satisfied nor dissatisfied (the average score was 4 on a scale of 1 to 5). The reasons they gave were “the movement of the CAD model is not so obvious” and “the profile does not match the real chair”. This indicated: 1) the match in accuracy between the physical and virtual model needed to be improved; 2) the CAD model should look the same to the physical model.

The third question was “Do you think the process of the trial was easy or difficult to follow?”

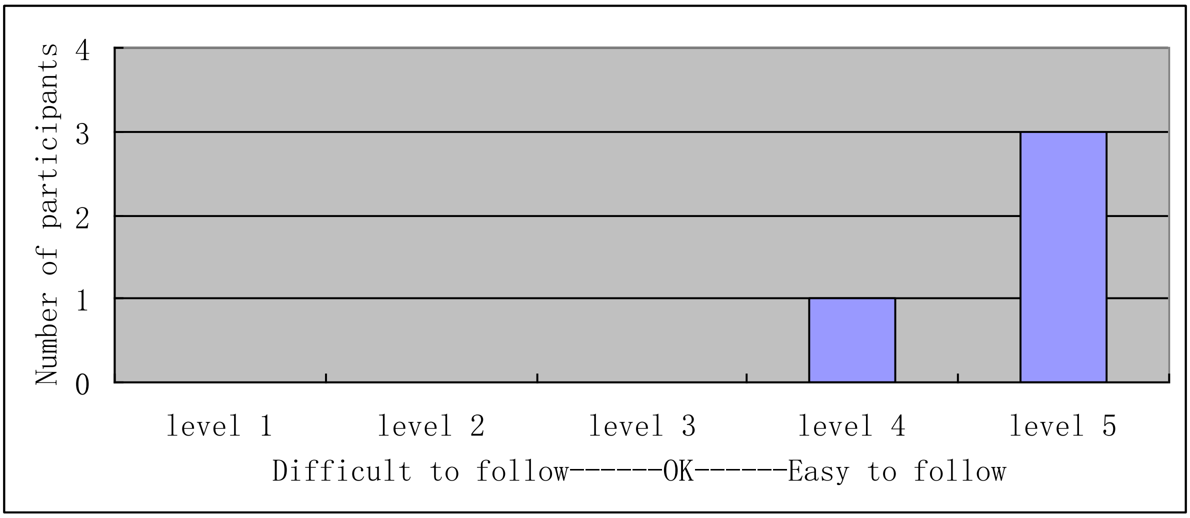

Figure 69: Responses about the general process of the trial

Figure 69 shows the result that an average of 4.75 was obtained on a scale of 1 to 5. It showed that the process of the trial was quite easy for the participants to follow. This also indicated that, as a conceptual system, it did not cause obvious difficulties for users to use.

6.2.6 Summary of the first stage trial

Based on the previous research and the proposed method discussed in Chapter 5, a workable system that could simultaneously integrate physical and virtual prototypes was developed. In this system, a rebuilt computer mouse was applied to act as the connection media between the two types of prototypes. A basic trial was then conducted to test this system. The feedback from the participants showed that this system was helpful in reducing testing time and getting users involved in the product design and development process. However, the main purposes of this trial were to identify the potential problems with the set-up of this system. The trial results showed that most of the problems with this system were technical. For example, the structure of the physical mock-up was not robust enough and caused some difficulties for the participants when operating it; the connection between the physical mock up and computer was not stable enough; the appearances of the physical and virtual prototype were not similar enough to each other. In order to further interpret the benefits of this system in integrating physical and virtual prototypes in design, an upgraded system which should be more robust needed to be built.

6.3 The second stage trial

Based on the technical problems identified in the first stage trial, the author upgraded the system in several aspects. For the physical mock up, a wooden base was built to support the chair. This base contained two wooden tubes. The size of the inner tube made it just possible to insert it into the outer one as shown in figure 70. Therefore, with the support of the electrical car jack installed inside a wooden box underneath the chair (to hide it and to reduce noise coming from it), the inner tube could move up and down smoothly like a piston and hence the chair could move smoothly in the vertical direction. Figure 71 shows a couple of photos of the improved physical mock up.

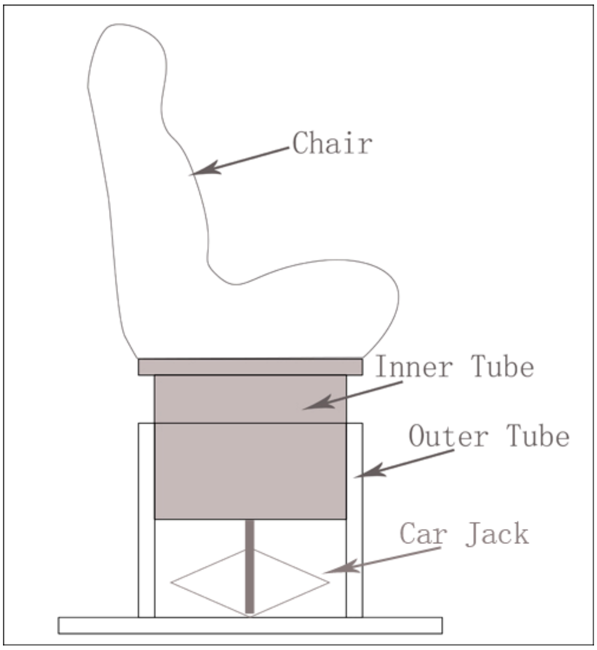

Figure 70: The structure of the physical mock up

Front view

Back view

Figure 71: The improved physical model of the chair

The virtual model was still built using Rhino. This time, its appearance was quite similar to the physical prototype and it was projected onto a large screen to give the user a view of the virtual model that had a similar size to the physical model (as shown in figure 72).

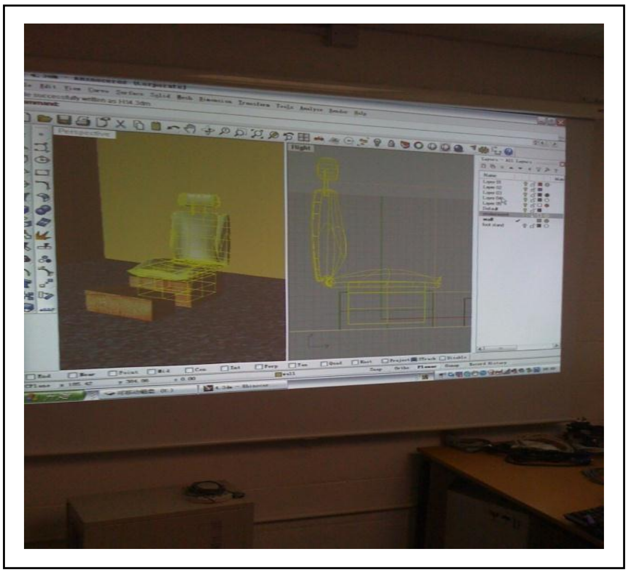

Figure 72: The virtual model of chair projected onto a large screen

Similar to the previous trial, the physical model of the chair was used to test the ergonomics elements, while the virtual model was used to test the aesthetics aspects. The height of the chair and angle of the backrest could both be adjusted by the user through pressing relevant switches which operated two electric motors (see figure 73). The backrest angle was controlled through a motor fixed under the seat of the chair. Figure 74 shows an overview scene of the trial. The user sat on the chair and adjusted the height and backrest angle. The designer sat in front of the computer and instructing the user during the trial. The virtual model was projected simultaneously onto the large screen so that the user could see the changes of the CAD model at the same time as he/she adjusted the chair and was able to give instant feedback to the designer.

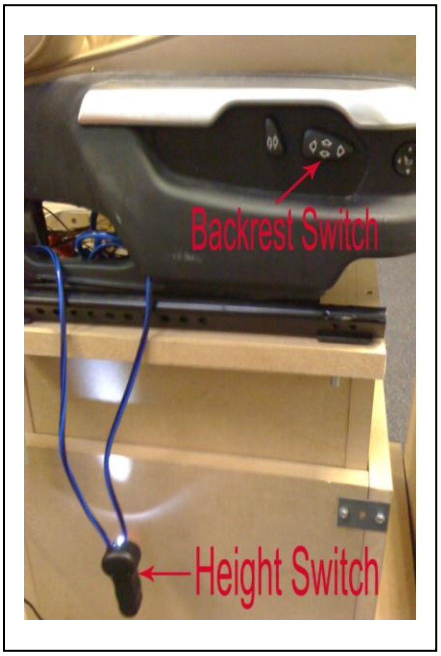

Figure 73: The switches that controlled the backrest angle and height of the chair

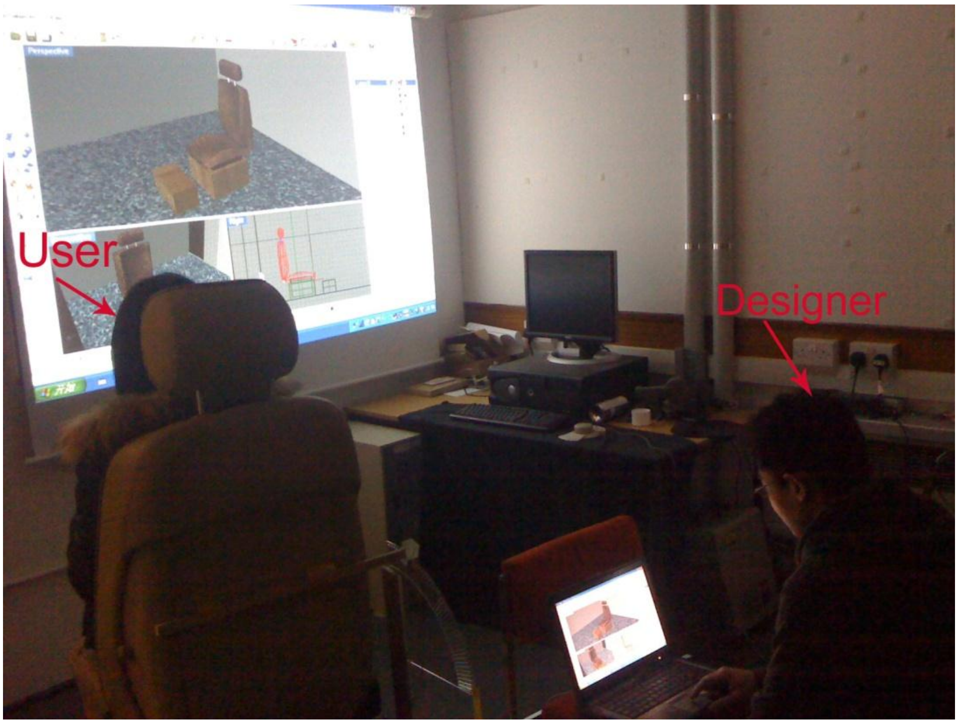

Figure 74: The positions of the user and designer during the trial

Eight pairs of participants (a user and designer) were involved this time. In order to compare the proposed method and the traditional product testing method (where the physical and virtual models are tested separately), the trial process was also modified. The whole trial was undertaken in two modes. In the “Disconnected” mode, the participants were asked to undergo the trial when the physical and CAD models were disconnected. In this mode, the user was asked to adjust the chair height and seatback angle to comfortable positions. After this, the designer measured the changes with a ruler and goniometer and then typed the collected data into the CAD model to update it. In the “Connected” mode the user was asked to do the same again. However, the CAD model was now updated automatically and simultaneously while the real chair was being adjusted. Considering that the participants would become familiar with the testing process after the first mode and could consequently spend less time on the second mode, four pairs of participants undertook the “Disconnected” mode first whilst the other four pairs undertook the “Connected” mode first. However, the grouped results from both sets of participants showed no significant differences and so responses from all eight pairs were analysed together.

6.3.1 Questionnaire for the second stage trial

As before, in order to collect participant feedback from the trial, one questionnaire was designed for the designers (see appendix V) and a different questionnaire designed for the users (see appendix VI).

Outcomes of the questionnaire to the ‘designers’

The first group of questions were general questions regarding the designers’ background and experiences

The first question was “Have you ever used Rhino in a designing activity and if not, what kind of 3D modelling software have you used?”
According to the responses, none of the eight designer participants had ever used Rhino to create a CAD model. However, they had used other types of CAD modelling software packages, such as Pro/Engineer, Autodesk, Alias, 3D Max, SolidWorks, etc. This meant that all the participants had to adjust the CAD model without previous experience in using Rhino. However, none of the participants found this to be a difficult task.

The second question was “Have you ever built a physical mock-up to test one of your designs and if yes, what aspects have you tested with it?”

Except for one participant, everyone answered “Yes” to this question. Regarding the aspects that they had tested with a mock-up, the participants were asked to choose multiply from ergonomics, functionality, aesthetics and others. Figure 75 shows the frequency of the choices.

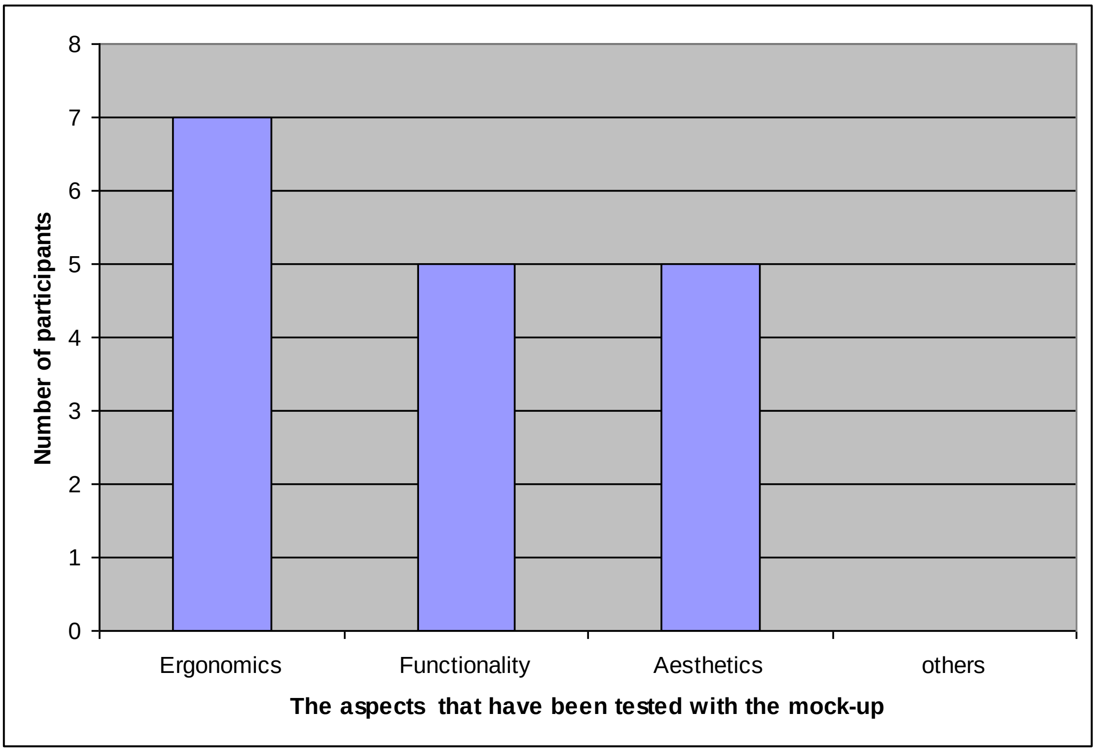

Figure 75: The aspects that have been tested with the mock-up

The figure shows that physical mock-ups were most often used to test ergonomics issues. Besides that, functionality and aesthetics were also commonly tested with physical models.

The third question was “Have you ever built a CAD model as well as a physical mock-up for one of your designs and if yes, have you ever used both of them simultaneously to test your design?”

All the participants said they had built a CAD model as well as a physical mock-up for at least one of their designs. However, only one participant claimed he had simultaneously used both of them to test his design. The example he gave was in the analysis of a new car control system, where the real model worked simultaneously with a simulation in the SAMMIE CAD system. However, it was found that SAMMIE itself is a computer based

Human Modelling tool [SAMMIE.com 2011]. In another word, it is just a virtual prototyping tool. There is no evidence showing that there is direct and real time connection with physical prototype.

The second group of questions was only relevant to the “Connected” mode of the trial. They were aimed at collecting feedback on the proposed integration method. The first three questions were answered on a five point Likert scale where 1 was the most negative response and 5 the most positive. Each question was followed by a space on the questionnaire where participants could give an explanation for their answer.

The first question was “How do you feel about the ease of operation of the CAD model?” Figure 76 shows the spread of the responses.

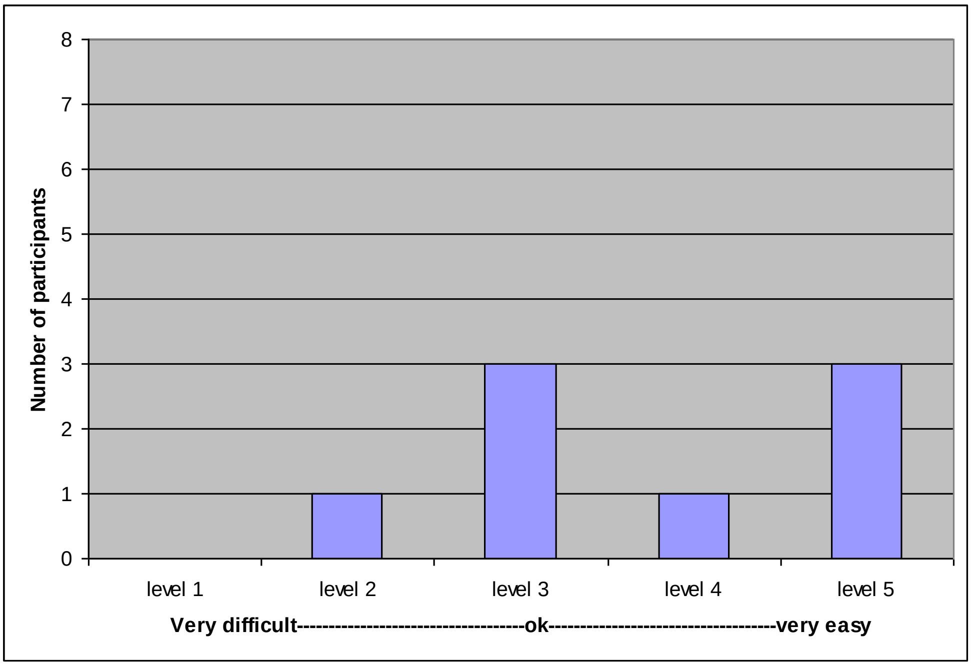

Figure 76: How the participants felt about the ease of the operation of the CAD model

According to the responses, most participants chose level 3 and above and an average of 3.75 was obtained on a scale of 1 to 5 (the score was 3.5 for the similar question in the previous trial). However, one chose level 2. This person stated that the main reason for his choice was he had never used Rhino before. However, all the other participants had also not used Rhino before, but they still felt it was quite easy to operate the CAD model under the instruction, and chose levels 3, 4 and 5. This shows that the perception of ease of use can be affected both by the technicalities of the system but also by past experiences of the individual user.

The second question was "How do you feel about the level of difficulty of the process of the trial?" Figure 77 shows the spread of the responses.

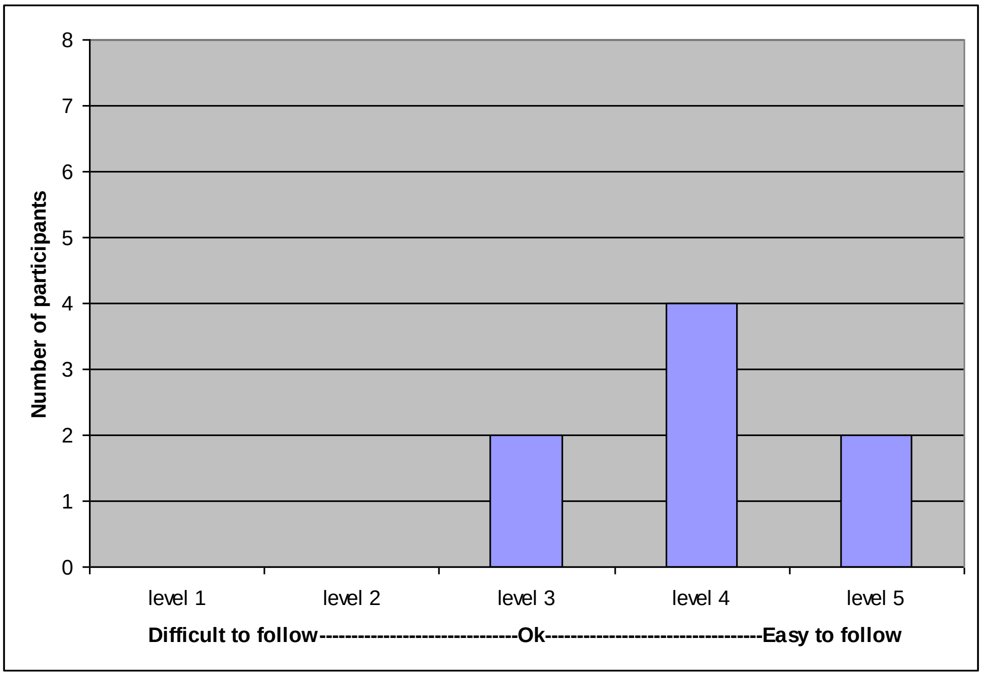

Figure 77: The response to the process of the trial

The responses show that most participants felt the process was easy to follow. An average of 4 was obtained on a scale of 1 to 5 (the score was 3.75 for the similar question in the previous trial). There were two main reasons given for most participants choosing level 3 or 4 rather than level 5. One was they did not have experience in using the Rhino software, hence the difficulty in following the process; another was the quality of the matching between the physical mock-up and the CAD model – sometimes the CAD model was not sufficiently responsive to the movement of the physical mock-up. There might be two reasons for this. One was vibration in the physical mock-up causing the encoding elements to move irregularly between the LEDs and the sensors. Another was that the size of the holes was too large to track very small movements.

The third question was “Do you think this method is helpful in modifying your design more quickly than traditional methods?” Figure 78 shows the spread of the responses.

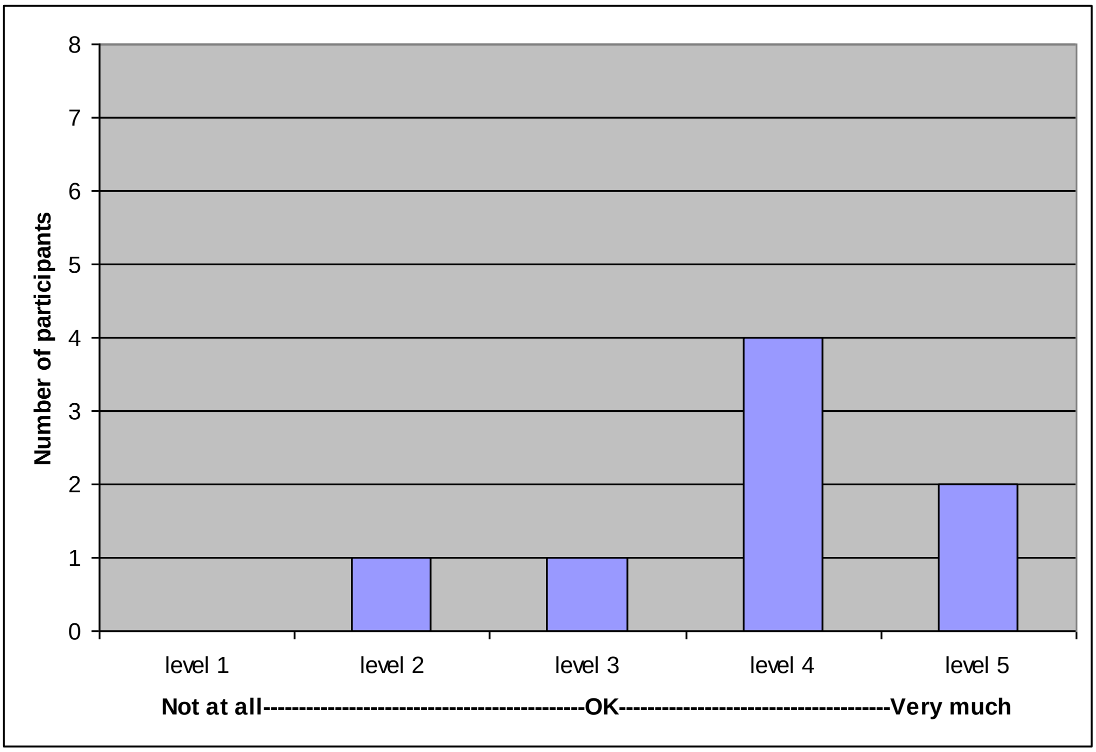

Figure 78: The level of the helpfulness of the method in quickly modifying the design

The figure shows that an average of 3.875 was obtained from a scale of 1 to 5 (the score was 3.75 for the similar question in the previous trial). Most participants chose level 4 and 5, which indicated that they recognised the helpfulness of the method in quickly modifying the design. However, the participants who thought it was not so helpful indicated that the method would only be useful when the designers need to test a product with a number of people and/or test a number of elements within the product, otherwise, it would be not necessary.

The fourth question was "Do you think this method is a valuable way of getting users more involved in the design activity and, what is the reason for your choice?"

All the participants answered "Yes" to this question. Five participants stated their reasons as follows:

1. Users can see the physical model and test it at the same time. Users can modify the virtual model through the connection.
2. They can see the changes in front of them. It is more fun.
3. It is an interactive way in designing, where users can see the impact of the test on the design.
4. Users can experience the related process of changing the design and can make their input during the process to help them better understand their needs.
5. Users can see the changes immediately.

After the above questions regarding the proposed method, the participants were asked to compare the two modes of the trial, i.e. the Connected and the Disconnected.

The first question here was “In which mode do you think the trial is easier to operate?”
All the participants chose the connected mode in which the proposed integration method was applied.

The second question was “Which mode do you think is more efficient?”
Six participants chose the connected mode, however the other two chose the disconnected mode. The reason given by these two participants was similar: the accuracy of the match between the physical mock-up and the CAD model, especially when the backrest angle was tested. For example, when the backrest angle of the physical mock-up moved 13 degrees, the same element of the CAD model might have moved 15 degrees. This again highlighted the need for good accuracy between the two prototypes if designers are to be fully satisfied with this method.

There was an additional open question to ask advice from participants about this proposed method: “what other products do you think we could apply this method to and what elements could be evaluated?”

The suggested products were:

- Sports equipment
- Home appliances
- Any product that needs adjustment to accommodate people with different body characteristics.

- Any product that needs to consider ergonomics, such as bicycles, motorbikes, etc.

The elements that were suggested for evaluation were:

- The position of the handlebars and brakes of a bike
- Scale or proportion of a product
- The material of the product surface, such as leather for chair surface?
- Pressure

Outcomes of the questionnaire to the 'users'

Once again, the first three questions were answered using a five point Likert scale, the same as the questions to the designers.

The first question was "How do you feel about operating the physical chair prototype?"

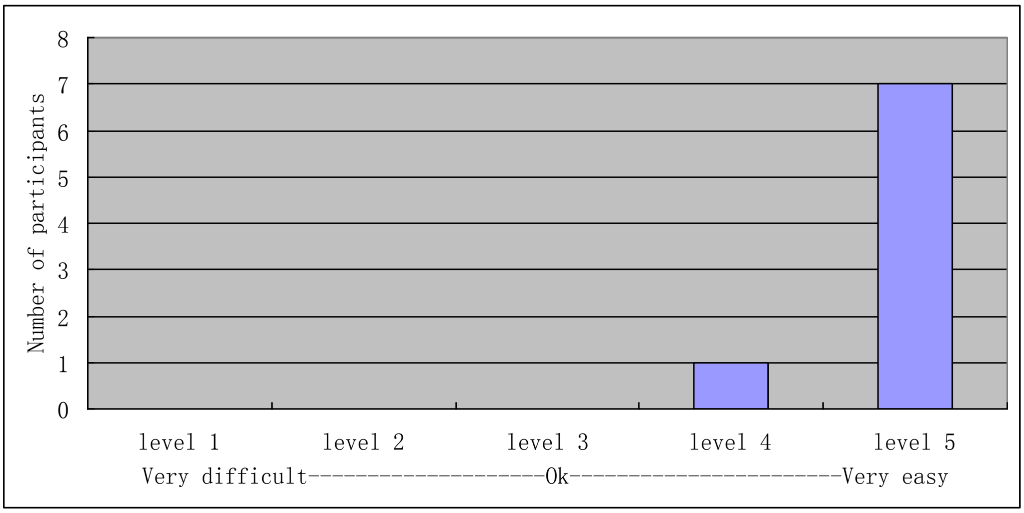

Figure 79: Ease of operating the physical chair prototype

Figure 79 shows the result that an average of 4.875 was obtained on a scale of 1 to 5 (the result was 4 to the same question in the previous trial). The figure shows that most of the participants felt the physical prototype was very easy to operate. This also indicated that the new physical mock-up had been improved significantly compared to the old one.

The second question was “How do you feel the visibility of the CAD model?”

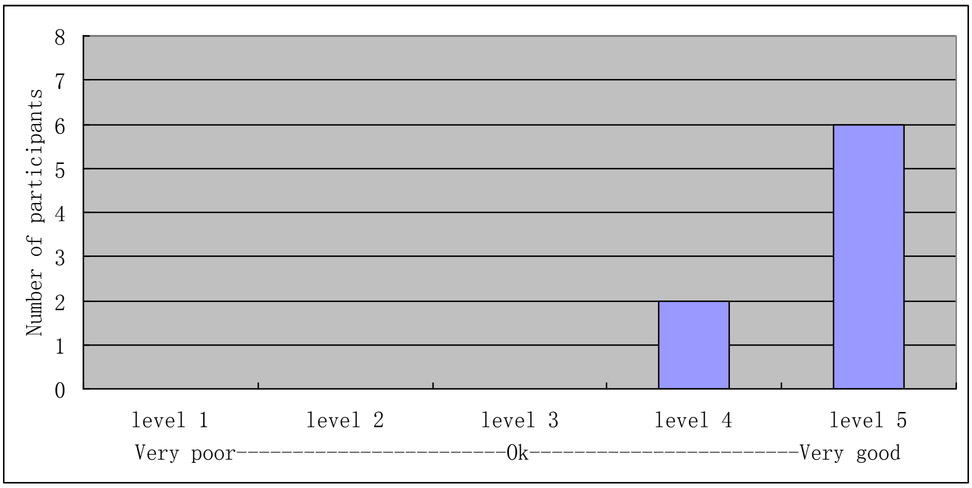

Figure 80: The visibility of the CAD model

Figure 80 shows the result that an average of 4.75 was obtained on a scale of 1 to 5 (the result was 4 to the same question in the previous trial). This demonstrated that after the adjustment to the physical and CAD model, the match between them had been improved. As one of the users said “I can clearly see the CAD model changing following the physical one.”

The third question was “Do you think the process of the trial was easy or difficult to follow?”

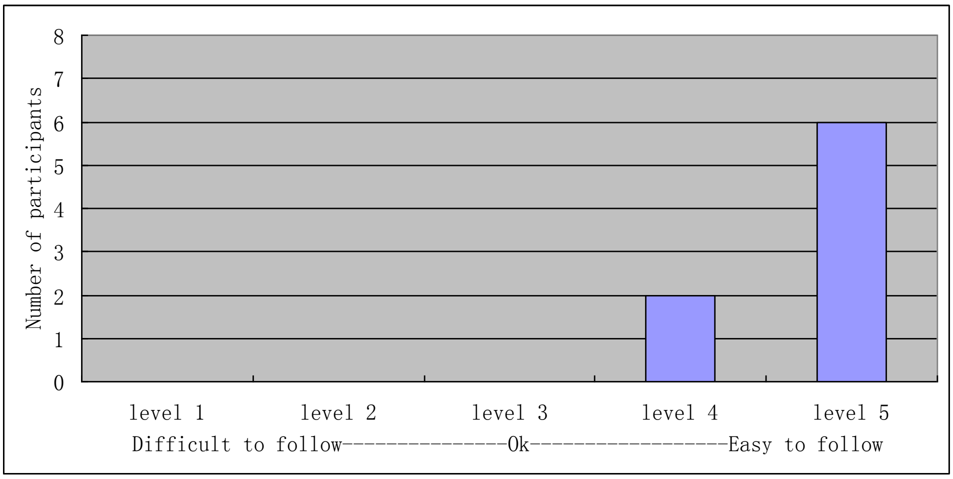

Figure 81: Comments about the general process of the trial

Figure 81 shows the result that an average of 4.75 was obtained (equal to the result to the same question in the previous question). The result again showed that most users felt the process of the trial was very easy to follow. One user stated “The trial was very straightforward” and another “The process is very easy to follow”.

The fourth question was “Which mode of the trial do you prefer and what are the reasons for your choice?”

All the users chose the “Connected mode”. The reasons they stated are summarised:

- On Connected mode, the trial was easier to follow;
- The Connected mode took less time to finish the same task
- Because the physical mock-up and CAD model were updated at the same time, it was easier for the user to understand the design.

6. 4 Discussion

In this chapter, an integration system named Loughborough University Prototyping Integration System was introduced. Although this conceptual system was not fully-functional, it has explored a novel way to achieve real time integration between physical and virtual prototypes. Because both the physical and virtual prototypes were synchronous and adjustable, the prototyping iterations were significantly speeded up. For designers, the system can help them to modify their design more quickly and easily. For the users, the real-time integration of the two types of prototypes was helpful for them to understand the design and to get involved in the testing of the design. In addition, compared to other related technologies, this system is more advantageous in compatibility with 3D modelling software packages and there was no programming work needed.

By comparing the two stages of trials presented in this chapter, it showed that after the upgrade of the system, the testing results were improved in several aspects. This indicated that technical issues were key to the performance of the system. The quality of the prototypes and integration equipment heavily influences the application of this system. To use this system, the designers would need to spend a significant amount of time and money building prototypes of sufficient quality, for example, using rapid prototyping to create a high grade physical prototype. This characteristic could be a limitation to the application of this method, especially in regard to more complex products. This aspect is addressed in the next chapter.

Chapter Seven

Developing a Generic Approach to Prototyping Integration

In the early chapters of this thesis, substantial knowledge of the generic process of product design and prototyping has been presented. In the later chapters, a specific prototype integration system called LUPIS was developed and validated through several experiments. In this chapter, the remaining objective of the research is met through the development of a generic method of prototype integration that aims to help product designers working in a wide range of product sectors

7.1 Introduction

Although LUPIS has shown its significance in testing prototypes, it is still in its infancy and only the ‘chair’ design was used as a platform to test its feasibility. In order to develop LUPIS to make it become a generic integration approach, it should meet the following basic requirements:

1. it should be suitable for products with a range of sizes and complexity whilst recognising that not all products are suited to the LUPIS approach
2. it should transfer all possible changes of the physical prototype to the virtual prototype, including the variation of linear dimensions and the modification of free form shape
3. it should transfer the changes in real-time or at least at a rapid enough speed to support direct user involvement in design

To meet the above three points, it is necessary to use the knowledge obtained from literature reviews and the trials that have been conducted to extend the scope of the LUPIS method. The current limitations of the LUPIS approach need to be identified and the procedure for applying LUPIS to any given product must be defined.

7.2 Additional Integration Technologies

7.2.1 Capturing Complex Movements

In LUPIS, the sensors were sourced from a mechanical computer mouse. Although they have great advantages in being compatible with 3D modelling software packages, they also have limitations. For example, a mouse sensor just can only trace movement in one direction and so to trace movement in two directions, i.e. vertical and horizontal, two sensors had to be used. This would limit their applications when the prototype has many degrees of freedom as the resulting link with CAD would become too complex. Therefore, other integration technologies would need to be considered.

Motion capture technology has potential overcome the multi-dimensional problem. In the film industry, the technology can transfer any complex movement of the actor to the computer. This is done by placing “markers” at key locations on the actor, e.g. limb joints, and using them to deduce the movement of the actor’s frame and even skin (reference to Golem in Lord of the Rings). If this technology could be embodied to the LUPIS, it could significantly improve its applications and make it more generic. A system can be envisaged where markers are placed at key points on the physical prototype and their motion capture data used to calculate and display the overall prototype movement within the virtual environment.

7.2.2 Providing Sensory Feedback to the User

The virtual prototype created within LUPIS only provided visual feedback to the user via a computer screen or large screen projection. This could be enhanced by providing 3D visualisation which is now becoming more commonplace in computer applications, e.g. gaming. A further enhancement would be to provide additional sensory feedback such as sound or even smell. Haptic technology could be used to simulate the sensation of touching the virtual prototype. This is particularly useful if the prototype deforms when in contact with the user, e.g. a seat cushion. Haptics could be used to provide a resistant interface with the user where the movement of the user would be incorporated into deformation of the physical and hence virtual prototype. The user would feel this resistance, making their experience more realistic. Material could even be removed from the virtual prototype using the haptic interface without destroying the physical prototype. Therefore, embodying haptics into the generic integration tool could widen its application into areas where the “feel” of the product is critical.

7.2.3 Hand-held Prototype Interaction

The LUPIS, as currently formatted, is more suitable for medium to large-scale prototypes which interact with the user at a “whole-body” level. A significant improvement to the system would be if it was also suitable for smaller hand-held products. A “data glove” like that provided in the Webshaman Digiloop System would be a key enabling device for such an application. Wearing this glove and holding the prototype, the user could move their fingers to create the necessary movement of the prototype, which would then be transferred to the virtual prototype instantly. The generic integration approach should have the capability for testing such hand-held size prototypes as well as larger prototypes like the chair.

The potential contribution that the additional integration technologies could make are summarised in Table 11.

Integration Technologies	**Potential contributions to the requirements of a generic integration approach**
Motion capture	Transferring complex 3D movements of the physical prototype to the virtual prototype
Haptics	Simulating the sensation of deforming or even removing material from the physical prototype without damaging it.
Webshaman Digiloop System	Evaluating hand-held prototypes

Table 11: The potential contributions made by integration additional technologies

7.3 Improved Experimental Procedure

7.3.1 Increasing the Realism of the Virtual Environment

In the experiments with the chair, in order to enhance the realistic virtual environment, the virtual prototype was projected onto a large screen to present a similar size as the physical prototype. In a generic integration approach, the projection method would have to be chosen in line with the type of product being evaluated. For example, with a larger product like a car, a back-projection system could be used so that the user could walk right up to the screen, if necessary. Alternatively a CAVE (Cave Automatic Virtual Environment) projection system could be used. For a smaller, perhaps hand-held product, a preferred method might be to use a more immersive system where a head-mounted display (HMD) could be used to make the virtual prototype appear in front of the user's eyes. An augmented reality approach could be followed where the user would be simultaneously viewing the physical prototype and virtual prototype overlaid on top of it. Some aspects could be evaluated from the physical and others from the virtual. The overall aim would be to let the user interact with the virtual prototype in as natural a manner as possible.

7.3.2 Developing a Testing Protocol

In the trials with the chair prototypes, a guideline on how to progress the trial step by step was created. This was rather simple and only covered a few aspects of product evaluation. In a generic integration approach, a comprehensive testing protocol should be prepared before the evaluation begins. In this protocol, the elements of the product to be tested should be listed and the various steps of the trials should be indicated as well. For different products, the elements and testing steps will vary, sometimes dramatically, and the participants must be clear as to which aspects will be evaluated physically and which virtually. The participating designers and users must follow this guideline in order to conduct the experiment in the most effective manner.

7.3.3 Eliciting Feedback from the Participants

In the chair experiments, questionnaires were used to obtain feedback from the participants. However, these questionnaires were mainly related to the integration techniques used in the LUPIS, to prove the need for real time integration and to assess the effectiveness of the method. In a generic integration approach, where the integration tools will become more reliable, the questionnaire should concentrate on the issues of the product evaluation itself. The questions would have to be phrased in such a way as to deflect the user's attention away from the particular media being used (both physical and virtual) and towards the functionality, ergonomics and aesthetics of the product.

The potential contributions that improved experimental procedure could make are summarised in Table 12.

Experimental Procedure	**The potential contributions to the generic integration tool**
Careful selection of projection method	Better realism
Testing protocol	Specific and detailed guidelines for each prototype evaluation
Focused feedback questionnaire	Feedback related only to product and not to prototyping media

Table 12: The potential contributions made by experimental procedure

7.4 The Generic LUPIS Approach

When the LUPIS prototyping integration approach is further developed to meet all of the above requirements, it could become a generic decision support tool for a range of different types of product evaluation. Generally speaking, applying this integration approach will always involve the following steps:

1. Select the aspects of the product need to be evaluated
2. Decide which aspects should be evaluated physically and which virtually
3. Build adjustable physical and virtual prototypes
4. Link the physical and virtual prototype with appropriate sensor technologies
5. Calibrate the physical and virtual prototypes so that they move in line with one another
6. Select the virtual prototype presentation method so as to obtain a similar size as the physical prototype
7. Finalise and follow a detailed testing protocol
8. Obtain feedback from the participants through a questionnaire or interview

For different products, the execution of these eight steps will vary. The flow chart shown in Figure 82 (shown in the next page) indicates the decisions that a product development team would need to make in order to arrive at the optimum LUPIS configuration.

Figure 82: Flow chart for the LUPIS experimental procedure

7.5 Example Application of the Generic LUPIS Approach

As a form of transport, the motorcycle follows strongly the concerns of style as well as ergonomics. Here, it is chosen as an example to indicate the validity of a wider potential application of the generic prototyping integration tool. Each of the eight LUPIS steps, as applied to motorcycle evaluation, is described in the sections below.

7.5.1 Product aspects to be evaluated

Motorcycle manufactures, such as Triumph, aim to develop motorcycles with distinctive looks, sounds and performance [triumphmotorcycles 2011]. This indicates that the style, ergonomics, as well as engineering issues, are critical concerns for motorcycle design and manufacturing. All of these elements should be evaluated in the design development of the motorcycle. Figure 83 shows the main components of a motorcycle. The change to each of these components could influence its ergonomics and the body shape. For example, the position of the handlebars, footrest position, the seat height and seat cushion thickness, the paint colour and styling the body, etc. All of these aspects could be tested with LUPIS.

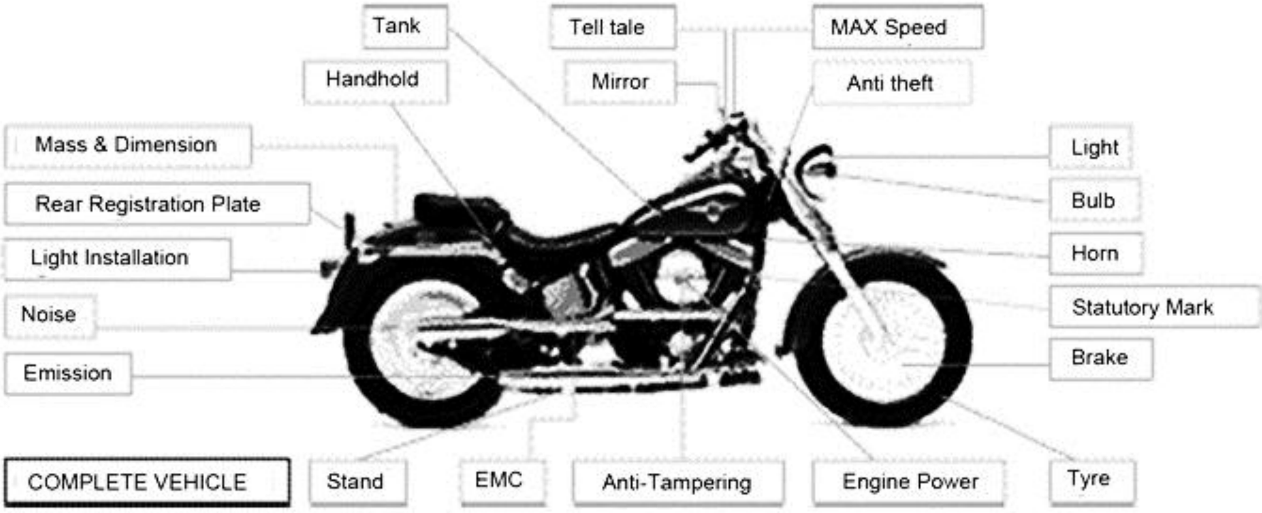

Figure 83: Motorcycle components [tuv.com 2011]

7.5.2 Aspects to be evaluated physically or virtually

According to the findings of this research, physical prototypes usually have the advantage in ergonomic issues, while virtual prototypes are believed to have more benefits in testing aesthetics and predicting performance. In the case of evaluating the motorcycle components, the footrest position, the seat height and the handlebars position, which attract more attention from an ergonomics perspective, could be evaluated physically. While the styling and the paint colour, which substantially represent the aesthetic aspects of the motorcycle design, could be evaluated virtually. In addition, the tank shape could also influence the ergonomics aspects of the motorcycle. Performance aspects such as aerodynamics and acceleration could also be evaluated using virtual prototypes.

7.5.3 Building the physical and virtual prototypes

According to the evaluation tasks required, the physical prototype should be built with fairly basic materials (to save cost and time) but still be good enough to present the ergonomic requirements. The evaluating elements, such as the footrest position, the seat height, the handlebar position and the tank shape should be adjustable. The virtual prototype should be built with aesthetic factors in mind, such as the body styling and the paint colour. The material for the components of the physical prototype could be various according to the testing tasks. For examples, the foot stand could be built with wood or metal, the cushion could be made of foam, while the tank could be produced with rubber so the shape of it could freely change when touched by the rider's legs. Figure 84 shows examples of how the virtual prototype of the motorbike (left) and the physical mock up (right) might appear.

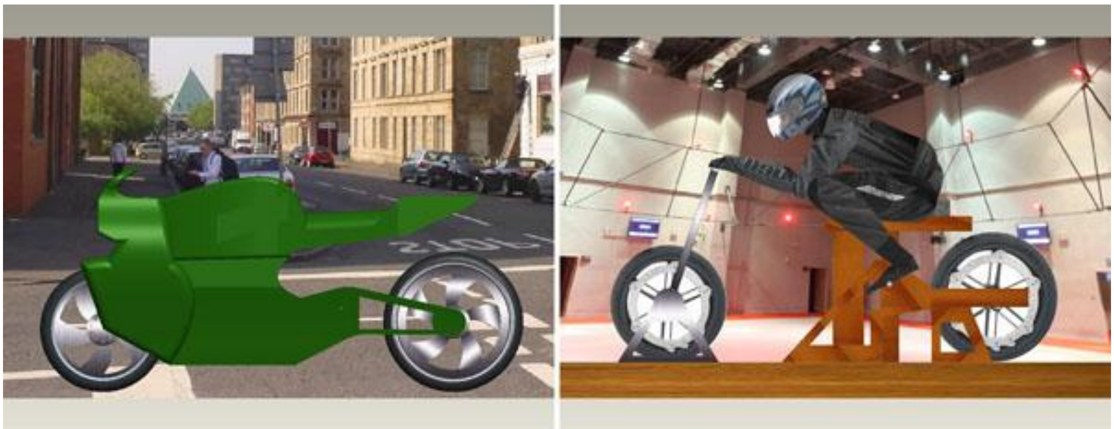

Figure 84: Virtual and physical prototype of the motorcycle

7.5.4 Linking the prototypes with appropriate sensor technologies

When the physical and virtual prototypes are ready, the next step is to link them with appropriate sensor technologies. For the seat height, handlebar and footrest positions, whose movements would be linear, sensors similar to those taken from a mechanical computer mouse could be used. For the seat cushion which will have shape deformation, haptic technology is a possible choice. For the tank shape which could change shape as an organic free form, motion capture technologies could be applied to it.

7.5.5 Calibrating the physical and virtual prototypes

When the prototypes are connected with sensors, calibration will be needed to make sure the virtual prototype could change correspondingly with the physical prototype. It is likely that each element of the prototype would first of all need to be tested and calibrated separately. Then this would be verified by simultaneous testing of all elements to check for interaction issues.

7.5.6. Selecting the virtual prototype presentation method

The testing of prototypes could take place in a specialised studio where the physical prototype could be located in front of a suitably projected virtual prototype (as shown in figure 85). In addition, some more specific simulators, such as Human-motorcycle interaction (HMI) created by the researchers based in the University of Nottingham [Stedmon 2010], also could be adopted to show the rider a realistic driving environment, such as traffic lights, junctions, etc. This would require a more complex physical prototype that would also enable the rider to lean into corners, etc., to have a more realistic evaluation experience.

Figure 85: The studio for the prototype testing

7.5.7 Finalising the testing protocol

When all the equipment has been properly calibrated and the realistic environment has been created, the testing can start by following a set protocol. The protocol should contain a list of all the components that will be tested and explain the procedure to test the components step by step. The protocol also needs to indicate how to operate the physical prototype; when to use the devices or equipment, such as the helmet for the HMD; when and how to record data, including recording video if needed. An example of what some of the motorcycle testing protocol might look like is shown in Figure 86. The feedback questionnaire or interview should also be designed at this stage.

Motorcycle testing protocol

Date_________________

Location_____________

Participant____________

Components to be tested:

Seat height, footrest position

Seat height

1. The rider rides the motorcycle mock up and adjust the seat height.
2. The virtual prototype changes. Ask the rider to see the updated version of the virtual prototype (Use HMD)
3. Change the virtual prototype according to the rider's opinion
4. Repeat above steps until the rider is happy with both the seat height and the virtual prototype
5. Record the seat height value and the version of the virtual prototype
6. To the next component evaluation

Footrest

Repeat the above six steps (use projected image instead of HMD when evaluating the virtual prototype)

Evaluation finished

Figure 86: An example of part of a testing protocol

7.5.8 Obtaining feedback from the participants

When the whole evaluation with one rider has been finished, feedback should been collected through either questionnaire or interview, or using both means. The designer would usually ask a number of participants to test the said components. After all of them have finished their evaluations, their feedback will be studied and analysed. The outcome of the feedbacks will be used for the further development of the motorcycle design.

7.6 Chapter summary

This chapter has presented the concept of a future generic version of the LUPIS integration approach. A decision-centred flow diagram has been developed that will enable other designers to apply this approach to their own products. It is a concept that has emerged from the research presented in this thesis and one that has not yet been practically developed and tested. However, the application of the approach to motorcycle design has indicated that it could provide a useful direction for future research in this area. Development of this generic approach brought the research project to an end and the next chapter closes the thesis by presenting conclusions from the research together with suggested future work.

Chapter Eight

Conclusions and suggestions for future work

This final chapter presents the conclusions drawn from the research work, discussion on the limitations of the research work and recommendations for future work. Also, the main contributions made by the research are listed

8.1 Conclusions

The conclusions of the project are assessed in regard to the research objectives stated in section 1.3 of Chapter One.

8.1.1 The role of prototypes and prototyping in product design process

Prototypes and prototyping play an important role at almost every stage of the product design process, from early concept development until preproduction. They help designers to identify problems and help users to get more involved in the design process. Prototyping is usually a costly and time consuming activity. Proper application of prototypes and prototyping will enhance any design project. However, improper planning and use of them will delay the launch of the product and even reduce the competitive edge of companies.

8.1.2 The strength and weakness of physical and virtual prototypes/prototyping

In the product development process, there are some situations where physical prototyping is more beneficial, while in many other situations virtual prototyping is to be preferred. As a conventional means of prototyping, physical prototyping technologies have a long history in contributing to design and manufacture. Although virtual prototyping has dramatically developed in recent decades, the role of physical prototyping still cannot be completely eliminated. As a tangible object, a physical prototype still holds significant advantages in many aspects, such as ergonomics testing, texture testing, size representation, etc. However, the trend of virtual prototyping replacing physical prototyping in many tasks is also obvious. Depending on the advanced computing technologies, virtual prototypes, which are usually 3D models, are able to bring time and cost savings in many circumstances compared to physical prototypes. Overall, the advantages and weaknesses of either physical or virtual prototyping are arguable and depend much on the application context. The designers should choose proper prototyping means according to the particular situation. In addition, the reality that both of physical and virtual prototype/prototyping has advantages and disadvantages brings the need for their integration.

8.1.3 Contributions and limitations of existing PP and VP integration technologies

The technologies that integrate physical and virtual prototyping such as CNC machining, Rapid Prototyping, Reverse Engineering, Parametric Prototyping, etc. have been investigated and discussed in Chapter four. All of these technologies have shown their strengths compared to stand alone physical or virtual prototyping and have made significant contributions to product design and development. However, the limitations of these technologies are significant. For example, they are still time consuming and costly; they do not pay enough attention to user involvement; they require specific and complex software to support, and so on. These limitations would cause problems for their application by product designers.

8.1.4 The need for real time integration of PP and VP

After the research on the characteristics of physical and virtual prototypes and the related technologies for their integration, a solution that could deal with the current problems was to integrate physical and virtual prototypes in a real time manner. Based on this premise, the literature review and a questionnaire survey were conducted. The results showed that the real time integration of physical and virtual prototypes is needed but still in its infancy. Following on from this, a method that integrates physical and virtual prototypes in a quick way was proposed and an initial pilot study was undertaken. Although within this version of the proposed method, the integration was still not ‘real time’, it showed again the significance of simultaneous integration to the product designers and the users. In addition, the pilot study also indicated the feasibility of the proposed integration method and the necessity to develop it further.

8.1.5 Develop a system for the integration of PP and VP

As a result of this research, a new integration system called LUPIS has been developed. This system took several main aims into consideration. Firstly, it should make the best use of the advantages of both physical and virtual prototypes; secondly, it should be compatible with most 3D modelling software that is commonly used by product designers; thirdly, it should improve the involvement of users in the design process.

With these considerations, a suitable sensor device became the key in this system to connect the physical and virtual prototype. After research on related technologies and devices, the mechanical computer mouse was finally chosen and modified to connect these two types of prototypes. Although the computer mouse is not seen as a complex or high-tech device nowadays, its compatibility with most computers and 3D modelling software is unmatched. In addition, it can achieve a simultaneous update from the physical to the virtual prototype.

From the initial proposal of the method, there were three main stages to developing the system, i.e. building the models, setting up the integration technology and performing some user trials. In the development process, a chair was used as the platform to demonstrate the feasibility of this system. However, the system was not just designed to work with chair prototypes, it could be expended to other product designs, such as an office table, a motorbike, etc. The trials showed that, this system could help improve design activities by shortening design time and get users more involved in the design on ergonomics and aesthetics issues. However, the accuracy of this system was a problem and more engineering work would be needed to improve it.

8.2 Research Contributions

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

1. The application of both physical and virtual prototypes in product design activities and their characteristics have been deeply analysed through literature review and questionnaire surveys. The need for real time integration of physical and virtual prototypes has been identified.

2. A wide range of technologies related to the integration of physical and virtual prototypes were investigated and analysed, including those already on the market (such as CNC machining, Rapid Prototyping, Reverse Engineering, etc.) and those still under research (such as Parametric Prototyping, WebShaman Digiloop system, etc.). The limitations of these technologies were identified and further demonstrated the need to

develop a different integration system.

3. The LUPIS system was developed to integrate physical and virtual prototypes for product designers and users. The system included the creative application of a mechanical computer mouse in connecting the two types of prototypes and achieving the real time integration from a physical to a virtual prototype. Several trials regarding this system were conducted and the feedbacks of the participants were analysed. The results of the trials showed that this system was compatible with the type of 3D modelling software that is commonly used by product designers and it was helpful in shortening testing time and improving user involvement.

This research project has been successful in that it has identified the requirement for the real time integration of physical and virtual prototypes, analysed the weaknesses of the related technologies and possible approaches and finally provided a new solution to the problem.

8.3 Limitations of LUPIS

As an approach to integrating physical and virtual prototypes in product design activities, LUPIS has shown its benefits in several aspects. However, there are some limitations to this system. The following gives a brief discussion of these issues:

8.3.1 The accuracy of the link between the physical and virtual prototype

In the trials testing the system, the unsteadiness of the physical prototype caused some problems. These problems have been discussed in detail in Chapter Six. Although the quality of the second physical prototype was improved significantly compared to the first, it still influenced the accuracy of the link between the physical and virtual prototype.

8.3.2 Two directional conversion has not been achieved

With this system, the movement of the physical prototype can be simultaneously transferred to the computer and used to drive the movement of the virtual model. However, the movement of the virtual prototype cannot be converted to the physical model (even though the designer could use some features of the 3D modelling software to quickly update the virtual prototype, for example, 'family table' in Pro/Engineer and 'Active Points' in Rhino).

8.3.3 This system might not be suitable for some products

This system has been tested with a chair design activity. However, with the restrictions of the size and accuracy of the computer mouse sensors, this system may not be suitable for some smaller sized products, such as pens, watches, and so on. This will limit the applications of this system.

8.4 Suggestions for future work

Although the current implementation of LUPIS provides a new direction in the real time integration of physical and virtual prototypes, it needs to be improved in several aspects in the future:

1. Within the trials, only the height and backrest angle of the chair was tested. In the future, more sensors should be embodied to this system so as to test more elements of the prototype.

2. Apart from the 3D modelling software that has been used in the trials, e.g.

Pro/Engineer, Rhino, more 3D modelling software packages should be tested with this system, such as Alias, SolidWorks, 3D Max, etc. to make sure the system could be compatible with them.

3. In the trials, the chair design was used as a platform to apply this system. In the future, the system could be modified and tried on more products, for instance, a motorcycle.

4. As stated previously, the system can only make the real time transfer from physical prototype to virtual, but not vice versa. In order to achieve conversion from the virtual to physical prototype, more research on other technologies needs to be undertaken, for example, robotic technology. In that case, new programming work might be needed and the compatibility of the new program with the current 3D modelling software would be a big challenge.

5. To further develop LUPIS in the future, the Intellectual Property aspects of this system will also be taken into considerations. Enterprise Office Intellectual Property team of Loughborough University will be consulted on this issue.

In conclusion, real time integration of physical and virtual prototypes/prototyping is an efficient way of helping product design activities, especially in the product evaluation process. This thesis has presented a research and development direction focusing on an integration system with great compatibility with commonly used 3D modelling software packages. However, more advanced technologies are needed to develop this system and make it more sophisticated.

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Appendix I

Questionnaire about Virtual and Physical Prototyping

Questionnaire

Questionnaire about Virtual and Physical Prototyping

Design School

Loughborough University

Questionnaire about Virtual and Physical Prototyping

Background: In the process of product development, virtual prototyping is playing a more and more important role. Some people expect that, in the future, physical prototyping may be completely replaced by virtual prototyping. However, there are some circumstances in which physical prototyping currently cannot be replaced by virtual prototyping. The purpose of this questionnaire is to identify the **benefits** and **limitations** of these two types of prototyping and to investigate if there is any requirement for them to be used simultaneously. The aim of the whole research project is to investigate the need for and implementation of real-time integration between virtual and physical prototypes, i.e. changes to a virtual prototype being immediately reflected in changes to the physical prototype, or vice versa.

Definitions: Within this research a virtual prototype is defined as a computer simulation of a physical product that can be presented, analysed, and tested from various product life-cycle aspects. The construction and testing of a virtual prototype is called virtual prototyping, e.g. photorealistic rendering, finite element analysis, computational fluid dynamics, etc. A physical prototype is defined as a model (often full-scale) of a structure or apparatus (or a product) used for testing and evaluating form, designing fit, performance and manufacturability. The construction and testing of a physical prototype is called physical prototyping, e.g. blue-foam modelling, high quality hand-made appearance models, rapid prototypes, etc.

Interviewee's details

Your name	
Your company/institution	
Your occupation	
Your email address (optional)	

Main questions

1. What type(s) of virtual prototyping do you use?

____

______

2. What types of products have you used virtual prototyping for?

____

____

3. What are the main benefits of using virtual prototyping compared with physical prototyping?

____

____

4. What problems/limitations have you encountered when using virtual prototyping?

____

____

5. What type(s) of physical prototyping do you use?

____

____

6. What types of products have you used physical prototyping for?

____

____

7. What are the main benefits of using physical prototyping compared with virtual prototyping?

____

____

8. What problems/limitations have you encountered when using physical prototyping?

____

____

9. In what situations is your use of physical prototyping still required because it cannot be replaced by virtual prototyping?

____

____

____

10. In what any situations (if any) has it been desirable for you to use virtual prototyping and physical prototyping **simultaneously**/**real-time**?

____

____

____

11. Have you been able to accomplish this and, if so, how?

____

____

____

12. Other comments:____

____

____

Thank you for your time and effort, it is much appreciated. Please return the completed questionnaire to Bingjian Liu, XX006, Dept of Design and Technology.

Appendix II

Questionnaire about the trial of integration between CAD model and physical mock-up

Questionnaire

Questionnaire about the trial of integration between CAD model and physical mock-up

Design School

Loughborough University

Questionnaire about the trial of integration between CAD model and physical mock-up

The aim of these questions is to find out:

1. If this method can help designers improve testing and modifying their design
2. If this method can help users getting involved in the testing activity.

For the designers

Name	
Occupation	
Contact information	

1. Have you ever used Pro/E in designing activity?

Yes no

If not, what kind of 3D software package do you use?

____

2. Have you ever built a physical mock-up to test your design?

Yes no

3. Do you think this method (combination of CAD model and Physical Mock-up) is helpful in reducing testing circle time?

A, very much

B, a little

C, not at all

D, disadvantageous

4. Do you think this method is helpful in modifying your design quickly?

A, very much

B, a little

C, not at all

D, disadvantageous

5. In summation, how do you think of this method for testing a design.

A, Not necessary

B, just OK

C, helpful

D, very helpful

6. Do you have any other comments or advice about this method?

____

Appendix III

Trial of integration between physical mock-up and CAD model

(For the designer)

Questionnaire

Trial of integration between physical mock-up and CAD model

(For the designer)

Design School

Loughborough University

Trial of integration between physical mock-up and CAD model

For the designer

In this trial, we will use a proposed method to test two aspects of a chair design: ergonomics and aesthetics. These two aspects will be tested in parallel. The physical mock-up is used to evaluate the ergonomics part while the CAD model is employed to assess the aesthetics.

The aim of these questions is to find out:

1. If this method can help designers improve evaluating and modifying their designs
2. If this method can help users to get more involved in the designing activity.

Questions

Common questions

☐ 1. Have you ever used Rhino in a designing activity?

○ Yes ○ No

If not, what kind of 3D software package do you use (if any)?

____

_

☐ 2. Have you ever built a physical mock-up to test one of your designs?

○ Yes ○ No

If yes, what aspects have you tested with the mock-up?

A. Ergonomics

B. Functionality

C. Aesthetics

D Others__________________________

☐ 3. Have you ever built a CAD model as well as a physical mock-up for one of your designs?

○ Yes ○ No

If your answer is yes, have you ever simultaneously used these two types of models to test your design?

○ Yes ○ No

If yes, how?

____

____

__

Questions for this trial

1. How do you feel about the ease of operation of the CAD model (tick a number)?

Very difficult ... Ok ... Very easy

←——————————————————————→

1 2 3 4 5

What is the reason of your choice?

____

____

__

2. What do you think about the process of the trial:

Difficult to follow Ok Easy to follow

1 2 3 4 5

What is the reason of your choice?

____

____

__

3. Do you think this method is helpful in modifying your design quickly?

Not at all Ok very much

1 2 3 4 5

4. Do you think this method is a valuable way of getting users more involved in the design activity?

○ Yes ○ No

What is the reason of your choice?

____

____

____

__

Other

comments:____

____

____

Thank you!

Appendix IV

Trial of integration between physical mock-up and CAD model

(For the user)

Questionnaire

Trial of integration between physical mock-up and CAD model

(For the user)

Design School

Loughborough University

Trial of integration between physical mock-up and CAD model

For the user

In this trial, we will use a proposed method to test two aspects of a chair design: ergonomics and aesthetics. These two aspects will be tested in parallel. The physical mock-up is used to evaluate the ergonomics part while the CAD model is employed to assess the aesthetics.

The aim of these questions is to find out:

1. If this method can help designers improve evaluating and modifying their design
2. If this method can help users to get more involved in the designing activity.

Questions:

☐ 1. How do you feel of operating the physical chair prototype?

Very difficult   Ok   Very easy

◄────────────────────────────►

1   2   3   4   5

What is the reason for your choice?

____

____

__

☐ 2. How do you feel the visibility of the CAD model?

Very poor Ok Very clear

1 2 3 4 5

What is the reason for your choice?

____

____

__

☐ 3. You think the process of the trial:

Difficult to follow Ok Easy to follow

1 2 3 4 5

What is the reason for your choice?

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☐ **Other comments about the whole trial**?

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Appendix V

Questionnaire -- Trial of integration between physical mock-up and CAD model (For the designer)

Questionnaire

Trial of integration between physical mock-up and CAD model

(For the designer)

Design School

Loughborough University

Trial of integration between physical mock-up and CAD model

For the designer

In this trial, we will use a proposed method to test two aspects of a chair design: ergonomics and aesthetics. These two aspects will be tested in parallel. The physical mock-up is used to evaluate the ergonomics part while the CAD model is employed to assess the aesthetics.

The aim of these questions is to find out:

1. If this method can help designers improve evaluating and modifying their designs
2. If this method can help users to get more involved in the designing activity.

This trial consists of two stages: first stage is when the two prototypes are disconnected; second stage is when they are connected through the mouse sensors.

Designer's information (personal information will not be shown to the third party)

Name: ____Today's date_______

Research subject (for researchers only):_______________________________

Email: ____

Questions

Common questions

☐ 1. Have you ever used Rhino in a designing activity?

○ Yes ○ No

If not, what kind of 3D software package do you use (if any)?

____

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☐ 2. Have you ever built a physical mock-up to test one of your designs?

○ Yes ○ No

If yes, what aspects have you tested with the mock-up?

A. Ergonomics

B. Functionality

C. Aesthetics

D Others___________________________

☐ 3. Have you ever built a CAD model as well as a physical mock-up for one of your designs?

○ Yes ○ No

If your answer is yes, have you ever simultaneously used these two types of models to test your design?

○ Yes ○ No

If yes, how?

____

____

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Questions for the second stage trial

☐ 1. How do you feel about the ease of operation of the CAD model (tick a number)?

Very difficult Ok Very easy

1 2 3 4 5

What is the reason of your choice?

____

____

__

☐ 2. What do you think about the process of the trial:

Difficult to follow Ok Easy to follow

1 2 3 4 5

What is the reason of your choice?

____

____

__

☐ 3. Do you think this method is helpful in modifying your design quickly?

Not at all Ok Very much

1 2 3 4 5

What is the reason of your choice?

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____

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☐ 4. Do you think this method is a valuable way of getting users more involved in the design activity?

○ Yes ○ No

What is the reason of your choice?

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Comparison with the two stages of trial

☐ 1. In which stage do you think the trial is easier to operate?

A, First one

B, Second one

☐ 2. Which stage do you think is more efficient?

A, First one

B, Second one

☐ **Other comments**:

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Thank you.

Appendix VI

Questionnaire -- Trial of integration between physical mock-up and CAD model (For the user)

Questionnaire

Trial of integration between physical mock-up and CAD model

(For the user)

Design School

Loughborough University

Trial of integration between physical mock-up and CAD model

For the user

In this trial, we will use a proposed method to test two aspects of a chair design: ergonomics and aesthetics. These two aspects will be tested in parallel. The physical mock-up is used to evaluate the ergonomics part while the CAD model is employed to assess the aesthetics.

The aim of these questions is to find out:

1. If this method can help designers improve evaluating and modifying their design
2. If this method can help users to get more involved in the designing activity.

This trial consists of two stages: first stage is when the two prototypes are connected; second stage is when they are disconnected through mouse sensors.

User's Information (personal information will not be shown to the third party)

Today's date:__________________

Gender:☐ male ☐ female

Height: ___________________cm. Age:________________

Weight :___________________kg

Occupation/major:

___________________Email:_______________________

Questions:

☐ 1. How do you feel of operating the physical chair prototype?

Very difficult Ok Very easy

←——————————————————————→

1 2 3 4 5

What is the reason for your choice?

____

____

__

☐ 2. How do you feel the visibility of the CAD model?

Very poor Ok Very clear

1 2 3 4

5

What is the reason for your choice?

____

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__

☐ 3. You think the process of the trial:

Difficult to follow Ok Easy to follow

1 2 3 4 5

What is the reason for your choice?

____

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☐ 4. Which stage do you prefer?

A, first stage B, second stage

What are the reasons for your choice?

A. easy to follow
B. easy to understand the design
C. save time
D. interesting
E. others ____

☐ **Other comments about the whole trial**?

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