Design for rapid manufacture: developing an appropriate knowledge transfer tool for industrial designers

FACULTY OF SOCIAL SCIENCES AND HUMANITIES
DEPARTMENT OF DESIGN AND TECHNOLOGY

DESIGN FOR RAPID MANUFACTURE: DEVELOPING AN APPROPRIATE KNOWLEDGE TRANSFER TOOL FOR INDUSTRIAL DESIGNERS

BY
MICHAEL JOHN BURTON

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for
the award of
Doctor of Philosophy of Loughborough University

Acknowledgements

I would like to thank the following:

- My parents, for all of the moral support and encouragement that they have given me over the years
- My research supervisors, Doctors Ian Campbell and Richard Hague, for their guidance and editorial input during the writing of this thesis
- John Smith and George Torrens, who were both instrumental in my initial return to Loughborough University and the Design Technology Department
- The Rapid Manufacturing Research Group and its members, for their co-operation and support in providing access to laboratory facilities and various research materials
- The industrial design professionals and students who took part in various research trials and contributed valuable feedback during the course of this project
- My colleagues in the Design Technology Postgraduate Research Office, for providing a sociable working environment and a good sounding board against which to bounce various ideas

Abstract

Numerous works have been produced on the topic of Design for Manufacturing (DFM) to better educate the designers of products as to various methods of manufacturing and their specific requirements. It is the common aim of these works to eliminate so called "over the wall" product development in which procedurally ignorant designers pass largely un-producible design concepts to manufacturers, who are then required to make necessary refinements and changes. When applied correctly, DFM results in the efficient and economical production of well-designed products, whose forms have been attuned to the particular requirements of their final method of production at an early stage of development. However, one aspect of using such approaches is that design intent is frequently compromised for the sake of manufacturability and innovative design concepts are often dismissed as being unfeasible.

Recent advances in additive manufacturing technologies and their use in the direct manufacture of end-use products from digital data sources has brought about a new method of production that is known as Rapid Manufacturing (RM). Unlike conventional subtractive machining processes, such as milling and turning which generate forms by removing material from a stock billet, RM parts are grown from an empty part bed using the controlled addition of specialised build materials. Additive manufacturing requires no forming tools, is unrestricted by many conventional process considerations and is capable of producing practically any geometry. The freedoms that are associated with this technology facilitate the design and realisation of product concepts that would be unachievable with any other method of production. This promotes an almost boundless design philosophy in which innovative product solutions can be designed to best meet the needs of specification criteria, rather than the production process with which they are to be made. However, unlike other forms of manufacturing, the newness of this technology means that there is no proven aid or tool to assist industrial designers in exploiting the freedoms that it offers.

Hypothesising that existing strategies can be applied to the formulation of an effective Design For Rapid Manufacturing (DFRM) tool, it is the aim of this research project to develop and test a system that is suitable for use by industrial designers. To achieve this, a literature review has been conducted to observe the approaches that are commonly applied by industrial designers during the development of new products. A study was made of supporting design media to ascertain the realisation tools that a design aid would need to be compatible with. The procedural benefits and capabilities of Rapid Manufacturing were noted in a literature review and a series of practical case study projects, along with the predicted effects that the process will have upon designing.

Using information that was collated in the literature review and case study projects, a systematic design approach was proposed and then tested in a series of user trials with groups of industrial design students and practicing industrial design professionals. The results of these trials are discussed, showing a common acknowledgement from both groups that the proposed DFRM tool was of assistance and that it had an influence upon their design work. However, whilst the student group were generally receptive toward tool uptake, the experienced designers showed more of a reluctance to abandon their own "tried and tested" methods in favour of the unknown and unproven approach. It is concluded that this attitude would be fairly representative of wider opinion and that the future uptake of any such tool would be reliant upon sufficient evidence of its successful application. Hence, suggestions are made for future work to continue tool development and for more validation trials to be conducted with its intended user group.

Key Words

Product Development, Industrial Design, Additive Manufacturing, Knowledge Transfer

About The Author

Mike Burton graduated from Loughborough University with a Bachelor's Degree in Industrial Design and Technology. His professional career began with approximately three years in the Rapid Prototyping (RP) industry. During this time he worked for two separate service bureaus, providing a wide range of industries with various types of product development prototypes.

Following a year's sabbatical and much worldwide travel, Mike took the opportunity to diversify and found employment in the technical department of a small contract manufacturer of plastic goods. Here he assisted in the design and development of new products, along with advising the best practice use of outsourced RP processes. After spending two years in this role, Mike returned to Loughborough University to conduct research, undertaking the work that is described in this thesis.

Used Acronyms / Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
ABS	Acrylonitrile-Butadiene Styrene
CAD	Computer Aided Design
CAID	Computer Aided Industrial Design
CAM	Computer Aided Manufacturing
CMM	Co-ordinate Measurement Machine
CNC	Computer Numerical Control
DFA	Design For Assembly
DFM	Design For Manufacture
DFRM	Design For Rapid Manufacture
DMLS	Direct Metal Laser Sintering
FDM	Fused Deposition Modelling
HIPS	High Impact Poly-Styrene
IGES	International Graphics Exchange Specification
LENS	Laser Engineered Net Shaping
NPD	New Product Development
NURBS	Non-Uniform Rational B-Spline
QA	Quality Assurance
RE	Reverse Engineering
RM	Rapid Manufacturing
RP	Rapid Prototyping
SLA	Stereolithography (apparatus)
SLS	Selective Laser Sintering
STL	Stereolithography (exchange file format)
UV	Ultra Violet
VA	Value Analysis
VE	Value Engineering

Table of Contents

1 INTRODUCTION

1.1 Overview

This chapter provides a context for the research project's execution and final outcome, which is the recommendation of a systematic approach to assist industrial designers in the generation of concepts suited to production by Rapid Manufacturing (RM). The process of New Product Development (NPD) is first defined before introducing the phenomena of time compression that has increased the need for efficient systematic approaches within NPD. Various stakeholders involved in the development of new products are introduced, emphasising the importance of industrial designers as key stakeholders. From this a case is made as to the need for an organisational approach that is specific to the design and concept generation process. Finally, the overall objectives of the research project are stated before presenting the thesis' structure.

1.2 Scope of the Research

1.2.1 Definition of New Product Development

New Product Development (NPD) is the process through which all designed products come into being. Included in this process are all of the activities and decisions that are required to generate a marketable product that meets the requirements of a previously identified need. Whilst the term "product" may extend beyond that of physical artefact to include less tangible outcomes, such as services or computer software, its sole reference in this text is that of real world items that perform a physical function or functions.

1.2.2 Time Compression

The average time between the introduction and peak production of a group of consumer products in the 1920's was approximately 28 years (Barclay, 2000, p11). By the 1960's and 1970's this time had been reduced to 10 years.. A survey conducted in 1987, which included 149 UK based engineering firms, showed the average product life cycle to be 12 years, with a development time of 22 months (Barclay, 2000, p11). When the same survey was repeated in 1996 these figures had changed to 8 years and 15 months respectfully.

The introduction and evolution of new product development technologies, such as Computer Aided Design (CAD) and Rapid Prototyping (RP), have had much effect in reducing product development times (Baxter, 1996). These technologies have become commonplace in all but a few NPD cycles and their experimental application has even led to developments in the field of Rapid Manufacturing (RM). Here the progression from virtual CAD model to final end use product takes place in one single step. This removes the need for typical intermediary processes, such as the fabrication of forming tools, and allows development times to be shortened even further. However, whilst the advancement of such technologies enable the compression of product development times, it is commercial competition that may be accredited with being the actual cause behind such time reductions.

A study conducted by technology consulting firm Booze Hamilton and Allen in 1982 (Sivadas, 1998), including more than 700 of the fortune 1000 companies, revealed that approximately 33% of all profits could be directly attributed to new products. Similar findings are shown by Baxter (1996, p3), whose figures demonstrate a general upturn in the percentage of sales generated by new products, with figures climbing from 33% in the mid 1980's to 46% in the mid 1990's. From this it is possible to see the widespread importance that new products have throughout industry, hence fuelling the constant need to produce new products. In this drive to deliver new products there comes a need for speed and, in a competitive commercial environment, the ability of any company to best exploit a market opportunity is often reliant upon its ability to be first in delivering a marketable product or concept.

It was the Japanese who first pioneered the rapid introduction of new products and shortening of product market life as a strategic business weapon against slower moving competitors (Lorenz, 1986). However, since it was first used, the approach has become widespread and is now common practice, with competing companies scrambling to produce a greater and faster flow of new products.

Cooper (1995) states that "by being first to launch a new product, manufacturers usually manage to achieve a larger market share, not only in the first few months but often throughout production". Effectively this means that any product developer who is able to successfully launch a product into a market in which no competition exists is able to take early control of both market and price structure. Potentially this allows the developer to achieve a greater financial return in not having to price their product to compete with those of others. The resulting effect is a race between vying companies, in which product development process are continually speeded up in an attempt to shorten the time in which new products may be delivered.

1.2.3 The Need for a Strategic Approach

The quickening of product life cycles and increased demand for new replacement products indicates the need for an efficient product development process in which the optimum amount of project resources are used to produce the highest number of successful products. However, research conducted into the rate of success and failure within product development showed that the rate of failure had remained at an almost constant 30% for 60 years (Barclay, 2000, p11).

With an apparently static level of success amongst new products, the need for a more efficient application of resources by those responsible for product development became clear. The realisation of this has led to an increasingly widespread implementation of structured organisational approaches throughout industry. Strategies that have been applied to this end include such approaches as Value Engineering (VE) and Quality Function Deployment (QFD) amongst numerous others.

A growth in the usage of specific methods is emphasised in the studies of Barclay (Barclay, 2000, p11) that were conducted during the 1980's and 1990's, in which he observes the increasing importance of structured new product development strategies. The number of companies using specific new product development guides or procedures in his 1987 survey was 40%, whereas in 1997 the figure had grown to over 90%.

1.2.4 NPD Stakeholders

Within any product development project a number of stakeholders exist. The term "stakeholder" is used in this instance to describe those with a particular interest or "stake" in a product development project. This includes anyone who will or may influence a project decision, as well as those who are affected by the decision outcomes. Encompassed within this group are all parties from the initial project instigator to the final end user of the resulting product. Specific titles include those of client; designer; supplier; manufacturer; marketer and end user. The individual needs of each stakeholder are likely to vary depending upon which particular role they play within the project. However, one common requirement shared by all is that the final product is delivered within the shortest time possible and for the optimum cost.

1.2.5 Industrial Designers

Industrial designers are assigned the distinct remit of defining product appearance and functionality within a commercial manufacturing environment (Evans, 2002). In this role they act as intermediary facilitators between the various project stakeholders and it is their responsibility to provide product concepts that best meet the requirements of all concerned.

The actual activity of design generally takes place within the early stages of the NPD process and accounts for approximately 5% of total expenditure within a typical project (Boothroyd et al, 2001, p4). However, it is widely accepted that over 70% of final product costs are determined during the design phase (Boothroyd et al, 2001, p4). As such, industrial designers may be seen as key stakeholders whose far-reaching actions are felt throughout the NPD process. Naturally, the implementation of any approach to assist or increase the efficiency of their specific activities would be of great benefit to all associated NPD stakeholders.

1.3 Research Objectives

Computer assisted technologies, such as Rapid Prototyping, have enabled the increasing compression of product development cycle times. As these cycle times decrease, the need for efficiency within NPD increases. In response to this, a number of strategic organisational tools and approaches have been adopted throughout industry as aids to those who are responsible for the development of new products. Industrial designers have been identified as causing the greatest overall affect during NPD and are the stakeholders most likely to benefit from the use of such strategies and approaches.

Rapid Manufacturing (RM) is emerging as a new form of production that presents a significant opportunity with which to revolutionise the NPD process. The ideology associated with this new form of manufacturing is fundamentally different to all that has gone before, offering users much greater design freedoms and capabilities than were previously possible. However, in order to best exploit the benefits that this new process offers, it is necessary that designers are made aware of the characteristics associated with Design For Rapid Manufacture (DFRM). Hence it is the aim of this research project to develop a strategic tool with which to educate and assist industrial designers who are new to the generation of RM design concepts.

With this aim in mind the following research objectives were formulated:

- To identify the methods, tools and strategies that have been formulated and applied to the New Product Development process
- To determine the key technologies that are commonly applied within the practice of industrial design and concept generation
- To track the development of Rapid Manufacturing and assess the impact that it has upon product design and development
- To recommend and test a strategic tool or approach that would assist industrial designers in the generation of product concepts to be produced by Rapid Manufacturing
- To identify future research and development that would be required to transform the recommended approach into a commercial package

1.4 Thesis Structure

Following this first introductory chapter, the next three chapters are used to present a literature review that was conducted in areas of relevance to the previously stated research objectives. The topics reviewed in these chapters are those of designing, design media used within the practice of industrial design and developments in the emerging field of Rapid Manufacturing. Chapter 5 isolates the specific research questions that arose from the literature review, before discussing various research methods and the strategy that has been applied to this particular project. Chapter 6 details a number of practical case studies, in which different products were designed for production via conventional processes and Rapid Manufacturing to gain a greater understanding of Design For Rapid Manufacture (DFRM). Chapter 7 details the approach that was used to develop an appropriate DFRM tool, including user trials that were conducted with sets of novice and professional industrial designers. Chapter 8 discusses the project objectives and research questions which have led to the final outcome. Lastly, Chapter 9 offers surmised conclusions of the work that has been conducted and identifies potential directions for future research and development.

2 DESIGNING

2.1 Overview

The aim of this chapter is to describe industrial design practice and to identify a number of recognised systematic methods that have been applied to the design of consumer products. An attempt is made to define the practice of industrial design, distinguishing it from that of engineering design. Observations will be made as to the key stages involved within typical industrial design practice before establishing degrees of product "newness" and identifying what has been referred to as product status. A review of various design strategies is made, ending with a focus upon specific strategies that have been developed around areas of key importance. Finally, the chapter ends with a brief summary that links to the next chapter, which deals with the tools and technologies that are used in concept realisation.

2.2 Industrial Design

Numerous attempts have been made to produce a universal and concise definition as to what industrial design is, although it seems to be a common failing of most that they are unable to satisfactorily capture all of the aspects that are involved (Sener, 2004). A useful starting point comes from Archer (1964) who defined design as "*a goal directed problem solving activity*", and Taylor (2002) who described the design process as, "*the transformation of abstract concepts into tangible entities*". When referring specifically to industrial design, The International Council of Societies of Industrial Design (ICSID) identifies this practice as, "*a creative activity whose aim is to establish the multi-faceted qualities of objects, processes, services and their systems in whole life-cycles*" (ICSID, 2004).

Holmes (1995) presents a selection of definitions from around the world as to various perceptions of industrial design. These may be seen below in figure 2.1.

Country	**Profession Title**	**Definition**
England	Industrial Design	*"making designs for objects to be produced by machines"*
America	Industrial Design	*"design is concerned with the appearance of three dimensional machine made products"*
Italy	Disegno Industriale	*"giving products a beautiful attractive form"*
Germany	Industrielle Formgeburg	*"design of the external appearance of products used in industry"*
Japan	In-da-su-toa-tu de-za-in	*"Design which taking both usefulness and attractiveness into account"*

Figure 2.1 - World definitions of industrial design (Holmes, 1995)

Whilst each of these definitions goes some way to conveying something of what the generic act of designing involves, it is evident that the term "design" and "industrial design" in particular mean different things to different people.

Throughout the development of any new product it is possible to identify a number of activities that are characterised as "design". A number of specialist fields are encompassed within this general classification, so for the purpose of this text a generalisation is made of industrial design so as to distinguish it from the others. Previously this was done in part by Holmes (1995), who studied the relationships that exist between the two fields of "industrial design" and "engineering design". The block diagrams shown below in Figures 2.2 and 2.3 were used by Holmes to differentiate the Industrial Design process from that of Engineering Design.

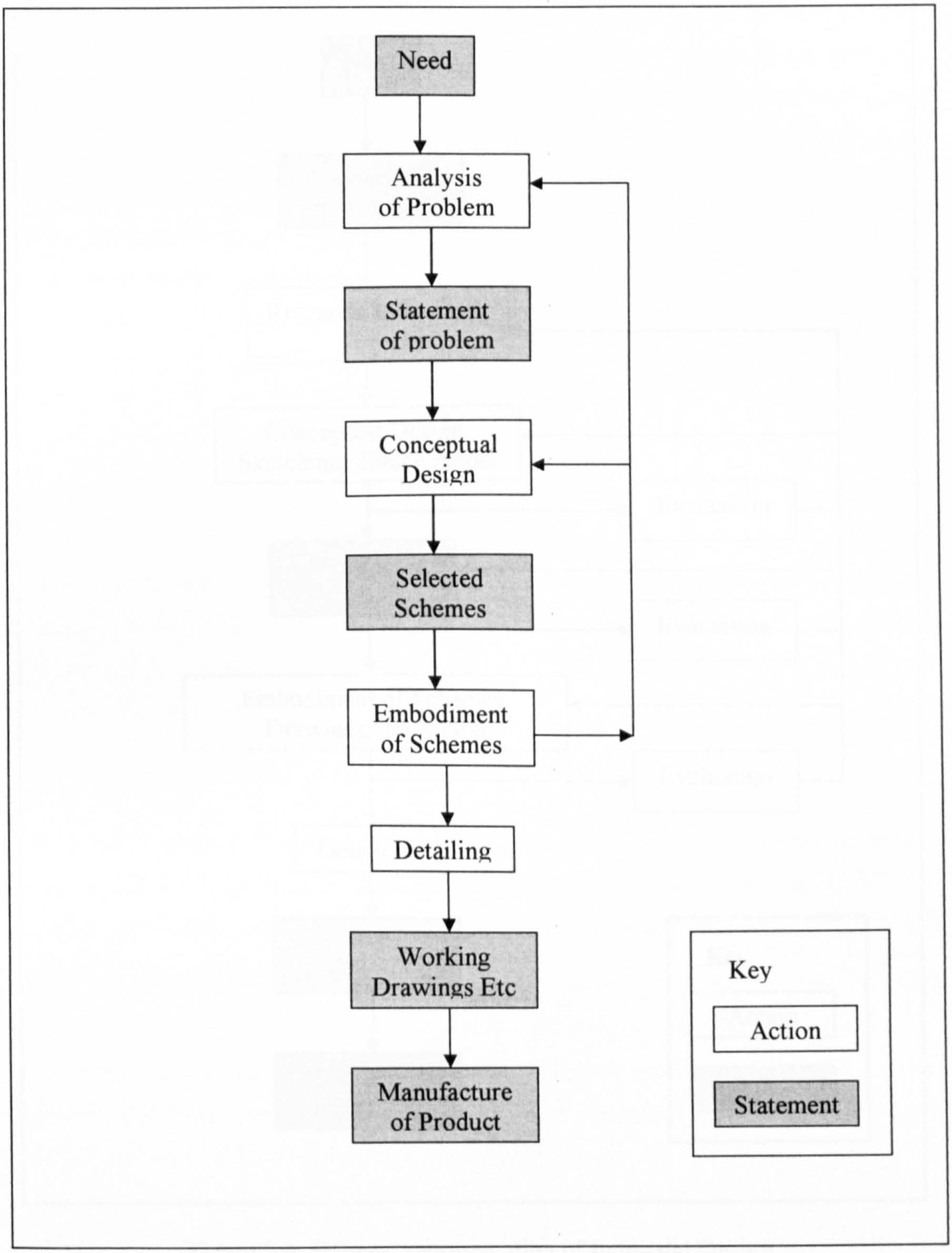


Figure 2.2: Holmes' representation of Engineering Design

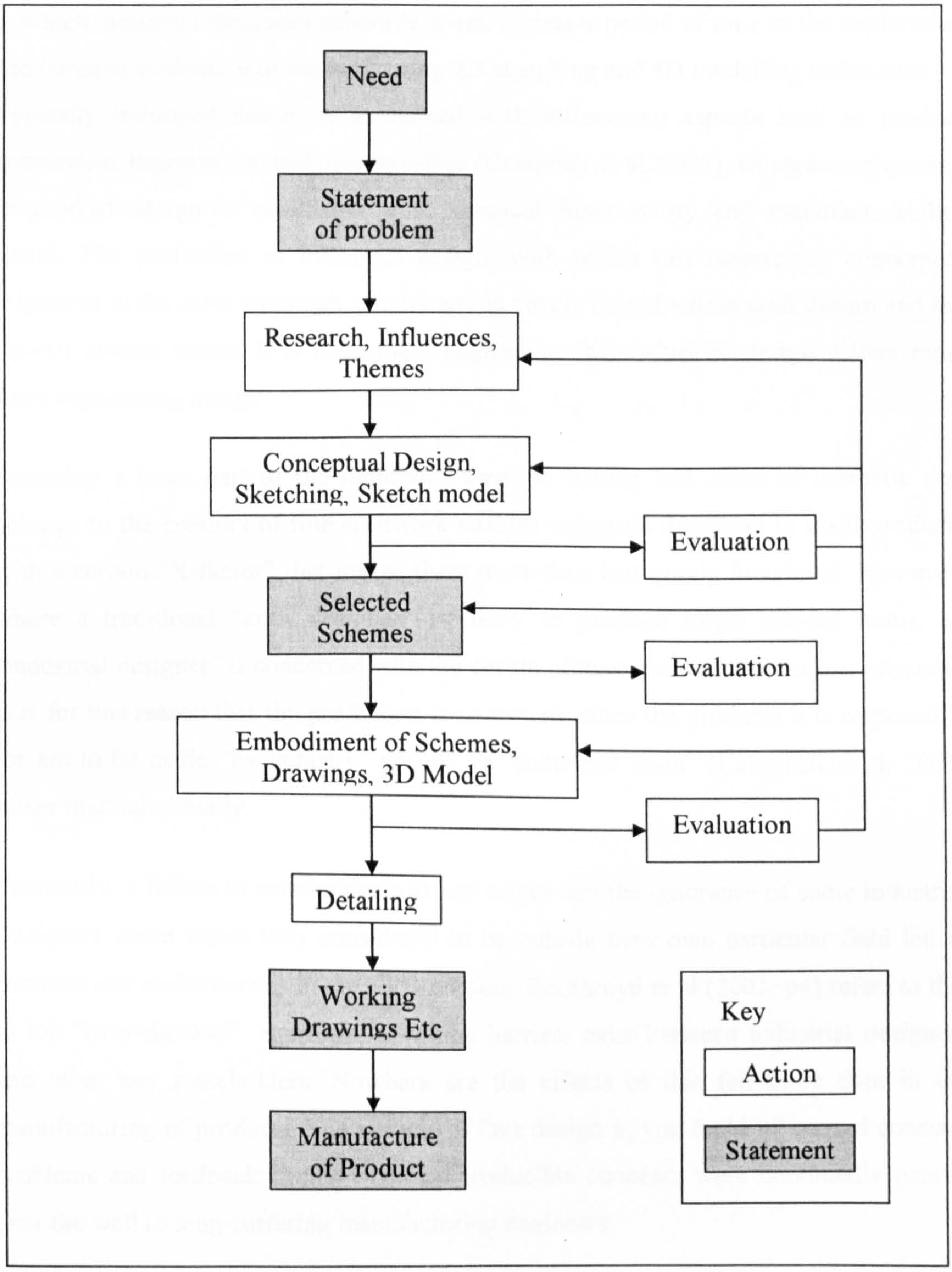


Figure 2.3: Holmes' representation of Industrial Design

Whilst similar in title and prefatory function, a number of procedural differences exist between these two fields. This may be seen most during the concept generation phase, in which industrial designers generally spend a greater period of time in the exploration and iterative evaluation of schemes using 2D sketching and 3D modelling techniques. Typically industrial design is associated with influencing aspects such as product appearance, ergonomics, and user interface (Campbell et al, 2003), whereas engineering or product design is associated with technical functionality and manufacturability issues. The profession of industrial design, with which this research is concerned, originates in the early twentieth century and is deeply rooted within craft design and the various artisan trades. It is from these beginnings that industrial design differs most from engineering design.

Retaining a large part of the intuitive / emotive feeling and sense of aesthetic that belongs to the creators of fine craftwork enables industrial designers to instil products with a certain "X-factor" that makes them more than just purely functional. However, where a traditional "craft designer" is likely to produce single one-off items, an "industrial designer" is concerned with the design of mass-produced consumer products. It is for this reason that the profession is so named, since the products it is responsible for are to be made "by industry" and on an "industrial scale" (Campbell et al, 2003) rather that individually.

Previously, a failure to communicate at key stages and the ignorance of some Industrial Designers about topics they considered to be outside their own particular field led to frictions and inefficiencies in the NPD process. Boothroyd et al (2001, p4) refers to this as the "over-the-wall" approach, in which barriers exist between industrial designers and other key stakeholders. Nowhere are the effects of this felt more than in the manufacturing of products. The attitude of "we design it, you build it" caused constant problems and feedback cycles when un-producible concepts were continually passed over the wall to long-suffering manufacturing engineers.

In order to resolve such issues numerous methodological approaches have been developed to better educate and assist those involved in product design and development. The use of such methods and approaches, along with a broader design education, has made industrial designers much more aware of process issues that exist outside of what was traditionally accepted as their sphere of responsibility. This has been instrumental in the rise of industrial designers who are more process aware and better equipped to produce realistically achievable product concepts that require fewer manufacturing driven changes. Combined with the increasing amount of digital technologies that are being used by designers, the profession of industrial design has become a very evenly balanced mixture of science and art.

2.3 The Design Process

The act of designing involves a series of procedural activities that are performed so that a new product may come into being. Many attempts have been made to define the various stages that are involved within this process, mapping out a route from start to finish. However, the difficulty in identifying any single generic design process comes not only from the fact that there are usually several different ways to approach the same problem, but also from the fact that no two industrial design commissions are ever identical (Evans 2002, p44). Nevertheless, it has been recognised that certain common design outputs exist which are required throughout all projects.

Dhillon (1988) observed the design process from an engineer's perspective, stating that the number of steps or stages associated with such activities may vary from five to twenty five. As examples he introduces the work of Dieter (1983) who describes the design process as involving six steps and Hill (1970) whose definition uses twelve. Following these introductions Dhillon (1988) makes his own proposal using the following six stages:

Stage 1: Need Recognition

Before a solution is discovered it is necessary for the designer or any others involved with the design to clearly understand and identify the needs of the user. This involves the identification of customer needs, which customer needs are to be satisfied and the identification of a suitable mechanism to analyse customer needs.

Stage 2: Problem Definition

It is necessary to develop a concise problem statement that identifies the problem requirements, the limitations associated with it and information pertaining to the problem in question. The investigation of these factors requires both, data collection and analysis.

Stage 3: Information Gathering

The sources from which necessary project information might be acquired may include library sources, handbooks, journals, specifications and codes, vendor catalogs, patent records, technical experts and so on.

Stage 4: Conceptualisation

Creativity is a critical element of finding a solution to most problems. Inspiration for useful ideas may come from information held in catalogues, textbooks or patent files. Alternatively, techniques such as brainstorming or mind mapping may be used to generate preliminary and conceptual solutions.

Stage 5: Evaluation

In order to decide upon the best solution it is necessary to compare all of the potentials. Evaluation includes both comparison and decision making and may take the following forms:

- Evaluation based on Go/No-Go screening
- Evaluation based on feasibility judgment
- Evaluation based on technology-readiness assessment

Stage 6: Communication of Design

The final solution to an engineering problem is either the generation of documents or artifacts that represent a product or the product itself. Typically design documentation would include engineering drawings, quality assurance information, bills of materials and instructions for operation, maintenance and retirement along with patent applications.

Another more simplified definition was offered by Holmes (1995), who saw the design process as involving the following 4 stages:

Stage 1: Absorption

"The accumulation of information relevant to gain understanding of the problem at hand."

Stage 2: Investigation

"The investigation of the problem and all criteria affecting the problem" and "The investigation of a solution or the means for a solution"

Stage 3: Development

"The Development and refinement of one or more of the proposed solutions"

Stage 4: Communication

"The communication, by whatever means, of the solution to others"

The classification of generic design activities in this way is used to create process models and maps that provide designers with assistance during their own design projects. However, the function of such models is not necessarily to dictate the precise route that each project will take but rather to provide a series of approximate guidelines that designers may follow. Baxter (1995, p16) makes an analogy that compares a similar process model with a schematic of one of Britain's Motorway systems, which shows a section of road, some junctions and various intersections. This may be seen below in Figure 2.4.

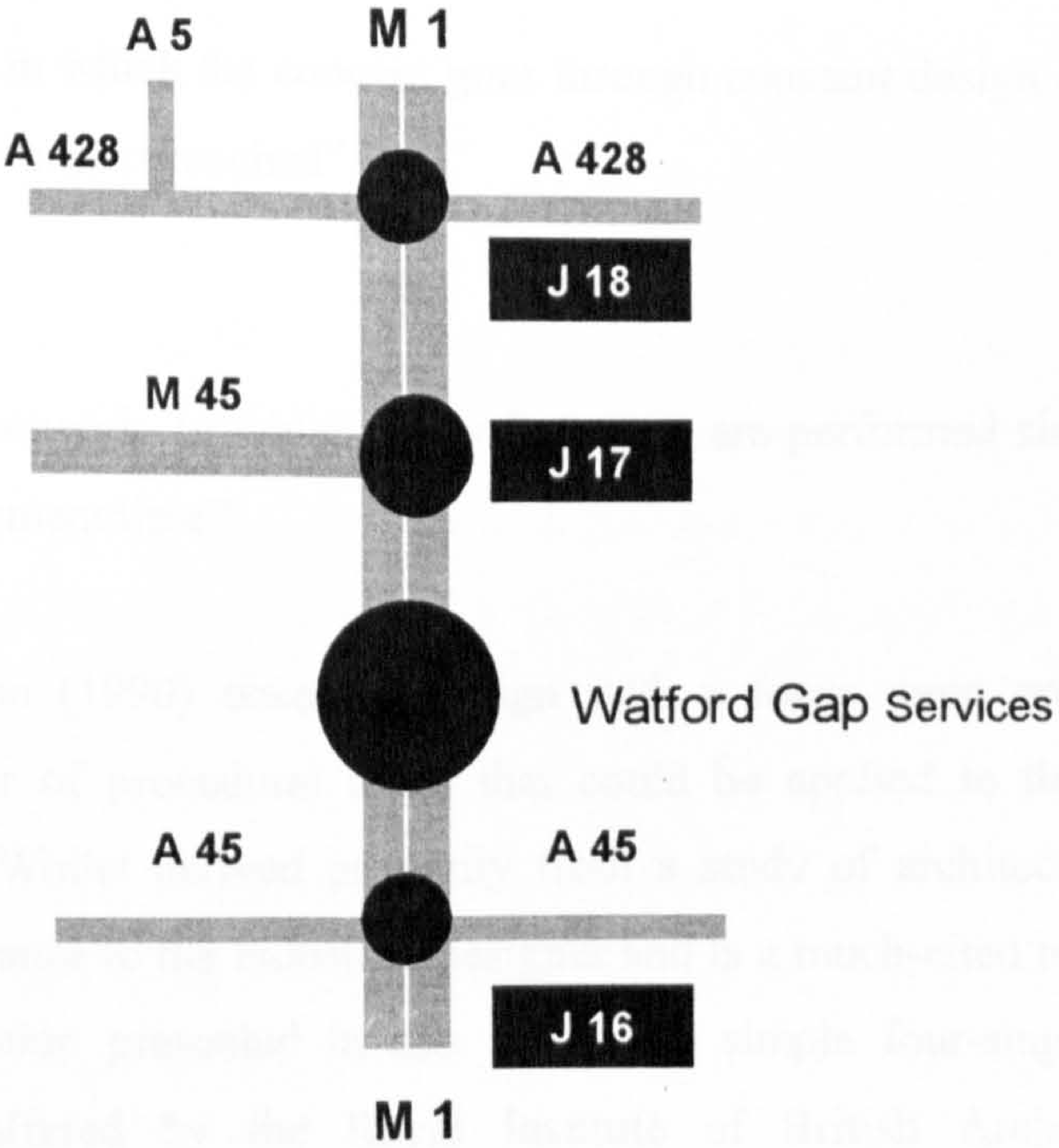


Figure 2.4 – Process Model Analogy (Baxter, 1995, p16)

The road schematic does not suggest that the motorway is entirely straight any more than it suggests that all the junctions form perfect right angles or that that the service area is in the middle of the motorway, where it would block the traffic. It simply shows an overview of the road system, displaying the available options from which a driver must choose when navigating their route. The actual activities that are required to drive along a stretch of motorway such as this are quite complex. Corners must be negotiated, other traffic must be avoided and if the driver misses a junction they must proceed to the next one where they may turn around. None of these instructions are given in the schematic, although the information that it does contain is all that an experienced driver will need to successfully navigate a journey. In the same way, an experienced designer may adapt the overall route that is suggested by a procedural model to suit his or her own particular project.

Holmes (1995) categorises the order in which design stages are applied using the following three procedural groups:

- **Sequential**
  "a linear, step-by-step process in which each stage is completed sequentially"

- **Iterative**
  "a spiral process in which the concept goes through constant design and test steps until a satisfactory outcome is reached"

- **Simultaneous**
  "reliant upon teamwork, in which many functions are performed simultaneously, thus reducing development time"

Prior to this, Lawson (1990) observed design with a focus upon architectural design, identifying a number of procedural maps that could be applied to the development of consumer products. Whilst derived primarily from a study of architectural practice, this work has much relevance to the industrial designer and is a much-cited text within research circles. One observation presented in this work is a simple four-stage generic map of design, which is offered by the Royal Institute of British Architects (RIBA). A representation of this may be seen below in Figure 2.5.

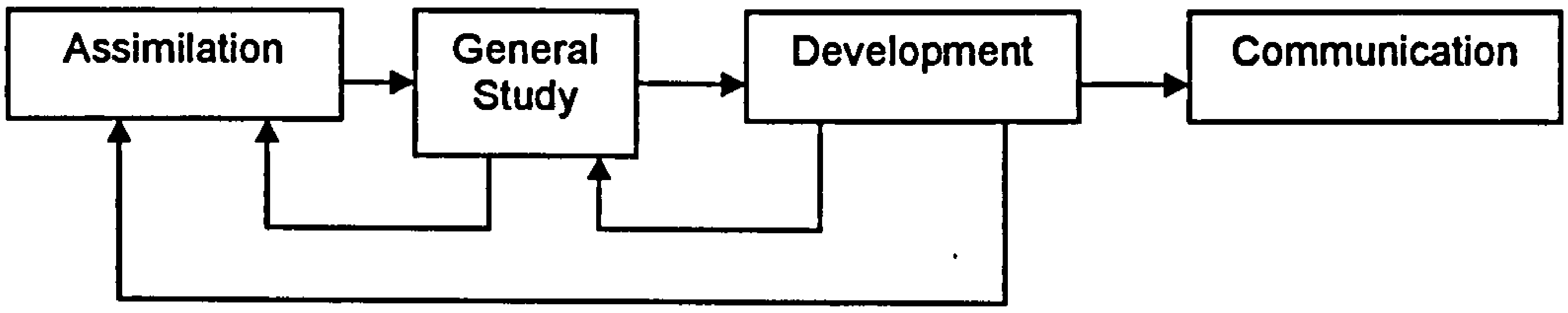


Figure 2.5: RIBA design process map (Lawson, 1990)

The design stages involved in this map are:

- **Assimilation**

  The accumulation and ordering of general information related to the project at hand

- **General Study**

  Investigating the nature of the problem as well as solution and means of solution

- **Development**

  Development and refinement of one or more tentative solutions

- **Communication**

  Communication of one or more solutions to people who may be either inside or outside the design team

One element that features strongly in the RIBA map and others discussed by Lawson (1990) is the possible return of a designer to earlier stages of the design process. He later suggests that the provision of such return loops is crucial to practically all process models. The implication of this is that whilst designers strive to achieve a linear and "*sequential*" product development process, it is likely that their project will at some point involve a cyclic "*iterative*" stage. In general design practice, it would appear that the specific procedural stages and iterations involved in any given project are to a large extent dependent upon the degree of product complexity and criteria that it must meet. Whilst there is no single generally accepted design model, it seems that the majority of designer's use a process that is mostly linear in nature and allows iterative feedback cycles when needed.

Before approaching the topic of design methods, it is necessary to gain an understanding of two critical factors that have particular influence upon the type of design method used. These are product newness and product status, each of which are now discussed.

2.4 Degrees of Newness

Krishnan (2001) defines product development as the transformation of a market opportunity into a product that is available for sale. Within this scope of activity it is the aim of the developer (i.e. any stakeholder involved in getting the product to market) to present markets with new products and capitalise from their exploitation. The magnitude of actual "newness" involved in New Product Development (NPD) projects ranges from the minor redesign or modification of something that has gone before to the generation of something that is entirely new to the world. In each instance, it is the degree of product newness that dictates a project's scale and the complexity of associated systems and recourses.

Ulrich and Eppinger (2003, p38) identify four different types of product development project that they classify as:

- Fundamentally new products
- New product platforms
- Derivatives of new product platforms
- Incremental improvements to existing products

A more comprehensive classification was introduced by Barclay (2000, p12), who used a table similar to the one shown in Table 2.1, to display the six categories of design that were previously identified by technology consultants Booze, Allen and Hamilton.

Definition	**Nature**
New to the World	Entirely New
New Product Lines	New Market Entry
Additional Lines	Supplements
Improvements	Additional "value"
Re-positioning	Into new markets
Cost Reductions	For same performance

Table 2.1: Booze, Allen and Hamilton's newness (Barclay 2000, p12)

Barclay goes on to discuss major and incremental product development, suggesting that incremental changes account for the largest portion of design activity to be observed within typical product development. He substantiates this with Table 2.2 (Barclay 2000, p13), which indicates the results from a survey of 5,000 product development projects as to the nature of product development that was involved.

Development type	**% of total**
Establishes whole new category	Nil
First type on the market in existing category	2
Significant improvement on existing technology	12
Modest improvement/update to existing product	86

Table 2.2: The "newness" of product development (Barclay 2000, p13)

It is from this that Barclay states that "small, incremental changes in products are the rule and major product changes the exception".

Such degrees of product newness can be a key factor in establishing the volume of activity and complexity of organizational approaches that are applied within any product development project. For example, a simple change to an existing product to meet the wants or needs of an established market is likely to involve far fewer resources and stakeholder inputs than the development of a product that is entirely new to the world. However, it is the initial market opportunity and "product status" that dictates what degree of newness is required from the product in question.

2.5 Product Status

When identifying a market opportunity for commercial exploitation an assessment is made of the performance criteria that a product solution would need to meet as well as its potential for capital gain. For a product to be commercially feasible it needs to provide maximum performance for minimum outlay, achieving market expectations without exceeding resource limitations. Here, the definition of "product status" may be used to establish the activities that will be most appropriate for the project in question. This is a concept that was discussed by Hollins and Pugh (1990), who observed design activities as being directed by product status.

Effectively, it is the status of a product that determines the level of innovation that is required for it to either attain or maintain acceptance within a specific market place. For example, the manufacturer of a garden spade has a relatively simple product and, once in general circulation, it is unlikely that they would need to make any sort of revision to maintain their market share. In contrast, an organisation that is involved with mobile telecommunications produces a complex product for a highly volatile market and they would more than likely be expected to make almost constant iterative changes in order to keep their product inline with market expectations and those of other competing companies.

In this example it is possible to identify a divide that exists between two different product groups. This is something that was noted by Pugh and Smith (1976), who observed two distinct boundaries in which product design is fundamentally different.

Pugh (1983) later defines these two groups as being "Static" and "Dynamic". Around the same time Klein (1977) used the same descriptive terms to note the existence of two distinct product groups in which design activity differed. Using S-shaped curves to illustrate the rate of performance function against time, he demonstrates how design activity changes for each group. This may be seen in Figure 2.6, where static and dynamic design phases are indicated by "a" and "b" respectively.

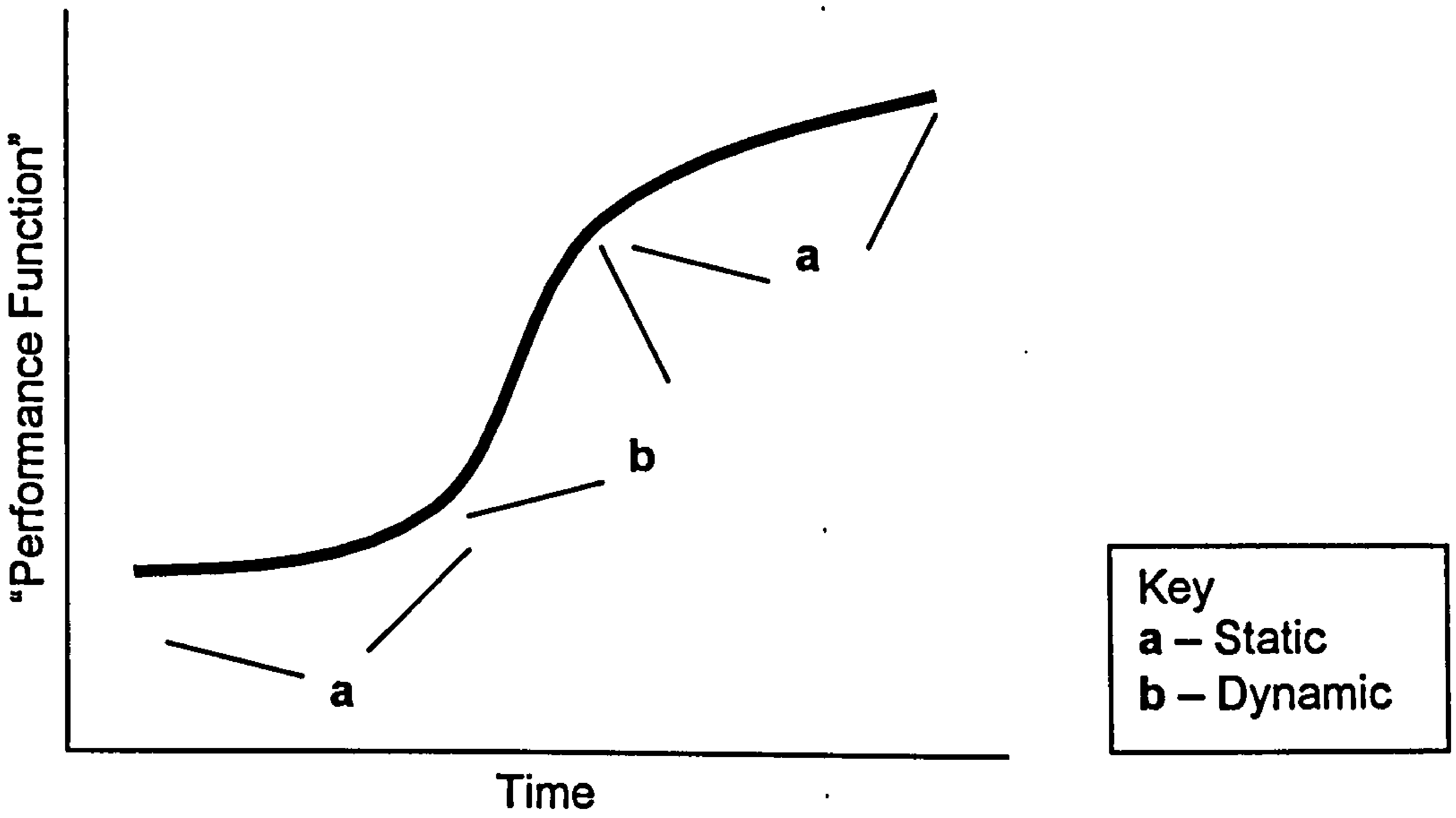


Figure 2.6 - Static and Dynamic Design Phases (Kline, 1977)

Kline (1977) describes dynamic behaviour as that "associated with pioneering new products and processes". He differentiates the two, stating that a static process involves types of change that can be predicted on the basis of initial conditions, whereas dynamic involves unpredictable change in initial conditions.

Hollins and Pugh (1990, p18) note similar observations of product status that were made by others, describing dynamic products with words such as "innovative", "fast", "radical" or even "high tech", and using words such as "evolutionary", "incremental", "dominant", "mature", "slow" or "traditional" to define static products. A two-stage questionnaire is used by Hollins and Hollins (1991, pp106-109) to define a product's status as being either static or dynamic and a series of factors are identified that could be used to classify product status. Compiled from a study of industry, the following list was considered by Hollins and Pugh (1990, pp24-25) as being factors that would classify a product as being Static:

- Limited design time
- Customers not willing to change
- Stable effective product design specification
- Dedicated machinery, automation, CAD, Purchasing new machinery
- Few large producers
- Reducing or stable number of producers
- Poor Market Research
- Stable technology (product static for a long time)
- Market Infrastructure based on existing designs
- Stable/improving environment for existing design
- Conformance to standards
- User familiarity
- Restricted Design (at any level e.g. value analysis)
- Using experience in design
- Using imitation in design
- Restricted product design specification (e.g. same sale outlet, extension of existing range)
- Using rationalisation or commonality of parts between several product components in design
- Assembling components made by others
- Product interfaces with, or is part of, an assembly made elsewhere
- Product available in its present form for a long time (static)
- Insufficient design/finance resources/management commitment

This second list was offered by Hollins and Pugh (1990, p25) to represent the factors that would define a product as being dynamic:

- Adequate time allowed for design
- Customers willing to change
- Change in service design specification
- Flexible machinery, subcontracted features of the service
- Many small producers
- Increasing number of producers
- Wide effective market research (innovative seeking, market pull)
- Technology change
- Ill-defined market infrastructure or infrastructure incapable of accepting new design
- Changing external environment (legislation, economic climate, resources)
- No conformance standards
- Open management design guidelines
- Companies seeking new concepts

An increase in the rate at which new products are developed and introduced (Barclay, 2000) suggests a trend in which the majority of today's products are dynamic rather than static. The effect of this is a general shortening of product development times and an increase of pressure upon product development stakeholders to perform their tasks efficiently. With over 70% of final product costs determined during the design phase (Boothroyd et al, 2001, p4), much focus is placed upon the actions and approaches applied by industrial designers. This has led to the study, generation and application of numerous formalised design approaches.

2.6 Design Methods

Literature on design methods began to appear in most industrialsed countries during the 1950's and 1960's. In these writings attempts are made to formalise the design process and produce comprehensive design strategies. The proceedings of design research conferences provide a rich source of such work. An early example of this is the compilation of Jones and Thomley (1963), which includes the seminal works of Archer (1963) and Alexander (1963)

Pahl and Beitz (1984) provide an extensive account of various strategies that have been developed and applied to the design and development of products, as do Ulrich and Eppinger (2000). Other authors to produce similar literature include Buggie (1981), Suh (1990), Cross (1994), Jones (1997), Wright (1998) and Stoll (1999). One reference of particular use in the study of various design methods is that of Jones (1992), which gives a detailed description of thirty-five specific design strategies, along with his own views and design hypotheses.

In the book written by Jones (1992) two design methodologies are observed in which designers exist as either "Black Boxes" or "Glass Boxes" in an analogy that is used to symbolise two different design approaches. Here "Black Boxes" are shown to be intuitive problem solvers who move from problem to solution in a single step that involves little or no external processes, their thoughts shrouded in mysticism. Jones argues that this type of designer does not have total control over their creative thoughts, implying that their creativity occurs as if it were an involuntary reflex response. In this design approach it is difficult to observe the continuity required to formulate any replicable method or methods. In contrast however, Jones (1992) defines the design process applied by "Glass Boxes" as being entirely explicable, even though some designers are unable to give convincing reasons for all of the decisions that they make. This group is well suited to externalised thinking and it is from such that the majority of design methods are derived, based more upon systematic order and rationale than intuitive assumptions.

A method of systematic design is offered in the early work of Jones (1963) that was based largely upon methods appearing in publications of the day and those of the previous ten years. Around the same time, and with same objectives, Archer (1963) produced similar material regarding a systematic method for designers. Analysis and evaluation were strong components of these methodologies, both of which employed the use of tools such as Interaction Matrices and Charts.

2.6.1 Matrix Based Methods

The use of matrices appear in many of the methodological approaches that have been constructed and applied to the development of new products. An early example is that of Alexander (1963) whose use of matrices has been adopted and applied to many different areas. Jones (1992) provides a detailed overview of Alexander's method and its application in product development projects. Other specific matrix methods applied to product development include Design Structure Matrix (DSM) and Quality Function Deployment (QFD).

In Design Structure Matrix (DSM) a matrix is used that may contain the internal relationships of any system. Figure 2.7 shows a basic DSM matrix. System features are aligned along horizontal and vertical axis with the diagonal axis that runs through the middle of the matrix used to represent the correlation of each of these features. If any two features are related, the information regarding that relationship is entered in the linking cell. This is shown in the following diagram where the relationship between F1 and F4 is marked with a star.

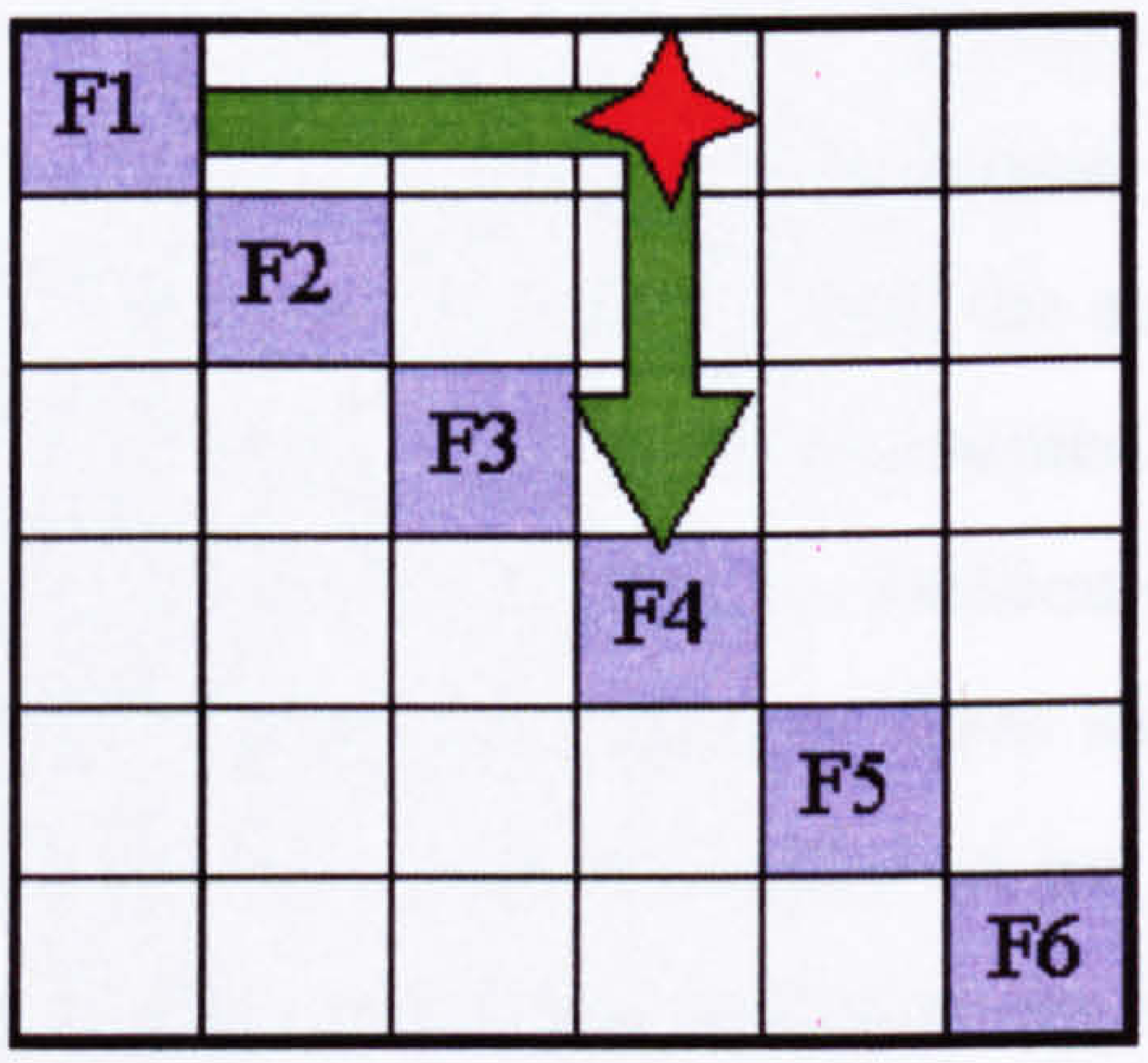


Figure 2.7 – Basic DSM matrix structure (Battersby, 2005)

DSM matrices are directional and it is possible to plot a backwards path. This is shown in below Figure 2.8 in the relationship that exists between F5 and F2.

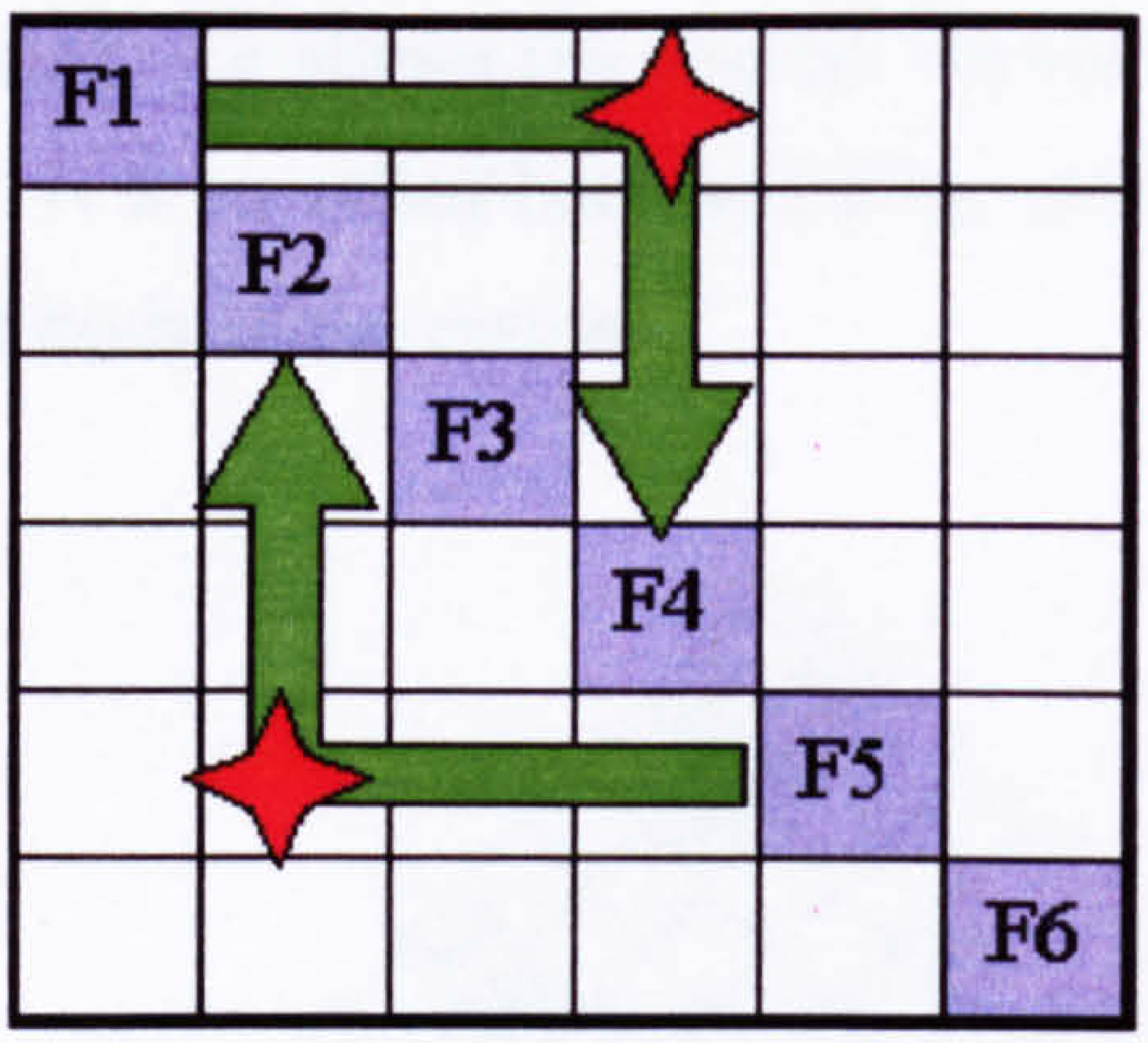


Figure 2.8 – Bi-directional function of DSM matrix (Battersby, 2005)

Typically DSM is applied to any application where relationships exist between the entities of a system. Product development examples include project management relationships between departments or the definition of interrelated requirements within a design specification. Carrascosa (1998) observes one such application, in which DSM is used in the estimation of product development time.

Quality Function Deployment (QFD) is a more complex matrix-based tool that is applied within the sphere of Total Quality Management (TQM). Whilst it is the Japanese who are often credited with conceiving TQM, the approach actually originated in America, and it was the Americans who first implemented its use in Japan at the end of World War II. The definition of TQM given by Dhillon (1988, p151) is "a quality emphasis that encompasses the entire organisation, from supplier of parts/services to customer". In achieving total quality, and the ability to get things right first time, an organisation is able to minimise waste and improve the efficiency with which its resources are used. In this quality-centred approach, QFD is a tool that is used to correlate the various "whats" and "hows" of a project, and establish how they are to be achieved. Detailed explanations as to the structure and application of QFD within product development cycles may be found in the work of Ulrich and Eppinger (2000) and Cross (1994), amongst others.

The diagram below in Figure 2.9 shows the typical "house of quality" matrix applied within the stages of QFD. It is so called because of the roof shaped correlation matrix that sits on top of the main body of the matrix.

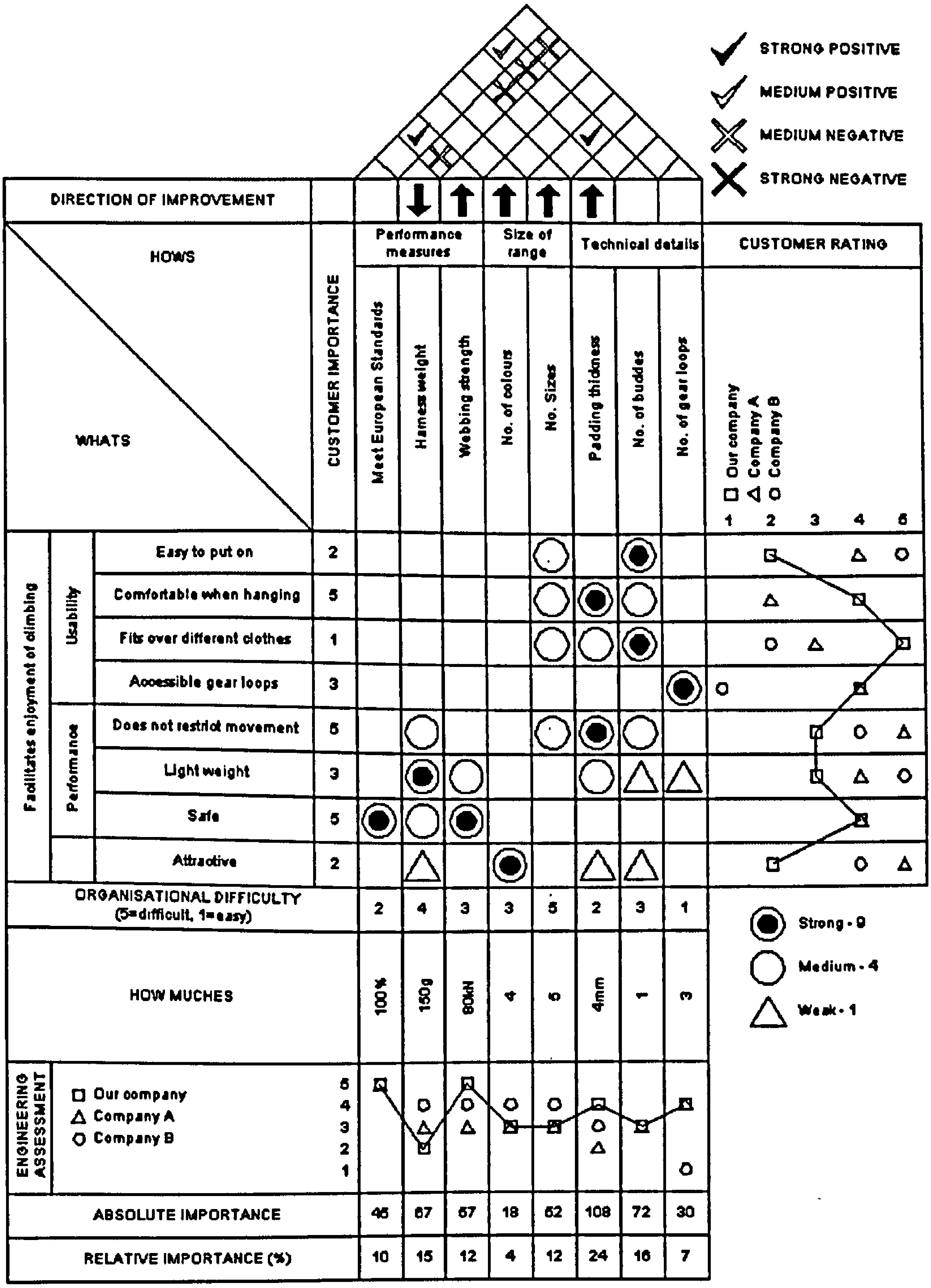


Figure 2.9 – "House of Quality" matrix (Lowe, 2005)

Other approaches and tools that have evolved from the TQM philosophy include Just In Time (JIT), the Kanban system and the Taguchi method. Details of these may be found in work of Lu (1986) and Suh (1990).

A key principle of the TQM approach is that it considers and involves input from all of the stakeholders that are involved in the development of a product. This concept is common to another approach that is discussed by Pugh (1990, p5).

2.6.2 Total Design

In the book "Total Design", Pugh (1990) introduces the idea of "Total" and "Partial" design in terms of the sectors that are involved within a typical product development project. It is stated that "total design" includes everything from identifying a market need, through concept design, development, manufacture and sale of the product, whereas "partial design" concerns itself only with the incremental activities that go to make the whole. A similar view is taken by Hollins and Hollins (1991, p200) who discusses total design stating that, "Design is the total activity necessary to bring about new products, whereas innovation is only one aspect".

Pugh (1990) describes how the success or failure of a product is dependent upon how effectively it meets each and every one of numerous stakeholder requirements and expectations. For example, a company may produce a product that is perfectly engineered but if it fails to meet the cost expectations of either the customer or the finance department it will be unacceptable and deemed a failure. Total Design encompasses everything from the initial conceptualisation of an idea through to the sale of the final product. In this approach, effective product development relies upon collaboration of all the sectors involved. A model is offered by Pugh to represent the various sectors that are involved in this approach and the different interactions that take place between each. This model may be seen in Figure 2.10.

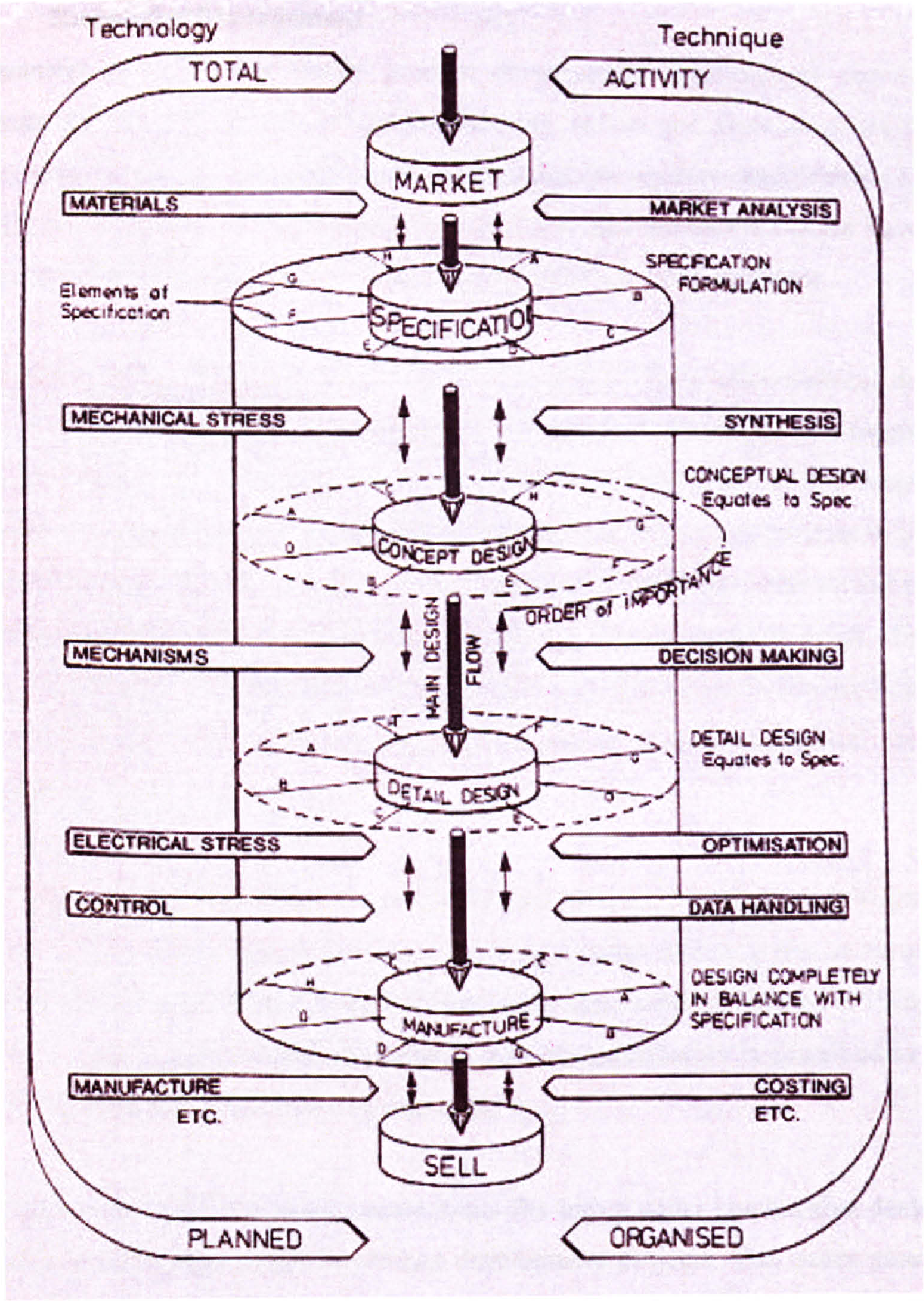


Figure 2.10 - Total Design Activity Model (Pugh 1990, p11)

Communication between project stakeholders at key stages of development is a strong feature of this design approach, in which various tools are used for the transference of project information and knowledge.

2.6.3 Knowledge Management

The transfer of knowledge within product development organisations ensures that resources are used efficiently, shortening learning curves and preventing individuals from constantly "re-inventing the wheel". Knowledge management and decision support tools play an important role in product development, and numerous studies have been conducted to develop various knowledge-based problem-solving strategies.

The actual definition of knowledge has been the goal of many philosophical debates, some of which are noted by Freeman (2001). In this work he offers an interpretation based on a hierarchic order that is composed of three categories. He lists these three categories as being data, information and knowledge. The first or lowest level to be used in the classification of "that which is known" is *data*, or "raw facts". The second level is *information*, derived from "interpretations of the data from a particular point of view". Finally, the third level is that of *knowledge*, which is described as "information that has been validated and is thought to be true, and equivalent to the philosophical 'justified true belief'".

In an observation of knowledge usage within new product development, Rodgers and Clarkson (1998) differentiate information from knowledge before going on to classify various types and areas of knowledge. In this work, knowledge is defined as being "the part that is held in an individual's memory", whereas information is described as being "everything recorded external to a human mind".

This observation aside, the study's main focus fits into a wider context that deals with the issues of knowledge usage in product development projects. The issues associated with this area include storage, retrieval and application of useful knowledge. This in part leads to the vast field of Decision Support Systems, in which Knowledge Based problem solving tools and strategies are applied. Included in this area are tools such as Databases, Knowledge Bases, Case Based Reasoning and Artificial Intelligence systems. Introductions to these may be found in the work of Frost (1986), Kowalik (1986) Sprague (1993), Finlay (1994) and Turban (2001).

2.6.4 Design For Manufacture and Assembly

As mentioned earlier in this chapter, frictions between industrial design and manufacturing have been greatly reduced through the application of strategies that increase designer awareness of various manufacturing needs. An approach that has been instrumental in this is Design For Manufacture and Assembly (DFMA). This approach has been widely used throughout industry for over twenty years and is responsible for a revolution in the way that products are designed and developed (Boothroyd, 2001). Greater consideration at the design stage as to how products will be manufactured has also given rise to the increased use of what is known as Concurrent Engineering, in which the simultaneous action of designer and engineer replace previous linear cycles described by Lawson (1990) and Holmes (1995).

Whilst Design For Manufacture (DFM) has only become commonly recognised and used by industry within the latter part of the 20th century, there are documented examples of its principles that date back at over two hundred years. One example is that of a Frenchman called LeBlanc, who devised a concept for use in the manufacture of muskets in 1788 (O'Driscoll, 2002).

The approach used by LeBlanc was to take parts that had previously been individually hand made and replace them with ones that were interchangeably standardised. Basic manufacturing processes were developed for repeatability and a series of limited tolerances were implemented as to which all components were made. The result was that muskets made using LeBlanc's approach could be produced more quickly, cheaply and reliably than any other craftsmen had previously been able to achieve. In this example, and in other more recent ones, it is the aim of DFM to improve the ease with which a product can be made, hence reducing the costs required to manufacture it. In each instance this is achieved by equipping the designer with procedural knowledge of manufacturing systems and their best use requirements.

Stoll (1991) makes an observation of general product design for efficient manufacturing and outlines the following knowledge based principles as being components of an effective Design For Manufacture Assembly strategy:

- Minimise the total number of parts:
- Develop a modular design:
- Use standard components
- Design parts to be multi-functional
- Design parts for multi-use
- Design parts for ease of fabrication
- Avoid separate fasteners
- Minimise assembly directions
- Maximise compliance
- Minimise handling

DFM principles such as these are commonly applied unknowingly by experienced designers and engineers with whom lies a tacit knowledge derived from the understanding of a particular manufacturing process. Effective DFM relies upon the efficient storage, retrieval and application of such knowledge. Research in the areas of DFM and DFA has produced a number of formalised systems that do just this.

Commercially exploited DFMA techniques in current use include the Hitachi Assemblability Evaluation Method (AEM), the Boothroyd Dewhurst method and the CSC design for assembly / manufacturing analysis DFA/MA technique (first developed by Lucas Industries). These approaches are discussed by Miles and Swift (1989), who's conclusion is that, whilst such methods require more initial input than certain other design methods, their overall effect is to considerably reduce the time taken to bring products to market.

The first formalised DFMA systems to appear in the 1970's and early 1980's were paper-based, using tables and booklets. However, in recent years the advancement of digital technology has led to the evolution of advanced DFMA computer software tools for designers and engineers. The Internet website of Boothroyd and Dewhurst (2005) details one such example. With a computer on virtually every desk and a growing number of computer literate designers, software tools such as these are being used throughout industry and in a variety of product development projects.

2.6.5 Value Analysis / Engineering

Design for manufacture and assembly strategies enable designers and engineers to conduct their work with more economical throughput and fewer manufacturing related design revisions. However, the overriding factor that is present throughout all of these strategies, and the product design process as a whole, is that of cost. Whilst it is the manufacturability of a concept that dictates its feasibility for possible production, it is budgetary constraints imposed by the project's financial controllers that will often be the deciding factor in what is actually produced. Hence it is just as important to have systems to aid the design of products in terms of cost criteria as those of manufacturability. Of such cost centred design approaches, it is perhaps Value Engineering (VE) that is most widely recognised.

Value Engineering first originated in the 1940's during the Second World War, when strategic materials to support the war effort were in short supply. Harry Erlicker and Lawrence D. Miles of the General Electric Company in America pioneered a systematic system that they called Value Analysis. When applied to production processes their method was found to make significant improvements. The approach was developed and applied successfully to other industries, where it later became known as Value Engineering (Neap, 1999).

Essentially, Value Analysis strategies enable decision makers acting within various product design and development processes to assess a product in terms of value and worth, looking beyond the simple bottom line costs.

In defining Value, Miles (1972, pp4-5) states that:

1. Value is increased by decreasing costs whilst maintaining performance

2. Value is increased by increasing performance if the customer needs, wants and is willing to pay for more performance

He points out that "maximum value" is probably never achieved, as the degree of value in any product is dependent upon the effectiveness with which every usable idea, process, material and approach is identified, studied and utilised. In this instance it must be assumed that human fallibility accounts for less than 100% efficacy. Hence the purpose of value analysis is to provide a means of assistance in establishing what are the best value combinations.

Kermode (2000) observes the techniques employed within Value Analysis, and defines value as follows:

$$\textbf{Value} = \frac{\textbf{Function Cost}}{\textbf{Actual Cost}}$$

In which:

Function Cost = the lowest possible cost for reliably providing the required function at the desired time and place and with the essential quality.

Actual Cost = the cost of providing the function in the existing design; this is higher than the function cost owing to superfluous design features.

Value = the efficiency of the design, i.e. how well the product provides the function.

In this definition, an increase in value is achieved through an increase in functionality and / or the reduction of cost. The assumption is that, once a product design is frozen in terms of functionality, there is one theoretical "function cost" and it is the least possible "actual cost" that provides all of the functions at an acceptable quality. It is the purpose of Value Analysis to achieve this cost with the real-world products.

Examples of Value Analysis may be found in manufacturing processes that involve high capital investment, such as plastic injection moulding. The cost of manufacturing production tooling for the plastic injection moulding industry is often seen as being exorbitantly high, something that attracts much attention from value analysts. Typically these high costs are amortized through the massive production volumes that the tools are capable of producing. In such cases, a well-made injection mould tool may produce millions of components in its lifetime and by dividing the initial purchase price by the number of units made usually results in a relatively small price per unit. On this basis it is often possible to cover the tool purchase cost within the profits that are generated from the sale of the first year's production quota. In this instance the tool's value is basically offset against the production volumes it is capable of producing and the revenue it is likely to return. However, there are many other factors that would be considered in the generation of a tool specification made prior to commissioning the build of a tool, which lend themselves very well to Value Analysis techniques.

For example, an injection mould tool may have multiple impression cavities so that it can be used for producing more than one component at a time. Naturally the complexity and manufacturing of multi-impression tools is reflected in their price, which is usually much greater than it is for those with more simple single cavities. An inexperienced individual may attempt to reduce initial overheads by specifying a tool with a lesser amount of cavities. However, with no consideration given to downstream production requirements, it is likely that this will be a false saving. There may be a demand for the tool to produce five million components within a particular timescale. In this instance, increasing the number of tool cavities would increase the number and speed at which products may be produced. As a result, not only are the factory overheads during manufacture minimised but so is the time taken to get the product to market and the time taken for profit revenues to be recouped.

Another example would be the addition of a mechanical feature within a mould tool's construction that cleanly removes and separates waste feed material from the moulded part. The inclusion of such a feature may add extra expense to the cost of a procured tool although it would likely prove it's worth during subsequent manufacturing processes. Firstly, any automated device removing the need for an employee to spend numerous hours manually cutting and separating moulded parts from sprues would also remove the need to spend the money needed to pay them. Secondly, by making the process autonomous, the level of standardisation in sprue removal and associated witness marks would be improved adding to the perception of product quality.

In each of these instances, savings are made in the form of reduced factory overheads that would have otherwise eaten into potential profits. Savings such as these are often more than likely to cover the additional tooling expenditure and it is through the application of value analysis strategies that they become easily apparent.

2.7 Chapter Summary

In this chapter a number of interpretations have been offered to define the practice of industrial design. The industrial design process has been shown to encompass numerous activities that take place between the initial identification of market opportunity and final production of saleable product. The degree of newness that is involved within any product development project has been shown to vary in scale from something that is completely new to the world to the slight or minor modification of an existing product. The concept of product status was discussed, identifying both static and dynamic categories. An introduction has been made to some of the many approaches that have been formalised and applied to the design and development of new products. From this, specific attention has been given to design strategies developed around the key areas of product manufacturability and economic viability.

It is intended that this chapter provide a methodological study of industrial design prior to a continued discussion in which some more commonly applied design communication and realization tools are observed. This discussion takes place in the next chapter, which looks at the increasingly large array of design media that form an essential part of any NPD project.

3 DESIGN MEDIA

3.1 Overview

In the previous chapter a number of formal design strategies were discussed, although little mention was made of the increasingly large array of creative media that form an essential part of any design project. Therefore, it is the aim of this chapter to provide an overview of various tools, techniques and technologies that are applied to the design and development of new products. Design For Manufacture (DFM) and Design For Assembly (DFA) were previously observed as strategies that facilitate efficient product design through increased process awareness. Similarly, it is intended that this latest discussion be used to foster an understanding of general design media upon which recommendations for a process-specific design strategy or aid may be made.

Traditionally, paper-based drawing and sketching has been used alongside physical three-dimensional models and prototypes for the communication and evaluation of design intent within development projects. However, the advancement of computer-based technologies in recent years has resulted in their widespread application within the field of product design and development. Early Computer Aided Design (CAD) systems enabled the two-dimensional drafting of plans and engineering drawings in such a way as to make them easily repeatable and transferable. Developments in three-dimensional CAD enabled entirely new levels of communication and representation within product design. When combined with Computer Numerical Control (CNC) machining systems it became quicker and easier to manufacture complex parts using code generated from CAD data. Later, the arrival of Rapid Prototyping (RP) systems introduced another medium through which to produce physical objects directly from 3D

CAD data. All of these different systems will now be discussed, noting the role that each plays in the design and development of new products. Ultimately, these observations will be used to ascertain how and where a process specific design aid may be best applied.

3.2 Drawing and Sketching

Purcell (1998) notes that the use of different types of drawings is a characteristic that is present in all areas of design. Powell (1990) advocates the importance of drawing in the design process, stating that "an industrial designer who cannot draw is certainly less efficient and almost always less creative than one who can".

The marks made on paper by designers and engineers during the design process are identified by Ullman (1990) as belonging to two categories, which he defines as "formal drafting" and "informal sketches". He describes how drafting is used to represent the final designs that are the end result of the design process, whereas sketching is more associated with rough ideas and used as a method to assist in making ideas take shape.

The formal drafting of technical engineering drawings, which is identified by Ullman (1990), is a practice that designers and engineers must be taught. Various standards and specifications exist to which each drawing must conform. Examples of these include International Organisation for Standardisation (ISO) standards and BS 8888:2004 Technical Product Documentation (TPD). The latter of these examples is the current British Standard for defining, specifying and graphically representing products. Such drawings are used in the archiving and communication of completed designs between different designers and manufacturing personnel. The application of standard drafting approaches ensures that such engineering drawings have a universal comprehensibility. Hence it is possible for a trained eye to "read", rather than "interpret", these drawings, no mater where they were created or by whom. Figure 3.1 shows the layout of a typical engineering drawing.

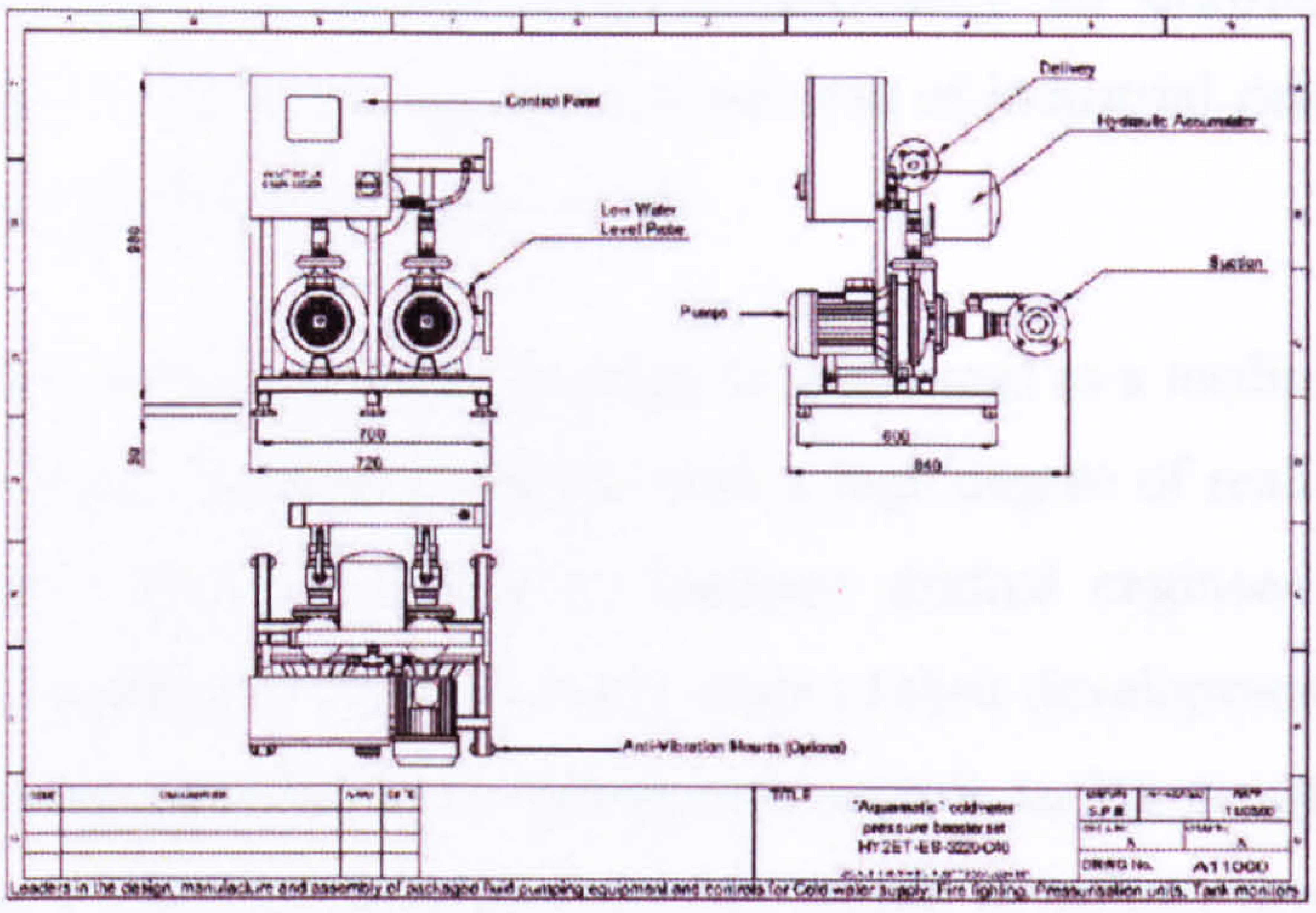


Figure 3.1: technical drawing of a product

(Source: < http://www.cad-bureau.co.uk > 18/05/05)

In contrast, informal sketching is an intuitive action that may be performed by anyone and requires little or no specialist training. However, the quality of visualisation and representation in sketches is largely dependent upon the skill and ability of their creator. An individual's styling and technique will often influence the composition of sketches and, with little need to conform to fixed rules or conventions, their interpretation is often quite open. The resulting vagueness that occurs in many sketches mean that they are often unsuitable as a means of communication with those who are outside of the immediate sphere of design. Figure 3.2 shows concept sketches of a hand brake lever design, the form of which might not be immediately apparent to those who are unused to viewing such design sketches.

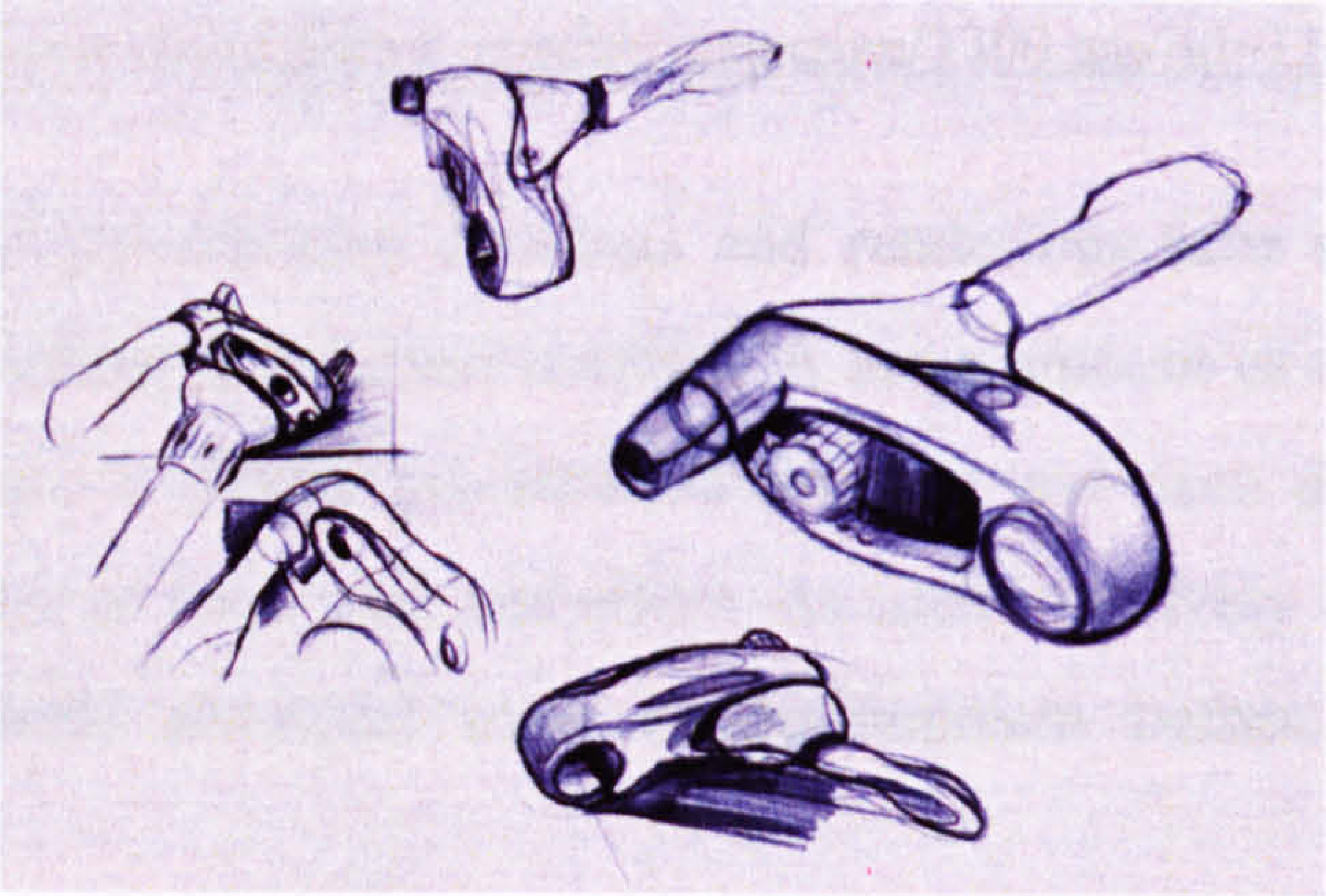


Figure 3.2: A loosely sketched design concept

(Source: < http://www.cadinfo.net/editorial/sram.htm > 18/05/05)

The two aforementioned categories classify practically all drawings produced by engineering designers. However, the same is not true of industrial designers for whom an entirely different additional category exists.

Industrial designers use presentation drawings or renderings as a medium through which they are able to convey conceptual designs with a high degree of realism. This enables project stakeholders, who are unable to interpret drafted engineering drawings, to visualise design concepts at a relatively early stage of their development, something that is often crucial in securing funds for subsequent manufacturing processes. Hence it is not uncommon for a whole product development project to balance upon the strength of an industrial designer's presentation rendering. A highly instructional work in the area of presentation drawing and rendering is that of Powell (1990), which is often cited as required reading amongst students of industrial design. Figure 3.3 shows examples of typical presentation renderings that would be used in a product development project.

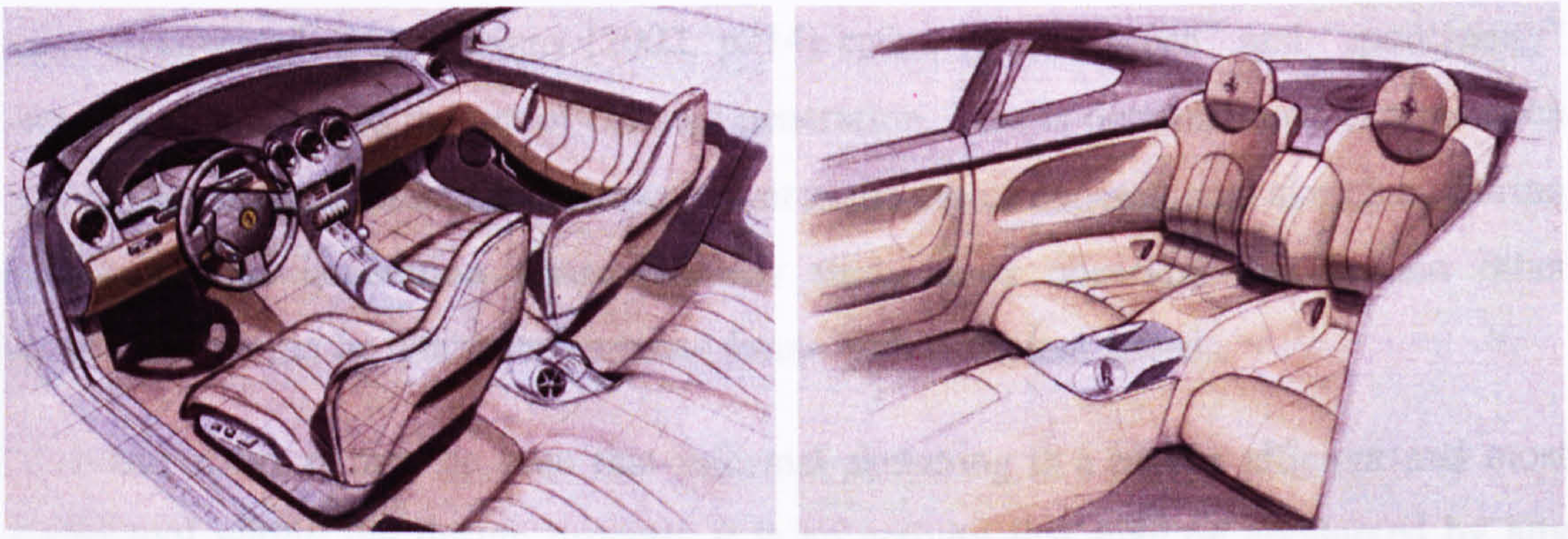


Figure 3.3: Presentation renderings of a proposed car interior
(Source: http://www.classicdriver.com/uk/magazine/3300.asp?id=11680 > 18/05/05)

The classification of presentation drawings and renderings falls somewhere between that of informal sketching and formal drafting. A large amount of training and practice is required to produce a quality presentation drawing and each drawing represents a substantial investment of both time and effort. As such it is likely that design concepts will be at a relatively advanced stage of development before such drawings are produced.

Of the categories introduced, the one that appears to be the most universal is that of informal sketching. In establishing the importance of sketching within design, Lipson (2000) identifies the instinctive reaction that occurs when first given a design problem, which is to reach for a pencil and paper. Acting upon this instinct, designers would traditionally grab the first thing to hand for sketching upon, spawning a number of terminologies that are used to describe initial design sketches. Even when the first thing to hand is a pad of quality drawing paper the phraseology often remains the same. Hence, the statement that a sketch is on the "back-of-an-envelope" is more likely to reflect the immediacy with which it was created rather than the medium upon which it was drawn.

In discussing the simplicity of materials involved, Evans (1998) observed how sketching enables the manipulation of design ideas using little more than a pen / pencil and piece of paper. In the same work he notes the comments of Kojima (1991), who regards sketching as being "most efficient in the sense that it is the cheapest and least time-consuming". Later, Evans (2002, p214) refers to the "speed" and "spontaneity" that sketches bring to the act of concept generation. This is demonstrated in a research case study, where preference is shown towards the use of conventional sketching during initial concept generation phase. In this study it is observed that certain other approaches would be unable to generate forms with sufficient speed.

From the above it may be seen that informal sketching is a highly efficient and most useful tool within the design process. It is an activity that may be conducted by any individual and in practically any environment. The relative cheapness and availability of materials required make it a highly accessible medium with which to rapidly generate concept designs. This combined with the instinctive reaction of a designer to reach for pen and paper during the early stages of problem solving ensures that sketching is likely to remain a key element within product design.

3.3 Models and Prototypes

Physical models and prototypes play an important role in the design of products and provide a means of conveying design concepts with a far greater sense of scale and realism than is possible with paper based techniques. Evans (1992) states that the translation of design ideas from the drawing board to a three dimensional representation marks a key stage in the development of a product. Vervis (1994) discusses the importance of physical models in design and their use in determining the suitability of products prior to final construction. The use of physical models over non-physical methods of representation is also supported by Broek (2000), who notes the role they have in communication and improved designer creativity.

An attempt is made by Vervis (1994) to describe differences between what he defines as "engineering models" and "industrial design models". In this definition engineering models are seen to range from simple card constructions to fully engineered representations of final product designs that are made prior to full-scale manufacturing. The scope of such models includes everything from proving a simple engineering principle to the construction of a fully working product simulation. In contrast, industrial design models are seen as being concerned with aesthetic form and the affect that it has upon product functionality.

Approaching the same topic from an industrial design perspective, Evans (1992) provides a definition that distinguishes "models" from "prototypes", before identifying various subsets within each group. In this definition, models are seen as being an approximation of a product whereas prototypes are more likely to reflect the qualities of the final article. In the same work it is noted that the scaling of size is considered to be an essential aspect of models when full size representation is uneconomic or impossible to achieve. It is pointed out that this is largely applicable to engineering designers, when the size and scope of their work calls for scaled representation. Industrial designers, who are more concerned with visual and ergonomic aspects of a product, will generally work in full scale. However, in either case there is a preference to work in full scale whenever feasible so as to ensure the most accurate assessment of the model.

Emori (1977) refers to two forms of models that he identifies as being "subjective" and "qualitative". Here subjective models represent a total concept that may have little or no feasibility as a production item. The example that is given by Evans (1992) is of a solar powered lawnmower, where the principle objectives are to identify form and use.

Qualitative models would have the outward appearance of a proposed product but lack proper functionality. Industrial designers commonly refer to this latter type of representation as being a block model.

In general prototypes are seen as being distinct from models in that they are always the same size as the system that they represent. This is supported by Luzadder (1975), who defines prototypes as being "a full-size working model of a physical system". However, the main difference that exists between a model and a prototype is the degree of realism that each one incorporates. A prototype that is produced in the latter stages of design should provide the closest representation of the final production part possible without employing the final production process or methods of manufacture. This is a view which is held by Mayall (1979) who believes a designer should get their prototype as close to the production model as possible.

Of the various different models and prototypes commonly applied to product design and development Evans (1992) identifies the following groups:

- Sketch model
- Foam model
- Principle Model
- Block Model
- System Prototype
- Tooling Prototype
- Off Tool Prototype
- Pre-Production Prototype
- Production Item

A hierarchic order exists amongst these different groups, which is commonly acknowledged as beginning with a rudimentary card or foam model and ending with a fully working realistic prototype product.

The use of preliminary sketch models, made from card, clay or foam, enables designers to realise conceptual ideas with a greater sense of scale and spatial awareness than is possible in paper based techniques. In later stages of product design and development, more advanced models and prototypes provide a highly effective means of communication between designers and other project stakeholders. Final pre-production prototypes allow user trials and testing to be conducted with a realistic product, highlighting potential need for change and preventing costly post-manufacturing product recalls.

Many designers would argue that no method of communicating conceptual product designs is more effective than the use of physical models and prototypes. When given a realistic physical representation of a final product there can be little room for any misunderstanding as to what it will look like or how it will perform. The result of this is better communication of product design amongst development stakeholders, leading to fewer mistakes and allowing any necessary design changes to be made at an early stage, before they become too costly. As such, the use of physical pre-production models and prototypes is likely to remain an integral part of the product design and development process.

3.4 Computer Aided Design

Computer Aided Design (CAD) has in recent years become an integral part of product design and development. A diverse selection of specialised packages and additional components has evolved to cater for specific professions and applications. Computer Aided Industrial Design (CAID) attempts to encompass typical industrial design activity by incorporating fluid sketching interfaces and advanced rendering capabilities alongside state of the art 3D modelling. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) represent two areas of CAD that are used for the analysis of structures in a virtual environment. Specialist software has also been developed to process data for various ancillary methods of computer-assisted manufacture. In addition to this is an increasing number of Reverse Engineering (RE) packages for dealing with surface data collected by 3D scanners and digitizers.

The origins of all these technologies date back to the late 1950's when Dr. Patrick Hanratty developed the first commercial numerical-control programming system called PRONTO in 1957. Three years later Ivan Sutherland developed SKETCHPAD, which is commonly acknowledged as being the first real precursor to the modern CAD industry. In 1962 Environectics of Chicago developed a machine called the Man-Mac for the drafting of plans for interior office space. Towards the end of the same decade ITEK and General Motors were in competition to produce vector-based design applications. As a result the Control Data Corporation produced Digigraphics, which was based upon the work of ITEK and became the first commercially available CAD system.

Throughout the 1970's several companies began to offer automated design/drafting systems, and by 1980's the number of companies creating and marketing software had grown to 85. Out of all of these it was AutoDesk that rose to the top and by the mid-eighties it had attained the strongest of holds on the commercial CAD market. Throughout the 1990s developments in 3-D modelling continued to advance, evolving from wire-frame into surfaces and solid models before moving on to constraint-based modelling, an element that is currently a mainstay of almost all CAD packages. Knoppers and Hague (2005) discuss the evolution of CAD technology, placing an emphasis upon the largely design driven developments that have taken place to enable the generation of increasingly complex part geometries.

A major development within the sphere of CAD technology was that of constraint-based modelling, which brought about many changes in 3D CAD drafting practices. Prior to this, CAD models were constructed as dumb fixed geometries and changes often meant the entire remodelling of parts. Constraint-based models differed in that they list the composite features that are used to make up the whole part. Each time a new feature is created the list of features, or "tree", is updated and the whole model is rebuilt. The benefit of this over earlier systems is that the constraining features may be changed at any time and in any order. Figure 3.4 shows a screen image that is taken from typical constraint based CAD package. The model's defining feature tree may be seen to the left of the image.

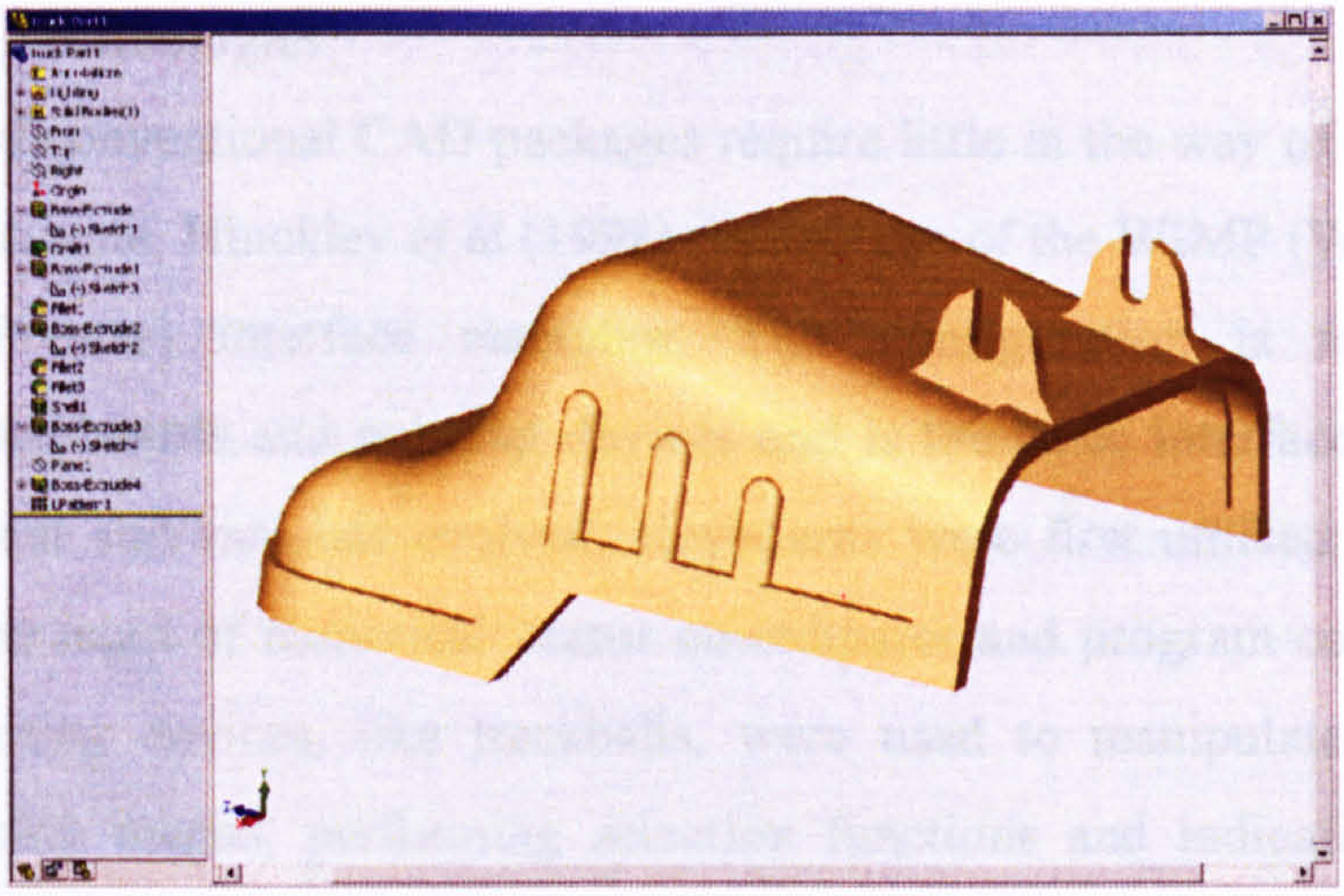


Figure 3.4: Constraint Based Modelling

The evolution of technology does not stand still and future CAD systems are likely to undergo many more changes and additions. As the performance of mainstream CPU's increases and software applications become more advanced the boundaries of what may be achieved in terms of geometric complexity are pushed further and further forward. At the present time, Automotive, Marine and Aerospace industries all produce vast CAD assemblies of their vehicles. An example of this is the Boeing 777, which was the first commercial aircraft to be designed with CAD solid modelling. The total CAD assembly for this particular aircraft contains over five million components, the display of which requires over 5 Gigabytes of computer memory. At the turn of the millennium, the Boeing Company was reported to dedicate around 14 Terabytes (14,000 Gigabytes) of computer disk space to the storage of commercial airplane geometries (Kasik, 2000).

3.5 CAD Input

MacKenzie (1995) states that one enduring trait of computing systems is the presence of the human operator. Currently no computer system exists that is entirely automated and for data to be processed it is necessary for human operators to conduct physical input by one means or another. The result of this is a diverse range of devices and technologies that exist so that users may interact with and control various computer systems and software. The CAD sector is no exception to this and an array of specialised technologies has been developed to generate, manipulate and interact with data in virtual 2D and 3D environments.

3.5.1 Input Technologies

The majority of conventional CAD packages require little in the way of specialist input devices. For example, Hinckley et al (1998) discuss use of the WIMP (Windows, Icons, Menus and Pointer) interface metaphor. This configuration is made up from alphanumeric keyboards and pointing devices and is the basic interface around which much subsequent software has evolved. Keyboards were first utilised by early CAD software for the input of numerical vector co-ordinates and program commands. Mice and other pointing devices, like trackballs, were used to manipulate the on-screen pointer, accessing menus, performing selection functions and indicating co-ordinate vectors. Even with the huge advances in computing capabilities that have taken place in recent years, these peripherals remain primary input devices for the majority of mainstream CAD applications.

An alternative WIMP device of particular interest to designers is the digitizing tablet, which is used in conjunction with a stylus or puck. Moving either puck or stylus across a tablet's surface will move the on-screen curser, replicating the various functions of other pointing devices. Figure 3.5 shows a typical digitizing tablet, complete with pen-like stylus and mouse-like puck.

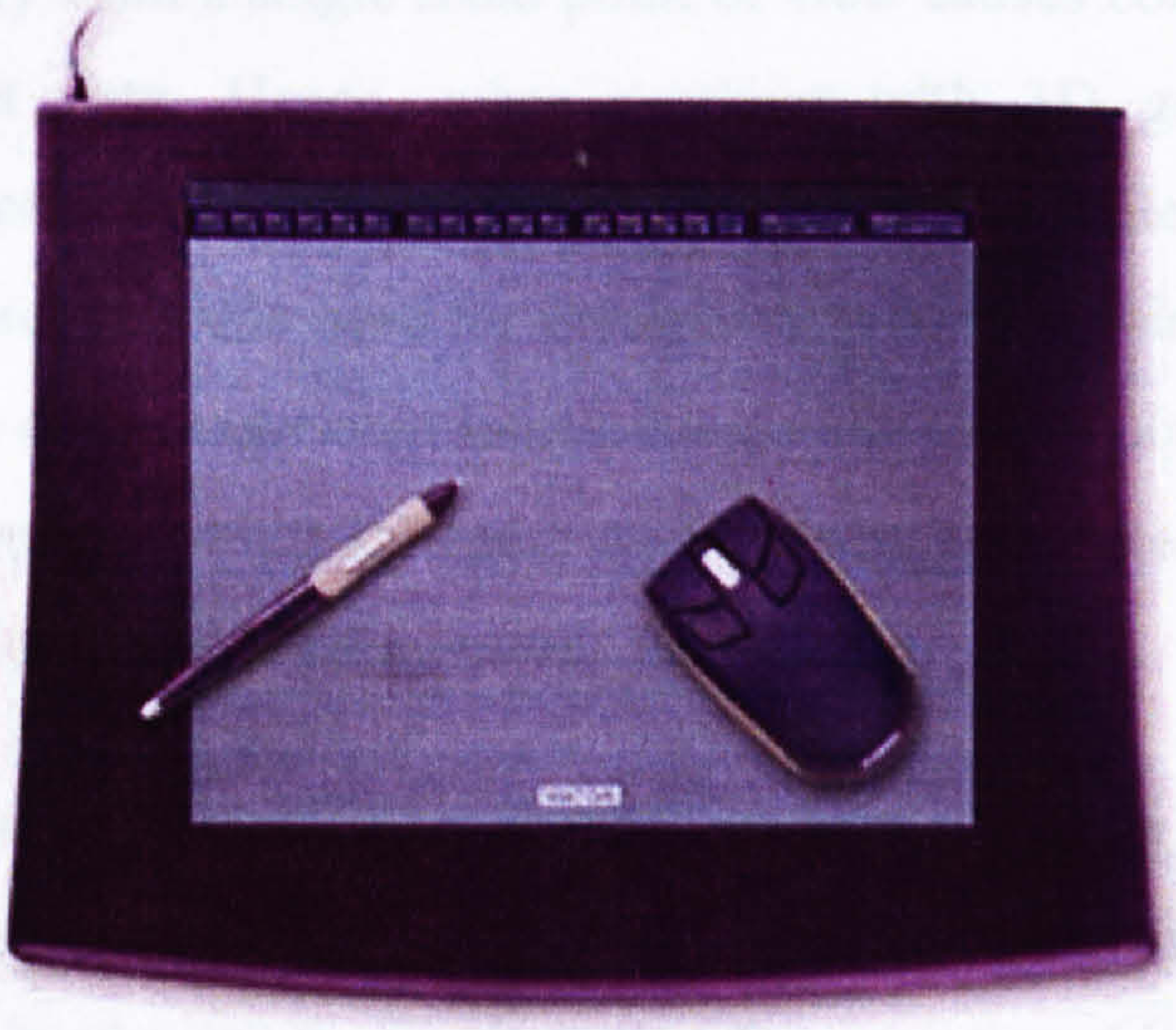


Figure 3.5: Digitizing Tablet, Stylus and Puck
(Source: < http://www.scannerplace.com.au/ wacom.htm > 28/01/05)

This system makes it possible to "sketch" lines and features with a fluid motion that is difficult to achieve with other devices like mice and trackballs. This peripheral is a valuable tool within 2D drafting and graphics applications. It is of particular use to CAID software operators, who need to generate freeform curves and digital concept sketches. Westin (1998) mentions use of electronic sketching at automotive company Ford along with some of its advantages over paper-based sketching. These include full-scale representation of vehicle sketches using data projectors and the dynamic display of alternate designs.

Use of all these technologies has been commonplace since the inception of the earliest commercial CAD packages. Price (1984) observes WIMP devices, discussing their continued use and appropriateness for CAD system operation. Twenty years later these peripherals remain the standard interface of almost all CAD software packages. However, advances in software and computing capabilities have created a number of additional devices with which to generate, manipulate and interact with virtual CAD geometries. Perhaps the single most attributable factor behind this expansion has been the transition of CAD environments from 2D to 3D.

Viewing 3D geometry from a single fixed point of view causes confusion and makes it easy to misinterpret data. Hence, when working with 3D geometries in a 3D environment it is necessary to make frequent changes to the angle and field of vision. Mackinlay (1990) discusses this need for manipulation of viewpoints within virtual 3D workspace and some of the associated issues. Mackinlay (1990) observes the controlled movement of a viewpoint within 3D space as involving six degrees of freedom: three dimensions for position and three dimensions for rotation.

Early 3D CAD software allowed view changes to be made using vector co-ordinates. However, in using this method the Point Of View (POV) would flicker from one angle to another in a disjointed manner, causing user disorientation. Little could be done to address this issue until improvements in computing power and graphic display allowed real-time display and high speed graphic refresh rates in CAD software. This made it possible to change a point of view or orientation whilst displaying the transition that takes place in moving from one view to another.

The ability to rotate, pan and zoom real-time displays created the need for new levels of interaction between user and software. Primarily mice and trackball devices enabled this through the use of "chording", which involves the simultaneous use of several control buttons. Price (1984) describes how this technique can be used to drive various software functions. The availability and versatility of mice and trackballs, using functions such as chording, ensured that they remained strong components within the operation of CAD software. However the need for manipulation of views and navigation within virtual 3D environments generated a market for additional better-equipped devices.

Use of joysticks, similar to those used on arcade machines, is noted by McMahon (1998, p117) as an early interface for the manipulation of views in CAD packages. Hinckley et al (1998) also describes a two-handed interface in which users would operate a joystick with one hand whilst using a standard WIMP device in the other. This made it possible to simultaneously control the angle of view and orientation whilst accessing and operating various control functions. The resulting interaction is akin to that of a sculptor holding and turning a piece of work with one hand whilst using the other to control a shaping tool.

This two-handed approach has been instrumental in the development and proliferation of other specialised devices. The SpaceBall® and SpaceMouse® are two such devices that have been developed to be used alongside other standard peripherals for the manipulation of viewing angles within 3D CAD environments. The appearance and operation of each device is very similar. Central to each is a ball or dial that is seated in the palm of the user. Twisting, rocking, elevating or depressing this will respectively tilt, pan, and zoom the view that is displayed on-screen. Additional buttons may be programmed to perform specific functions and access menus within the software package. Figure 3.6 shows an illustration of a SpaceMouse® and the degrees of motion that it is able to control.

Figure 3.6: Operation of a SpaceMouse®
(Source: <http://www.hsicom.cz/?a=cad&b=spaceball> 28/01/05)

Glove-based systems are another technology that has been applied to the control and manipulation within virtual 3D environments. These devices enable control of CAD software through hand articulation and gesticulation. Sturman (1993) describes some of the uses and functions associated with these technologies, which include the ability to "point", "reach" and "grab" within a virtual 3D environment. Figure 3.7 depicts a CyberGlove®, which is one of the technologies available in this area.

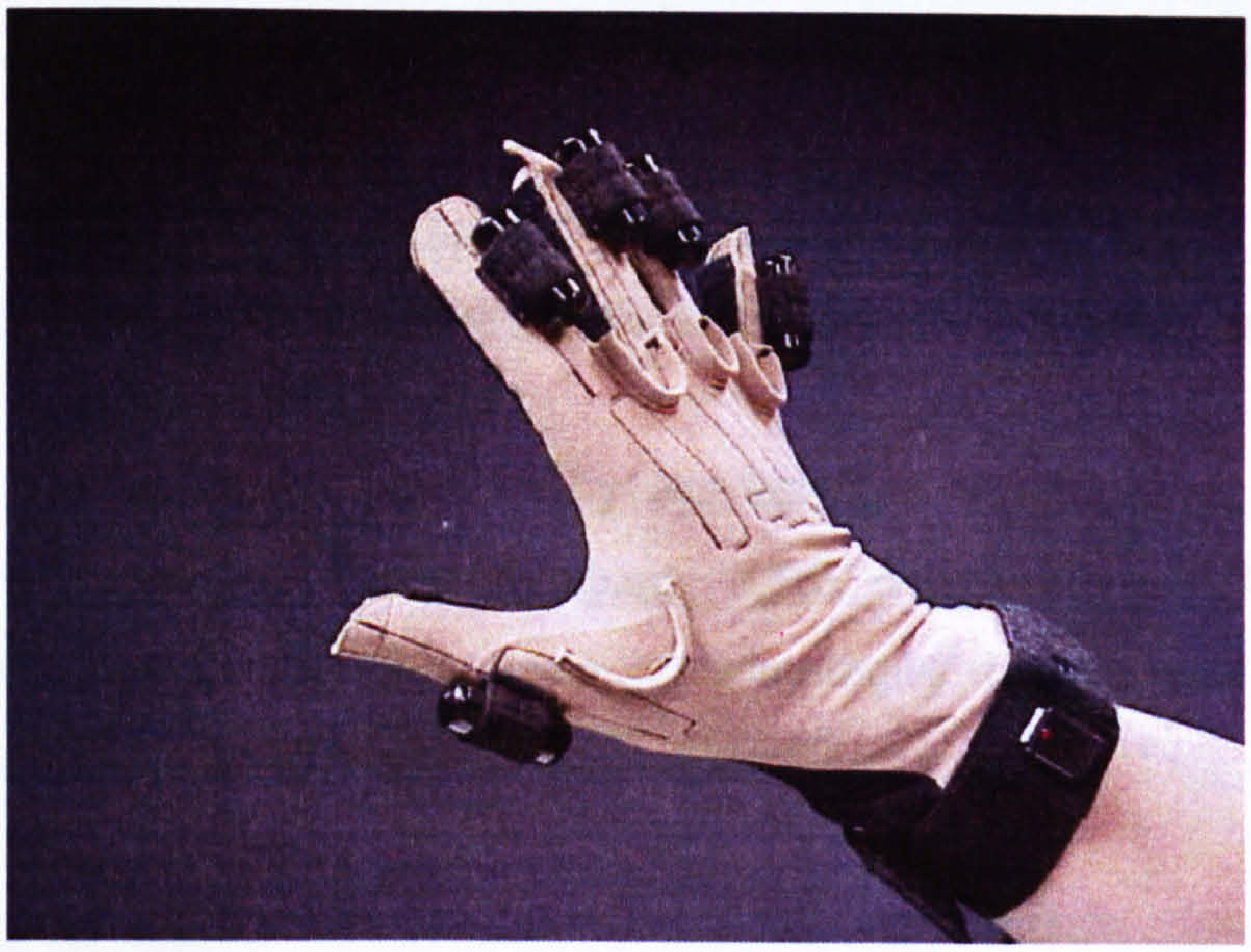


Figure 3.7: CyberGlove®
(Source: <http://www.sd.polyu.edu.hk/gvds/info/cyberglove2.jpg> 28/01/05)

Effective use of gloves was previously dependent upon user hand-eye co-ordination. However, recent innovations in technology have enabled the use of additional senses in operation. Originally developed for military use, the CyberGrasp™ interface enables CyberGlove® users to "touch" virtual computer-generated objects and experience realistic force feedback with their hands. This is made possible with a force-reflecting exoskeleton that is fitted to a CyberGlove® so as to provide force feedback to each of the user's digits. Figure 3.8 shows a CyberGlove® that has been fitted with a CyberGrasp™ interface.

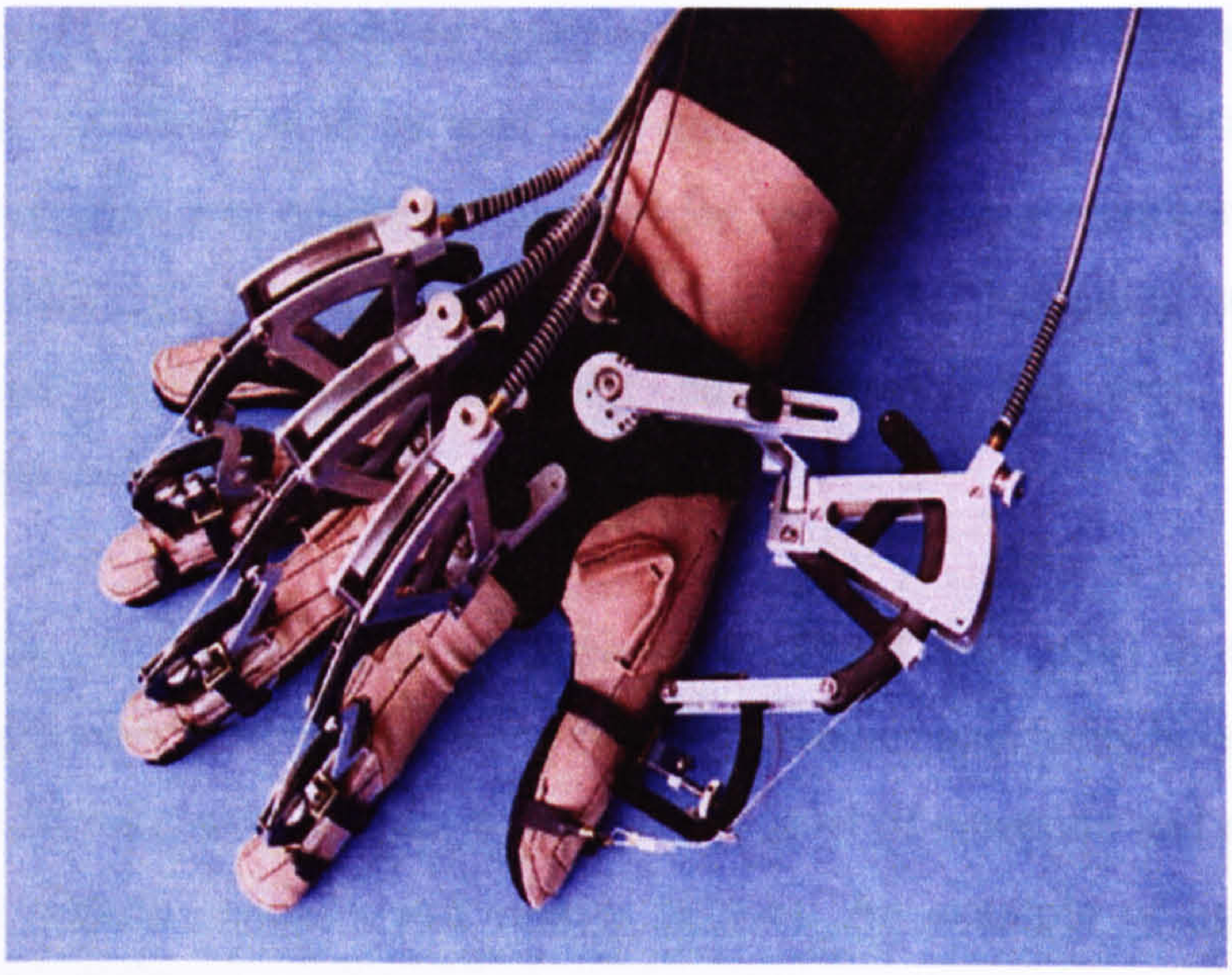


Figure 3.8: CyberGrasp™

(< http://www.inf.ed.ac.uk/teaching/courses/cg/Web/intro_graphics/cgrasp.jpg> 28/01/05)

The physical feedback that is provided by this interface introduces an area that is of growing interest amongst various computer aided design circles. Referred to as "haptics", this field encompasses a group of technologies that are used to exploit the sense of touch within data creation and manipulation.

3.5.2 Haptic Devices

A relatively new addition to the sphere of mainstream CAD input devices is that of haptic technologies. Sener (2002a, p545) defines haptics as "sensing and manipulation through the sense of touch". Thurfjell et al (2002, p210) observe haptic technologies as allowing touch-enabled interaction with virtual objects, whilst Evans (2000, p189) describes how haptic devices allow their operator to "feel" a virtual object.

Burdea (1999, p87) observes that haptic feedback in a Virtual Reality (VR) environment exists as a group of modalities, which he defines as force feedback, tactile feedback and proprioceptive feedback. Of these, force feedback provides data pertaining to a virtual object's hardness, weight and inertia. Tactile feedback is used to gauge surface contact geometry, smoothness, slippage and temperature. Finally, proprioceptive feedback provides data as to the user's body position or posture. Of these different modalities force feedback was the first to be used. The earliest example of this is a robotic tele-operation system that was developed in 1954 for use in nuclear environments. Burdea (1999, p88) offers a chronology of haptic development, beginning with this first application and charting significant later developments that took place as the millennium approached.

One application of the late 1990's noted by Burdea (1999, p88) is that of haptic joysticks in computer gaming. A variety of haptic control interfaces have been created in this area to provide game players with a greater level of emersion and realism than is possible with regular joysticks and control devices. An example of one such haptic controller is the Sidewinder steering wheel from Microsoft, a picture of which may be seen in Figure 3.9.

Figure 3.9: Microsoft's Sidewinder Force Feedback Steering wheel
(Source: < http://www.richleader.com/drivers_ed.htm > 02/02/05)

When this device is used to "drive" in a simulated game environment a variety of tactile sensations are relayed to the user through a series of electric motors and gears. This feedback attempts to replicate the sensation of racing over bumpy road surfaces and the difficulty of overcoming inertia that is experienced when turning a corner at speed. However, the haptic feedback that is provided by gaming devices such as these is seen to be of a relatively low level.

Sener (2002a, p547) identifies two categories of haptic device that are defined as being either 2D or 3D, depending upon the level of interaction and feedback provided. A device that allows users to "feel" textures of 2D objects with a pen or mouse-type interface is seen as belonging to 2D category. Whereas a glove or pen-type devices that allows the user to "touch" and manipulate 3D virtual objects would be classed as a 3D device. According to this classification, haptic game controllers are seen as being 2D along with haptic mice and pointers, an example of which may be seen in Figure 3.10.

Figure 3.10: The iFeel Haptic Mouse

(Source: < http://www.dansdata.com/ifeel.htm > 03/02/05)

The iFeel mouse from Logitech is a device that provides 2D haptic feedback within standard Window-based applications. The external appearance of this device is very similar to that of any other computer mouse. However, when used in conjunction with the appropriate software, an "Immersion Desktop" is created in which haptic feedback is generated. The result of this is a range of different clicks and buzzes when interacting with various on-screen windows, icons and taskbars.

The previously discussed CyberGrasp™, which was shown in Figure 3.8, represents one of several 3D haptic interfaces that currently allow users to "touch" and manipulate 3D objects in Virtual Reality environments. Use of this glove-based device enables the sampling of surface geometry as well as the deformation and manipulation of various features. However, the operational mechanics of this system mean that it is impossible to feel the "weight" of a virtual object (Sener, 2002a, p548).

The PHANToM haptic device from SensAble Technologies is a desktop interface that utilises an approach that is significantly different to any glove based technology. A picture of this device may be seen in Figure 3.11.

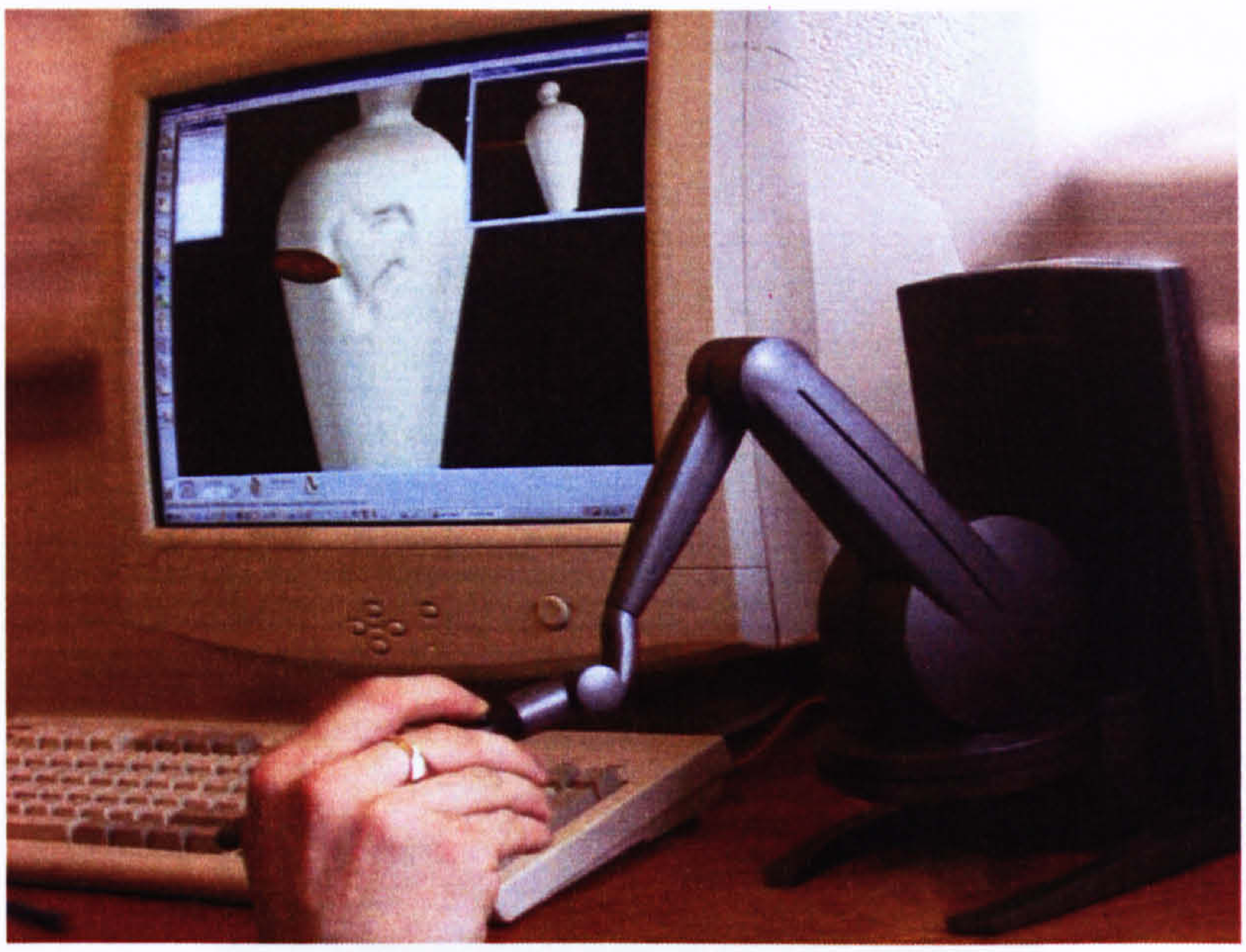


Figure 3.11: Using the PHANToM haptic device

Unlike glove based systems the PHANToM uses a pen-like stylus with which to interact with virtual 3D models. This stylus can be used to represent a series of virtual tools that vary in size, shape or function. Using these tools it is possible to "sculpt" a virtual 3D geometry that would be impossible to generate using conventional CAD software or interfaces. It is also possible for users to push or pick up virtual objects with the stylus, which transfers a sense of "weight" and "resistance" that glove technologies are unable to provide.

The PHANToM device and "Freeform" software from SensAble allow users to manipulate virtual 3D CAD geometries in a manner that has been likened to working with clay and other physical media. The term "virtual clay" is used by Sener (2002b, p165) to describe the medium that is presented in this environment, along with how it simulates real world modelling tools and techniques. The main advantage of this is the relative ease with which amorphous organic geometries may be created, a frequent requirement of industrial designers (Sener, 2001, p358). The picture in Figure 3.12 is taken from Evans (2000) and demonstrates the scope of geometrical creation that is possible with these technologies. The "hammered" effect featured is one that would be impossible to generate with more conventional CAD systems.

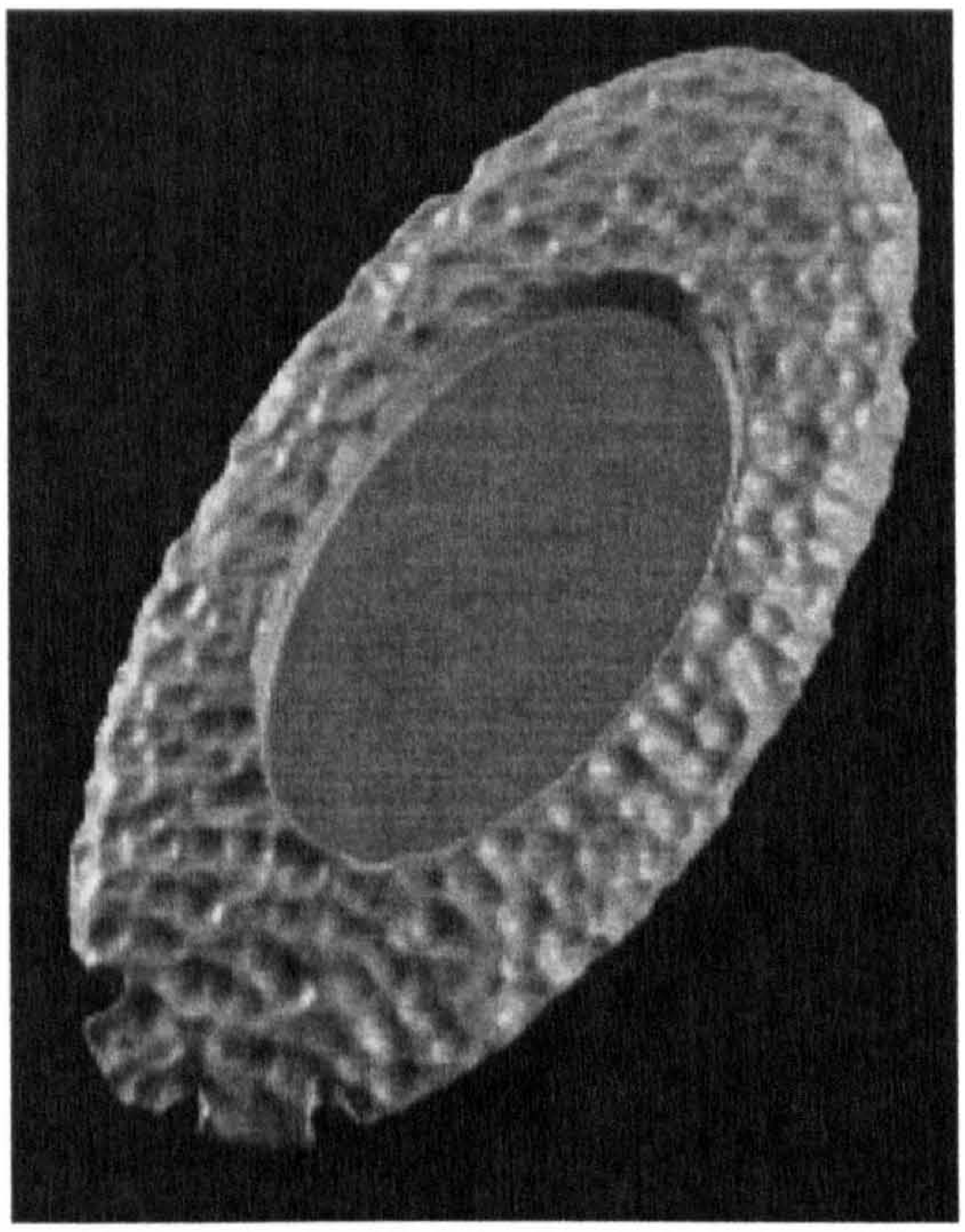


Figure 3.12: "Hammered" surface texture in 3D CAD
(Source: Evans 2000, p191)

Following a case study in which a PHANToM device was used in a design modelling exercise, Evans (2000, p193) concludes that the haptic system possess both strengths and weaknesses. The ability to create surface geometries, as pictured in Figure 3.9, is seen to afford users with a great deal of potential for form creation. However, it is stated that the system's general functionality was unable to meet certain preconceived expectations and that it was difficult to obtain certain desired surface qualities. These latter observations caused him to express a general preference toward real world physical modelling using traditional fabrication techniques. Even so, the final remark in his conclusion is one that acknowledges the potential capabilities of future haptic systems and the diminishing boundaries that exist between physical and virtual modelling.

Use of real world physical bodies in the generation and representation of form, as advocated by Evans (2000), is a design approach that lends itself particularly well to the next area of discussion. This is the group of 3D scanning and digitization technologies that are encompassed within the area of Reverse Engineering.

3.5.3 Reverse Engineering

Reverse Engineering has been defined as being the disassembly and measurement of an existing product so that it may be either replicated or improved upon (Ingle, 1994). This is not a new strategy, but in recent years there have been many advances and additions to the tools that are applied in its execution. New scanning and digitisation technologies enable virtual 3D CAD data to be generated directly from physical real world bodies. When using these systems, physical geometries are mapped as a series of points, each of which is represented by a single mathematical co-ordinate. These are all relative to the same tri-axis system that is used to describe all CAD geometry. The three “X”, “Y” and “Z” axis are used to define “width”, “height” and “depth”.

The level of detail represented is directly proportional to the amount of points used. In capturing a body’s every aspect, it is not uncommon for some systems to record several million data points. The term used to describe these massive collections of data is a “point cloud”. Viewed from a distance, these often appear to be solid black masses and it is only with close inspection that individual points become apparent Figure 3.13 shows a dense black point cloud (**A**), which reveals its many composite points upon magnification (**B**).

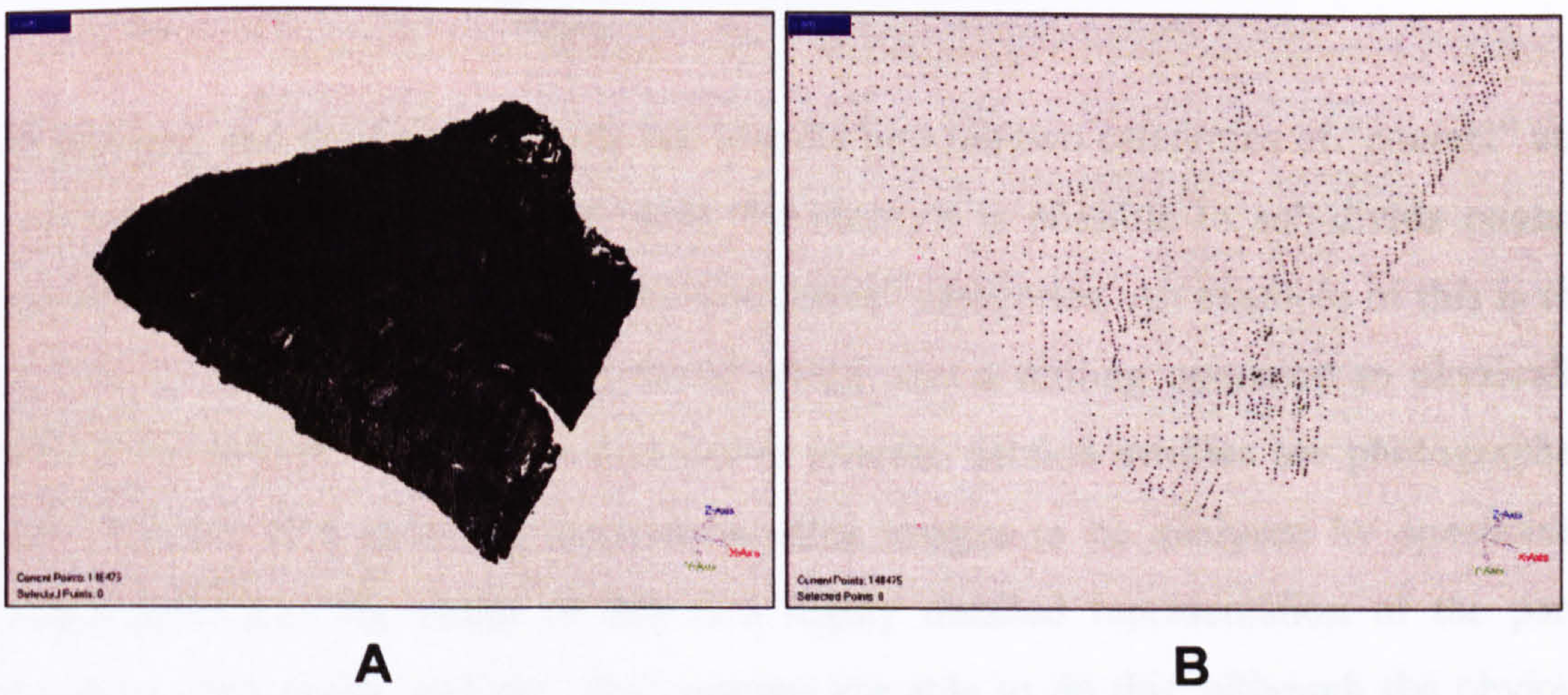


Figure 3.13: Point Cloud Data

Using specialist Reverse Engineering software it is possible to edit point clouds and produce 3D surfaces suitable for many CAD applications. This is achieved by using planar triangles to join every third data point within the cloud. The effect of this is a continuous flowing surface of tessellated triangles that replicates the original real world data source. As with the point cloud itself, the level of detail that is portrayed is in direct correlation with the number of triangles that are used to generate the surface. Figure 3.14 shows the tessellated surface generated using the previously illustrated point cloud.

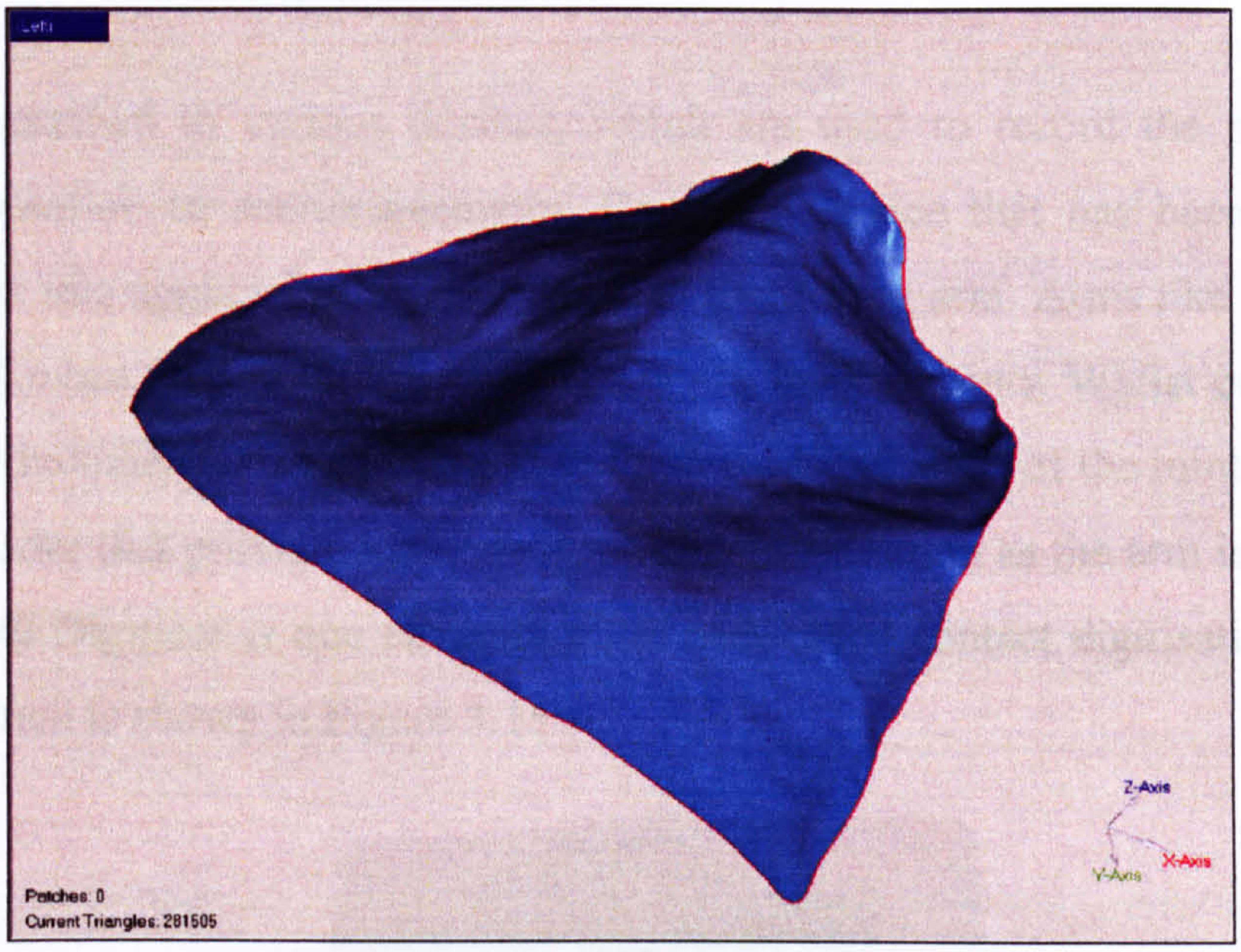


Figure 3.14: Tessellated 3D Surface

3D scanners and digitising systems fall broadly into the two categories of "contact" and "non-contact" systems (Li, 2002, p53). Of these, it is possible to sub-divide contact systems into "Destructive" and "Non-destructive" categories. An example of this is the Capture Geometry Inside (CGI) system, which uses a milling operation to physically section 3D objects. During this destructive process, section profiles are photographed and compiled as a series of consecutive slice images to be analysed by specialised system software. The result of this is a highly detailed representation of the parts geometry, both inside and out. Few systems are able to do this, although the obvious disadvantage with this particular approach is that the source object is completely destroyed during digitisation.

Most non-destructive contact devices have been developed around Co-ordinate Measurement Machines (CMM) as used in the Quality Assurance (QA) of fabricated items. These systems use a single probe to record points. The Renishaw Company has been a market leader in the manufacture of such contact probes for a number of years and their Internet Website (http://www.renishaw.com) provides details as to a host of different systems and applications.

Probes are attached to various devices, which are used to record the probe's exact position in relation to source geometry. One such device that has been specifically developed for this application is the articulated measuring arm. Arms like these consist of a series of tubes that are connected through mechanical joints. Whilst one end of the arm is fixed the other is free to move in relative freedom. Each of the joints is linked to a digital encoder that provides accurate positional information as the arm is moved. The MicroScribe® Digitiser is one example of an arm-based contact digitisation system, a picture of which is shown in Figure 3.15.

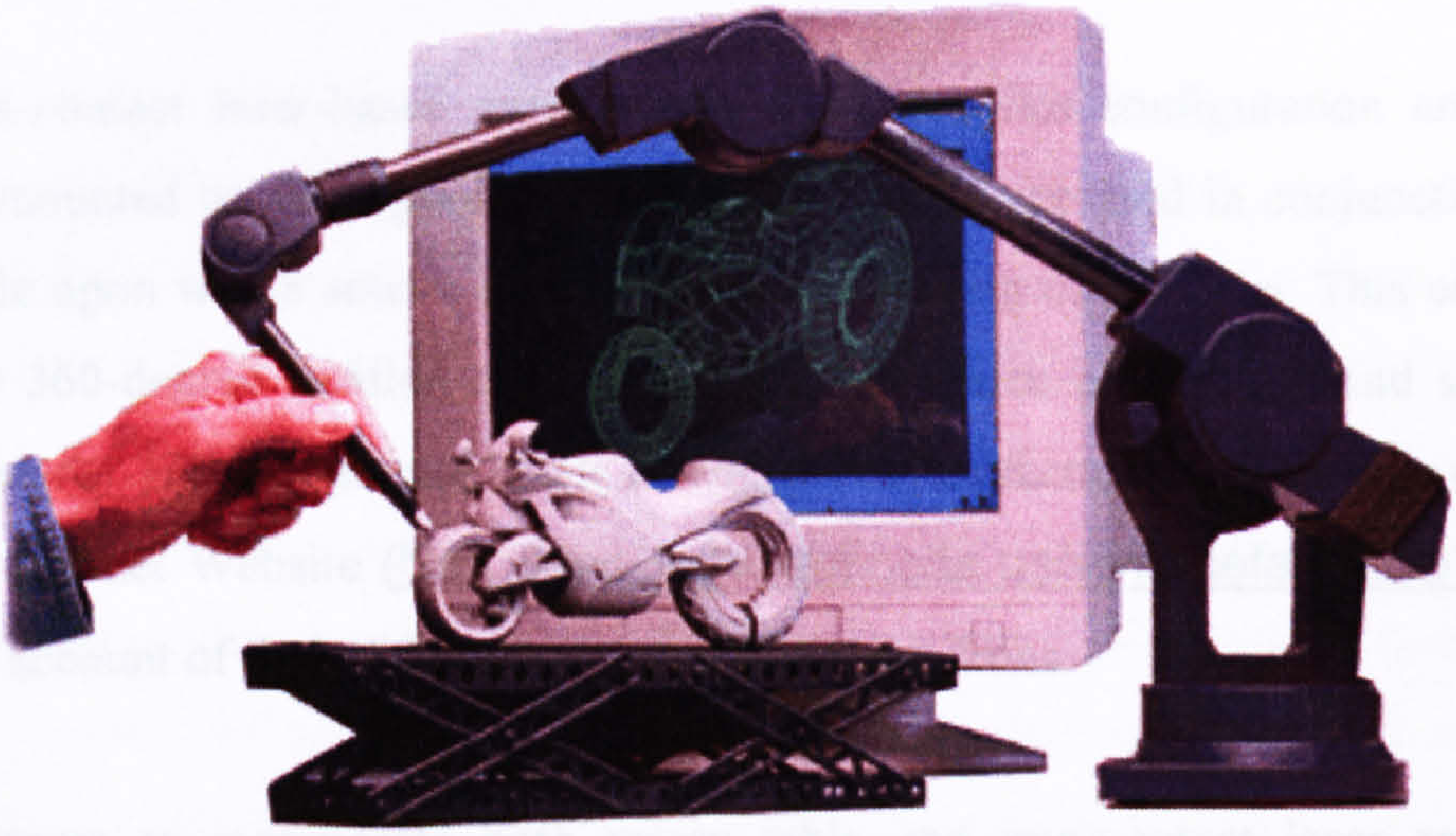


Figure 3.15: Using the MicroScribe® Digitiser
(Source: < http://www.immersion.com/digitizer.htm > 05/02/05)

Use of articulating measurement arms is also applied to non-contact digitising systems. Figure 3.16 shows a ModelMaker® digitiser used in conjunction a FaroArm®. The image was taken from a Reverse Engineering case study that was published on the Internet Website of software manufacturer Raindrop (http://www.geomagic.com).

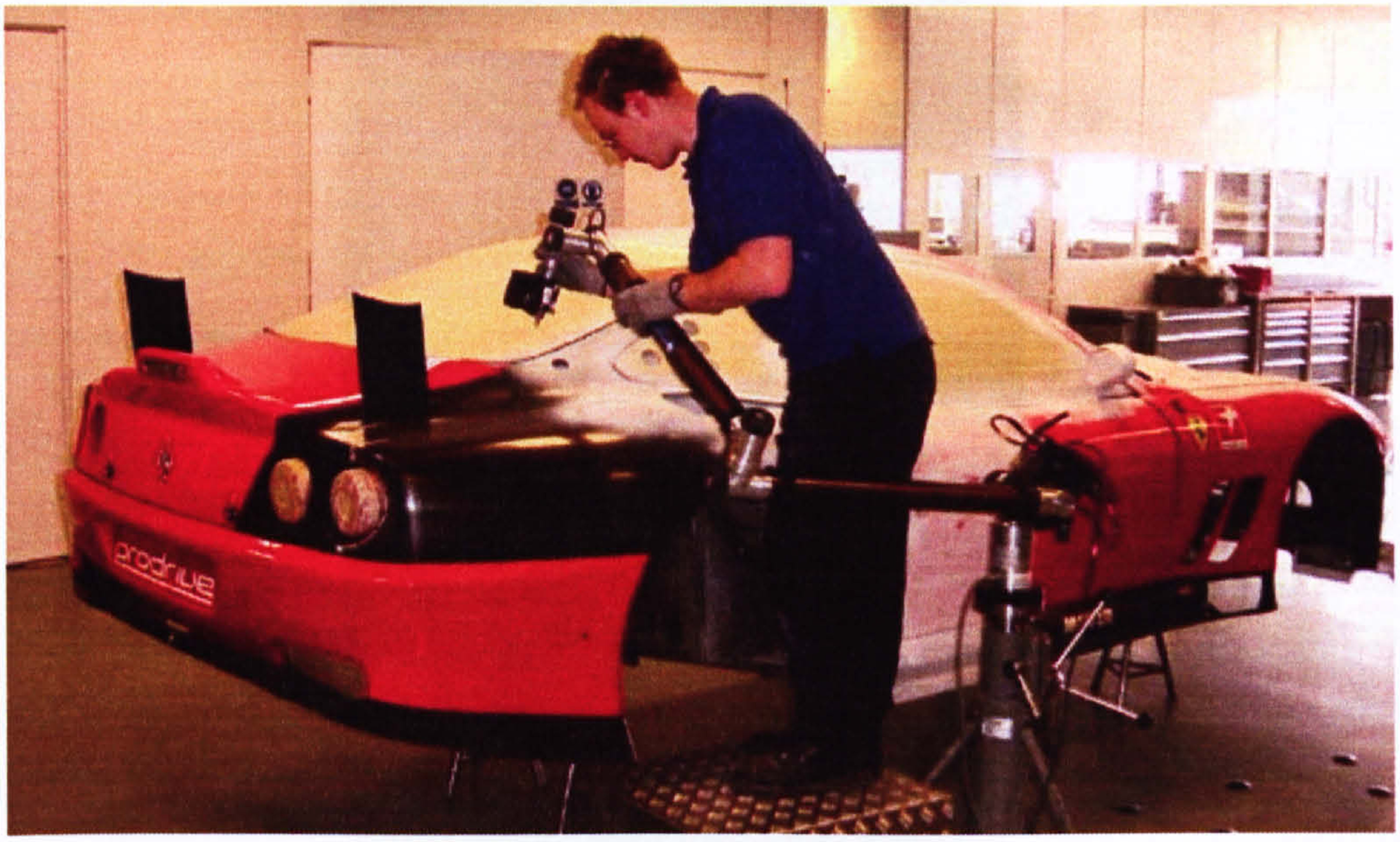


Figure 3.16: Using the ModelMaker Digitiser and FaroArm®

(Source: < http://www.geomagic.com/advantage/auto-air/prodrive-index.php3 > 05/02/05)

Other non-contact laser-based systems use a camera-like configuration and can be statically mounted on photographic tripods. Often these are used in conjunction with a rotary table upon which source objects are placed during digitisation. This enables the controlled 360-degree rotation of objects so as to reduce potential "blind spots" and hidden features. Konica Minolta is one of the main manufacturers of this type of system, and their Internet Website (http://kmpi.konicaminolta.us/vivid/default.asp) provides a detailed account of their different systems and capabilities.

Other systems to incorporate both rotary table and non-contact laser scanner are exemplified by those which are produced by the Roland DGA Corporation. Figure 3.17 shows one of their chamber-enclosed desktop systems. In this system, the scanner is mounted on an axis that allows controlled vertical movement, whilst a motor driven table enables the complete rotation of objects during digitisation.

Figure 3.17: The Roland LPX 250 Scanner

(Source: < http://www.rolanddga.com> 05/02/05)

The ability of these various technologies to capture geometric data directly from physical objects provides designers with numerous possibilities for developing new products. Hsiao (2003) provides one example that supports Evans' (1992) earlier preference for the use of physical models in form generation. In this Reverse Engineering approach to form generation, designers produce physical 3D models in typical "sketch model" mediums, such as clay or expanded polyurethane foam. Once a desirable form is achieved the model is digitised. The resulting point cloud is then used to generate virtual 3D CAD models that may be used in a variety of subsequent processes. Not only does this approach encompass the benefits associated with real world physical modelling, but it also enables the relatively easy capture of organic forms that may be difficult to model with conventional CAD software and techniques.

Reverse Engineering is frequently used for the capture of surface geometries that a new product or component will interact with. Clark (2000) identifies these as "legacy" parts, around whose geometry new products must be designed. Accurate measurement and the capture of pre-existing legacy details makes it possible to create better mating surfaces between new and old components. This is a technique that may be applied to surfaces both inanimate and animate. For example, Reverse Engineering may be used in the design of a new consumer product housing to record the geometry of the mechanical sub-assembly that the housing is to envelop. Alternately it could be used to detail the part of a human body with which the housing will eventually come into contact.

In recent years there has been an increase in the use of Reverse Engineering within the medical sector. Magnetic Resonance Imaging (MRI) and Computerised Tomography (CT) scanning technologies were first developed in the 1970's to provide medical practitioners with a non-invasive method of observing soft tissue, bone, and blood vessels. Advances in processing software have since enabled the data collected with these scanners to be represented as highly accurate 3D CAD files. The resulting output of these systems is similar to previously mentioned CGI system, although it has the advantage of being generated in a non-contact and non-destructive manner.

Negative issues associated with these technologies, such as high operating costs and the use of X-rays by CT scanners, frequently prohibits their use. However these issues may offset be offset against the advantages that are offered. For example, surgeons are now able to examine a patient's internal physiology long before either get to theatre. Exact models may be generated from patient scan data and used to practice surgical procedures reducing both time and risk in theatre (Harryson, 2003). The fabrication of customised bone substitutes from similar data allows for better fit and reduces a patient's pain and suffering (Yaxiong, 2003). Wang (2002) describes how non-contact Reverse Engineering technologies are used in the generation of prosthetic ears for patients who have been involved in trauma or subject to congenital birth defects. Li (2002) observes the use of Reverse Engineering in orthotic and prosthetic applications, as does Smith (2001) who notes the role of digitisation in measurement of stump geometry when designing custom fitting prosthetic limb sockets.

These latter applications highlight the area of customised user-fit products, in which the interaction of a product and its user requires a unique body fitting form. One example of this may be seen in the field of orthotics, where digitisation technologies are used to produce custom fitting insoles. Figure 3.18 shows the Amfit FootFax contact digitiser that is used to capture individual feet geometries.

Figure 3.18: The Amfit FootFax and Software
(Source: <http://www.amfit.com/ > 05/02/05)

At present, there are very few examples of custom user-fitting products outside the areas of medical and healthcare. However, with growing global competition and a demand for manufacturers to deliver better quality products it is likely that user-fit and customisation will infiltrate even more product sectors as an added value component.

The nature of user-fitting products dictates that they are generally organic in shape, which is also a frequent requirement of product forms generated by industrial designers (Sener, 2001, p358). Harryson (2003) sees traditional methods of producing patterns and forming tools as being too error prone to efficiently meet the demands required to make such forms. As a result, use of Reverse Engineering for downstream manufacturing operations is becoming widespread. The increasing use of Reverse Engineering show it to be a valuable tool and, as computer based manufacturing technologies evolve, it is likely to become even further entwined in their application.

3.6 CAD Output

MacKenzie (1995) discusses the human / machine interface in terms of input and output. In this discussion a model is offered to describe the nature of interaction between human and machine, where input into one involves output from the other. In this model, the input of data into a computer involves some form of output from the user. Typically, such user output is in the form of a motor response that is used to operate one of the previously discussed input devices, such as a mouse or keyboard. However, when the model is reversed, the symbiosis that exists between human and machine means that human interpretation of computer data (input) requires some form of output from the machine.

Just as a variety of interfaces exist for the input of data from humans into computers, so too are there a number devices and approaches which are used to generate output of data from computers for interpretation by humans. These output devices vary in function from the virtual display and visualisation of data to other forms of realisation that enable the physical production of real world artefacts.

3.6.1 Output Technologies

The earliest form of computer output and data representation still remains an integral part of practically all computer systems. Visual Display Units (VDU's) provide graphic representation of digital information and are a feature that is common to most computer applications. The earliest of these 2D display devices utilised Cathode Ray Tube (CRT) technology with to display data upon constantly refreshing viewing screens. In subsequent years numerous developments have taken place to increase the capabilities of CRT monitors and other modes of screen-based displays. However, whilst the various different screen formats of today have been endowed with much improved functionality, their basic format remains much the same as those of the late 1950's and early 1960's.

The graphic nature of CAD, and 3D CAD in particular, has been instrumental in the development of various specialised technologies with which to view data.

Representation of 3D virtual geometry is no longer restricted to simple 2D media, such as monitors and screen displays. Instead 3D imaging systems, as described by Strickland (2003) and Kawai (2002), are becoming more widespread and even used as standard workstation peripherals. Figure 3.19 shows a pair of Stereoscopic Shutter Glasses, some of the technology that is available for viewing 3D computer graphics.

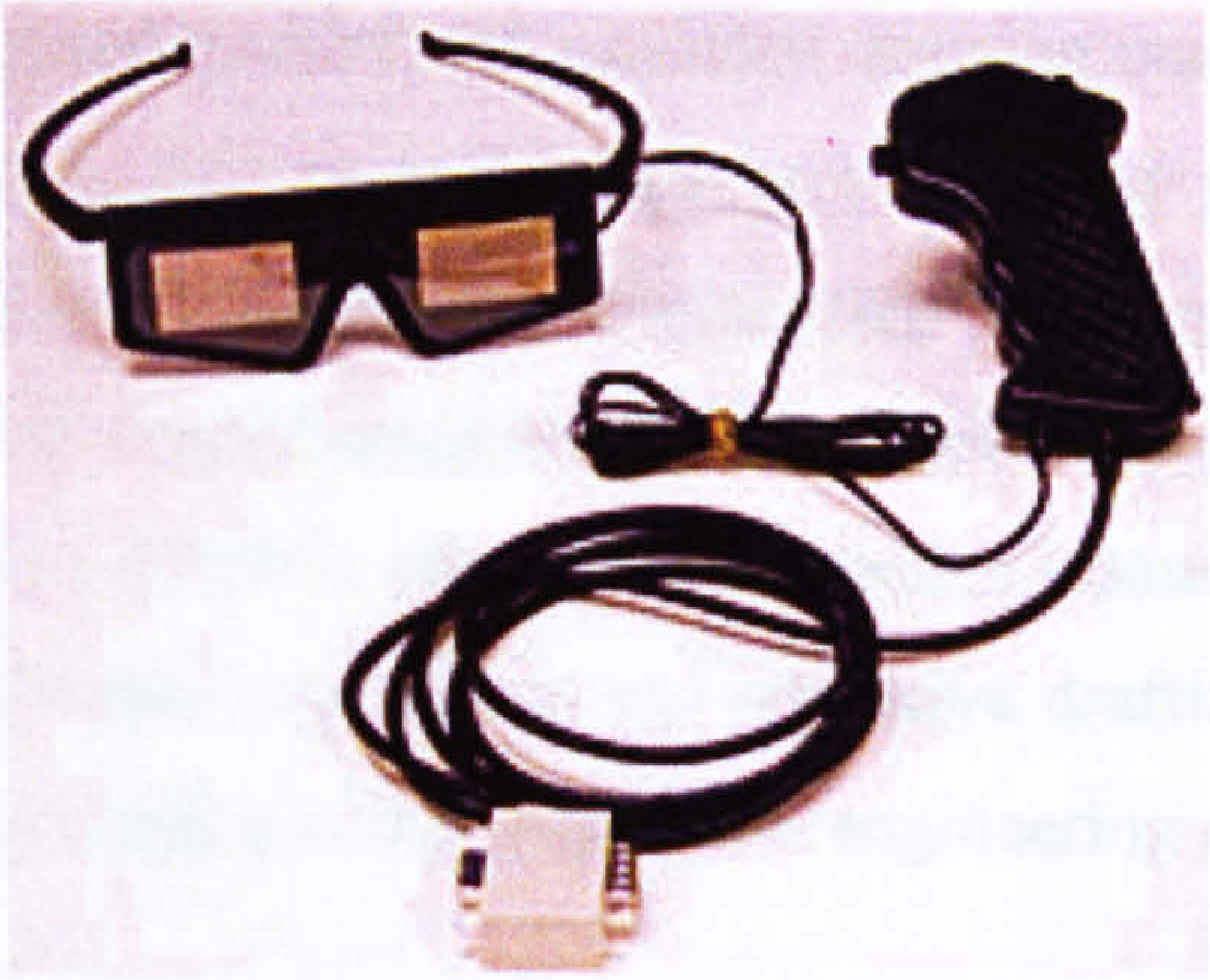


Figure 3.19: Stereoscopic Shutter Glasses

(Source: < http://www.vrex.com/about/ news/visualizer.shtml > 08/02/05)

Stereoscopic viewing systems work by independently displaying a slightly different screen image to each of the users' eyes. This system is used with standard 2D display screens but gives the illusion of 3D display. A similar but alternate approach to this is the use of Virtual Reality (VR) headsets. These headsets provide users with a much more immersive environment in which to experience virtual 3D geometries. Unlike shutter glasses, users wear a headset that fills their entire field of vision, blocking out the real world environment. The effect of this is very much akin to entering a virtual computer generated world. Displays like these are often used in conjunction with haptic feedback devices for greater effect and realism.

Visual displays undoubtedly provide an invaluable medium through which to communicate computer data and digital information. However, there are certain restrictions to their application that only physical output will overcome. From a time when the first computing systems were first developed, a variety of printing and plotting devices have been used to support visual displays with paper-based hard copies of drawings, images and textural information. In the context of CAD, it is easy to draw parallels between these various outputs and the previously described paper-based sketches, engineering drawings and presentation renderings that are applied to product design.

Early 2D CAD systems used plotters and specialist drawing machines to produce paper-based engineering drawings that could be transferred into any production environment. Generating these potentially large-scale engineering drawings from digital sources enabled the relatively high-speed reproduction of multiple drawing copies and revisions. This allowed a much more efficient use of drawing office resources, and greatly reduced the number of man-hours spent in tedious and repetitive drafting. Figure 3.20 shows a typical plotting device as used to create large scale engineering drawings.

Figure 3.20: 2D CAD Plotter
(Source: < http://www.encad.com/plotter.htm > 09/02/05)

Use of different plotting devices is still common practice amongst affiliates of 2D CAD. Some of the more common applications include the production of plans, schematics and engineering drawings in areas such as architecture, civil and production engineering.

A variety of different software packages have been developed to exploit the sketching capabilities of digitizing tablets and stylus type devices. The rendering capabilities of these and other CAD software packages are such that it is now possible to produce realistic sketches and photo-like images of virtual objects. This is supported by the recent explosion of highly affordable and accessible desktop printers that make it easy for the users of such software to print multiple copies of high quality full colour sketches and renderings.

The physical output of drawings and other computer-generated images provide designers with an effective means of communicating design intent. However, as with the more traditional paper-based approaches, the comments of Evans (1992), Vervis (1994) and Broek (2000) still apply. Whilst 2D and virtual 3D imagery is of undoubted use in the generation and communication of design concepts it is unable to convey the same degree of detail that is possible with a real-world physical 3D form. This is a shortfall that was bridged with the advent of Computer Aided Manufacturing (CAM) and the integration of CAD/CAM systems, which enabled the direct physical production of objects from virtual CAD data.

Numeric Control (NC) machining systems are used to manufacture parts using "subtractive" machining methods, such as milling and turning. The term "subtractive" is used here to describe machining processes in which parts are produced by the successive removal of material from a single stock piece. NC systems like these are controlled by a numeric code that is used to govern aspects such as cutter speed, position and material feed rate. The controlling code is composed of various path vectors and tri-axial co-ordinates, similar to the ones used in describing reverse engineered point clouds. Early NC systems required manual programming of code by users, which often resulted in blocky "2½ D" geometries. This is largely due to the programmer's inability to manually generate the complex vectors that are required to describe smooth flowing contours. However, in later Computer Numerical Control (CNC) systems code is generated autonomously by CAD software. One advantage of this is that it allows much more complicated machining operations to be performed, resulting in the capability to produce much more smooth flowing part geometries. The diagrams in Figure 3.21 demonstrate the difference between a typical 2 ½ D geometry and similar 3D geometry.

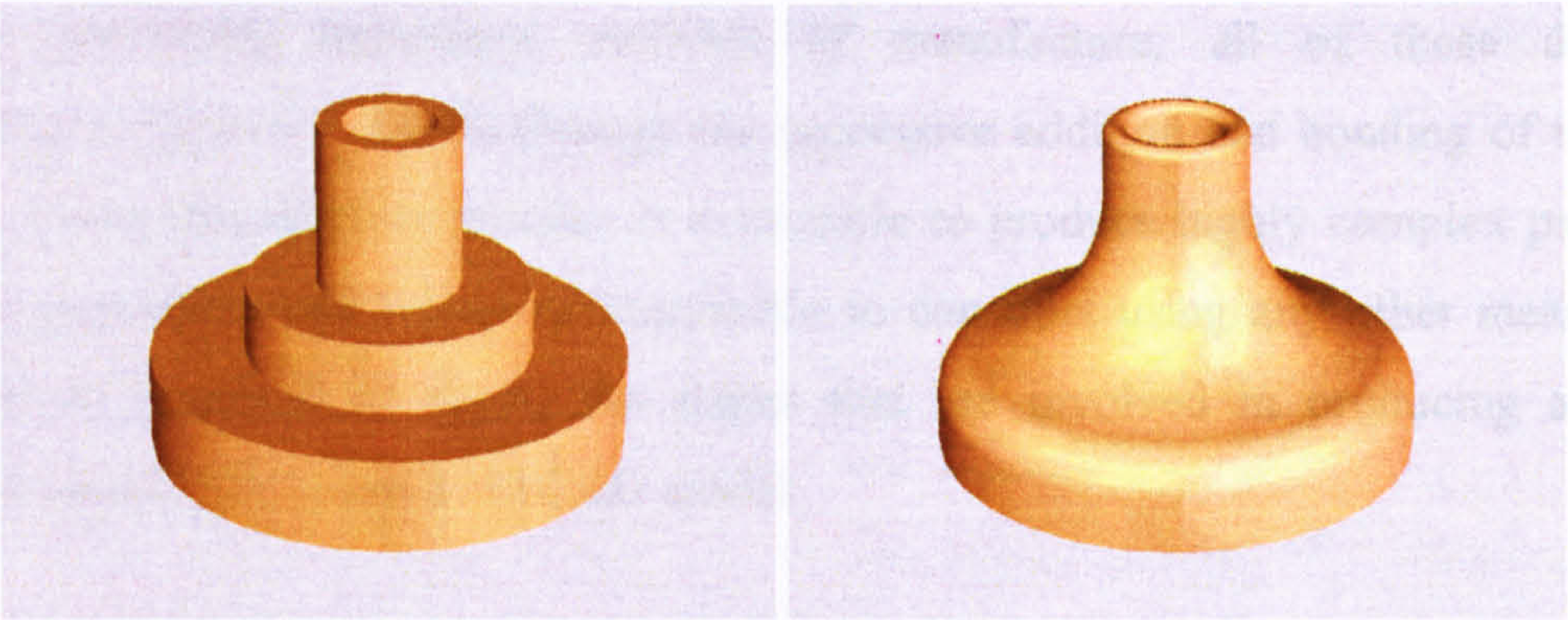


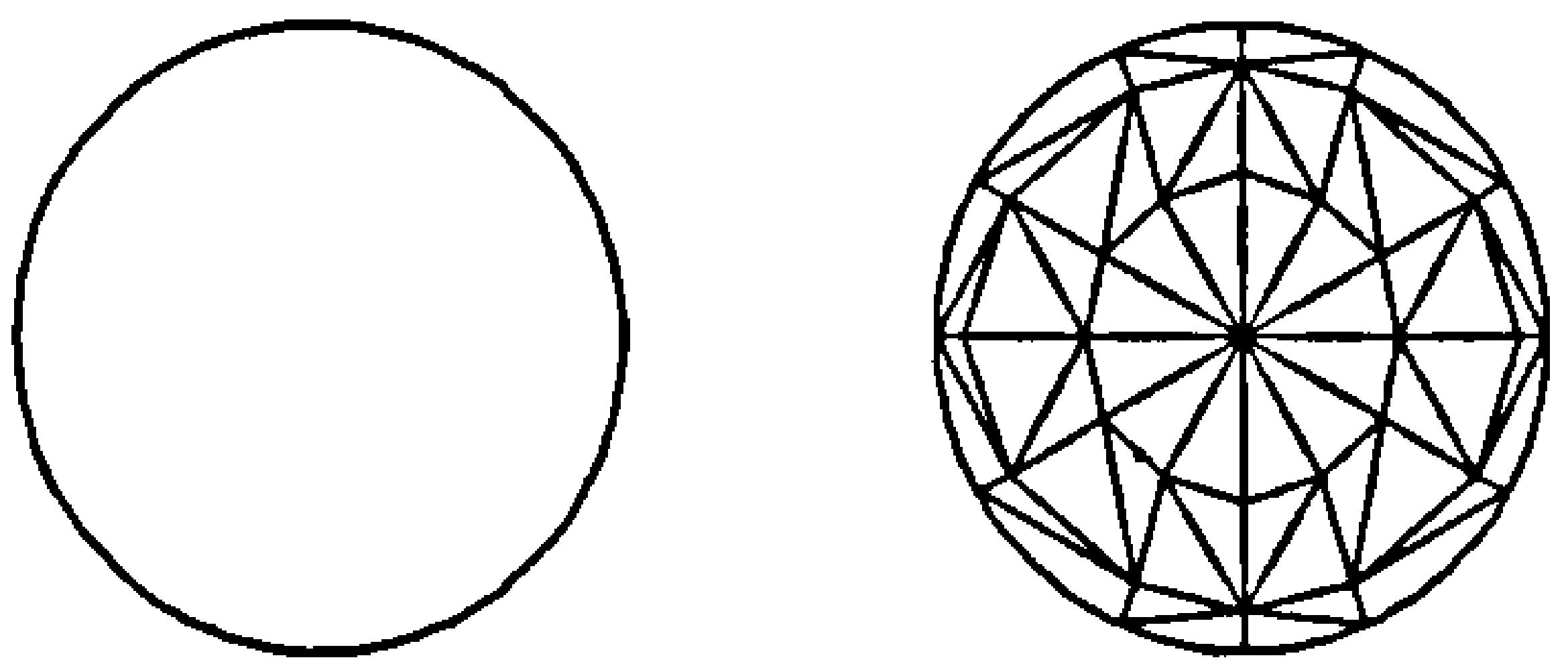
Figure 3.21: Comparison of 2½ D and 3D geometries

Subtractive CNC technologies are used in a variety of different applications that range from the production of initial form models, constructed from low-density polyurethane foam, to final production parts in high-grade steel. Direct production of objects from CAD data in this way ensures that each part is an exact physical replica of its original source data, removing the possibility of misinterpretation that is present in other manual methods of construction. However, as with most manufacturing processes, certain geometric restrictions are posed. In this instance it is that part geometries must accommodate the positioning and manipulation of cutting tools so that excess material may be removed. This is one restriction that has been overcome by additive manufacturing, a topic that is addressed in the next area of discussion.

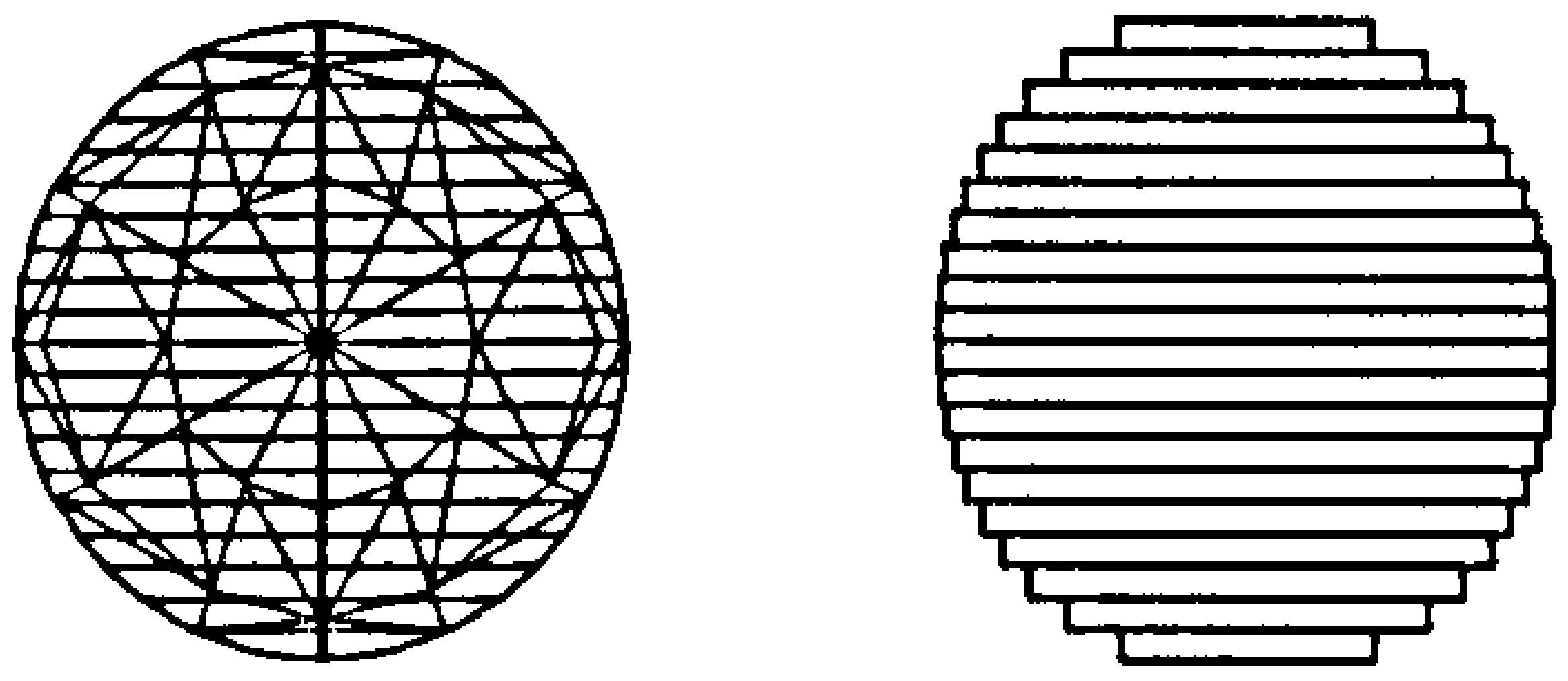
3.6.2 Rapid Prototyping

Rapid Prototyping (RP) is the collective name given to a group of technologies that are used to fabricate physical objects directly from 3D CAD data sources. This process is often also referred to as Freeform Fabrication (FFF), Solid Freeform Fabrication (SFF) and layered manufacturing (Pham, 2003). Many works have been published concerning the more prevalent systems to be used by industry, along with their various advantages and disadvantages. Useful titles in this area include the work of Chua (2003), Gebhardt (2003), and Grimm (2004). Castle Island's Worldwide Rapid Prototyping Directory (http://home.att.net/~castleisland/links.htm) is an additional and constantly updated source of information upon matters related to Rapid Prototyping.

Unlike previously mentioned methods of manufacture, all of these different technologies generate objects through the successive addition and bonding of material layers. Using this additive process, it is possible to produce highly complex parts and certain geometries that would be impossible to construct using any other means. The diagram in Figure 3.22 shows the stages that are involved in producing a layer-manufactured object from a 3D CAD model.



1. CAD Model 2. STL File



3. 2D Slices 4. Layered Model

Figure 3.22: The Transition of 3D CAD to Layered Model

The first stage in any RP process is for a three-dimensional CAD model to be converted into the faceted "Stereolithography" or "STL" file format that is common to all RP systems. Each STL file is a three dimensional mesh of tessellated triangles that are used to describe the original models geometry. Special preparation software is used to "slice" the STL file into layers that describe the model in plan view as a series of consecutive 2D profiles. The RP machine then uses these profiles to produce a solid object one layer at a time.

The major industrial sectors in which the different RP technologies are applied include medical, transport and consumer product design amongst others. De Beer (2004) observes the use of RP as a visualisation aid and its ability to construct complex freeform components that would be impossible by other means. Pham (2003) refers to the technology as a "time compression tool", expressing the ability of RP to shorten or compress the time taken to get new products to market. Chua (1999) identifies RP as being a preferred method with which to perform kinematic simulations, assembly fit and interface checking of prototype parts. Other common RP applications include visual aids; ergonomic studies; production tooling; patterns for casting processes and the direct manufacture of functional parts. The last example in this list is of particular interest and will be discussed later on.

In his 2002 report, Wohlers (2002), gives the advantages of RP technology over subtractive fabrication methods such as milling or turning as being:

- Objects can be formed with any geometric complexity or intricacy without the need for elaborate machine set-up or final assembly.
- Rapid prototyping systems reduce the construction of complex objects to a manageable, straightforward, and relatively fast process.

The disadvantages typically associated with RP technology include:

- Poor surface finish
- Low dimensional accuracy
- Restricted Build Materials

Pandey (2003) notes that the functionality of parts produced via RP methods is severely affected by the "staircase" effect, a result of the many consecutive build layers that are used to form RP parts. This is an issue that is addressed by Campbell (2002), who observes the surface roughness of RP parts caused by "stair-stepping". It is noted that the effect might be minimised through different part orientations during the build process. However, it is observed that whilst it is possible to minimise this effect using specific part orientations it is inevitable that some evidence of lamination will remain. Prior to these observations Lan (1996) made a similar study to determine the most appropriate orientation of parts built using the SLA process. In this study three factors are used to govern optimum orientation. These are the time required to build the part, the support structures needed to build the part and surface quality of the part in respect of evident stair stepping.

When considering the surface quality of RP parts it is important to take account of both stair-steps and support structures. All parts built using additive manufacturing processes need to be supported in the same way that a building requires scaffolding during their construction. Many systems employ a build process that requires additional supporting structures to be constructed in direct contact with the parts built. These supporting structures require manual removal and it is likely that they will leave witness marks upon any surface that they come into contact with. Hence, attaining an optimum surface quality is dependent upon achieving a build orientation that requires the least number of support contacts and least visible evidence of stair-steps. It is possible to apply post process finishing techniques to remove both support witnesses and laminate ridges, although this adds much to both cost and time required to produce parts so it is not always a feasible option.

RP production materials have come a long way since the earliest SLA photosensitive resins that were produced in the late 1980's. Greatly improved characteristics in terms of strength and their resilience to heat, moisture and UV attack are now exhibited. A number of materials are even available to simulate the properties of engineering grade polymers. However, suppliers state that these products are merely like the material they simulate and are not yet the actual thing. In addition the development costs involved in finding materials to meet the requirements of their users together with relatively low production volumes ensure that current RP production materials remain expensive. These are the facts that account for much of the expense involved in the production of RP parts.

It is predicted that improved materials and processes will produce better parts of increased functionality, inspiring a greater acceptance and more widespread application by users. It is unlikely that drastic changes will occur overnight and Wohlers (2002) indicated a predicted timescale for incremental change. This begins with an immediate short-term period of three years, moving through a mid-term transitional period of four to six years, culminating with a more long term period of seven to ten years in which sweeping change that are likely to take place.

Early indications within the first part of this timescale, would infer that the previously made predictions are being realised. Wohlers (2004) notes the introduction of several new RP materials, the functional testing of concept products using RP parts is observed (Wohlers, 2004, p29) and market trends point toward an overall growth in the use of RP worldwide. Wohlers (2004, p47) charts this growth, noting an increase of 18.4% over similar 2002 figures.

Other predicted developments in the field of Rapid Prototyping include:

- Office based concept modellers as standard PC peripherals
- Laboratory systems with build speeds ten times faster than those of current systems or even the total replacement of such laboratory systems with office-based machines.
- Direct production of polymer parts in the correct production material
- Fully functional metal parts produced directly via RP techniques.

It is not certain how long these predictions will take to materialise, although for some of the statements realisation is not that far away. For example, the production of functional RP parts is already being exploited by various product development industries. De Beer (2004b) demonstrates one case study in which fully functional Rapid Prototype parts were used to assist in the development of a concept product. Other similar examples may be seen in the case studies of Stratasys (2003) and DSM Somos (2004).

From these examples it is apparent that the use of RP technologies for production of functional prototypes parts is becoming an increasingly widespread and common practice. Dean (2003) observes further examples of functional prototypes, and the improvements in additive manufacturing technologies that made them possible. The resulting discussion introduces the concept of Direct Manufacturing and the production of end use products using RP based additive manufacturing systems. This topic is discussed at length in the next chapter, which deals with the area of Rapid Manufacturing.

3.7 Chapter Summary

In this chapter an introduction was given to various media and technologies that are used by industrial designers during the design and development of new products. To be effective, a design aid needs to take into account of (and be compatible with) the tools that are currently used and others that are emerging into mainstream application. Detailed knowledge of these tools is a necessary prerequisite for the development of any new design aid and, as such, is of direct relevance to this particular research project.

The chapter began with an observation of two-dimensional paper based drawing and sketching before moving on to the use of physical three-dimensional models. An overview of Computer Aided Design (CAD) was given, charting its history and development, before studying various modes of input devices that are applied to the creation and manipulation of CAD data. A special focus was placed upon the field of haptic devices and Reverse Engineering (RE) technologies, which enable the creation of highly amorphous CAD geometries. Various CAD output devices were observed, beginning with the visual display of virtual data using screens and other devices. This moved onto different forms of 2D paper-based output and was followed by Computer Aided Manufacture (CAM) of 3D objects using subtractive machining systems. Finally an introduction was given to Rapid Prototyping (RP), discussing the generic process, its advantages and constraints, some applications and a few predicted future developments.

The discussion ends with the mention of Rapid Manufacturing, which uses similar additive processes for the direct production of end use parts from 3D CAD data. The newness of this particular approach and limited number of current practitioners means that there is a shortage of suitably instructive material with which to guide the designers of Rapid Manufactured products. Assuming that the process is to evolve from its current "experimental" status to become a more mainstream method of production, it is apparent that a suitably assistive design aid would be of use. To this end, the next chapter will provide an overview of Rapid Manufacturing, its relationships with the aforementioned design media and concerns relevant to the formulation of a suitable design aid.

4 RAPID MANUFACTURING

4.1 Overview

In the previous chapter, an introduction was made as to a number of tools and computer-assisted technologies that have been applied to the field of product design and development. One of these technologies was Rapid Prototyping (RP), which enables the direct production of physical parts from virtual 3D CAD software using various "additive" manufacturing processes. There have been many advances in the field of RP since it's initial appearance in the late 1980's and much speculation has been made regarding its future use as the applicable technologies evolve. In recent years there have been a number of additions and improvements to different RP systems and the materials that they use. This has led to the current manufacture of parts that are much more functional than was previously possible.

There are several cases of functional RP parts being used in industry for the mechanical testing of certain concept products before they are manufactured using more conventional production processes. This has long been predicted and the ability of additive manufacturing systems to produce functional parts has caused some to consider their use in the fabrication of final end-use parts. This application has become known as Rapid Manufacturing (RM) and is the topic that is discussed in this chapter.

4.2 The RM Concept

Rapid Manufacturing (RM) is not the high-speed fabrication of parts, as its name might first suggest, but rather the use of additive manufacturing systems for the direct production of finished goods from digital data (Bak, 2003). Similar definitions of this process may be found in the work of Campbell (2003), Hague (2003), Hopkinson (2003), Mansour (2003) and Dickens (2004).

The term "Rapid" is used in a holistic sense to express the relative speed with which products can be made when less-direct production methods, such as moulding or casting, are bypassed. Direct manufacture of physical parts from virtual CAD data negates the requirement for any kind of forming tool and any of the related lead-times. As a result, "first-off" Rapid Manufactured parts are available in a matter of hours and minutes, instead of the months and weeks associated with more conventional tool-based methods of manufacture. Pham (2003) describes this shortening of production lead times as Time Compression Engineering (TCE). The computer-assisted devices associated with this phenomenon are commonly referred to as being Time Compression Technologies.

Use of additive manufacturing technologies for the production of final, end-use parts is a relatively new application and, at the present time, no true Rapid Manufacturing systems exist (Dickens, 2004, p169). As a result, all current Rapid Manufacturing applications are performed using Rapid Prototyping systems. Whilst initial experimentation with these systems has been favourable, it is apparent that they were never designed for the final manufacture of products and are limited by a number of factors. These prohibitive factors are noted by Hopkinson (2003) as being: costly production materials; an absence of many true engineering material grades; slow build times; relatively low accuracy and poor surface finishes.

Improvements to both RP materials and systems have enabled far greater functionality of parts than was previously possible, leading to an increased number of RP parts built for mechanical pre-production testing of products. Examples of some of these may be found in the work of Dean (2003), Zhengying (2003), De Beer (2004) and Dickens (2004, p29). A raised awareness of such capabilities is doing much to dispel negative perceptions derived from inefficiencies of early RP systems and giving credence to earlier predictions and promises of true functionality in RP parts. This has caused many to consider the direct manufacture of end-use parts as a serious possibility and has spawned much experimentation.

Beaman et al (2004, p25) identify the focus of most academic, commercial and government funded research as concentrating upon the advanced development of standard Solid Freeform Fabrication (SFF) processes. These are named as Selective Laser Sintering (SLS), Stereolithography (SLA), Fused Deposition Modelling (FDM), Inkjet Printing, and direct metal cladding. An overview is then given as to various systems and applications that fall under current scrutiny, along with a summary of newly available commercial technologies (Beaman et al, 2004, p30).

General observation reveals that current practitioners of Rapid Manufacturing apply a variety of different technologies to the production of parts. However, it would appear that the most prevalent format is that of powder-based systems and technologies, which use the thermal action of high-power lasers to bind various powdered materials.

Previously much work was conducted to develop metal powder-based systems for the production of Rapid Tooling. In this application additive manufacturing processes are used for the direct production of injection mold tools, bypassing conventional routes and shortening lead times. However, in recent years a shift of focus has resulted in these technologies now being applied to the direct manufacture of other functional metal parts. For example, Pham (2003a) discusses different Rapid Prototyping and Tooling technologies as key enablers for Rapid Manufacturing. Prior to this, Hänninen (2001) notes the movement of Direct Metal Laser Sintering (DMLS) from rapid tooling to Rapid Manufacturing, predicting developments in material properties and system capabilities. In a relatively short timeframe many such developments have taken place and there has been an increased uptake of different systems for this particular application.

Kruth et al (2005) observe the different binding mechanisms that are applied in the more dominant selective laser sintering and selective laser melting processes. In their discussion, four different categories of binding mechanism are identified. These are classified as being solid state sintering, chemically induced binding, liquid phase sintering (also referred to as partial melting) and full melting. Items produced using these different approaches range in scale from parts that are composed of porously fused powder to objects that are very close to being fully dense. Obviously, parts at the top end of this scale are more likely to demonstrate the mechanical properties that are sought in many functional applications.

A possible reason for the popularity of powder-based systems over other forms of additive manufacturing may lie in the mechanical advantages that they offer, for example:

- Certain powder deposition systems are self-supporting, which does away with the need for support structures and the negative issues associated with their removal.
- A variety of different production materials are available, ranging from low-density polymers to high-grade steel, titanium and other metal alloys.
- Certain powder deposition systems allow the consolidation of multiple build materials in the fabrication of individual parts whose subsequent structure may demonstrate a range of different mechanical properties.

Whatever reason is used to establish the type of system used, there is one factor that remains common to all technologies and that is a relatively high operating cost. Hopkinson (2001 and 2003) notes the prohibitive effect of cost upon process uptake and application, offering comparative studies as to the economic feasibility of Rapid Manufacturing against more traditional processes. High perceived costs have restricted initial experimentation with Rapid Manufacturing almost exclusively to the production of "high-value" products. Typically these include products related to the medical and healthcare sectors or automotive and aerospace industries, where cost is often outweighed by function. However, value engineering and cost analysis exercises, as performed by Hopkinson (2001 and 2003), are proving the feasibility of Rapid Manufacturing in more widespread applications.

Initial analysis from these exercises reveals that much expense lies in the cost of machines and materials. However, it is concluded that this is dictated by the user group's size. For example, if adoption of Rapid Manufacturing were to increase, the economy of scale would allow for reduced machine costs, resulting in lower part production costs. This is a point that is echoed by Dove (2004, p31).

The elimination of forming tools is also seen to help in reducing the unit cost of individual parts. When producing low part production volumes, Rapid Manufacturing is even shown to be an economically feasible alternative to injection moulding. The relatively slow build speeds that are associated with additive systems mean that they are generally better suited to the production of small parts. However, the process is noted as being capable of producing highly complex part geometries with low labour costs that other methods of manufacture would struggle to match.

4.3 RM Practitioners

Whilst the cost implications of additive manufacturing processes previously restricted their use to the production of relatively high-value goods, exemplar products may now be found across a variety of different market sectors. Raised awareness as to the capabilities of Rapid Manufacturing and its potential affordability has generated much curiosity and speculation, resulting in a constantly expanding number of affiliates and practitioners. Experimental use of Rapid Manufacture for the production of end-use products is currently conducted by a diverse range of academic, commercial, military and other government funded agencies.

4.3.1 University Research

Much university research has been conducted in the area of Rapid Prototyping and associated applications. The Rapid Manufacturing Research Group (RMRG) at Loughborough University is one example that has been identified as leading worldwide research in the field of Rapid Manufacturing (Beaman et al, 2004). An account is given by Rooks (2002) of the group's structure and technical resources. More recently, the World Technology Evaluation Center (WTEC) produced a panel report that includes an outline of the group's makeup, facilities and some of its activities (Beaman et al, 2004).

Early research projects conducted by the group include "Design for Rapid Manufacture" (Dickens and Hague, 2001), the aim of which was to investigate the affects that Rapid Manufacturing has upon the product design process. One of the group's current studies is the "Material Analysis and Design Optimisation" project. This project looks at the functional characteristics of existing RP build materials and the effect that associated freedoms of creation have on the design of products. The main objective of this is to enable the generation of parts that are of an optimum geometry for both manufacturing and end use function.

Other exemplar institutions include the University of Texas in Austin, which is home to the Laboratory for Freeform Fabrication where the Selective Laser Sintering (SLS) process was first developed and where numerous other research programs still continue. The Rapid Prototyping and Manufacturing Institute at the Georgia Institute of Technology has a well equipped facility and conducts research into various additive manufacturing processes. The University of Birmingham conducts research relating to the direct laser fabrication of fully dense metal and intermetallic components, with similar work being conducted at the University of Liverpool. Processes used by the latter of these institutions include Laser Direct Casting (LDC), which injects metal powder into a laser generated melt pool, and Cold Gas Dynamic Manufacturing (CDGM), which uses a supersonic gas jet to blast unheated particles against a substrate, where the intense energy of impact causes them to bond. A comprehensive listing of these and many other worldwide institutions may be found on the Castle Island Internet Website (http://home.att.net/~castleisland/u_lks.htm).

4.3.2 Other Research Agencies

Taminger (2002) describes the interest of NASA (National Aeronautics and Space Administration) in the use of Solid Freeform Fabrication for space-based manufacturing applications. Here an introduction is given to the Electron Beam Freeform Fabrication (EBF^3) process, which was developed by NASA for the direct production of structural metal parts from CAD data. Later, this system is discussed in more detail by Taminger(2003) who offers speculations as to its future applications and development. Another NASA project observed by Dickens et al (2004, p173) is that of sintering technologies in the direct manufacture of miniature unmanned high-altitude vehicles known as Free Flying Magnetometers (FFM).

The Fraunhofer Institute in Germany conducts government-funded research into a various different manufacturing technologies. One project resulted in the development of a selective laser melting process for the direct production of metal parts, which was announced at the Euromold 2003 conference (Beaman, 2004, p14).

In Italy, Treviso Tecnologia (http://www.tvtecnologia.it/) is a special agency for innovation technology, which was created in 1989 by the Treviso Chamber of Commerce, Industry, Crafts and Agriculture. Recent work includes a project in which Rapid Manufacturing was used to produce a mass-market consumer product. In this example, selective laser sintering was used to produce a series of limited edition sunglasses, an image of which may be seen in Figure 4.1.

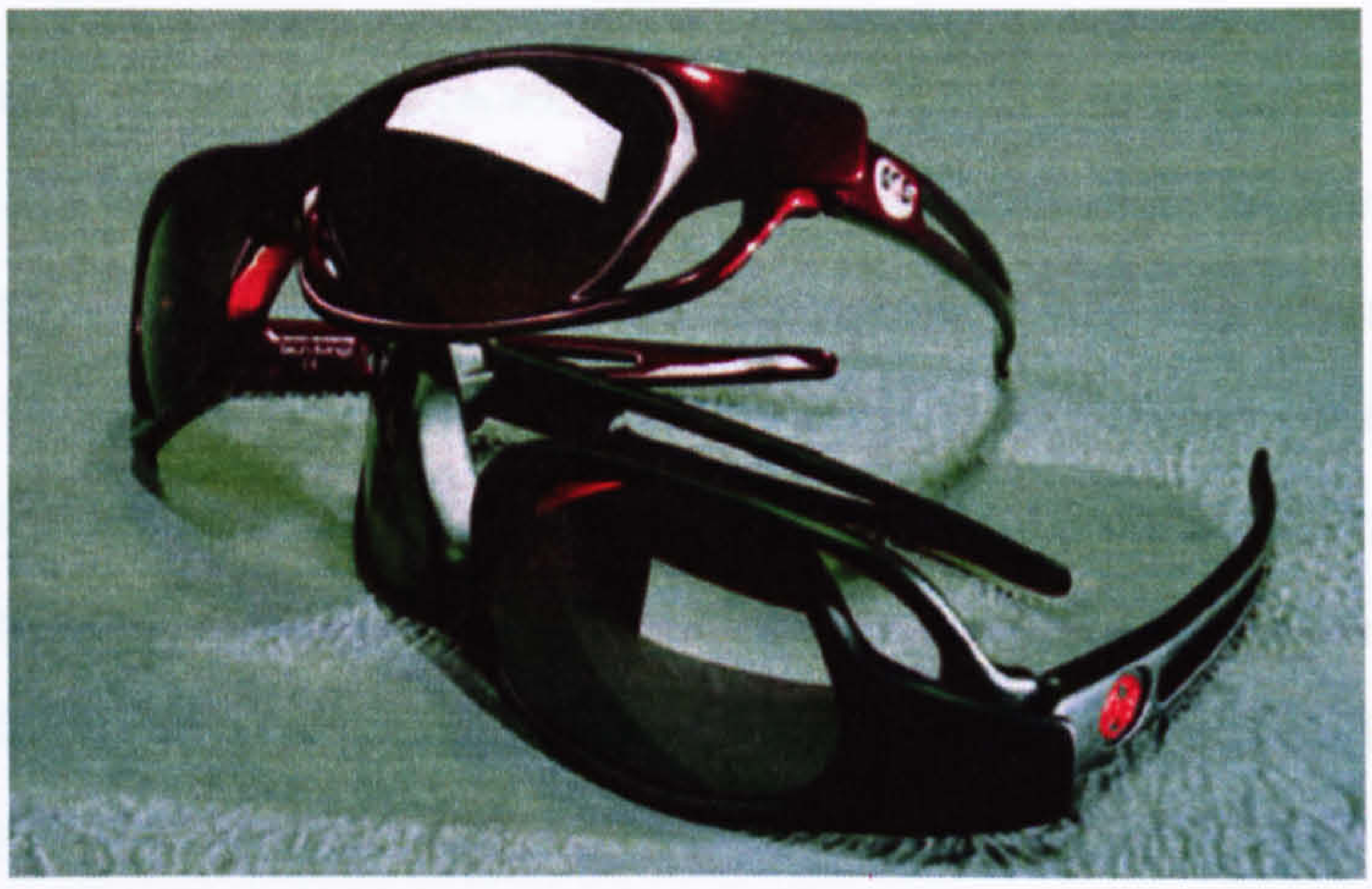


Figure 4.1: Rapid Manufactured Sunglasses by Treviso Tecnologia
Source: Prototype Magazine, p8, Issue 1, Autumn 2003

Normally, a product such as these would be manufactured in high volumes using techniques such as injection moulding. As previously discussed in Chapter 2, it is possible to offset high tooling costs associated with this method of production against high part volumes to enable a relatively low individual part cost. However, production of low batch numbers using this same process becomes very costly as the burden of tool cost must be shouldered by a fewer number of parts. In this instance Rapid Manufacturing was used to remove all tooling considerations, making the low volume production numbers associated with a limited edition product an economic feasibility. This allowed numerous different design variations and provided designers with greater freedom and fewer manufacturing related restrictions when creating the product's form (Dean, 2003).

4.3.3 Military Applications

Current military applications of Rapid Manufacture include the Mobile Parts Hospital (MPH) of United States Army's Tank-automotive and Armaments Command (TACOM). Likened to Mobile Army Surgical Hospital (MASH) units that return soldiers to health whilst still in the battlefield, MPH units are used to perform a similar function for army equipment. MPH units can be deployed to various field locations for the manufacture of replacement parts so that damaged or dysfunctional military equipment can be quickly returned to fully operational combat ready status.

The unit's primary Rapid Manufacturing System (RMS) uses Laser Engineered Net Shaping (LENS ®) technology, which was developed by Sandia National Laboratories. This is considered to be a Directed Material Deposition (DMD ®) process and falls into the "full melt" category, as defined by Kruth et al (2005). This process is stated to produce fully dense metal parts and also has the ability to consolidate numerous high performance alloys, such as high alloy steel and Titanium. A comprehensive description of the MPH and the technologies that it utilises may be found on the Internet website: http://www.mobilepartshospital.com.

4.3.4 Medical and Healthcare

The medical sector is one area in which much Rapid Manufacturing has been performed. The ability of the process to create organically shaped part geometries is of much use when constructing various surgical implants and a number of examples are given to illustrate such work. Landers et al (2002) observe biomaterial requirements for the construction of "scaffold" implants that are used in reconstructive surgery to repair deformities and mimic patient cartilage structures. Later, Yan et al (2003) discusses the process of Bio-manufacturing and describes a specific RP based system developed for the production of custom scaffold implants. Hieu et al (2003) observe the production of cranioplasty implants using RP processes and reverse engineering technology. In this work an introduction is made to the concept of physical "bio-models", created from virtual 3D data captured using Computerised Tomography (CT) scans of patients. Yaxiong et al (2003) note the use of similar approaches in the production of bone substitutes highlighting an example in which a customised mandible substitute is made to better fit a patient's existing bone structure.

A well-publicised example of Rapid Manufacturing in the healthcare sector may be found in the production custom fitting in-the-ear type hearing aids. Siemens Hearing Solutions and Phonak Hearing Systems were amongst the first commercial organisations to produce substantial volumes of these using current RP systems. This particular product has been used as an example to demonstrate how additive manufacturing can be an economic feasibility (Dickens, 2004, p174). The images from left to right in Figure 4.2 show the hearing aid and its progression through the early stages of development to final finished product.

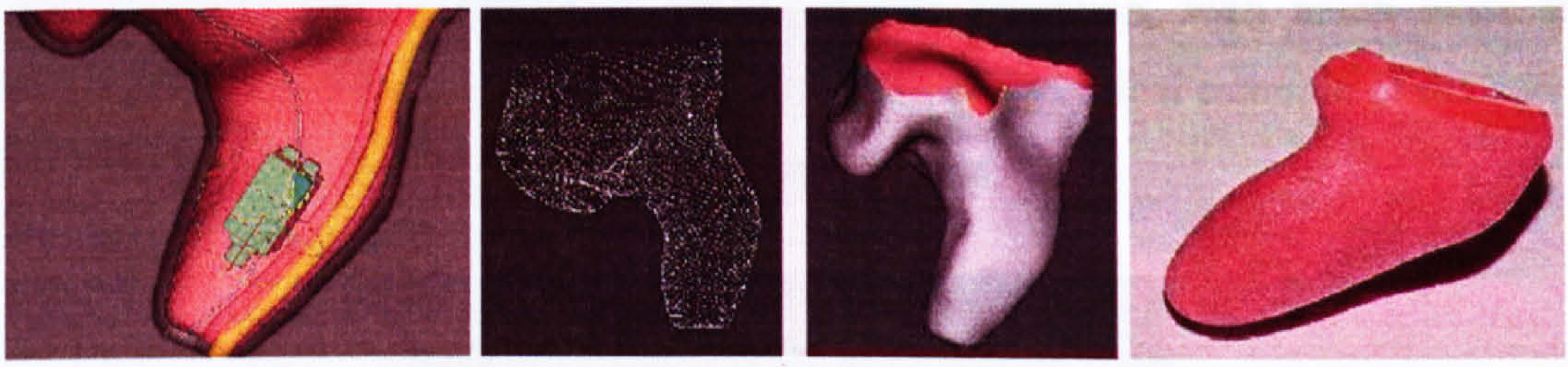


Figure 4.2: Rapid Manufactured In-the-Ear hearing aid

Source: < http://home.att.net/~edgrenda/pow/pow17.htm > 11/02/05

The methods that were previously used to construct similar hearing aids were labour intensive and offered no scope for automation or the application of digital technology. These were facts that made replicating a lost or damaged hearing aid quite difficult.

The method applied to creating new RM hearing aids utilises reverse engineering techniques to generate a three-dimensional point cloud of the patient's inner ear from a scanned impression of their ear canal. Using this reverse engineered data it is possible to generate an exact geometric replica from which to form the hearing aids outer shell. Once a CAD model of this shell is generated provision is made for the internal electronic components that fit inside. Archiving finalised CAD files ensures the quick and easy reproduction of numerous exact copy replacement hearing aids should the original become either lost or damaged. Following production on either SLA or SLS system, the manufactured parts require minimal finishing and only a basic surface coating before assembly and end-use.

4.3.5 Transport

The aerospace industry was quick to adopt Rapid Manufacturing technology for the production of low volume, complex parts. In 2002, the Boeing subsidiary On-Demand Manufacture (http://www.odm.bz/) was formed as a spin out company to pursue the market for Rapid Manufactured parts. The organisation claims to be the only company in the world established specifically for the Rapid Manufacture of structural components using layer-build technology. Using this process enables the production of items as single pieces without tooling and provides significant savings over more conventional methods. The fabrication of items such as aircraft air-ducts and ventilating components form the mainstay of the companies operation, with much work still coming from parent company Boeing. Figure 4.3 shows a typical example of the sort of part geometries produced by On-Demand Manufacture.

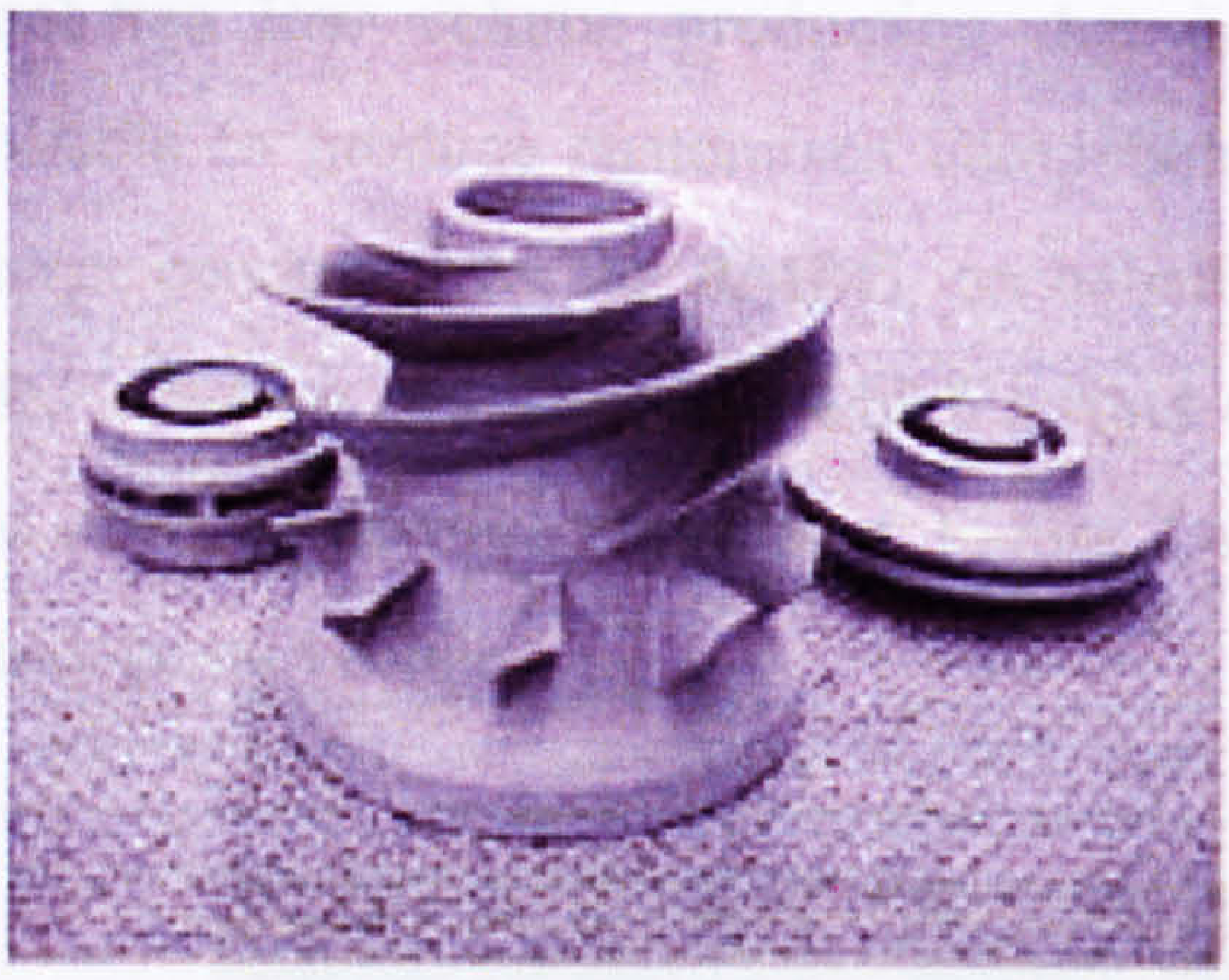


Figure 4.3: Structural Superalloy Parts from Rapid Manufacturer ODM

Source: < http://www.odm.bz/current_capabilities.html > 14/02/05

The fabrication of jet engine components using additive technologies has been of interest to aerospace organisations for several years now. Typical parts include jet turbine blades, which often have highly complex shapes and need to meet a rigorous set of specifications. This has resulted in much research into manufacturing systems capable of producing high-strength metal blades. The Castle Island Internet website (http://home.att.net/~castleisland/rm_24.htm) discusses some of the different projects in this area, including the use of powder-based technologies for the fabrication of turbine blades with in-built electronic sensors.

Rapid prototyping technologies have been used in the automotive industry for many years, although there is evidence to suggest that their application is now expanding to include the manufacture of production parts. An example of this is the use of additive technologies by Formula 1 racing teams to produce functional parts. Wohlers (2004) notes this particular application, Kochan (2003) describes the use of SLA machines to produce parts for wind tunnel testing and, more recently, a series of case study examples were presented in Time Compression Technologies (TCT 2005).

Mass customisation has been an added-value component of the automotive industry for some time, with customers defining their vehicle's makeup with variable options that include things such as paint colour, type of upholstery and other non-standard extras. However, use of previously described Reverse Engineering technologies now enables the capture of and replication of organic surfaces geometry as CAD data. When combined with the tool-free low volume production that is possible with Rapid Manufacturing it is possible to produce customised components that are build to fit individual users. A project conducted by the RMRG, on behalf of consortium partner MG Rover, demonstrates one such application in which a rigid custom-fitting seat was produced to incorporate a unique derrière impression. Figure 4.4 shows pictures of this seat and the recipient road-going vehicle.

Figure 4.4: Customised seating for MG Rover

4.3.6 Consumer Products

As previously stated, the cost of additive manufacturing processes has been a prohibitive factor in their uptake for the production of less high-value mass-market products. However, projects like the Treviso Tecnologia sunglasses and Phonak hearing aids are inspiring companies to take up the challenge and apply additive technologies to the production of mass-market consumer products. One such company is the Dutch Freedom of Creation (FOC), who produces a variety of high design artefacts that range from fashion accessories to interior design goods. The company's Internet website (http://www.freedomofcreation.com) gives details of their different products and ongoing projects. The picture that is shown in figure 4.5 illustrates one of their interior design products.

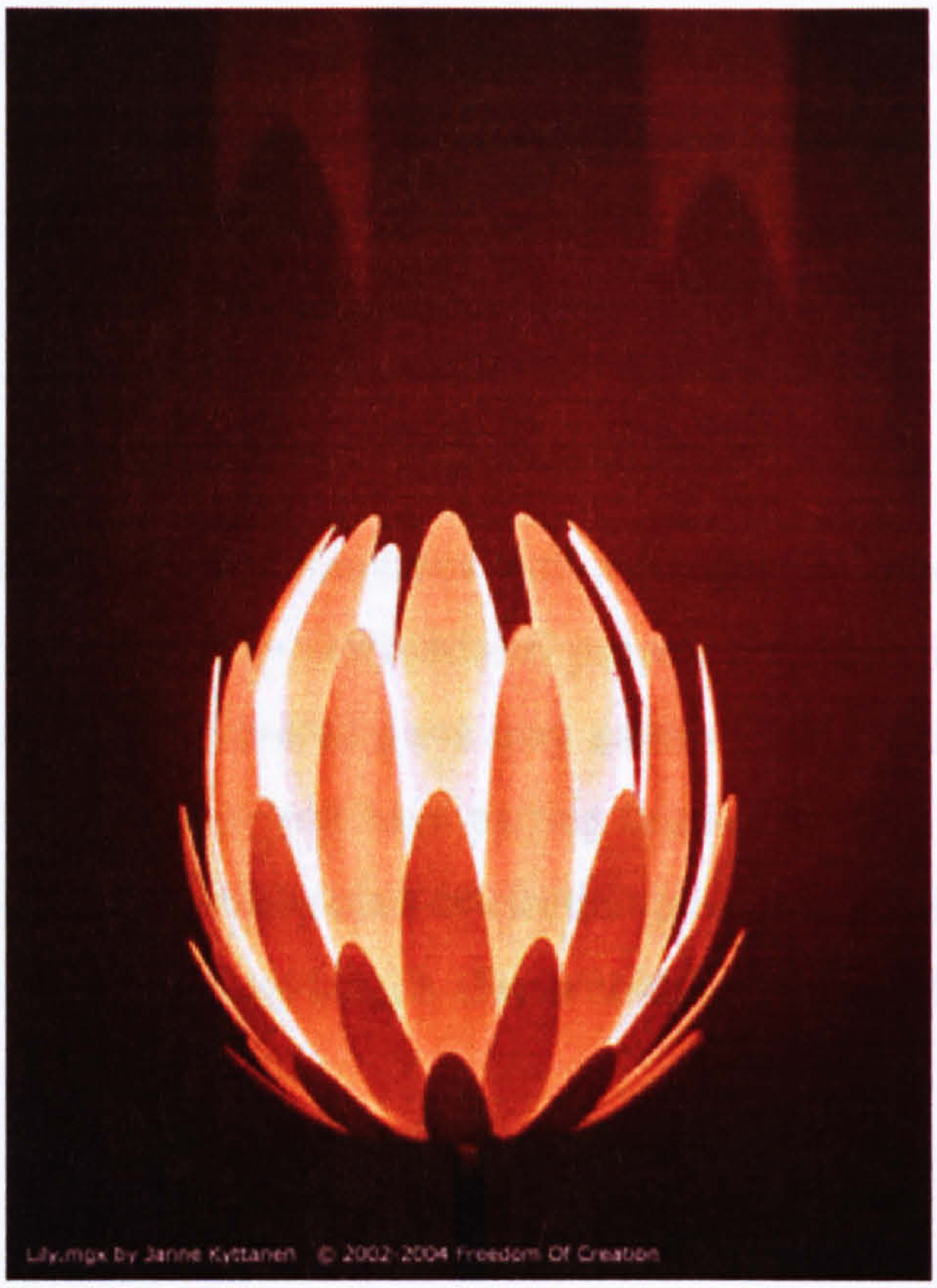


Figure 4.5: Rapid Manufactured light shade by Freedom of Creation

Source: < http://www.freedomofcreation.com > 14/04/04

4.4 Benefits of RM

Many of the shortfalls associated with Rapid Prototyping have still to be eliminated from additive manufacturing systems, and their current use remains restricted. However, as technological evolution takes place, it is expected that true Rapid Manufacturing systems will become available. Some believe that the introduction of systems such as these will amount to a new industrial revolution (Griffiths, 2002) and that the days of tool-reliant production methods are numbered (Anon, 2002). Assuming that the current problems facing additive manufacturing technologies will be resolved, Hague et al (2003 and 2003a) discusses some of the design implications and opportunities afforded by Rapid Manufacturing. The points raised include the following:

- **Geometry For Free**

  The additive manufacturing process is able to produce any complexity of geometry at no extra cost, something unheard of in other more conventional processes. With Rapid Manufactured part cost is determined by size; volume and build time, the last of which may be determined by build orientation.

- **Design Freedom**

  Rapid Manufacturing provides designers with a freedom to produce practically any geometry and is unrestricted by conventional process considerations and constraints. For example, Rapid Manufactured parts may have variable wall thickness with no need for draft angles. Parts do not have parting lines or witness marks, as would be caused by mold tool splits, feed points or ejection pins. It is possible to produce parts with re-entrant features and undercuts that would be impossible to extract from a mold cavity.

- **Materials**

  Using Rapid Manufacturing it is possible to produce individual parts using multiple materials. Conventionally this is achieved in a crude manner using over-moulding, which uses multiple materials of different mechanical properties to instil a product with increased functionality. Toothbrushes are an exemplar product in which this technique is used to produce a stiff core body with an over-moulded handle grip that is soft and tactile. The ability of Rapid Manufacturing to replicate this action, but on a far greater scale of complexity, holds numerous implications for the functionality and aesthetics that may be designed into graded material parts.

- **Custom Parts**

  Rapid Manufacturing is free of tool-based cost restrictions, making the production of low volumes and economic feasibility. In recent years there has been a trend toward mass customisation in products such as mobile phones. However, the ability to produce one-off items supports a move from mass customisation towards parts that are customised to meet the specific wants or needs of individual users.

- **Innovative Interfaces**

  New computer interfaces, such as the previously discussed haptic technologies and reverse engineering tools, provide new approaches with which to create CAD data. Using these, designers are less inhibited or constrained during form creation than they would be using more conventional CAD techniques. Other devices for the improved viewing and manipulation of virtual data will aid perception and reduce the likelihood of undesirable and wasteful builds.

- **Collaborative Design**

  Being a digital process, Rapid Manufacturing supports greater interaction and communication between stakeholders during the design stage, as was previously indicated by Evans (1998). Visualisation aids and collaborative software allow virtual conferencing between multiple stakeholders. Use of the Internet enables such conferencing to be conducted via any number of worldwide locations. An alternative to this direct collaboration would be the use of Knowledge Based (KB) tools. A noted example is the web-based Cybercut™, which was developed by the University of California in Berkeley to provide a design-to-prototype service. However, at the present time, it would appear that there is no such tool that is specific to the Rapid Manufacturing process.

4.5 Current Constraints

Whilst the ability of Rapid Manufacturing to create practically any geometry provides designers with much freedom, it is noted that certain constraints still affect the design of Rapid Manufactured products. For example, it is necessary to consider assembly and maintenance, as well as the inclusion of what Clark (2000) refers to as legacy parts. Very few products exist in isolation and it is necessary that most include items such as circuit boards, batteries or existing parts from previous designs. Since Rapid Manufactured parts are constructed using an additive process it is recognised there is potential for items to be imbedded during construction. However, this raises a number of issues regarding complexity of the manufacturing system, post-production maintenance of products and the recovery of materials once the product has reached the end of its life cycle. Other constraints noted by Hague et al (2003) include:

- **Surface finish and build speed**

  As previously mentioned, significant issues have yet to be overcome. The main problem affecting parts is that of the stair steps, which are a result of the laminar construction process. It is indicated that stair step evidence may be reduced with thinner build layers, although the effect of this would be even longer build times.

- **CAD**

  The Rapid Manufacturing process will allow the production of individual parts with different materials and microstructures throughout, but existing CAD systems are only able to represent this on small parts with course resolutions. It is predicted that if CAD does not evolve in line with the new manufacturing capabilities, a situation will quickly arise in which software is unable to generate the structures that the hardware is capable of building.

- **Materials**

  At present, there are only a few available materials and they are all very expensive when compared to more standard engineering materials. This is largely due to the specialist nature of RP materials and their relatively small market. With limited sale figures, material manufacturers have little justification for the development of new materials and must recoup current development costs with high sale prices.

- **Recycling**

  The ability to construct individual parts from multiple materials raises a number of issues as to how these materials would be separated for disposal or re-use at the end of the products life. At the present time, a restricted number of applications mean that this is not an issue. However, as a more mainstream process manufacturing a variety of consumer goods, it would be subject to legislation like the soon to be imposed Waste Electrical and Electronic Equipment (WEEE) directive, which is detailed on the Department of Trade and Industry website (http://www.dti.gov.uk/sustainability/weee).

- **Product Liability and IPR**

  In recent years, society has developed an increasingly litigious nature, in which accountability is of key importance for remuneration of success and apportion of blame for failure. Hence, if consumers were involved in design and construction of products, as is possible with Rapid Manufacturing, a number of product liability and Intellectual Property Rights (IPR) issues would be raised.

4.6 Effect of RM Upon Designing

Hague et al (2003a) discusses how Rapid Manufacturing will affect the way that products are designed, predicted a change to the divide that exists between mechanical and aesthetic design. The result of this would be a "hybrid" industrial designer, versed with cross-disciplinary knowledge and capable of actions that would normally be undertaken by engineers. For years this has been the implicit aim of strategies such as DFM and DFA, which strive to eliminate the "over the wall" design approach that was described by Boothroyd et al (2001, p4). As discussed in Chapter 2, strategies such as these form repositories of procedural knowledge that may be used to assist inexperienced designers and engineers. However, whilst these resources are available for virtually all forms of production, it would appear that there is not yet a proven aid for the design of products that are to be constructed using Rapid Manufacturing technologies.

With the potential that Rapid Manufacturing has to become a mainstream production process, it is likely that there will be an increasing demand for a suitable procedural aid. The changing remit of industrial designers, as noted by Hague et al (2003a), indicates that their profession is one that would benefit much from such an aid. With this in mind, it is imperative that a "Design For Rapid Manufacture" (DFRM) strategy be identified that would be of use to industrial designers. A summary of the procedural benefits that any such DFRM strategy would need to convey includes:

- **Manufacture For Design instead of Design For Manufacture**
  The freedom of geometrical creation enables the design and manufacture of products that are uninhibited by the restraints of conventional production processes. This enables designers to work more freely and ignore prior manufacturing related considerations, such as draft angles and undercuts.

- **Greater Part Complexity**
  The freedom of creation offered by additive manufacturing removes the constraints of conventional production methods and allows the manufacture of much more complex part geometries.

- **Part Consolidation**
  The ability to produce parts of increased complexity provides greater scope for the merging of multiple assembly components, allowing the production of highly complex multi-functional single parts.

- **Design Customisation**
  The removal of production tooling and associated cost restraints makes it economically feasible to produce single "one off" items and products that are unique to individual user specifications.

- **Elimination of Part Shipping and Storage**

  The ability to rapidly produce parts to order and on site using compact RM machines and electronic data removes the need to physically ship components from supplier to user. This also removes the need to predict what spare parts require storage, as they may be made on demand from a stock of raw material. Both of these are aspects that have attracted attention and experimental application within areas such as military logistics and space exploration.

4.7 Chapter Summary

In this chapter an introduction has been made to the relatively new field of Rapid Manufacturing. Following a brief overview, the Rapid Manufacturing concept was discussed. Identifying "time compression" within product development cycles, the word "rapid" has been defined as a term that is relative to other more conventional manufacturing strategies. Rapid Prototyping and Rapid Tooling technologies were noted as key enablers of Rapid Manufacture, in which the prevalent use of powder-based systems was observed. Current practitioners of Rapid Manufacturing have been identified, including various academic, commercial, military and other government funded bodies. Here a number of Rapid Manufacturing applications and products were noted. General observations were recorded as to the process as well as with some of the implications and opportunities that it affords designers. Finally, the need for a suitable aid to assist in the design of Rapid Manufactured products was identified.

This chapter forms the last part of a far-reaching literature review in which various strategies; tools and technologies applicable to the design; development and manufacture of new products have been observed. From this, Rapid Manufacturing has been identified as a new and developing area of technology for which little instructional material and no design aids exist. Having identified this gap in knowledge, it is the aim of this research project to recommend a suitable aid or approach that will assist industrial designers in the generation of design concepts for Rapid Manufacture. With this remit, a series of applicable research questions must now be determined and some appropriate research methods identified. These are to be the topics of discussion in the next chapter, which will focus upon research methodology.

5 RESEARCH METHODOLOGY

5.1 Overview

In previous chapters an introduction was made to various tools, technologies and approaches that may be applied by industrial designers during the NPD process. Recent years are shown to have witnessed a general quickening of product development cycle times (Barclay, 2000). These time reductions are seen to be the result of an almost universal strategy in which product developers aim to achieve earliest market entry so as to attain the greatest market share. This was first achieved with the use of managerial approaches and decision-support tools that promoted best practice use of resources for the quickest and most efficient throughput. However, advances in digital CAD/CAM technologies that have taken place during the past few decades have increased the potential for even shorter product development cycle times.

The constant desire of developers to be first into the marketplace with new products has generated much interest in the use of what Pham (2003) refers to as "time compression technologies". Since their initial appearance in the late 1980's, Rapid Prototyping (RP) systems have become widespread and have proved themselves to be key enablers of time compression. However, ongoing technical development and improved functionality amongst these systems has led their affiliates to consider the possibility of new applications. The most recent of these is Rapid Manufacturing, in which RP-based additive manufacturing systems are used for the direct production of end-use parts from virtual CAD data. Initial experimentation with RP technologies has proved favourable and whilst there are no true manufacturing systems at the present time (Dickens et al, 2004) many predict their imminent appearance as being inevitable. In fact, using examples like the previously described Phonak hearing aids, students in Loughborough University's Mechanical Engineering Department are taught that rudimentary Rapid Manufacturing already exists.

Additive manufacturing processes fabricate parts in a way that is fundamentally different to subtractive machining operations, such as milling and turning. Direct manufacture of parts from CAD data also negates the requirement for any kind of forming tool or cavity, as would be necessary in moulding or casting processes. It has been noted that this will have a number of implications for the design of products and that industrial designers will be one of the major stakeholder groups affected.

Various design strategies such as Design for Manufacture and Assembly (DFM and DFA) have been seen to assist the NPD process by raising awareness of manufacturing issues during the early stages of design. Whilst these strategies cater for a number of different manufacturing systems, no such aid exists for the design of products that are to be Rapid Manufactured. Hence, with this process set to become a much more mainstream form of manufacturing, it is suggested that a suitable "Design For Rapid Manufacture" (DFRM) tool or strategy be identified. Therefore, it is the purpose of this chapter to state the necessary research questions and highlight suitable methods with which to explore a viable proposal.

5.2 Hypothesis

- **Current gap in knowledge**

  Rapid Manufacturing has been identified as a newly emerging technology that is to have a profound effect upon the way that products are designed and made. However, at the present time, there is no proven approach with which to assist industrial designers in the generation of product concepts that are to be produced specifically using Rapid Manufacturing technologies.

- **Proposed solution**

  Having observed the use of strategic approaches to assist the design of products for conventional forms of manufacture, it is proposed that a similar approach may be developed and applied to the design of products for Rapid Manufacture.

5.3 Research Questions

Effective exploitation of any technology is dependent upon user understanding of its capabilities, requirements and restrictions. For industrial designers to successfully generate product concepts that are best suited to production by Rapid Manufacturing it is necessary that they possess a degree of procedural knowledge. Therefore, it is the aim of this research project to identify a suitable system for the transfer of process knowledge to industrial designers engaged in future Rapid Manufacturing projects.

In order to ascertain procedural knowledge and establish a suitable system for its subsequent dissemination, this investigation shall focus upon the following research questions:

- What are the capabilities of Rapid Manufacturing as a method of end-use part production?
- What impact will the process have upon the design of products from an industrial design perspective?
- How may industrial designers best exploit Rapid Manufacturing technologies to create optimum product design concepts?
- How may formal design strategies be used to assist the best practice use of Rapid Manufacturing technologies by industrial designers?

Additional questions to be covered in this project include the following:

- What are the tangible benefits of Rapid Manufacturing?
- What are the criteria that make a product particularly suitable for production by current rapid manufacturing technologies?
- What are the restrictions of current CAD technologies upon Rapid Manufacturing?

- To what extent are current design strategies applicable to the formulation of a specific Design For Rapid Manufacturing (DFRM) tool?
- How may a DFRM strategic tool be applied and what form might it take? (i.e. handbook, log table, matrix, computer software, etc)

Having identified these research questions it becomes necessary to establish an applicable method or approach with which to achieve a desirable set of results.

5.4 Research Methods

Much work has been conducted upon the topic of research methodology and many formal methods have been identified, all of which may be categorised as being either quantitive or qualitative. There is a clear divide between these two groups, in which the largely numeric methods applied to quantitive research contrast with the more literary based methods that are applied to qualitative research. Previously these differences have led to the groups being characterised with contrasting terms such as "hard" and "soft". Based on the earlier work of Halfpenny (1979), a table is presented by Silverman (2000) that offers descriptors of both qualitative and quantitive methods. This table is shown below in Figure 5.1.

Qualitative	**Quantitive**
Soft	Hard
Flexible	Fixed
Subjective	Objective
Political	Value-free
Case Study	Survey
Speculative	Hypothesis testing
Grounded	Abstract

Figure 5.1: Qualitative and quantitive research descriptors

Perceptions such as these promote a commonly held belief that quantitative research is the better of the two groups because of its more defined and easily quantifiable results. Silverman (2000) notes this tendency to pre-define quantitative methods as being "good" and qualitative methods as "bad". However, he goes on to suggest that choice of research method should really depend upon what the researcher needs to find out. For instance, to discover how a group of people intends to vote in an election, the most appropriate approach may be the application of a quantitive method such as a social survey. Alternately, if the focus of research is concerned with exploring people's life histories or everyday behaviour, then qualitative methods might be the favoured approach.

The main focus of this particular research project is to identify the capabilities of Rapid Manufacturing and to recommend an approach that would assist industrial designers in the generation and development of appropriate product concepts. Therefore it is necessary for the project to encompass both qualitative study of Rapid Manufacturing process and quantitative measurement of opinions as to the usability of any suggested strategy or assistive design approach.

When this project was first instigated, the newness of Rapid Manufacturing meant that few users existed and relatively little reference material had been published. However, working in close proximity to Loughborough University's Rapid Manufacturing Research Group (RMRG) provided an ideal opportunity with which to observe pioneering work first hand. This enabled qualitative case study observation of several Rapid Manufacturing projects, which are discussed in detail during the next chapter. The validity of this particular research method is discussed by Cohen (2000, p181), who identifies the ability of case studies to establish both cause and effect in contexts.

The RMRG works in collaboration with a consortium of industrial partner companies, who produce products for a variety of different market sectors and applications. Projects originating from these different industrial partners mean the group's research and deliverables are predominantly based upon real world demands, rather than "blue sky" academic exercises. Rooks (2002) notes this and the increasing frequency with which similar industry-orientated philosophies are being applied to university research. Regular project meetings between the group and its industrial stakeholders enable valuable and timely input as to ongoing work and future process expectations. This input may take the form of comments made following project reports and presentations or even group brainstorming sessions, in which conceptual ideas and possible future applications are generated.

Alongside these case study related activities was a parallel continuation of the literature review which first began at the research project's outset. The focus of this review was to concentrate upon continued developments within the area of Rapid Manufacturing and related technologies. Observations from this, together with knowledge generated from case studies and previously gathered reference materials, were to be used in the formulation of a suitably assistive product design approach.

Subsequent testing and validation of this design approach was to be such that data could be collected for quantitive assessment of perceived usability. In order to achieve this it was decided that a series of trials should be conducted in which user surveys were applied to record the measured responses of participants. A design exercise was devised to provide this study with a focus. In this exercise, participants were asked to apply the suggested design approach to the redesign a product for fabrication via Rapid Manufacturing.

Testing began with a pilot study that was conducted to appraise the suitability of the proposed exercise as a means of assessing the suggested design approach. Changes to the trial exercise were made as required at the end of each test on the basis of user surveys that were completed by each participant. Once necessary refinements had been made, a finalized test procedure was used to gather data in a second user trail. This was conducted under controlled conditions in which participants were asked to produce initial concepts for the redesign of a specific product for Rapid Manufacturing. Once this set of trials was complete, a third and final user trial was conducted in which different subjects were asked to apply the same suggested design approach to the redesign of several different products for Rapid Manufacturing. In each instance participants were asked to complete user surveys as to the usability and functionality of the suggested design approach. A more specific description of these different procedures and surveys will be offered in Chapter 7, which reports on the DFRM tool development.

Figure 5.2 shows a chart that gives a summarised description of the overall strategy that has been applied to this research project.

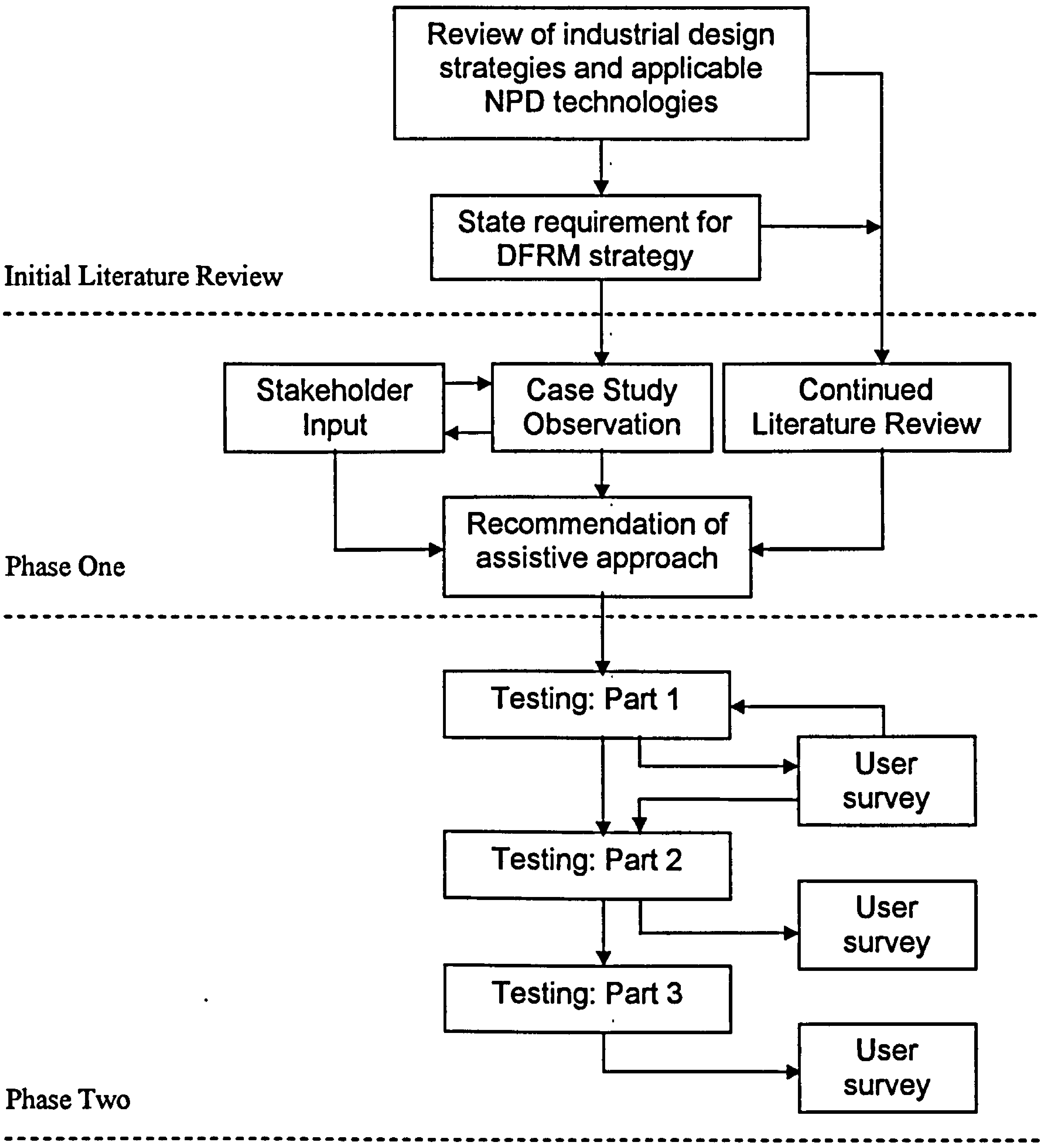


Figure 5.2: Research Structure

The project began with an initial review of various different NPD methods and technologies, from which the need for an assistive design approach was identified. This was followed by a series of detailed procedural observations that were used to formulate a suitably assistive design approach. Finally, the suggested approach was tested in a series of user trials.

5.5 Chapter Summary

In this chapter an overview has been given as to the research methodology and some of the observations that have been made during the initial stages of investigation. A general quickening of product development cycle times has been noted, the cause of which has been attributed to commercial desire for the earliest possible entrance of products into their respective marketplaces. The use of assistive design strategies was mentioned, along with a brief introduction to "time compression technologies" which enable even quicker development cycle times. Rapid Manufacturing was identified as an emerging technology driven process that is likely to have great affect upon the design, development and manufacture of future products. The accruement and transfer of procedural knowledge in this particular area of technology is noted as a key enabler for continued application, with industrial designers named as chief benefactors.

Following these observations a series of research questions and objectives were posed with regard to the impact of Rapid Manufacturing upon the design of products and the formulation of a suitably assistive design approach. A brief introduction was given to various research methods, identifying both qualitative and quantitative approaches. With the questions identified, an overview was given of the specific method that has been applied to this particular project. One of the main approaches mentioned in this was case study observation. This particular method is discussed during the next chapter, in which several applicable case study projects are present.

6 INDUSTRIAL DESIGN CASE STUDIES

6.1 Chapter Overview

In this chapter a series of case study projects are presented to observe the effects of Rapid Manufacturing upon industrial design. In each instance, the case studies were conducted at Loughborough University as part of more broad design research. Table 6.1 lists the case studies that were undertaken and the principal designer in each project.

Project Title	**Principal Industrial Designer(s)**
Remploy Hip Protector	Mike Burton / George Torrens
Bafbox Electronic Enclosure	Zhen Sun
MG Rover Handbrake	Hugh Newlyn / Zhen Sun
Land Rover Dashboard Console	Mike Burton
JCB Control Pod	Mike Burton / Darren Watts
Custom Handgrip Study	Mike Burton / Rebecca Cain

Table 6.1: RMRG Case Study Projects

The first case study in this group observes the development of a product for conventional forms of manufacture; some of the obstacles that were encountered and the compromises that were made to achieve an economically feasible design. This particular example is revisited in the final discussion section of this thesis, noting the impact that Rapid Manufacturing technologies would have had upon the product's design.

Subsequent case studies in this chapter focus upon the redesign of an existing product or component for manufacture using additive processes. Taking an item that was previously designed for production using conventional techniques, designers worked to develop new concepts of increased functionality or value (or both) by exploiting the capabilities of Rapid Manufacturing. In each instance, functional parts were generated using additive manufacturing systems, such as Stereolithography (SLA), Selective Laser Sintering (SLS) or Fused Deposition Modelling (FDM).

Many advocates of RP feel that the limited functionality of early machines and materials was detrimental to the process and led to current prejudice amongst engineers and technologists, whose perceptions are based upon negative experiences with early systems. With this in mind, and acknowledging that the experimental case studies were to be performed using prototype machines and materials rather than true manufacturing systems, a decision was made to disregard all cost related issues. The justification for this was that any monetary calculations based upon current machines and materials would be unrepresentative of future systems and could taint user perceptions of economic viability, in the same way that early RP system inefficiencies affect current uptake and application.

In each of the case study reports a brief overview is given as to the specific project scenario and existing product. From this, necessary objectives and criteria are identified for the subsequent Design For Rapid Manufacture (DFRM) exercise. Following a description of the different tools and approaches used during design and development, a brief discussion is presented that compares earlier products with those designed for Rapid Manufacture. This is used to highlight specific changes and improvements attributed to Design For Rapid Manufacture.

6.2 Remploy Hip Protector

6.2.1 Project Background

Remploy is a UK-based organisation that seeks to promote the independence of disabled people through their full inclusion in the labour market. The company operates a number of manufacturing and service sector businesses, employing almost 6,000 disabled people in 83 different factories and managed service divisions. Remploy Healthcare is one of the company's manufacturing sectors and is the UK's leading supplier of bespoke orthoses, supplying a wide variety of products that range from simple wrist braces to custom fitting corsetry and supports.

An orthotist working for Remploy Healthcare identified the need for a product that would reduce the likelihood of fall-related hip fractures amongst the elderly or infirm. These are highly debilitating injuries that often leave individuals with permanently impaired levels of mobility. Hip fractures such as these may occur when a person falls onto the greater trochanter, which is a bony prominence at the head of the femur (upper leg bone). Sufficient force on the trochanter will push it into the socket of the pelvis, fracturing both femur and pelvis. With little soft tissue over this bony prominence to protect it from impact forces, a relatively minor fall will often lead to severe injury.

Initial market research revealed that a number of protective products already existed in this area, both proving the need for such a product but also highlighting the presence of established competition. The picture in Figure 6.1 shows a selection of some of the hip protectors that any new product would need to compete with. The majority of these involve substantial undergarments with pockets that contain rigid thermoplastic shields or plates to absorb and deflect impact forces.

Figure 6.1: existing protective products

Managerial authorisation was granted for a project to begin and a spin out company from the Design Technology Department of Loughborough University called Dexterity Ltd. was commissioned to develop a product that would meet the previously identified need. Acting as both design agency and research body, the project was taken on as a commercial venture that would also be used to observe the application and integration of various technologies during the product development processes.

A brief study of other rival products highlighted two main perceived issues that were seen as potential shortcomings. These were the ineffective placement and location of protective elements and the poor dissipation and transfer of impact forces likely to be sustained in a fall. The ungainly appearance and restrictive nature imposed by substantial amounts of padding or large protective shields were seen to greatly reduce the acceptance of these products by their target users. It seemed that most existing products dealt with this issue by using smaller, less protective forms. However, these small compact protective elements have a restricted area of effective pressure redistribution on the body and require much more accurate positioning to ensure that the hip is adequately protected.

Many of the existing protectors used a rigid “bowl” shaped element, with a raised central area to absorb the initial impact forces sustained during a fall. However, the design team felt that the “rim” of such a bowl (which would be the only part of the structure to remain in contact with the user during a fall) was an insufficient surface area through which to dissipate impact forces. The perceived effect of this was to produce a “cutting edge” or “pressure raiser” that would cause severe and incapacitating bruising of soft tissue whenever substantial impact forces were applied. In addition to this, the plate’s rigid unyielding edge was seen to cause discomfort during normal wear and also whenever bed-ridden users rolled onto their side whilst wearing the device.

Taking the above into consideration it was seen that for a product to successfully enter and compete against other rivals in an existing marketplace it needed to fulfil a number of requirements. These were as follows:

- The product would need to have a greater level of acceptance with target users than other competing products
- The product should be shown to be more effective than competing products
- The pressure raising “cutting edge” should be eliminated from any rigid design
- The product should be commercially viable and capable of sustaining a retail price comparable to other rival products.

6.2.2 Product Development

During the initial project meeting a number of concepts were discussed and loosely sketched by hand. The sketches were then refined and developed until a viable concept was defined. An example of one of the sketches may be seen below in figure 6.2.

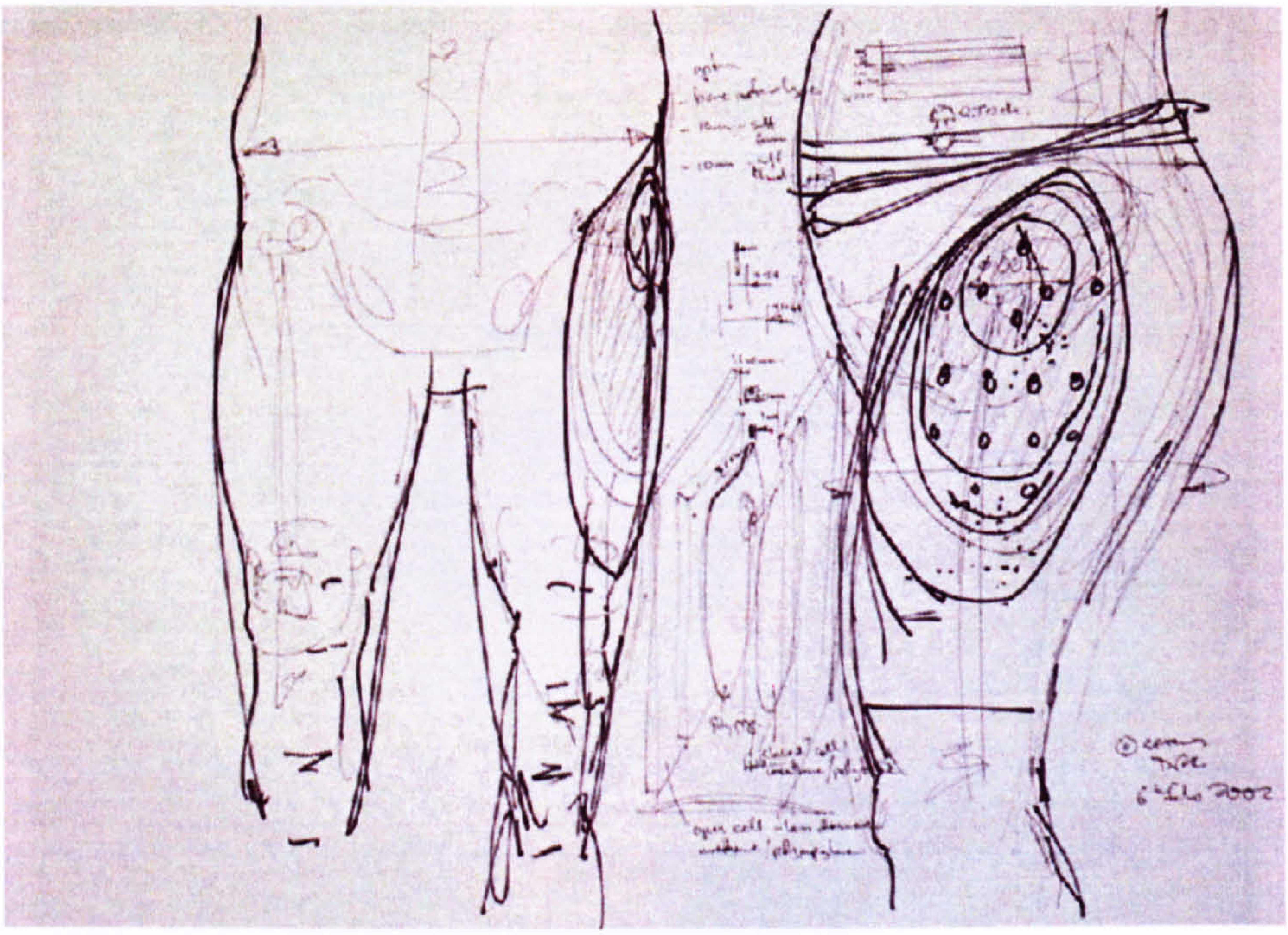


Figure 6.2: Sketched hip protector design

With approved paper-based concept sketches and a written proposal, a decision was made to move design work into 3D CAD. This involved the generation of a body shaped geometry to ensure the optimum fit of product with the user, which was a hard task to achieve with any level of certainty. However, using anthropometric data obtained from survey tables, it was possible to generate an approximate mathematically defined 3D CAD model of the trunk and hip region. Using this model it was then possible to produce different design variations, all of which incorporated the detailed multiple curvature that was required to fit the hip area. Using parametrically constrained CAD, it was relatively easy to make multiple changes and revisions to similarly themed designs.

High quality CAD rendering was used to assist the presentation of conceptual designs making it possible to share them with the client at a very early stage. Using virtual 3D manikins it was also possible to display the concepts in situ so as to increase the client's understanding of each design. Figure 6.3 shows one of the images used to display an early concept.

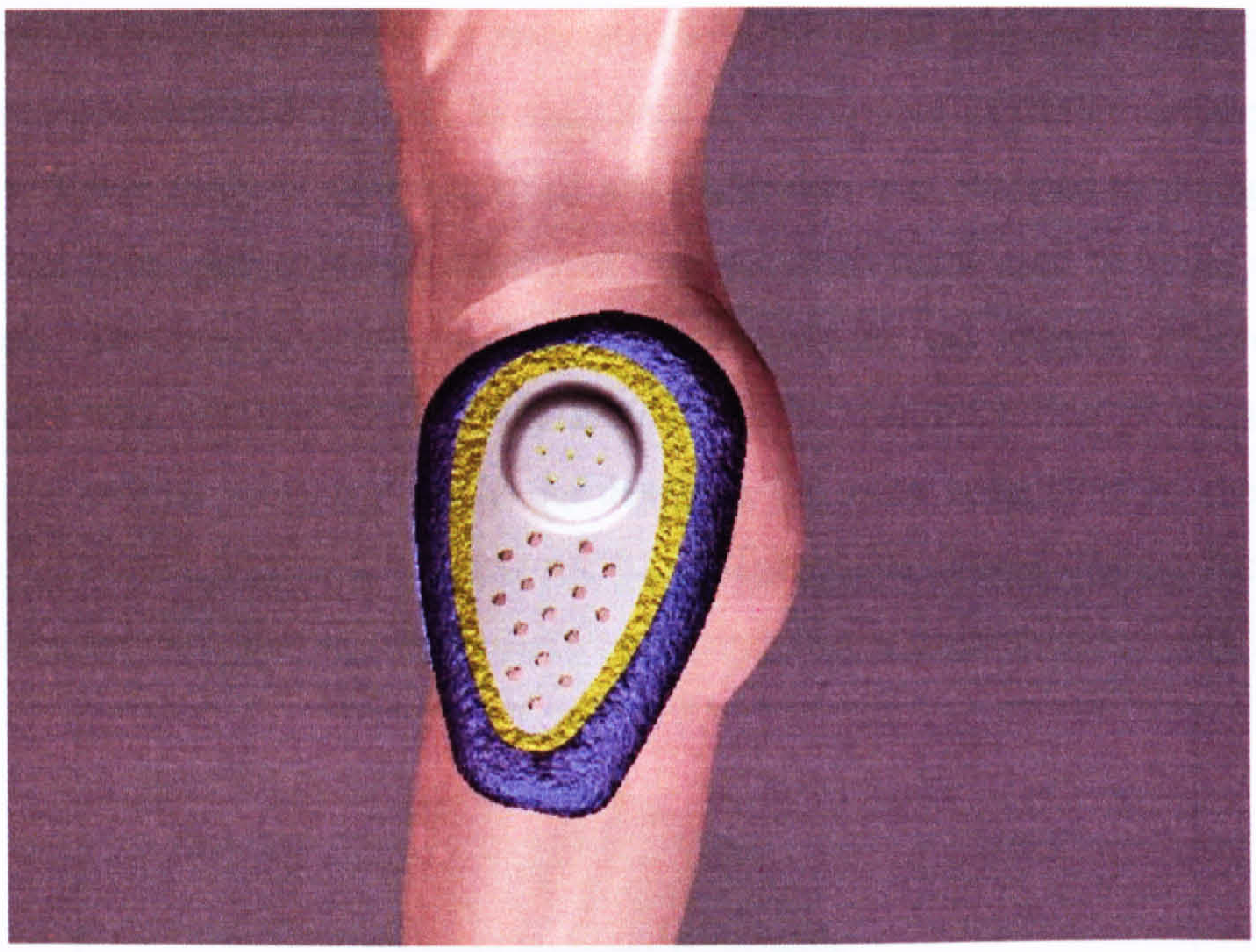


Figure 6.3: CAD image of an early concept on a virtual manikin.

It was decided at an early stage in the project that the design would conform to the apparent standard hip protector format, which was a protective insert that could be placed within a specially constructed undergarment. In this instance the protective element was to comprise of a rigid injection moulded plate over-moulded with expanded polyurethane foam. This would provide a product that was soft and semi-flexible with a rigid core element. Like the existing rigid dome designs, the plate had a raised section over the trochanter but addressed the "cutting edge" issue with a run-off section of material around its perimeter that dispersed impact forces over a greater surface area. In addition, two different densities of foam were to be used to provide the design with a gradual progression from a soft outer foam through a medium, semi rigid, foam to the rigid inner shield element. This was intended to provide a greater level of user comfort and fit, as given by the soft material, whilst maintaining the absorption properties afforded by the medium semi-rigid foam. However, the main noticeable change from existing products was to be the introduction of an asymmetric design with left and right-handed versions available in a number of sizes so as to achieve optimal user fit.

Unfortunately, the production costs associated with the initial proposal were too high to meet the targets that had been set by the client and a number of design revisions were necessary. Value analysis was performed and the design was changed to a single sized symmetrical form with only one density of over-moulded foam used to house the rigid inner plate. The incorporation of these changes reduced the amount of production tooling that was required and greatly simplified the manufacturing processes. This reduced the overall costs and made the design a lot more acceptable to the client's finance department. Figure 6.4 shows a CAD image of the altered design, including a partly sectioned view that shows the rigid inner plate that is over-moulded with foam.

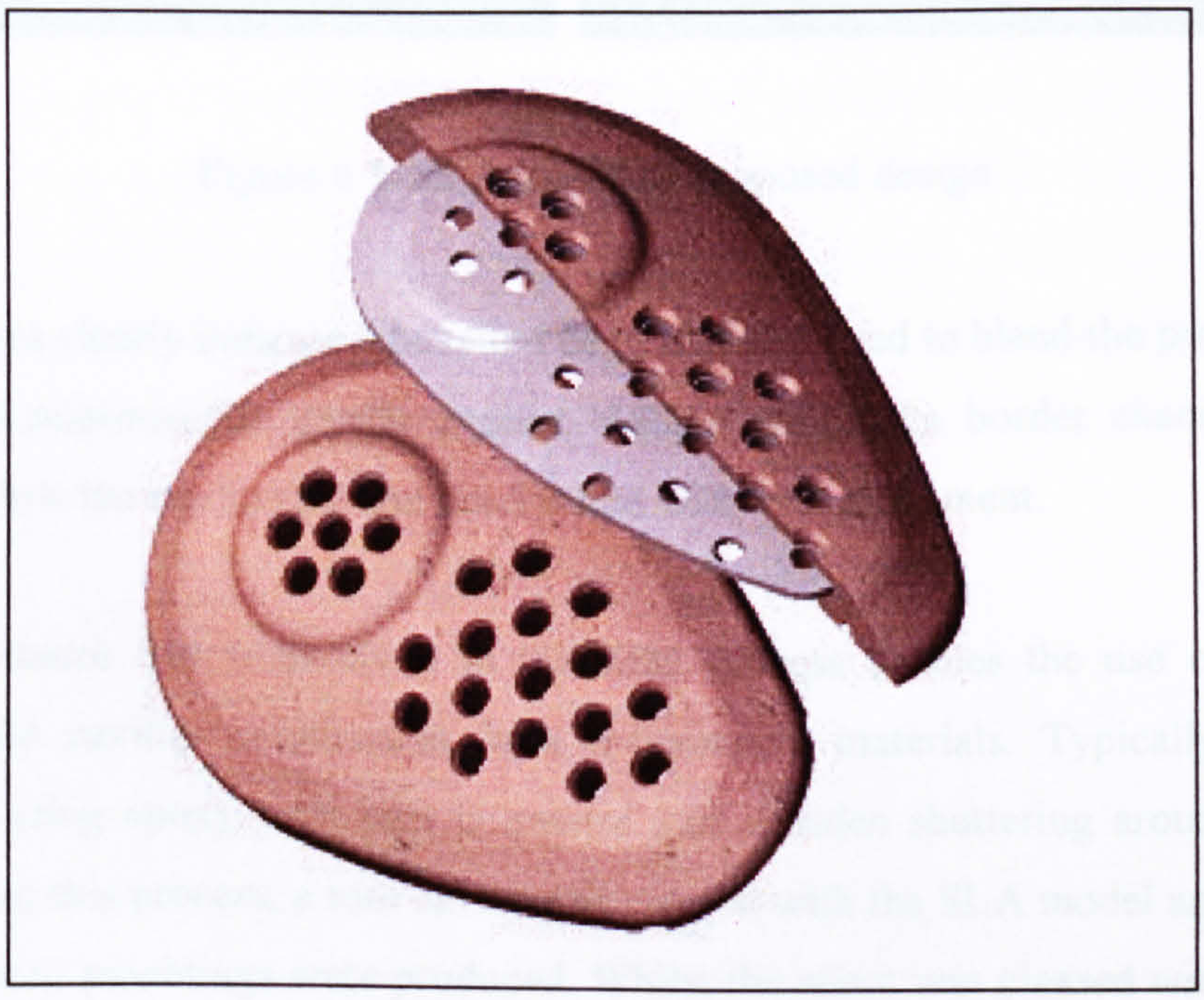


Figure 6.4: symmetrical over-moulded hip protector

With approval given for the altered design, CAD files were finalised and a series of RP models were made. It was the function of these to demonstrate the design's size and shape, as well as acting as forming patterns for the final production processes. In the instance of the Reaction Injection Moulding (RIM) process that was to be used to over-mould the rigid plate section with polyurethane foam, a mould cavity was formed using a Stereolithography (SLA) master pattern. The pictures in Figure 6.5 show the SLA model that was created for this.

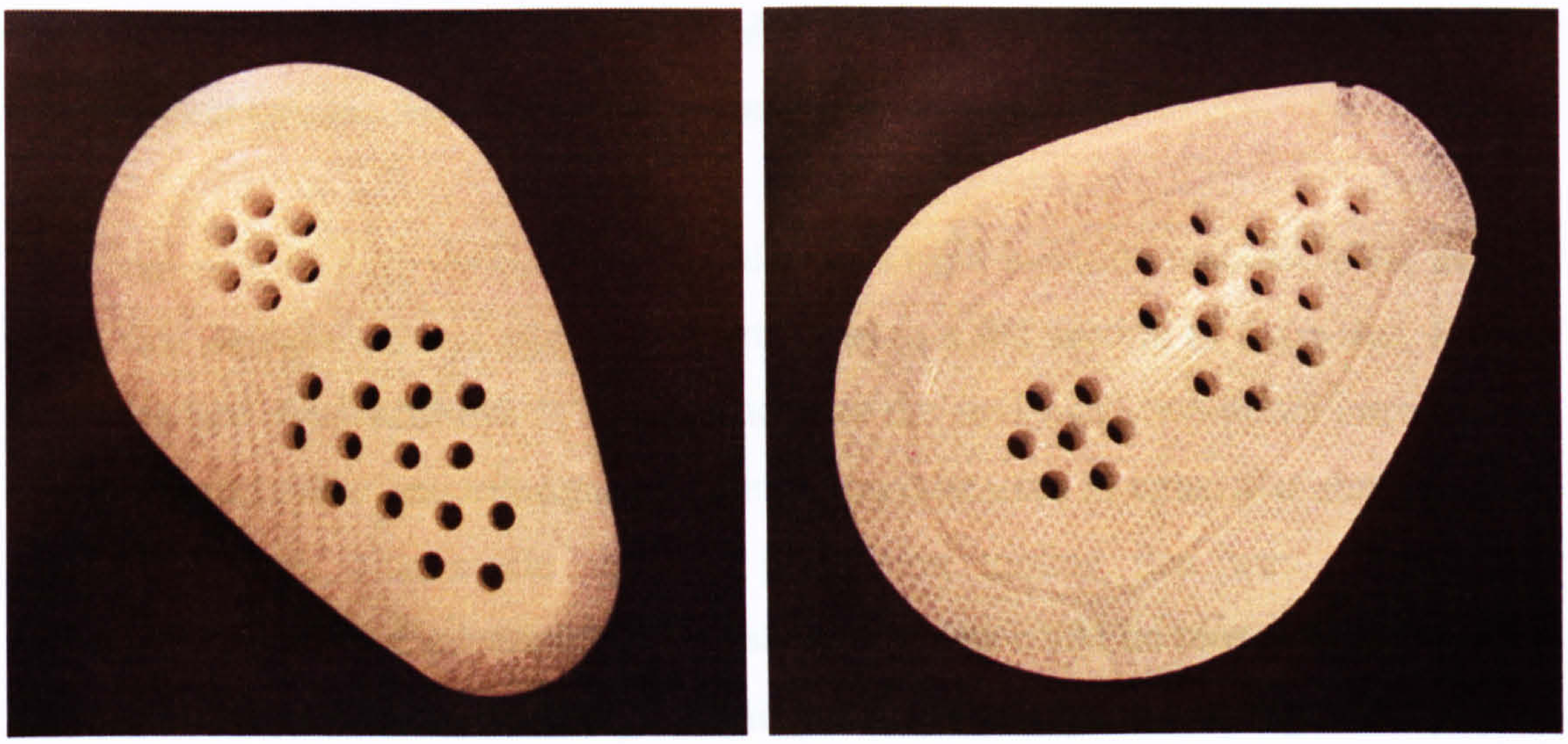


Figure 6.5: SLA model of proposed design

These pictures clearly indicate a bevelled edge that was used to blend the protector with its user and minimise its profile against the hip whilst the border channels on the underside allow the rim to flex and bend inline with user movement.

The low pressure that is involved in the RIM process enables the use of relatively simple mould cavities constructed from inexpensive materials. Typically these are constructed using epoxy resin that is poured into wooden shuttering around a master pattern. Using this process, a tool cavity was created with the SLA model and a number of polyurethane mouldings were produced. Whilst the client was pleased with the initial outcome, costing exercises were performed using established production figures and a request was made for further cost reductions and the generation of a simpler more economical product.

With very little investment in RIM tooling, it was feasible to abandon the over-moulded concept in favour of something more economical that was in-line with existing products. However, rather than do this, it was suggested that an interim product be devised around the existing design so that the over-moulded concept could be taken up at a later date. With this proposal it was intended that a low-cost product be produced to enter the marketplace and generate capital to reinvest in a more costly derivative that would appeal to users who had already established brand loyalty.

The result was a design that incorporated the same rigid injection moulded plate as used in the first design, but was more simply attached to a flat section of foam that was cut from standard sheet material. In order to achieve the envisaged two-phase introduction, the rigid insert plate was redesigned so that it could be used in either flat-sheet or over-moulded format. This meant that the production tooling that was procured for manufacturing the first generation of flat-sheet products could be reused to make plates for the second over-moulded design. Adding a series of lugs to the edges of the plate meant that it would be possible to fix it to the sheet material using stitches, something that could be done using the client's own factory facilities to further reduce the amount of outsourced overheads. Figure 6.6 shows CAD images of the two concepts; design A which has a rigid inner plate that is over-moulded with foam and design B which has a rigid plate that attached to sheet foam via stitches through integrally moulded "lugs".

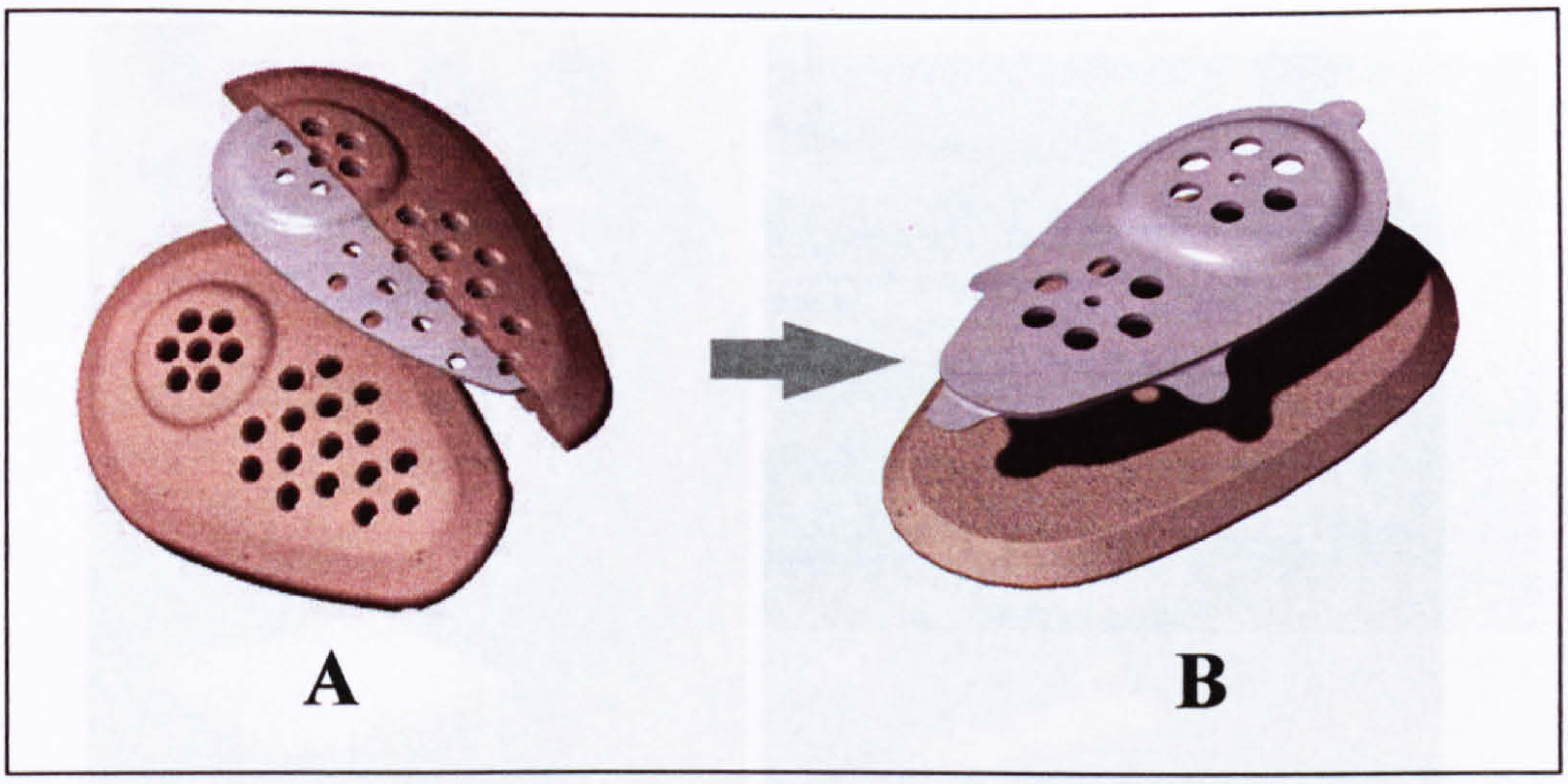


Figure 6.6: CAD images of the two design variations

Functional prototypes of the proposed design were constructed for use in impact tests to establish which material grades and thicknesses were best suited to final construction and to benchmark their performance against rival products. The models were constructed by hand from various thermoplastics and readily available stock grades of expanded foam sheets. A manual thermoforming process was performed to replicate the complex contours of the injection moulded plate element. Figure 6.7 shows pictures of the plate elements being formed and some of the different materials that were tested.

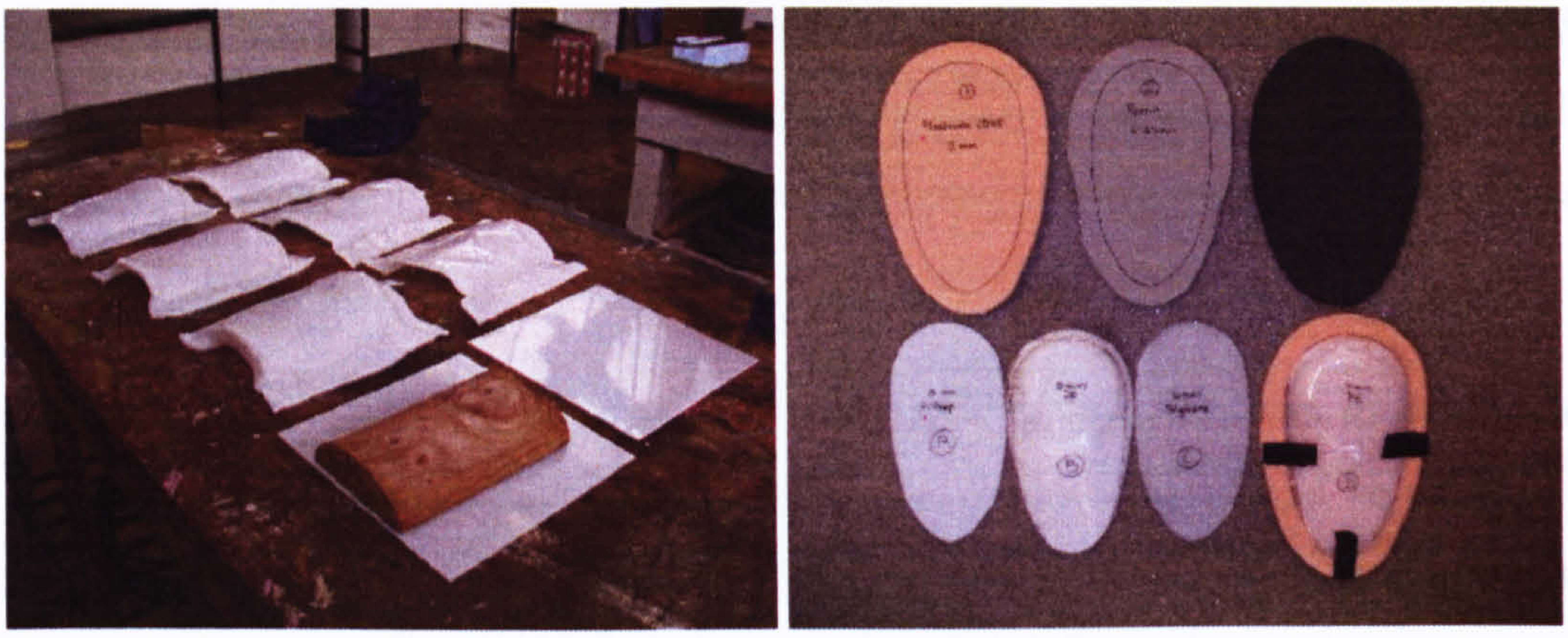


Figure 6.7: Functional prototypes constructed for impact testing

A special drop rig was constructed around a weighted life-size manikin to replicate the approximate forces that would occur in an extreme sideways fall onto the hip region. Electronic sensors were fitted to the rig to measure various accelerations and pressure distributions on impact. Figure 6.8 shows pictures of the test in process

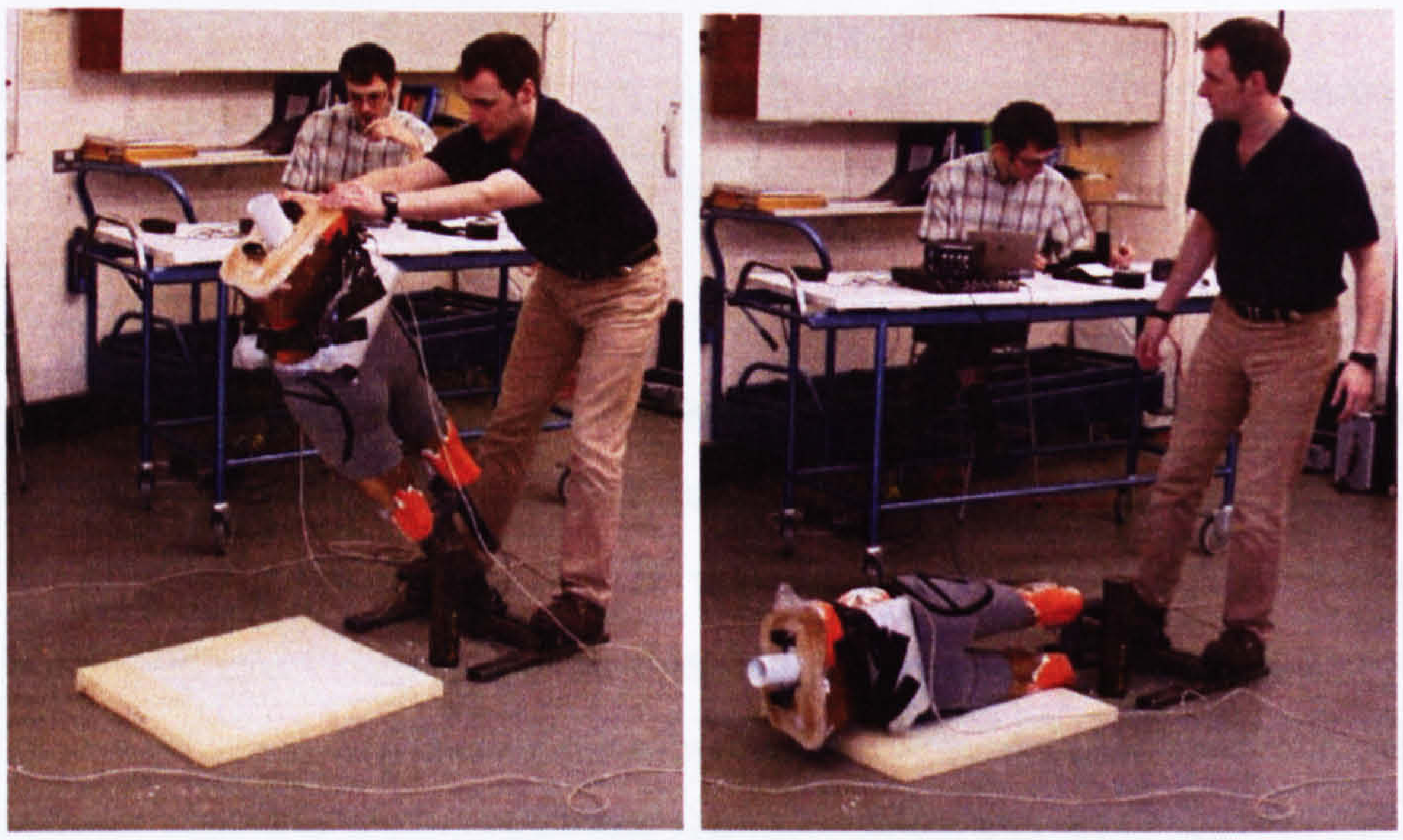


Figure 6.8: Testing hip protectors with a purpose built drop rig

Results from the drop test were favourable and a material configuration was chosen that was shown to outperform competing products. Having gained client approval for the finalised proposal, and confident that no more refinements would be needed, commitment was made to injection mould the rigid plate which was needed for final manufacturing.

Production quantities for the final product were predicted as being approximately fifteen thousand (15,000) units per annum for a period of three years, making a total requirement of forty-five thousand (45,000) units. In terms of injection moulding this figure is quite low and did not justify using the type of hardened steel tool that is typically associated with the process. Instead, a number of low volume "development" alternatives were explored.

After considering various options that were available, a decision was made to use a combination of RP and manual techniques to produce a tool that would be suitable for the required production volumes. A tool-making contractor was chosen on the basis of proximity to the product development centre, quoted cost, lead-time and their perceived ability to perform work in line with other project requirements. The contractor in question used an investment casting process to produce injection mould tools from a zinc alloy known as Kirksite. It is claimed that Kirksite tools are suitable for production runs of up to 100,000 shots, which makes them ideal for relatively low production volumes and a perfect manufacturing solution for the project in question. The tool-making process requires a model or master pattern, which is used in a silicon rubber reproduction and plaster investment casting process to produce the zinc cavity and core castings. Following the casting procedure each tool is hand finished and made ready for production.

CAD data was used to produce an SLA model that could be used as a master pattern in the casting process. The thermal expansion and contraction of material in the final injection moulding stage meant that it was necessary to make an allowance for shrinkage when the tool was made. In this instance the shrinkage allowance was 2%, although this figure varies slightly depending upon intended production material. Use of CAD technology made it easy to add this required shrinkage allowance to the model by appropriately scaling the 3D CAD file that was used to make the RP model.

The Kirksite tool was produced for approximately one third of the cost that would be associated with a hardened steel tool of similar size and complexity. It was also supplied with a lead-time of less than two weeks, which is approximately half the time that a UK toolmaker would have taken to provide a hardened steel tool. Once complete, the tool was delivered to a moulding contractor and production of protector's rigid plate units began. Figure 6.9 shows a picture of the Kirksite tool and a sample moulding from the initial production run.

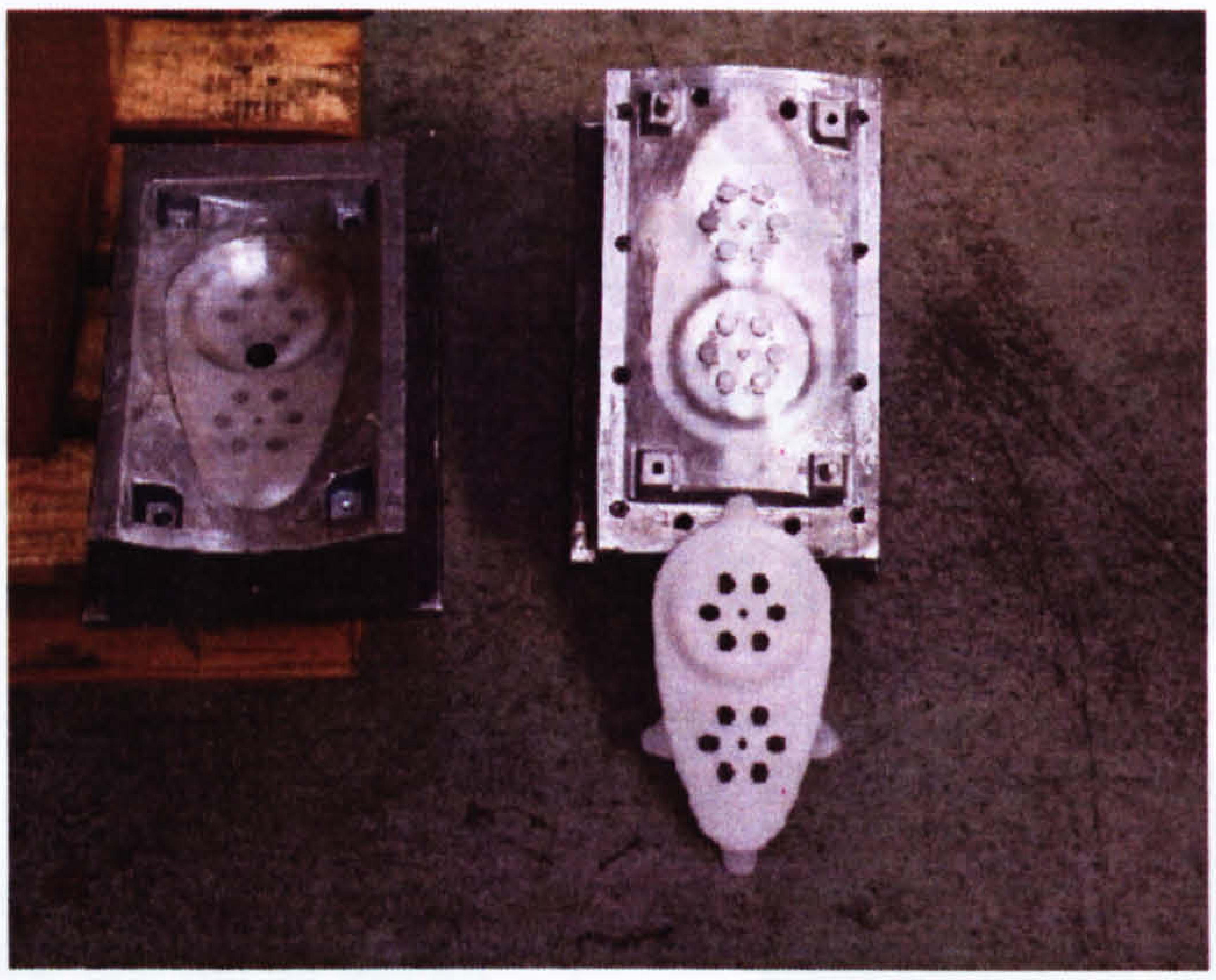


Figure 6.9: Kirksite tool and sample moulding

The final stages of manufacture involved the die cutting of foam pads, which were then shaved to add a chamfered edge and achieve a more discrete profile. These were assembled with injection-moulded plates and finally stitched into specially designed undergarments. Marketers at Remploy named the final product "Caresse™" and began to take orders at the end of 2002, including the product the following year's catalogue. Figure 6.10 shows a series of promotional pictures of the final article that were taken from a recent Remploy Healthcare catalogue.

Figure 6.10: The Remploy Caresse™ Hip Protector

6.2.3 Discussion

The table in Figure 6.11 lists some of the cost related constraints that were imposed during the project in designing a product that would be feasible to manufacture using conventional processes.

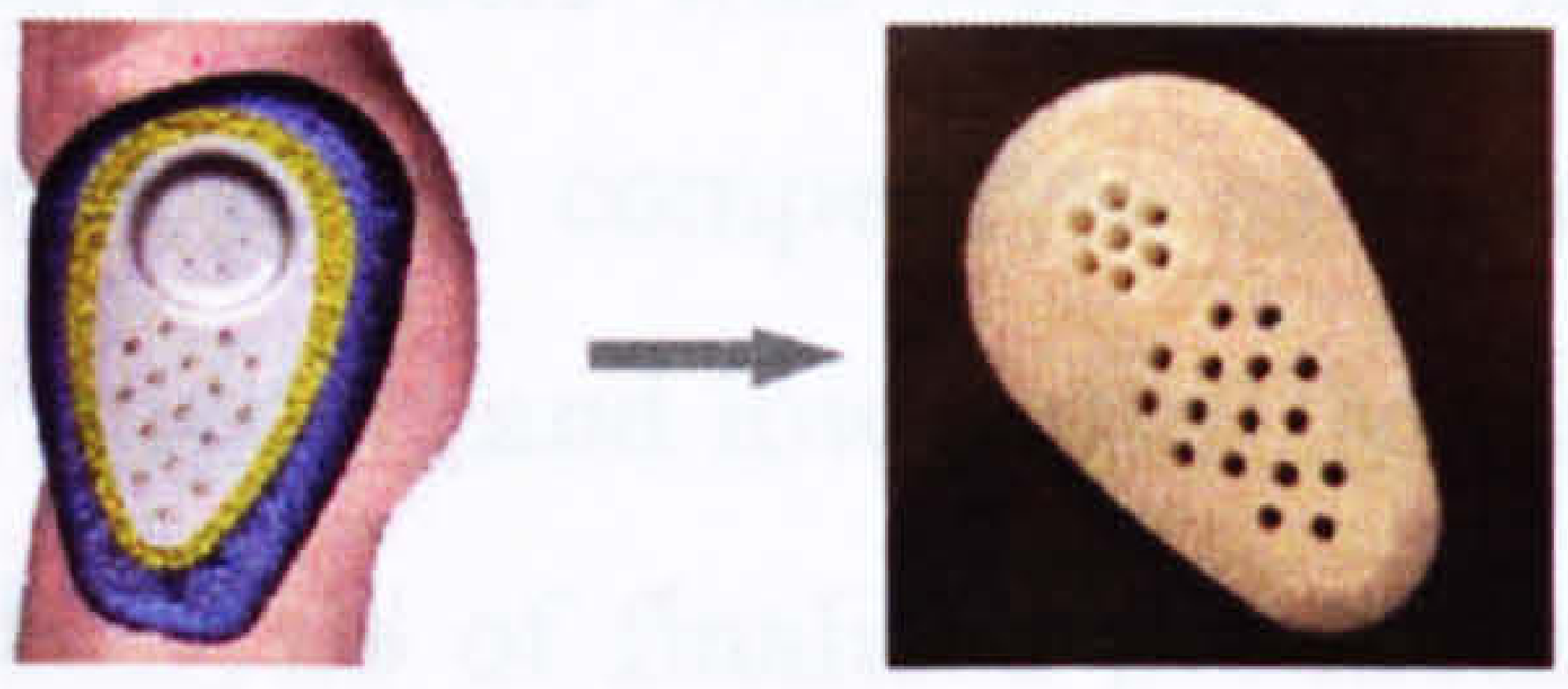
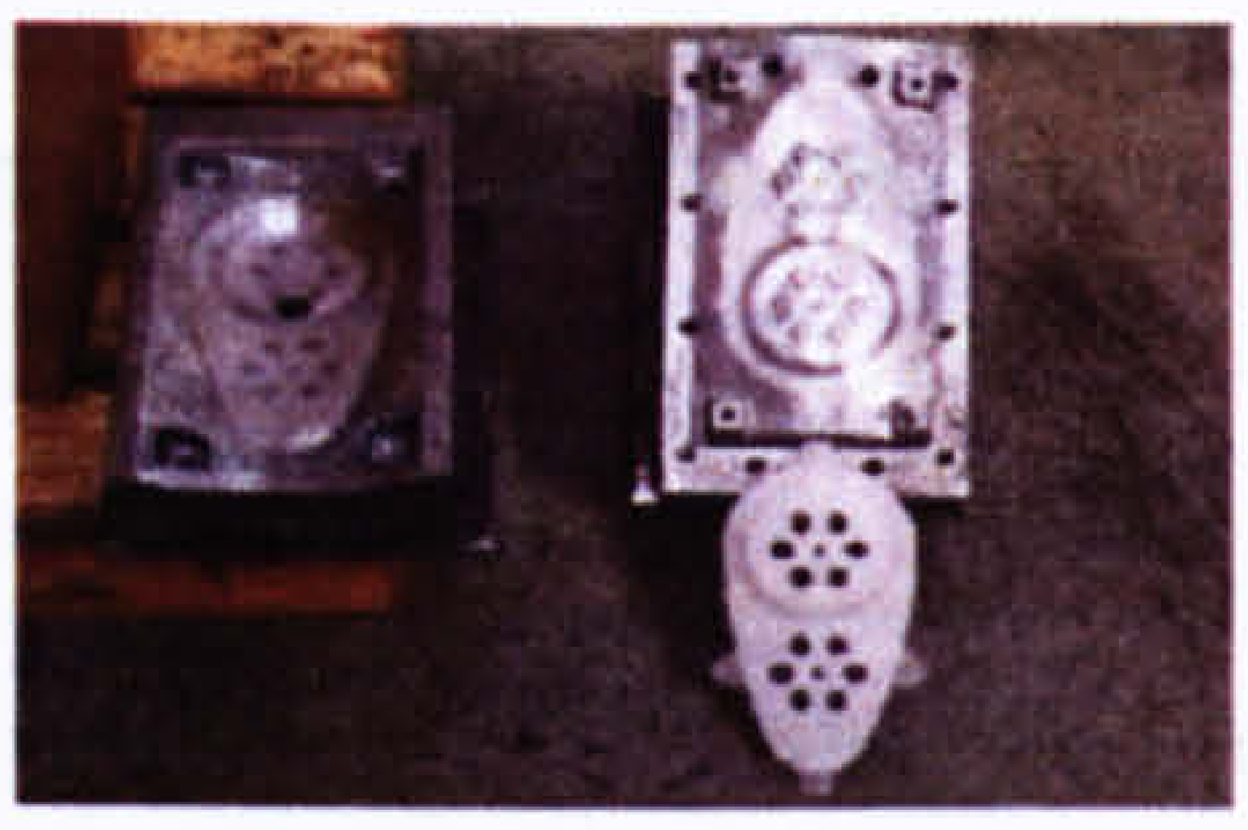
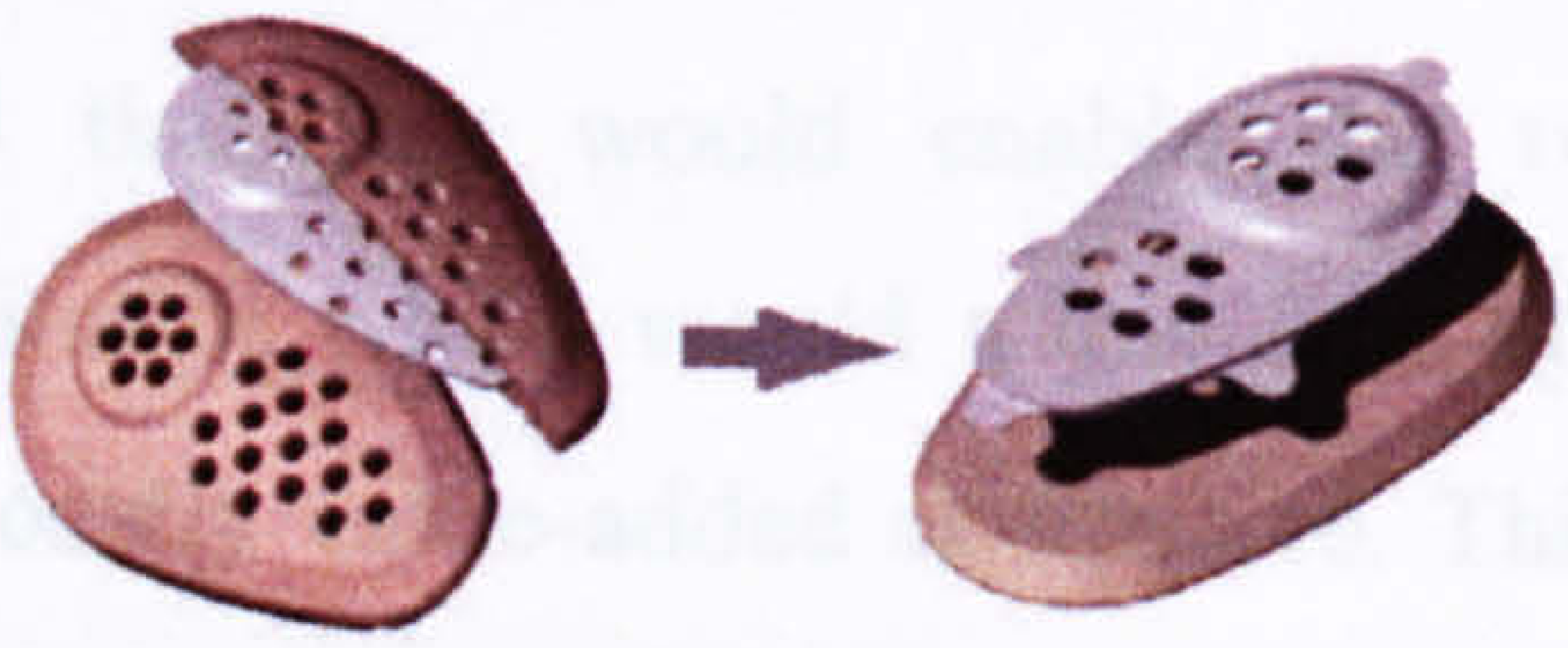
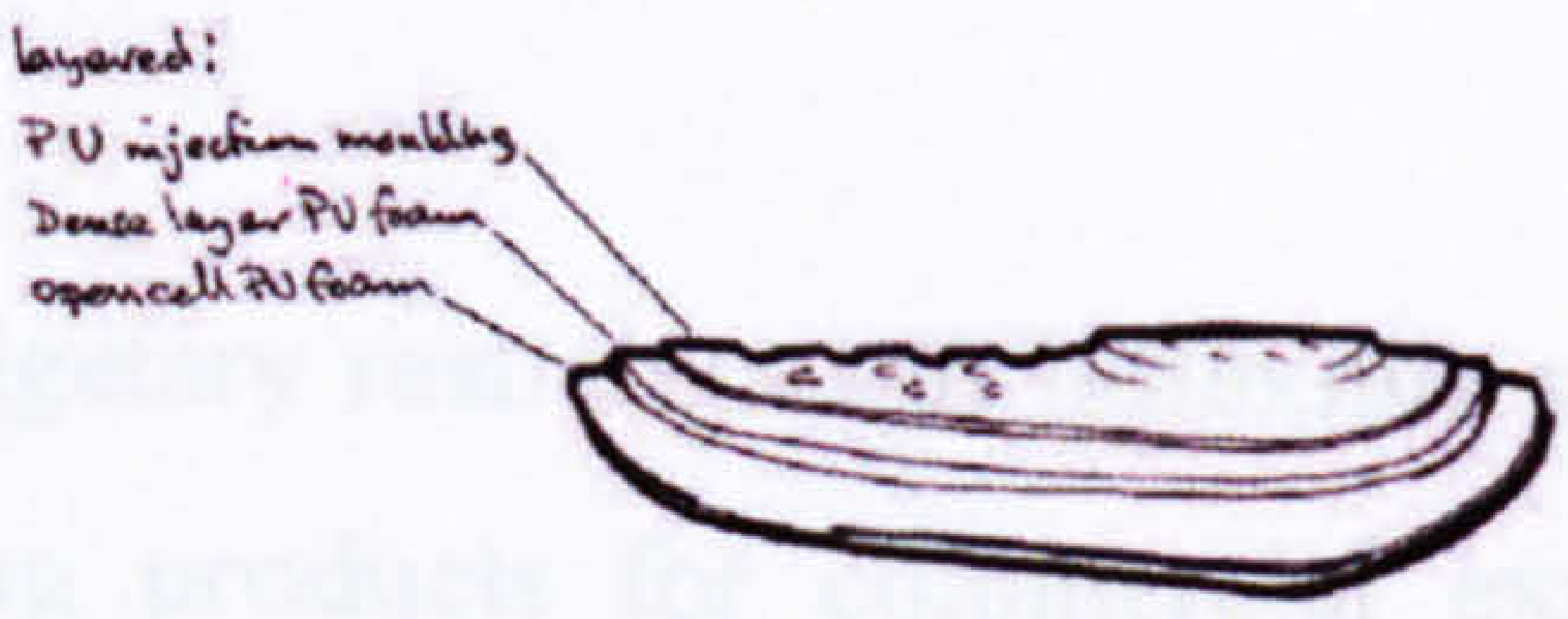
Economic constraints imposed by conventional manufacturing	
Asymmetric left and right hand versions changed to symmetrical design	
Multiple sizes restricted to a single one size fits all design	
Over-moulded foam design changed to a more simple sheet fabrication	
Use of smooth multiple material gradients was restricted to a course stepped transition	

Figure 6.11: Process imposed design constraints

In this study a new product was developed inline with conventional manufacturing processes to enter an established market. By entering a market that was already established, it was necessary for the new product to compete with a number of other similar devices at both functional and commercial levels. As the project progressed, the manufacturing costs associated with producing a feasible design became a primary and overriding concern that had much impact upon the final product's makeup.

An initial product design concept was quickly established that was seen to address the client's functional requirements. However, the cost implications that were attached to the realisation of this particular design made it too uneconomical. This resulted in the redesign of a derivative concept that was value-engineered to balance desired functional characteristics against manufacturing costs.

A number of design compromises were made in this second proposal and much of the functionality that made it unique from existing products was waived in favour of a simpler product that would be able to achieve a more competitive sale price. Work continued on the revised concept, producing RP models and low cost RIM tooling for a small quantity of sample products. However, analysis of finalised production costs at this point generated concerns from the client that there was insufficient profit margin between development outlay and the product's final worth. This resulted in a request for a third more cost effective design.

Rather than abandon previous work, a decision was made to implement a long-term product development strategy, designing a simplified product that utilised core elements of the previous design. It was intended that this would enable the two-phase introduction of two separate products, the first of which would a low-cost option that could be followed at a later date by a more costly value-added alternative. This proved to be an agreeable solution, so a design was proposed and positively tested before final production of the first-phase product began.

This particular project demonstrates how budgetary restraints and inflexible production processes force compromise when designing products for commercial exploitation. Costs that are associated with tool-based production methods will often prohibit the inclusion of many desirable design features, leading to products that have been designed around affordability and process capabilities rather than the wants or needs of their user.

Obviously, the adoption of a more flexible tool-free manufacturing approach would remove the aforementioned constraints and provide designers with freedom to produce less-compromised product concepts. This issue is to be the focus of the following series of case studies, each of which notes the impact of Rapid Manufacturing within typical industrial design projects.

6.3 Bafbox Electronic Enclosure

6.3.1 Project Background

Bafbox (now Custom Design Technologies Ltd) is a small contract manufacturer of low volume (1 to 1000's) custom designed electronic enclosures. The company fabricates each enclosure from flat sheets of plastic, bypassing other forms of mould-tool-based manufacture and their associated costs. This enables the manufacturers of low volume electronic devices to supply their product with custom-built housings, instead of the standard catalogue project boxes that they would otherwise be forced into using. However, the fabrication method used at Bafbox is labour intensive and severely restricts product form, producing angular products that lack many ergonomic qualities and look dated in today's market.

With this in mind, Rapid Manufacturing was identified as a possible solution that would enable Bafbox to maintain a tool-free manufacturing philosophy whilst increasing design freedom. In order to observe the effect of Rapid Manufacturing on product design a project was undertaken to redesign an existing Bafbox product for Rapid Manufacture. Figure 6.12 shows a picture of the enclosure that was to be redesigned.

Figure 6.12: Original Bafbox enclosure

The current Bafbox fabrication technique involves the Computer Numerical Control (CNC) machining of a flat sheet of plastic to cut necessary holes and fold lines. This results in a development or net shape of the desired final enclosure or one of its component parts. Once all the machining operations have been completed, component sections are the folded, assembled and glued as required. Figure 6.13 shows a flat section being machined.

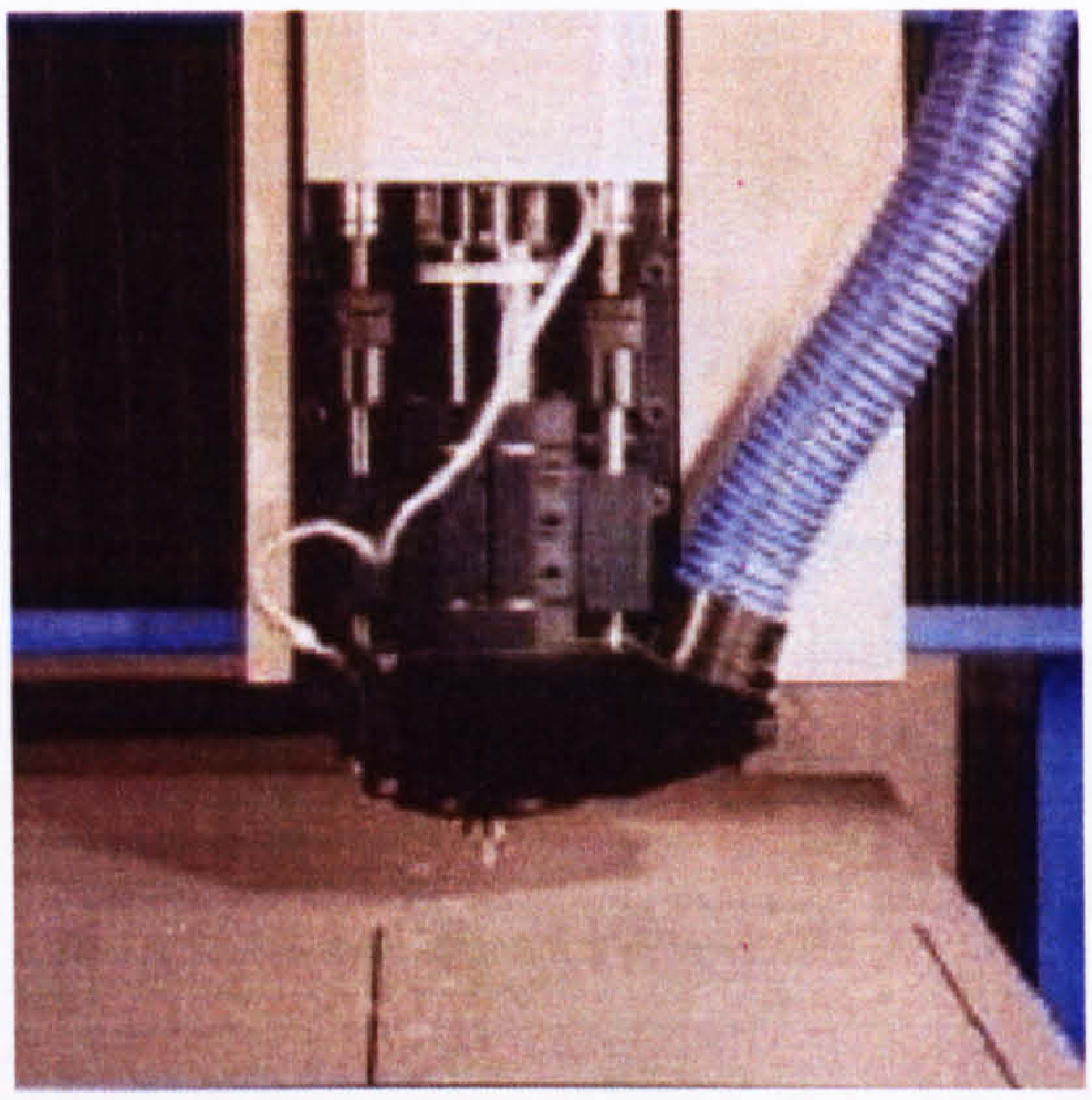


Figure 6.13: CNC machining of enclosure

Bafbox enclosures are generally constructed from either High Impact Polystyrene (HIPS) or Acrylonitrile Butadiene Styrene (ABS). Of these two materials, ABS is generally seen to be the toughest whilst HIPS has better resistance to chemical attack. However, it was noted that the choice of material used in most projects is largely dictated by customer preference as to colour and surface finish, rather than strength.

As stated previously, the current methods of fabrication used posed serious restrictions as to the sort of design concepts that may be produced, for example:

- Flat sheet fabrication methods mean it is impossible to create curved surfaces, resulting in products that are flat and angular. This has a negative affect upon both aesthetics and ergonomics.
- Constructed from standard sheet material, all enclosure designs are subject to constant wall thickness of either 3 or 4 mm.
- Enclosures usually consist of several component parts, making it necessary to perform multiple machining and assembly operations, all of which adds to cumulative product cost.

Figure 6.14 shows the different component parts of the disassembled Bafbox enclosure observed in this exercise and the electronic device that it contains.

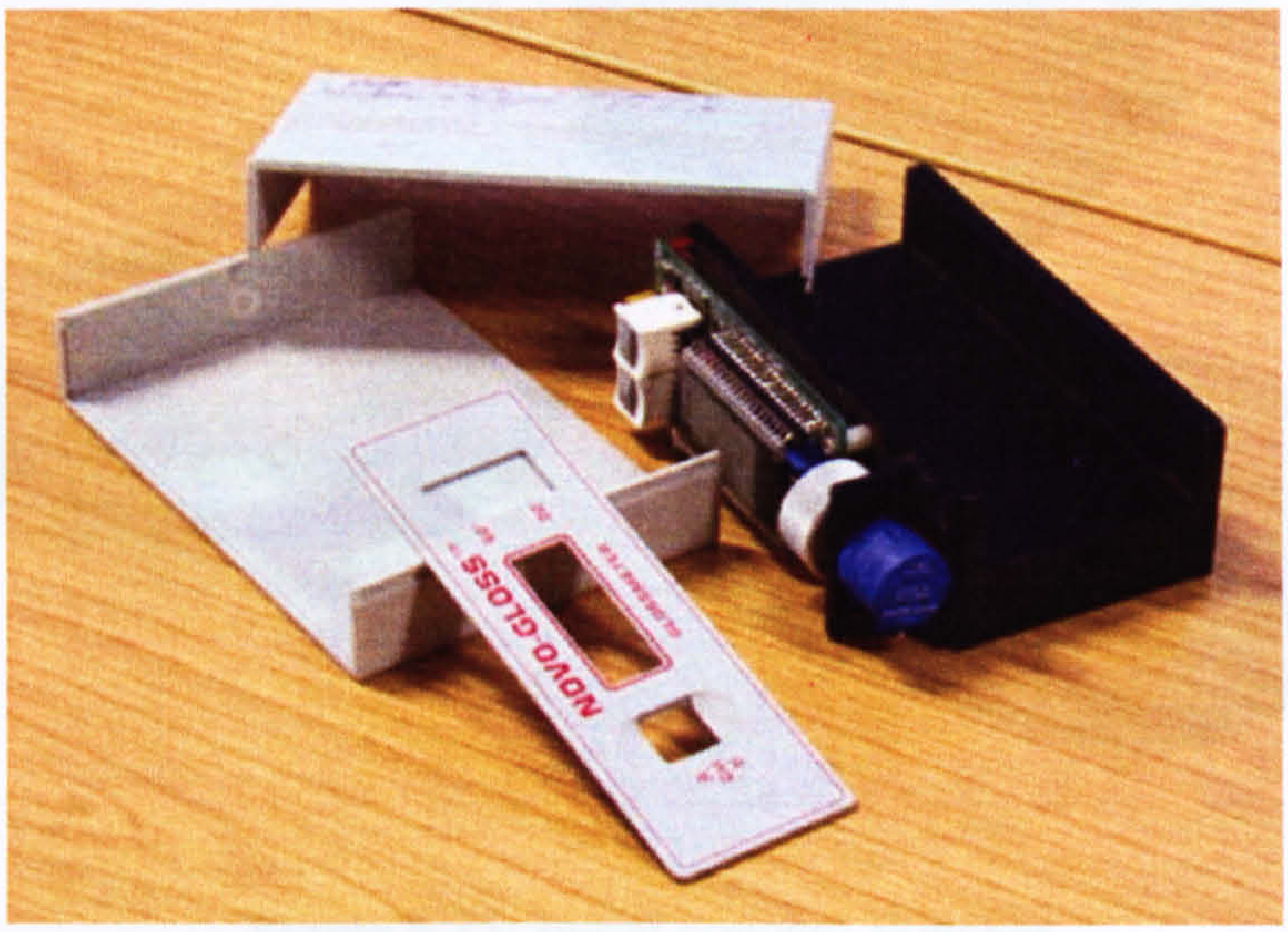


Figure 6.14: Disassembled Bafbox enclosure

In redesigning the previously mentioned enclosure for rapid manufacture a limited number of specification criteria were applied. These were as follows:

- The new design must accommodate the existing engineering components
- The new design should be user-friendly, having improved aesthetics and ergonomics
- The product should have enhanced saleability
- The new design should have fewer components than the existing enclosure so as to reduce assembly functions

6.3.2 RM Concept Generation

Redesign for Rapid Manufacture began with a concept generation phase that focused upon use of paper based 2D sketching to explore and document a range of ideas and concepts. Figure 6.15 shows some of the initial sketches that were produced.

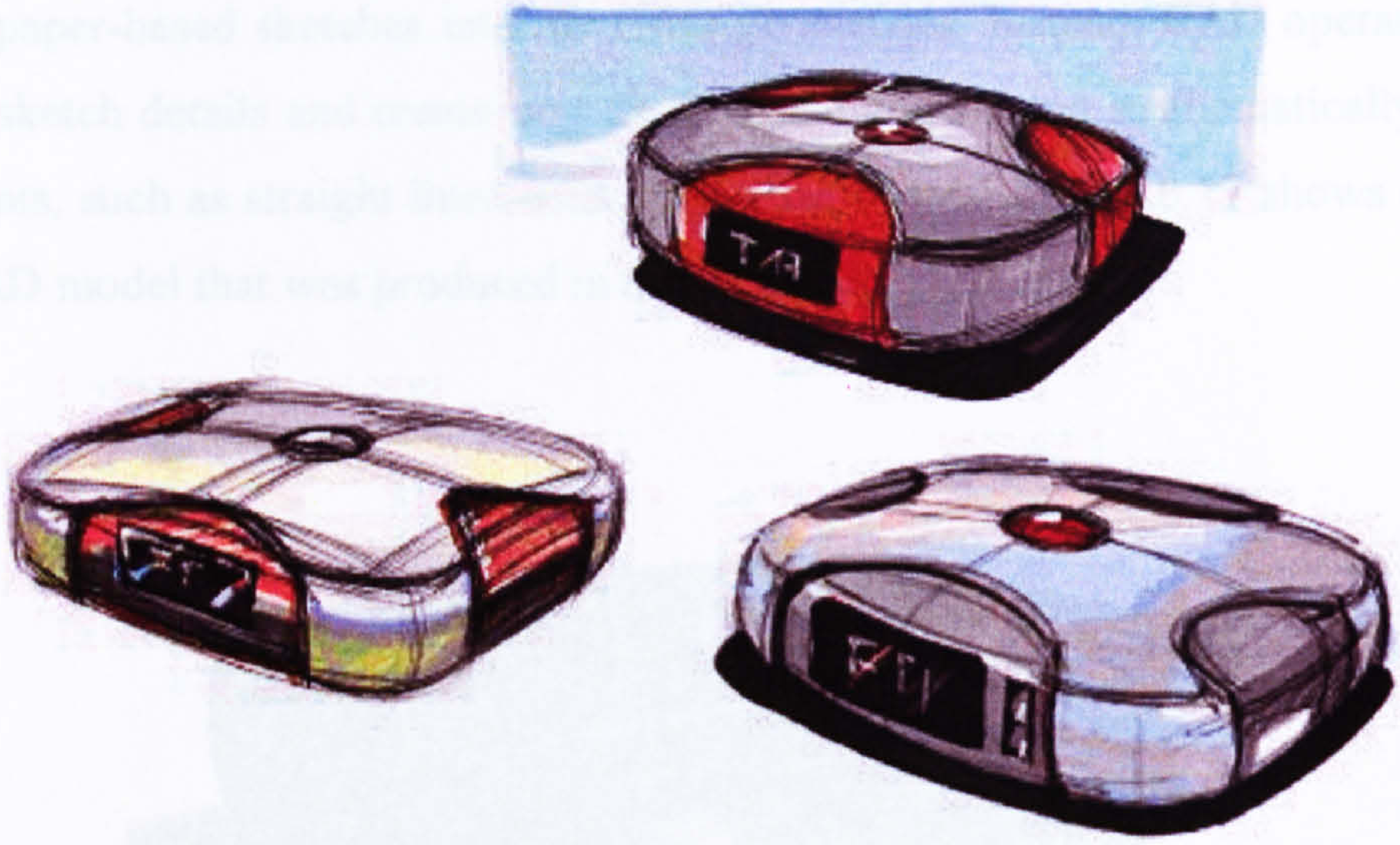


Figure 6.15: Initial concept sketches

Careful consideration was given to the various sketched concepts before selecting a single design that was seen to balance both functional and aesthetic qualities. It was felt that this particular concept would be well suited to the rapid manufacturing process as well as meeting the previously stated criteria. Figure 6.16 shows a picture of the chosen concept sketch.

Figure 6.16: Chosen Design

Using the selected concept sketch as a reference, work began to generate a 3D CAD model that suitably represented its features. However, initial attempts at modelling the chosen design proved difficult and a number of compromises were made. Whilst some CAID software packages allow fluid sketching of lines and curves using the sort of digitiser tablets that were described in chapter 3, it is not yet possible to directly translate paper-based sketches into 3D CAD geometries. Instead, CAD operators must interpret sketch details and create best-fit representations using mathematically defined components, such as straight lines, arcs and bezier curves. Figure 6.17 shows an image of the CAD model that was produced in this instance.

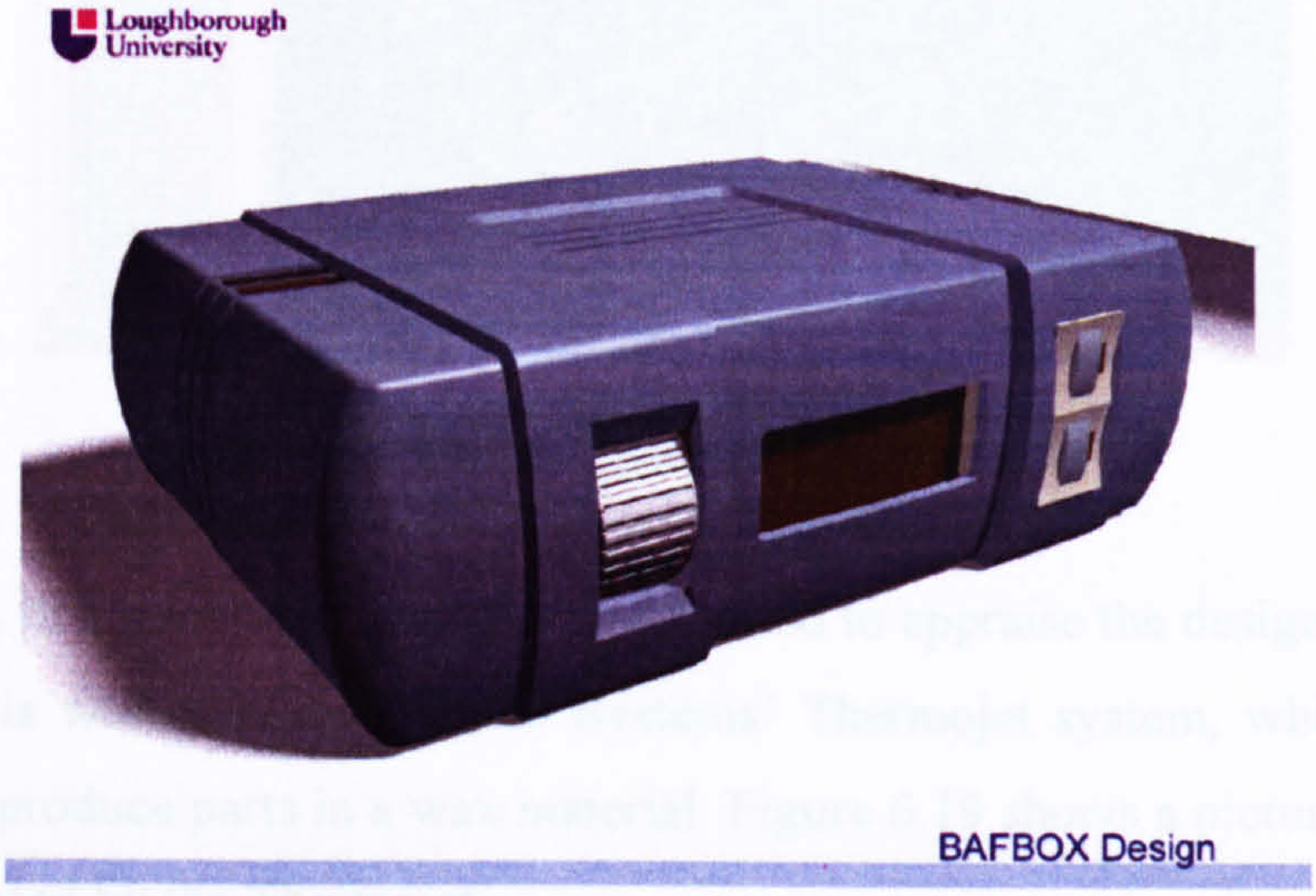


Figure 6.17: Rendered Image of CAD model

Whilst similar to the chosen concept sketch, a number of differences are clear to see, which highlight the sort of compromises that are often made in converting freehand sketches into 3D CAD models.

Having created a suitable 3D CAD model, it was possible to manufacture the design. The first stage of this was the generation of a faceted STL file, as described in Chapter 3. Figure 6.18 shows an image of the file that was created. The tessellated triangles from which the object is made are clearly evident.

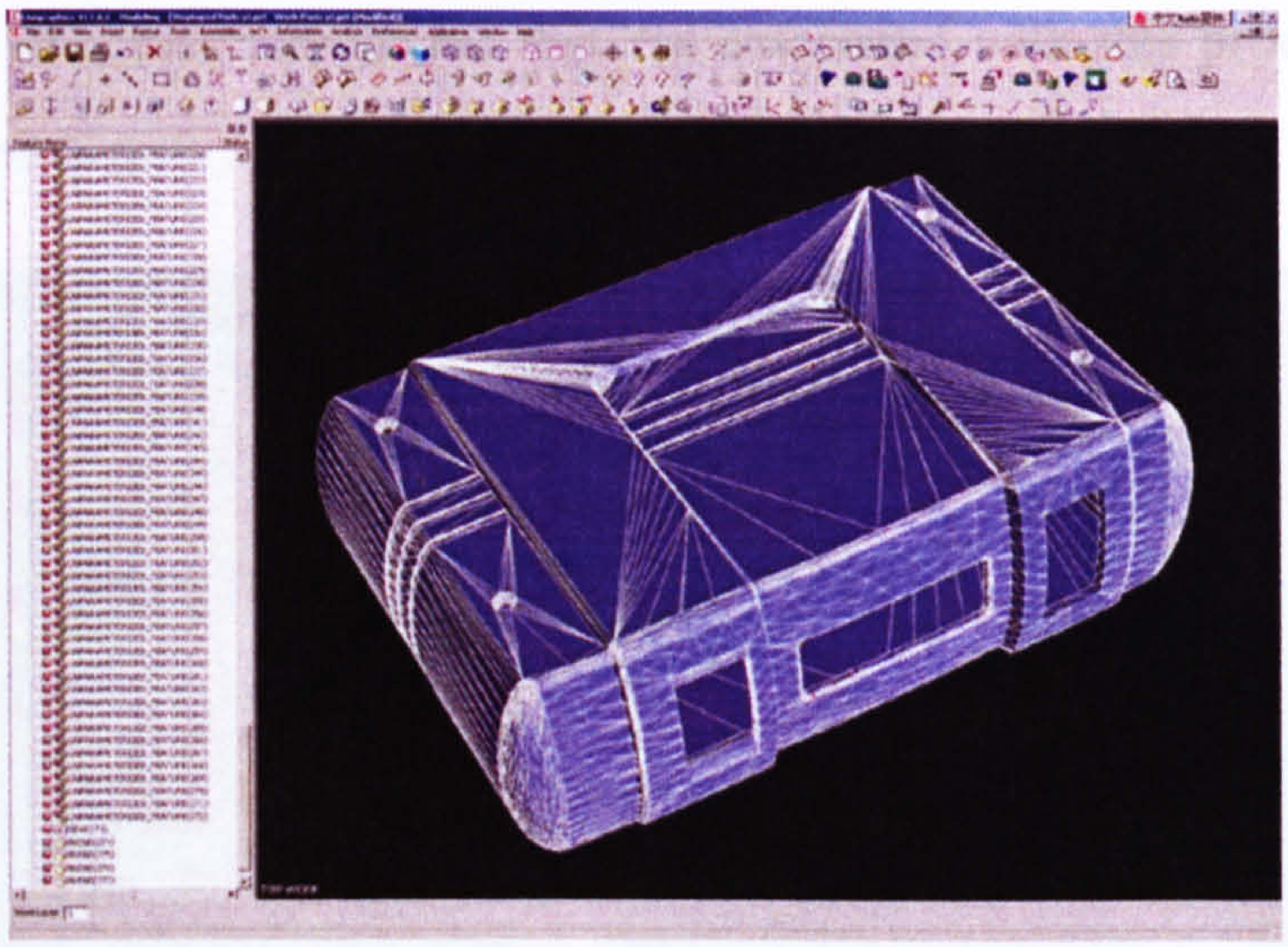


Figure 6.18: Tessellated STL file

Using the STL file, an initial RP model was created to appraise the design's general size and shape. This was done using a 3D Systems' Thermojet system, which uses inkjet technology to produce parts in a wax material. Figure 6.19 shows a picture of the model that was produced by the Thermojet.

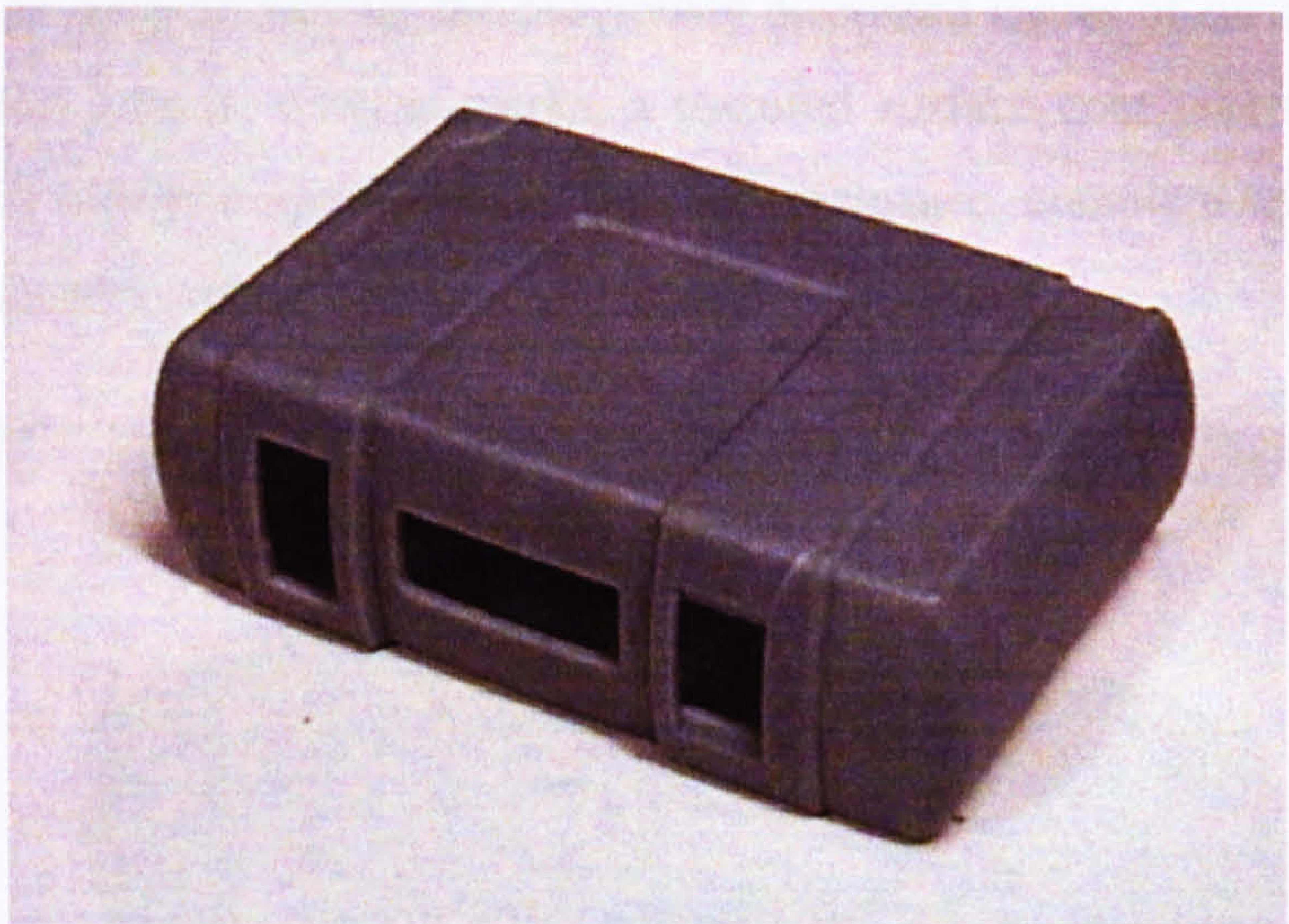


Figure 6.19: Thermojet model

Satisfied with the design, production began using a 3D Systems' SLA 7000 Stereolithography machine. The sizable build envelope of this machine enabled the simultaneous production of multiple parts. Figure 6.20 shows one such completed build of five units. The support structures that are associated with this process are clearly visible beneath each part.

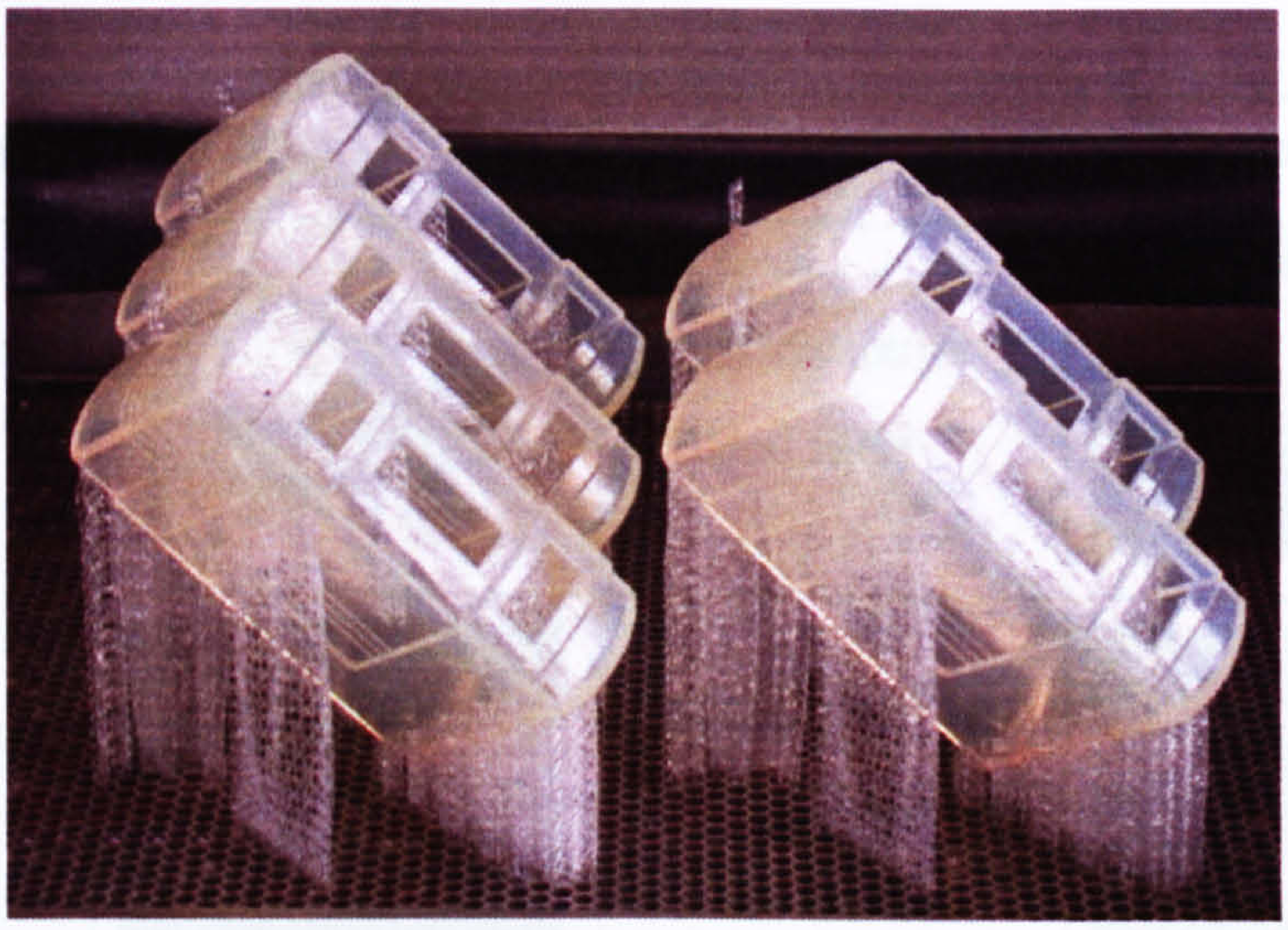


Figure 6.20: SLA build

The Total build time for this particular batch was approximately 18 hours with a further 5 hours for removal of supports and surface finishing. This equates to approximately 4½ hours per part. In order to address the previously discussed issues of surface finish, such as stair steps and support witness marks, a textured surface coat was applied to each part. Figure 6.21 shows a picture of the finished enclosure, complete with surface coat and internal electronic components.

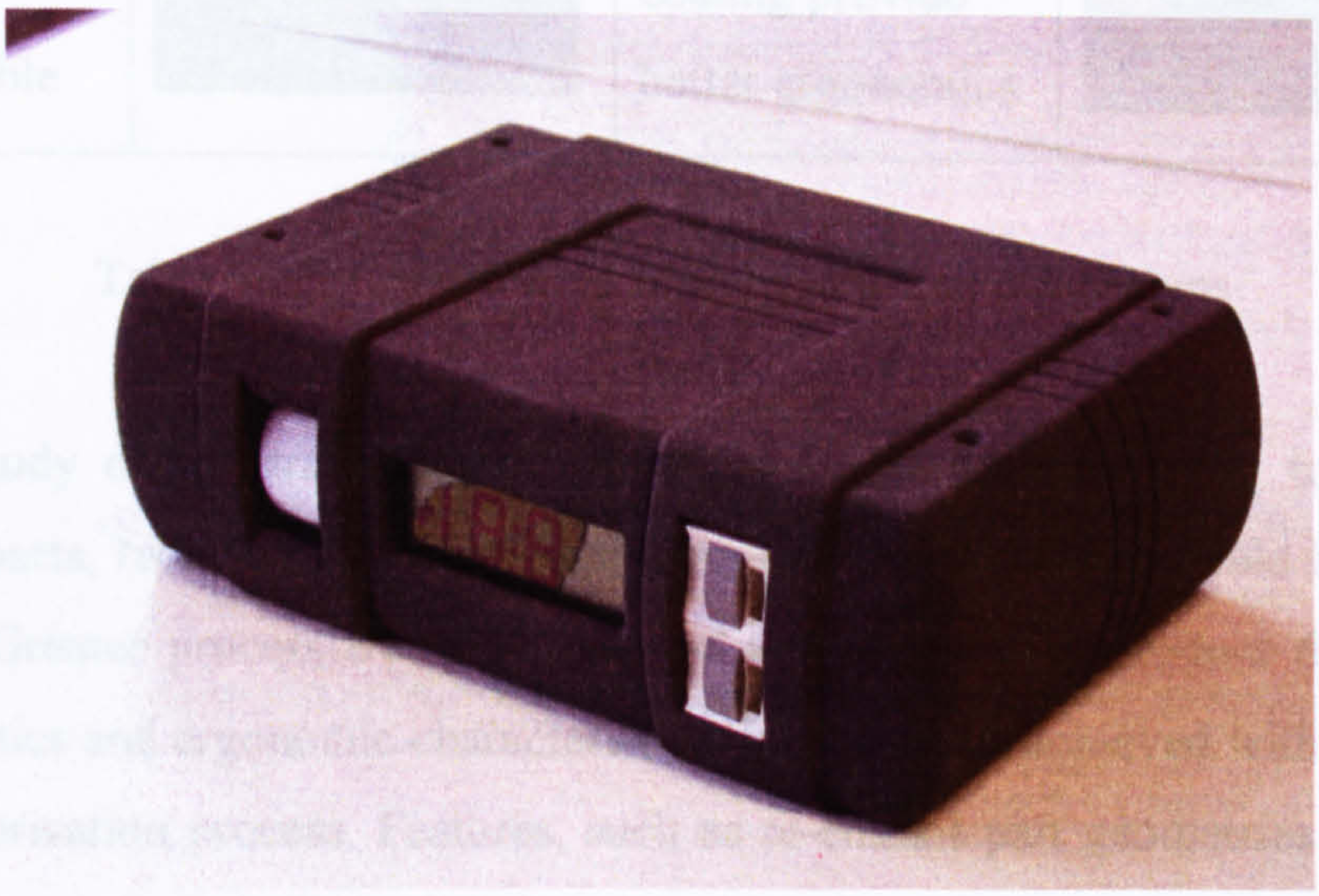


Figure 6.21: Finished Part

6.3.3 Discussion

The table in Figure 6.22 shows a comparison of new and old enclosure design.

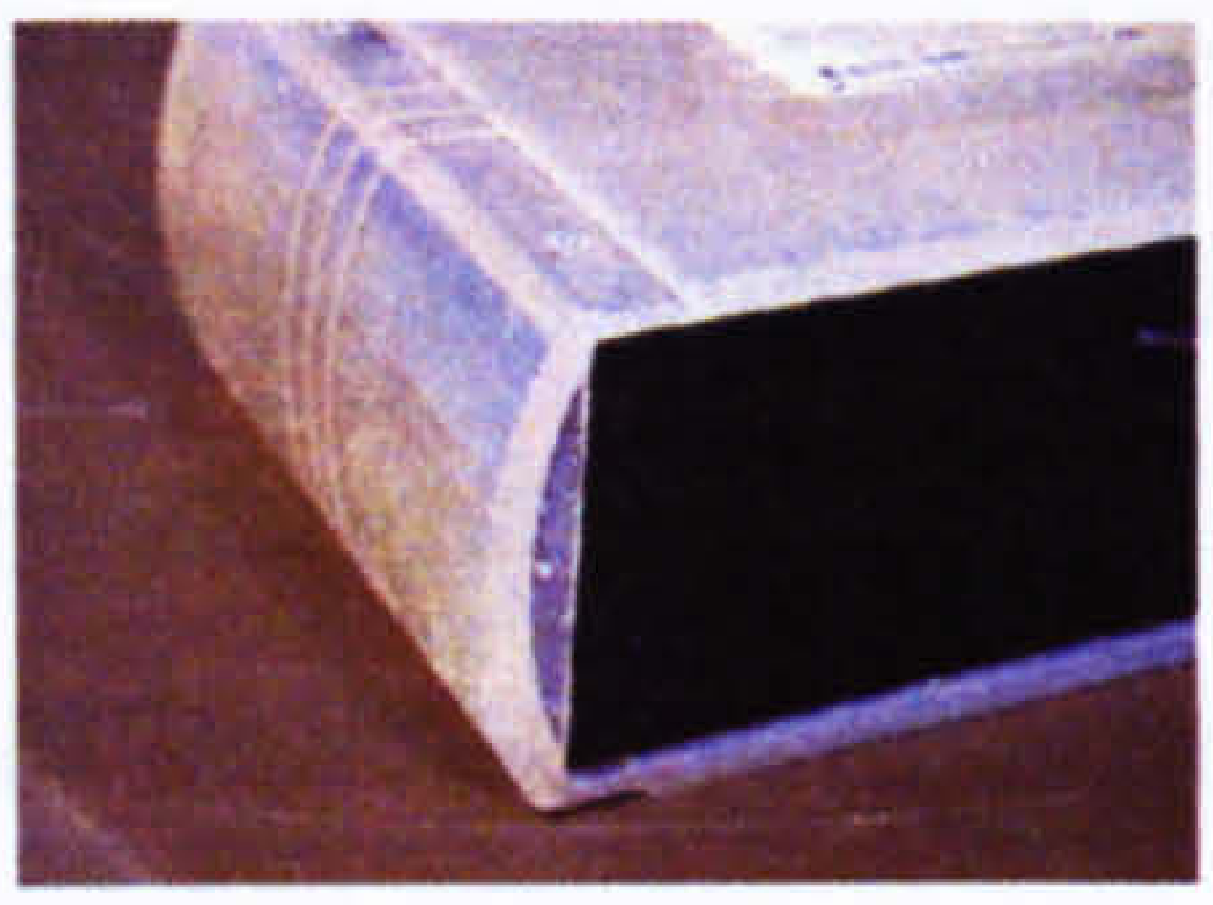
Original Enclosure		New RM Design	
Dated box-like design		More attractive stylised form	
Constant wall thickness		Variable wall thickness with re-entrant features	
Several parts that need to be assembled		Parts reduced from 3 to 1	
Corners and flat surfaces make handling uncomfortable		More round form and tactile surface coating provide better ergonomics	

Table 6.22: Comparative table of new and old designs

This case study demonstrates the capability of Rapid Manufacturing to consolidate component parts, reducing assembly operations and the costs that would be associated with them. Greater process freedoms enabled the design of a product that possesses better aesthetics and ergonomic characteristics than could be achieved with the previous flat sheet fabrication process. Features, such as re-entrant part geometries and variable wall thicknesses, have been included that would also be impossible to achieve using other processes like injection moulding.

The tool-free approach used allows the direct production of parts from CAD data, removing the initial cost and lead-time that would be associated with processes like injection moulding. With no investment in tooling, it is also feasible to produce low volume order numbers or multiple derivatives of the same product without having to account for tooling costs.

It has been noted that the translation of paper-based design sketches into useable CAD models is a problematic area and that the exact reproduction of true design intent is not always achieved. The high degree of user skill that is required to operate current CAD systems combined with their limited form creation capabilities is seen to inhibit designer creativity. The time taken to produce the final CAD model in this study greatly exceeded the time that was taken to manufacture the actual product. In more conventional production cycles, such as injection moulding, tool lead-time is often the longest part of the process and causes much delay between design and production. However, in this study, it would appear that it is CAD that represents the greatest bottleneck in the Rapid Manufacturing process.

The final SLA part produced in this study was seen as being sufficiently robust for functional end-use. However, it was assumed that the high price of current additive manufacturing systems would make the design too expensive. Hence, a basic costing exercise was conducted to assess the economic feasibility of the proposed Rapid Manufactured enclosure compared to current product. Figures were obtained from an RP bureau using SLA and SLS systems to produce a batch of 50 enclosures. It was revealed that an SLS part would be approximately five times the cost of the current enclosure and that an SLA would be ten times the cost. The initial results seem discouraging, but it must be remembered that figures are based upon current systems that many predict will become cheaper in the near future. Additionally, the plain monetary figures do not account for the Rapid Manufactured product's "added value" features that would be a part of any truly representative Value Analysis exercise.

6.4 MG Rover Handbrake

6.4.1 Project Background

MG Rover Group was an independent medium sized company that produced cars at the Longbridge plant in Birmingham. The Rover 25, 45 and 75 series all maintained respectable market positions in their sectors, whilst the MG TF was considered to be Britain's top-selling roadster. A recent investigation into cost efficiency sought whether it was possible for these vehicles to be modularised, so that common components could be fitted to each. One focus of interest in this was the handbrake, which is currently constructed as an assembly of pressed metal components and is uniquely designed for each model. Hence, a project was undertaken to create a single generic handbrake lever that could be produced more economically using injection moulding to form a one-piece structure capable of housing an underlying metal ratchet mechanism.

Alongside this project a similar investigation was conducted by Loughborough University's RMRG to assess how the design of a handbrake lever like this would change with the advent of Rapid Manufacturing. In this project, an RM concept was designed around the same ratchet mechanism as used by the injection-moulded lever. Design optimisation through minimum use of material became a key aspect of the project. This was achieved using Finite Element Analysis (FEA) of CAD models, so that material could be removed to minimise weight without compromising mechanical performance.

As previously stated, a sheet metal fabrication process is used to manufacture all handbrake designs. This process involves nesting, stamping, bending, forming and riveting of metallic parts. The final stage of construction involved the manual assembly of the different component parts to create the finished handbrake. Figure 6.23 shows a picture of the metal handbrake previously manufactured by MG Rover Group for use on the Rover 75 series.

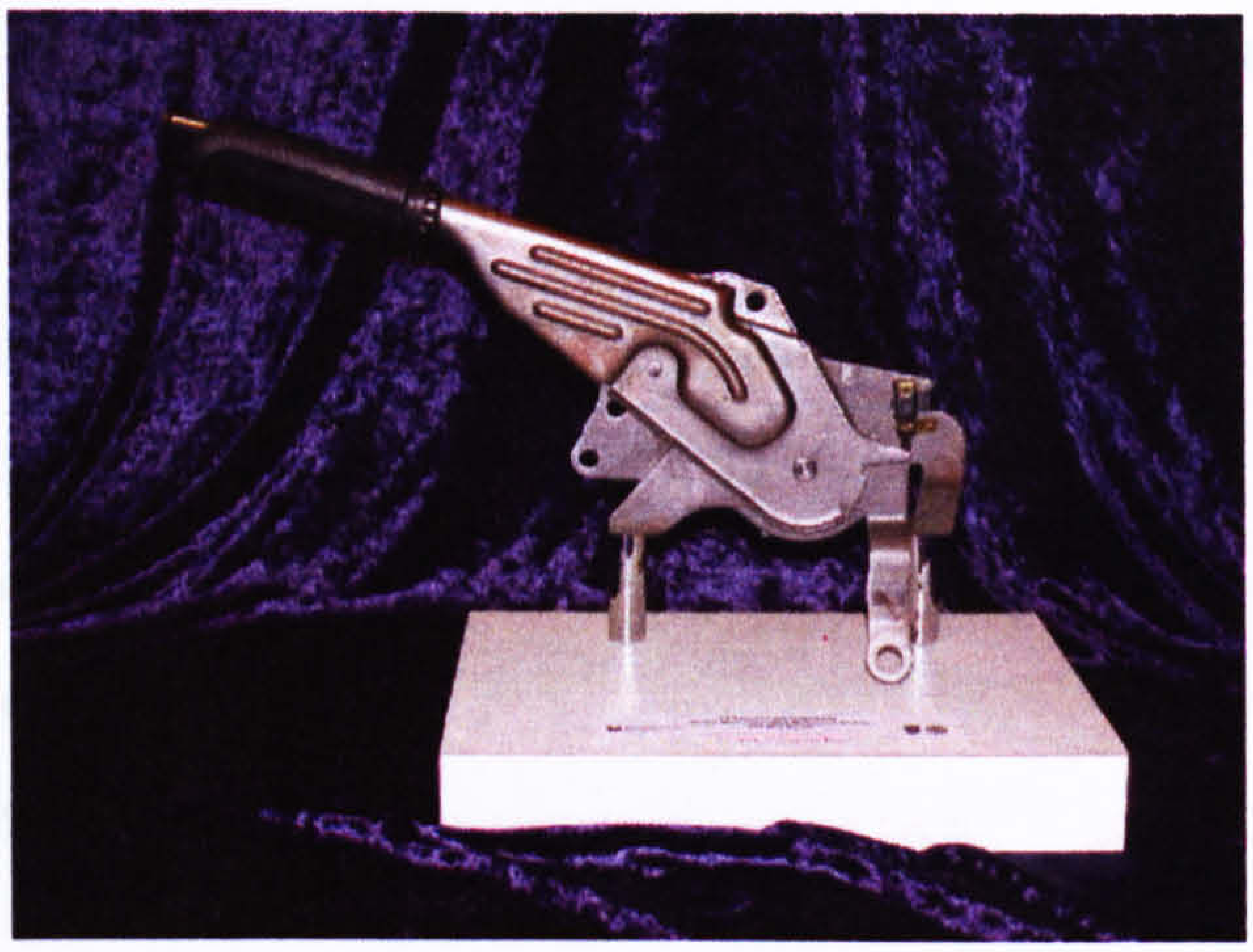


Figure 6.23: Metal handbrake assembly

The investigation of a cost-saving generic handbrake system that was to be adopted by all MG Rover's vehicles led toward the development of an injection-moulded design. For this project, Ricardo Consulting Engineering was contracted in their capacity as a leading vehicle engineering technology provider and strategic consultant to world automotive industries. Figure 6.24 shows a 3D CAD image of the final injection-moulded handle design that they produced.

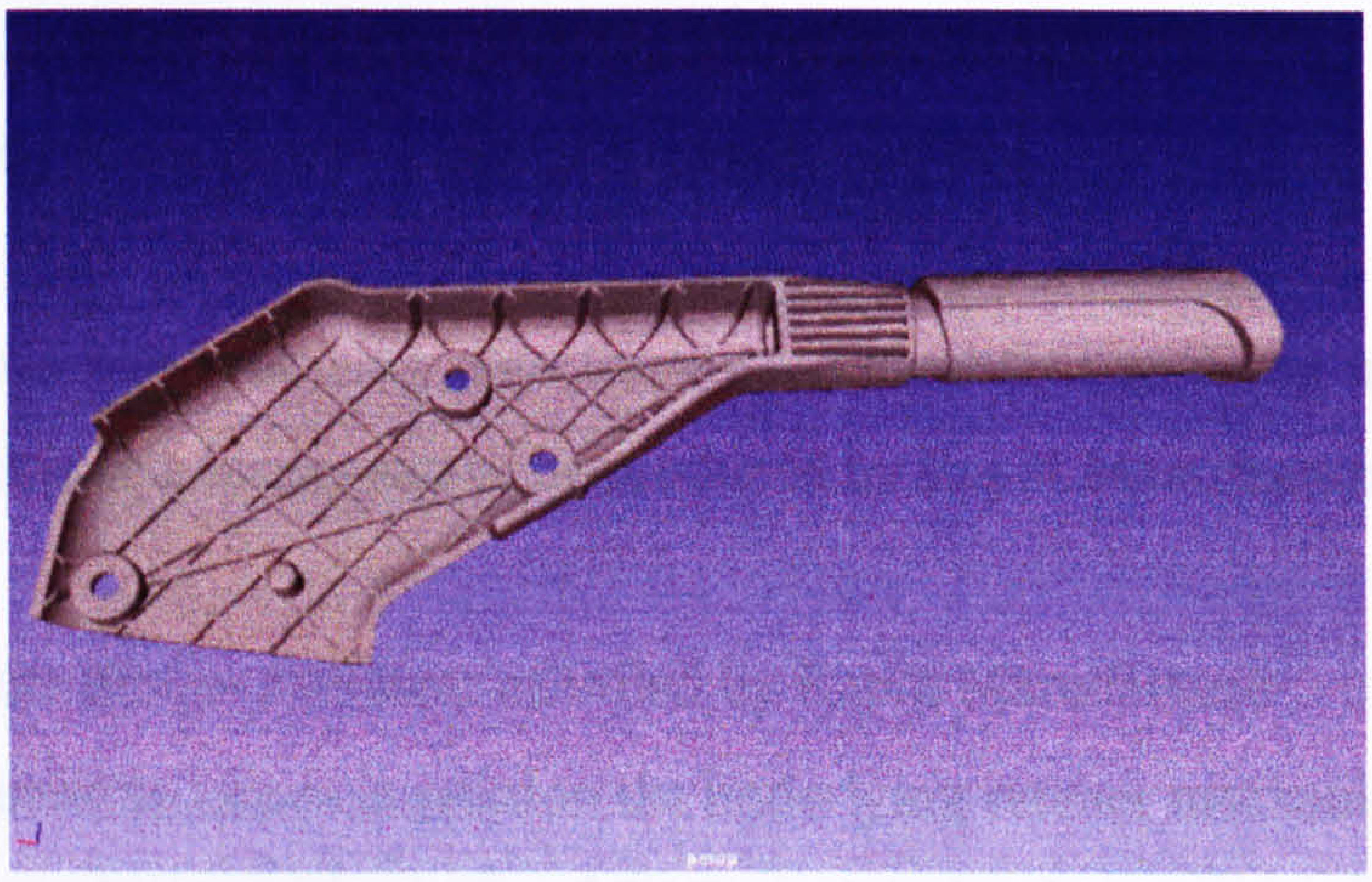


Figure 6.24: 3D CAD model of injection handbrake lever

The Ricardo part displays the characteristics of a typical "design for injection moulding" part, which include a predominantly constant wall thickness, use of strengthening ribs, draft angles to assist tool ejection and the consideration of tool parting lines. The part is designed for production with an uncomplicated open and shut tool, using a simple single sliding core to form the channel that runs through the inside of the handle.

The advantages claimed by the injection-moulded design include:

- Ease of assembly
- Ease of Manufacture
- Ease of adjustment
- Economical to manufacture

However, in order to produce this concept a number of compromises were made. For example, to extract the part from a simple open and shut tool, it was necessary that it be of a design that is effectively open and single sided. This left the ratchet mechanism partially exposed. Since the effected section is covered by a rubber gator when fitted to the vehicle this is not a major issue, although it is less than desirable and has an impact upon product symmetry and aesthetics. Other negative points include:

- A design that is mostly flat with little aesthetic style or appeal
- A form that is bulky and an overly robust looking design
- An apparently indiscriminate use of strengthening ribs

With this in mind, the following objectives were identified as being necessary for the redesign of an alternate handbrake to be produced by Rapid Manufacturing:

- Emphasise the design freedoms afforded by Rapid Manufacture
- Consider assembly issues in relation the underlying ratchet mechanism
- Conduct Finite Element Analysis of CAD models for design optimisation
- Apply styling to improve the parts aesthetic appearance
- Design should comply with applicable standards and test procedures

Utilising Finite Element Analysis (FEA) based optimisation, it was felt that an elegant "space frame" structure could be created that would fulfil all these requirements, and have none of the shortfalls associated with previous designs. It was envisaged that this design would also be of suitable aesthetic quality to remain exposed, doing away with the rubber gator that was used to cover previous designs.

6.4.2 RM Concept Generation

An initial design optimisation phase was conducted using FEA to establish an approximate product form that would achieve maximum performance with minimal usage of material. Using this approach it is possible to analyse stresses and deformation of physical structures in a virtual CAD environment. In this instance, a mechanical engineer with expert knowledge of FEA used the same forces as would be applied during MG Rover Group test procedures to evaluate potential product forms. Figure 6.25 shows an image of an initial box section with virtual forces being applied in ALGOR Finite Element Software.

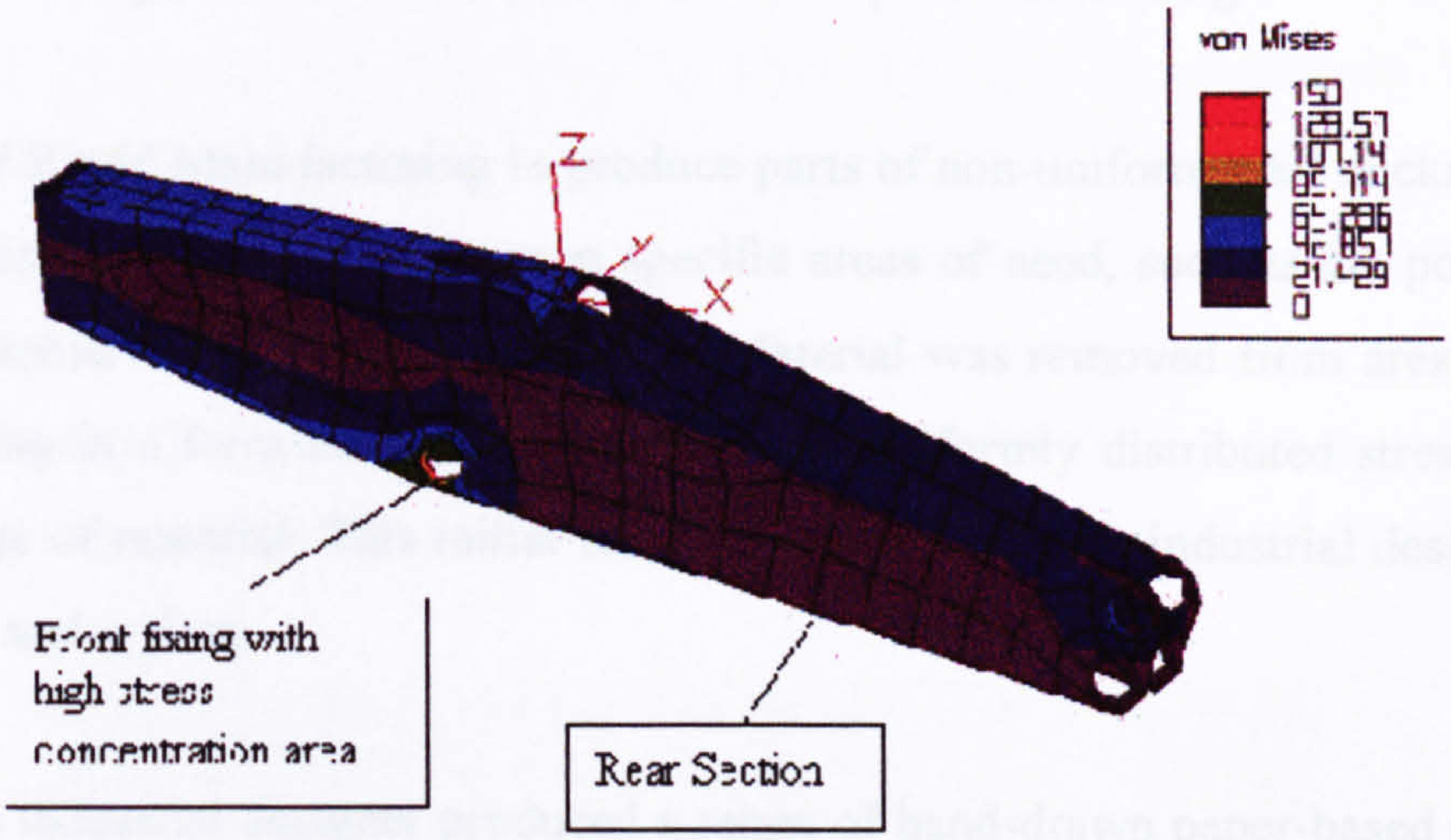


Figure 6.25: Stress plot for initial box section

Following initial FEA testing, a number of modifications were made to the part, which resulted in the optimised form that is shown in Figure 6.26.

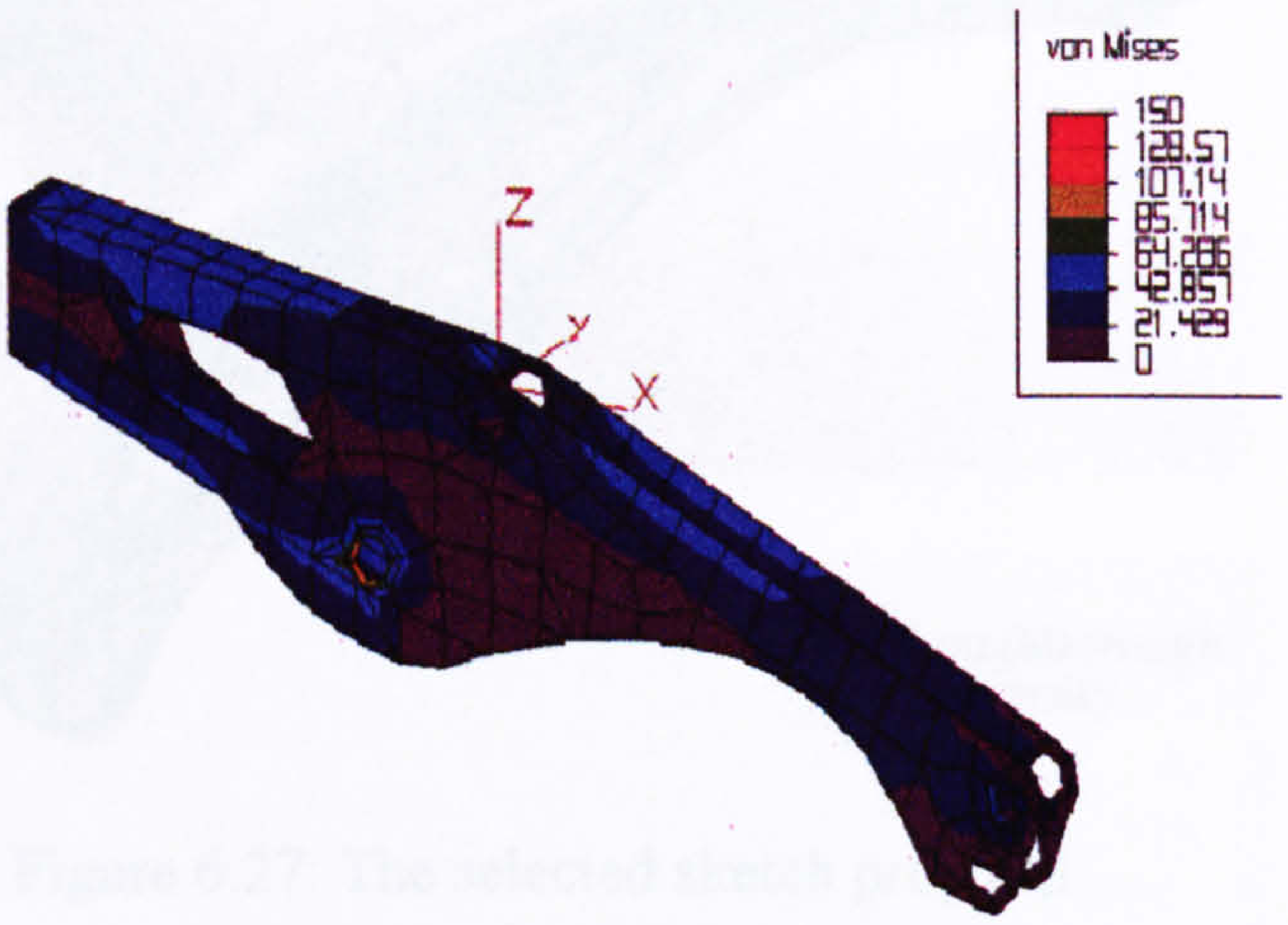


Figure 6.26: Stress plot for revised space frame design

The ability of Rapid Manufacturing to produce parts of non-uniform wall thickness was utilised to increase material thickness in specific areas of need, such as the points that would be attached to the ratchet mechanism. Material was removed from areas of low stress, resulting in a form that was seen to display uniformly distributed stresses with minimal usage of material. This initial form was taken up by an industrial designer for development and styling.

The project's industrial designer produced a range of hand-drawn paper-based sketches to explore and document various conceptual ideas. All of these were based around the form that had been derived from initial FE analysis. Finally a single design was chosen that was seen to balance both functional and aesthetic requirements. Figure 6.27 shows an image of the chosen sketch concept.

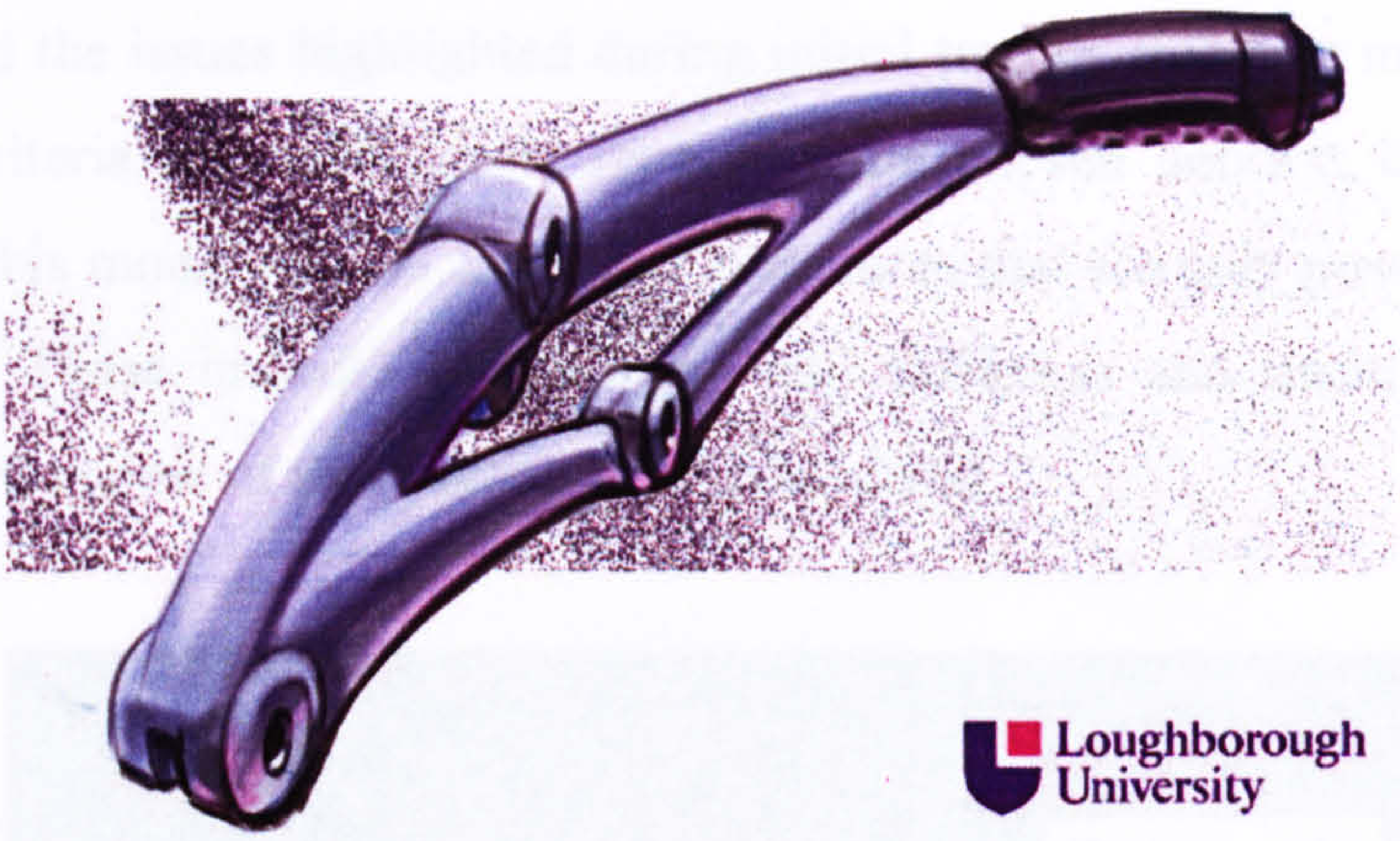


Figure 6.27: The selected sketch proposal

After selecting the chosen concept, CAD modelling was undertaken to produce a 3D model that was based upon the chosen 2D sketch. As witnessed in the previous Bafbox study, there was a slight compromise of form during translation from paper-based sketch to CAD model. However, this was so slight as to not warrant concern. Selective Laser Sintering was used to make a functional prototype of the model for assembly testing, during which a number of observations were made. It was found that the design made assembly difficult and that certain aspects were too flexible. Reflecting upon these observations and referring back to the original FEA results, the model was altered to address both issues. This resulted in the revised model that may be seen in Figure 6.28.

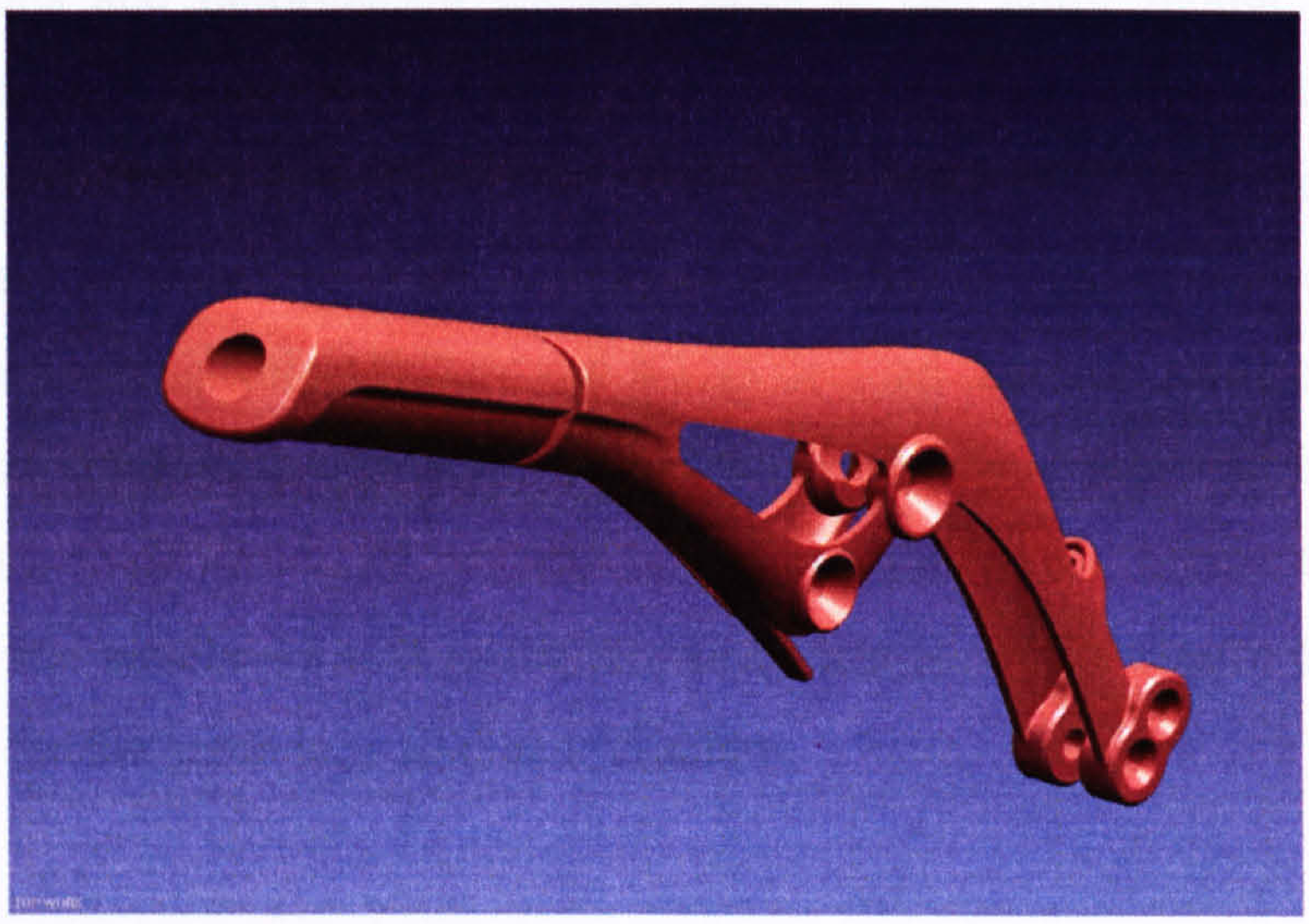


Figure 6.28: Rendered image of the final CAD model

Having resolved the issues highlighted during initial testing, this new model was felt to meet project criteria and sufficiently represent the chosen concept design. Detailed observation of this model reveals a number of features that are only possible with Rapid Manufacturing. These include non-uniform wall thickness and undercut geometries. Figure 6.29 shows some of these features in more detail.

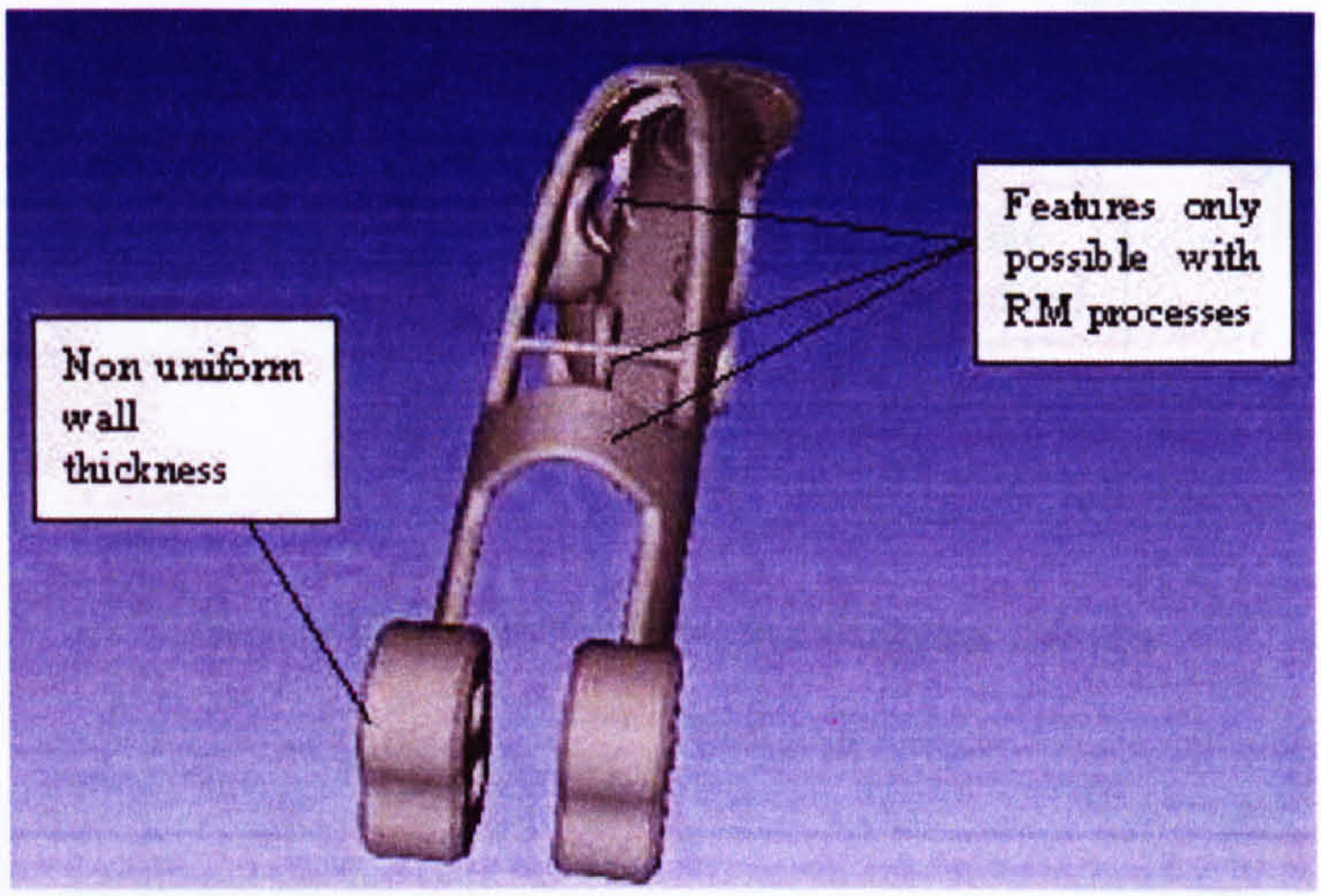


Figure 6.29: Features only available by RM

A final phase of FE analysis was then conducted using ALGOR to ascertain the general stress conditions and deformation characteristics of the latest model. This analysis revealed a relatively even stress distribution within the main body of the handbrake. However, the attachment points and rear pivot points were seen to be areas of possible concern. The abrupt transition of thickness in these areas of high stress was seen to be a potential cause for mechanical failure and it was decided that continued optimisation of form should be conducted. The simulated effect of this was achieved by altering the FEA model to include additional material in areas of high stress. Figure 6.30 shows the stress plot for the handbrake that prompted the concerns, whilst Figure 6.31 represents the stress plot for the same area after modification.

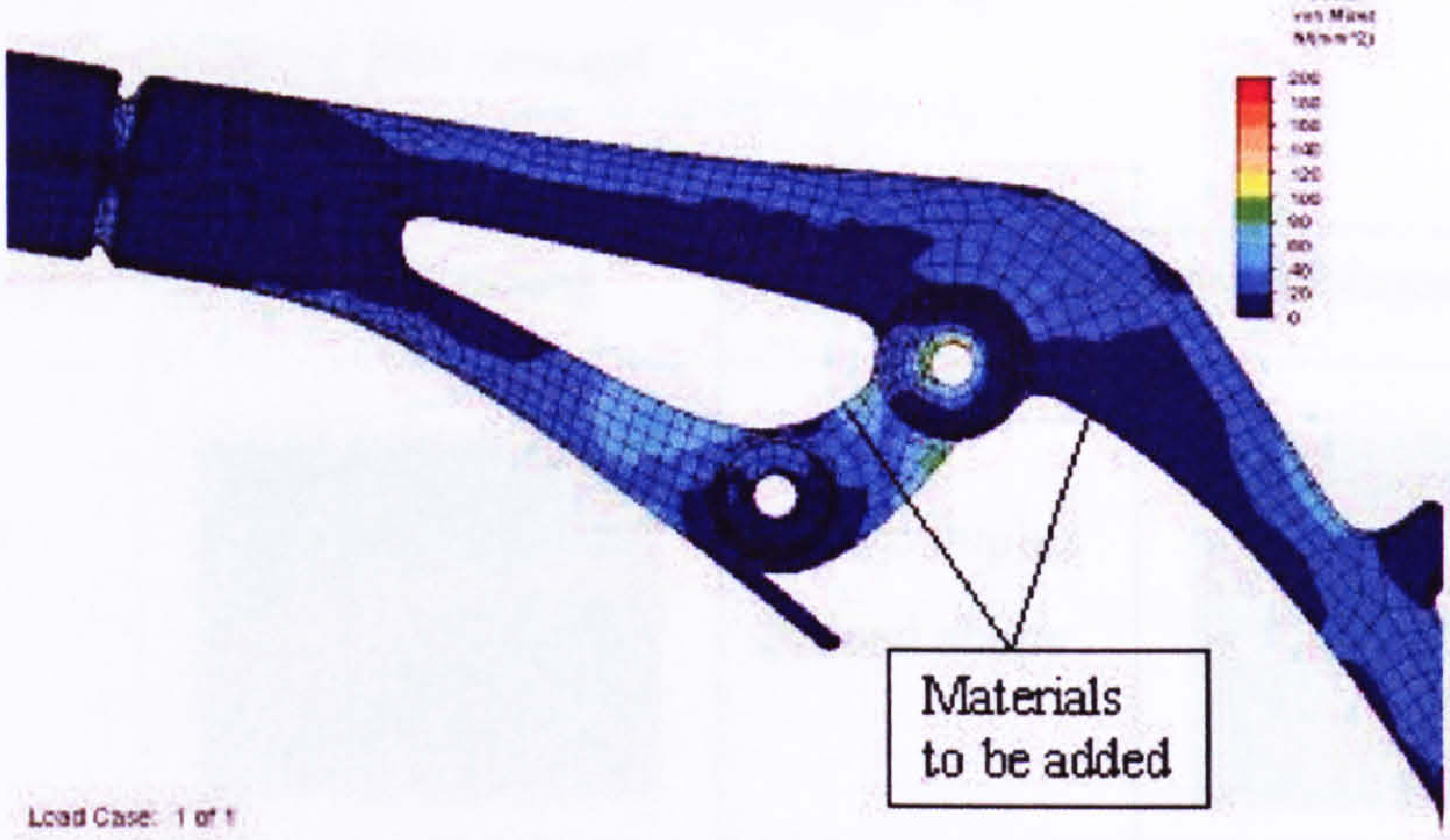


Figure 6.30: Stress plot for original design

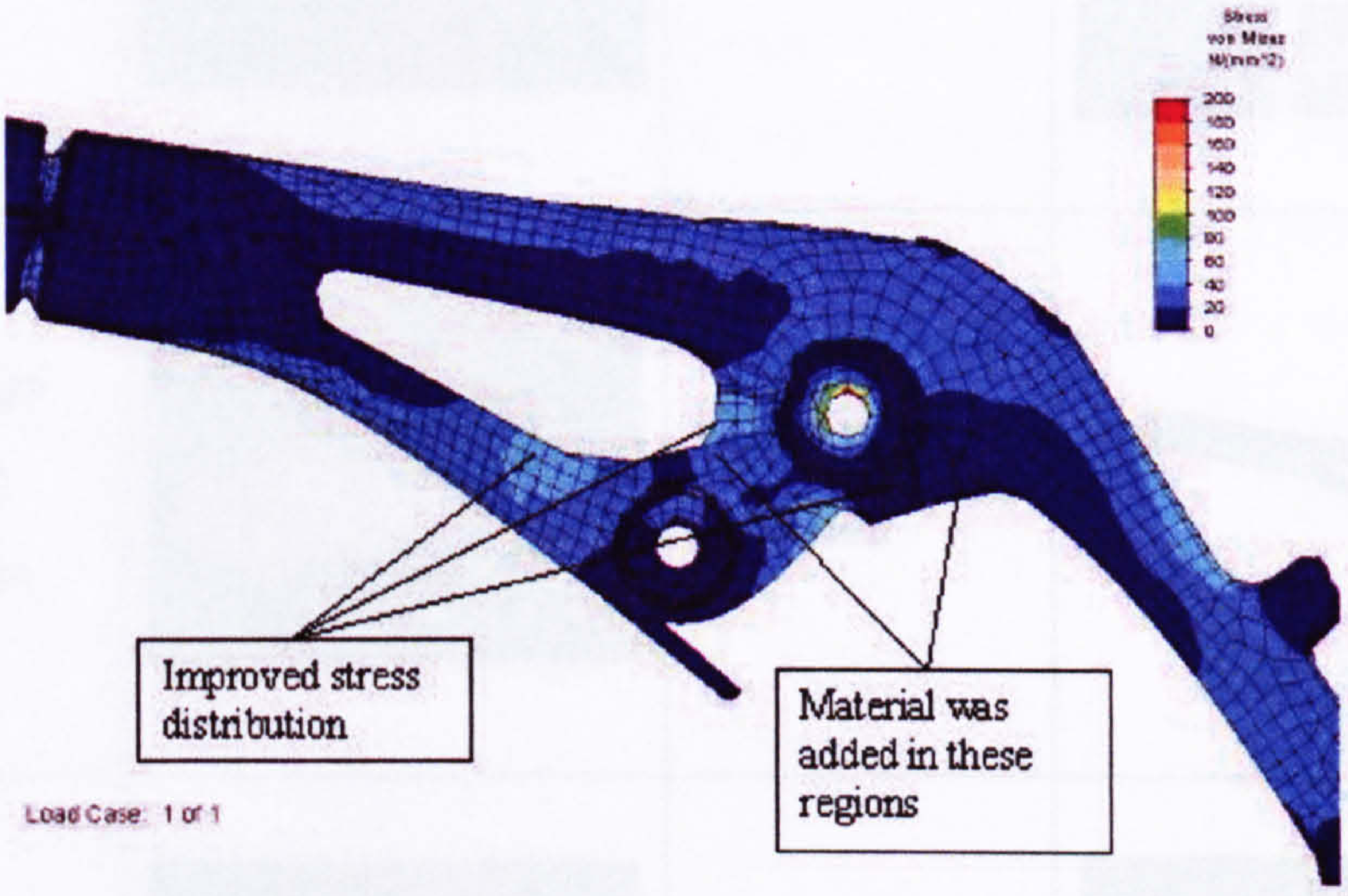


Figure 6.31: Stress plot for modified design

6.4.3 Discussion

Figure 6.32 shows a comparison of features associated with the injection-moulded handbrake and re-designed RM concept.

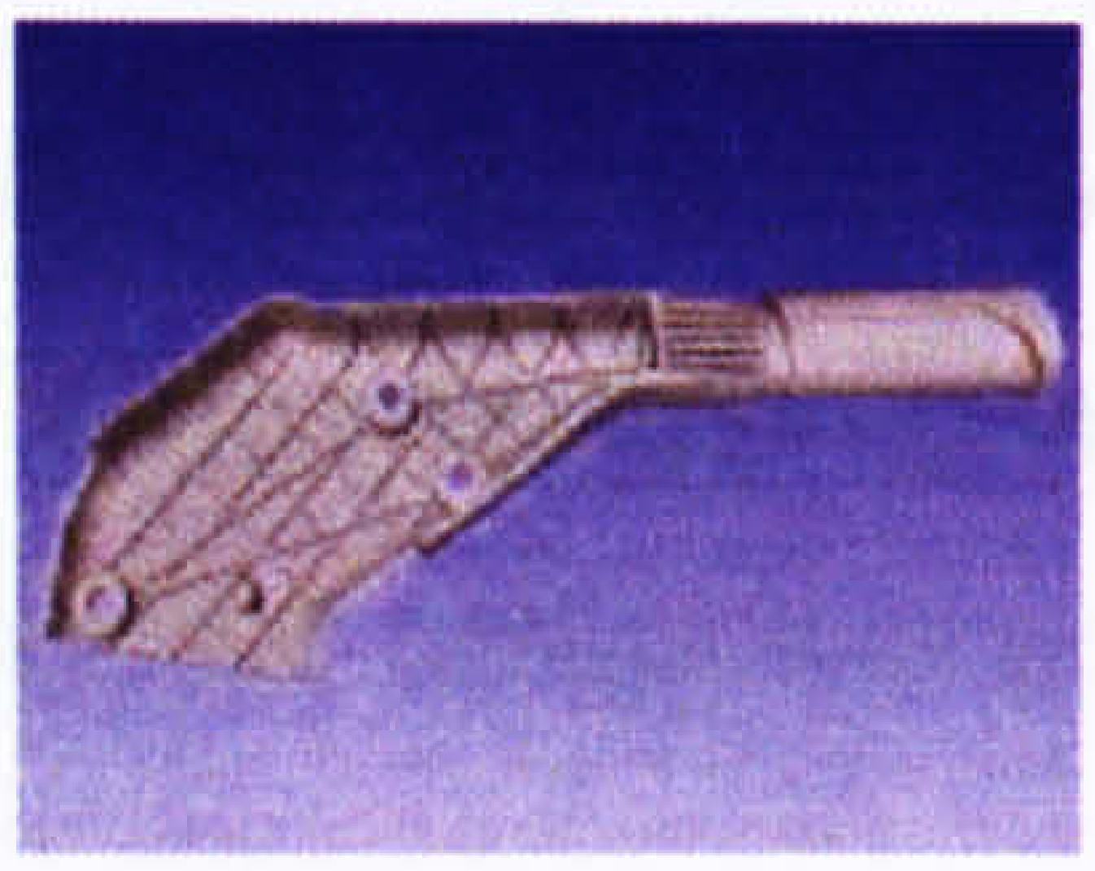
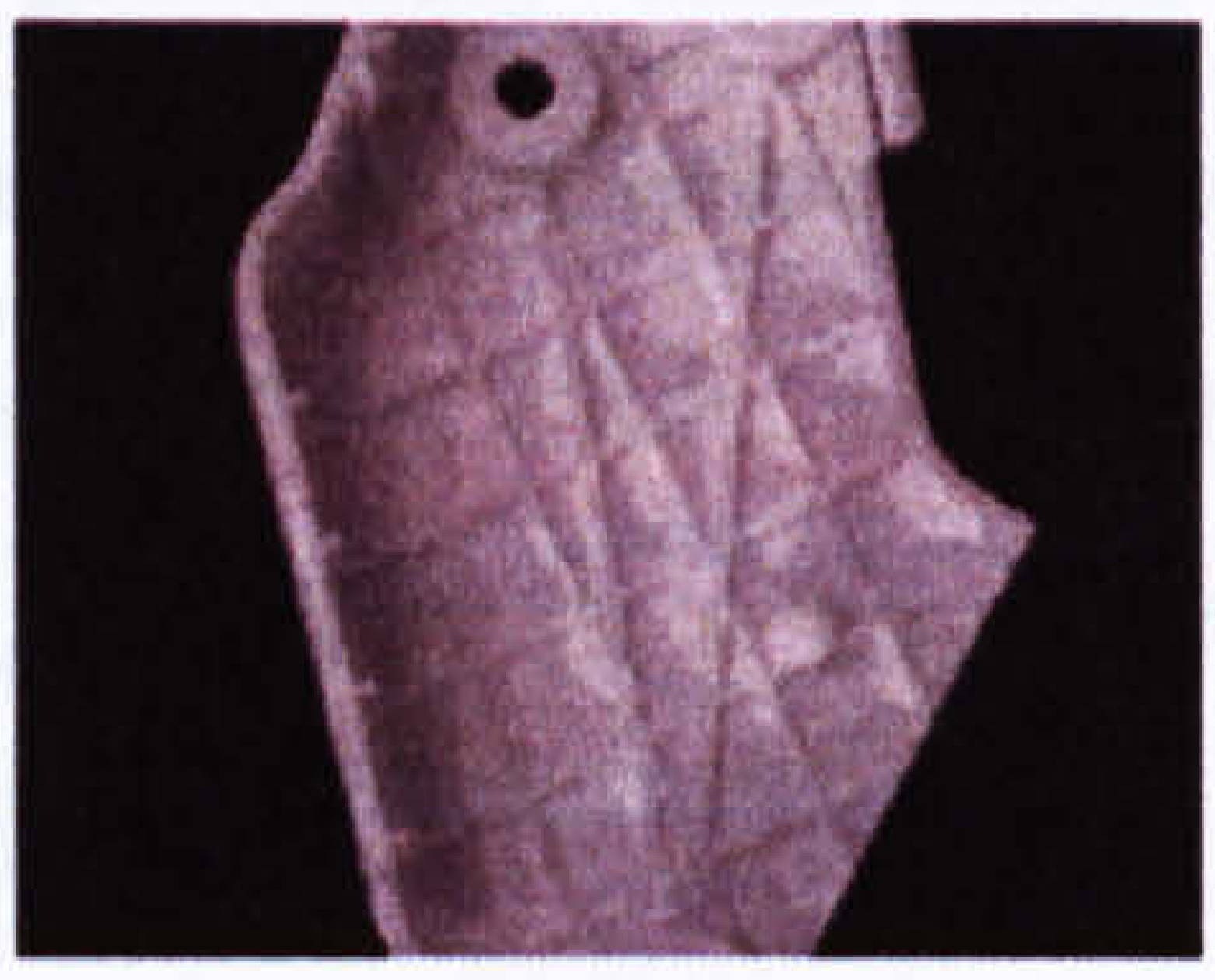
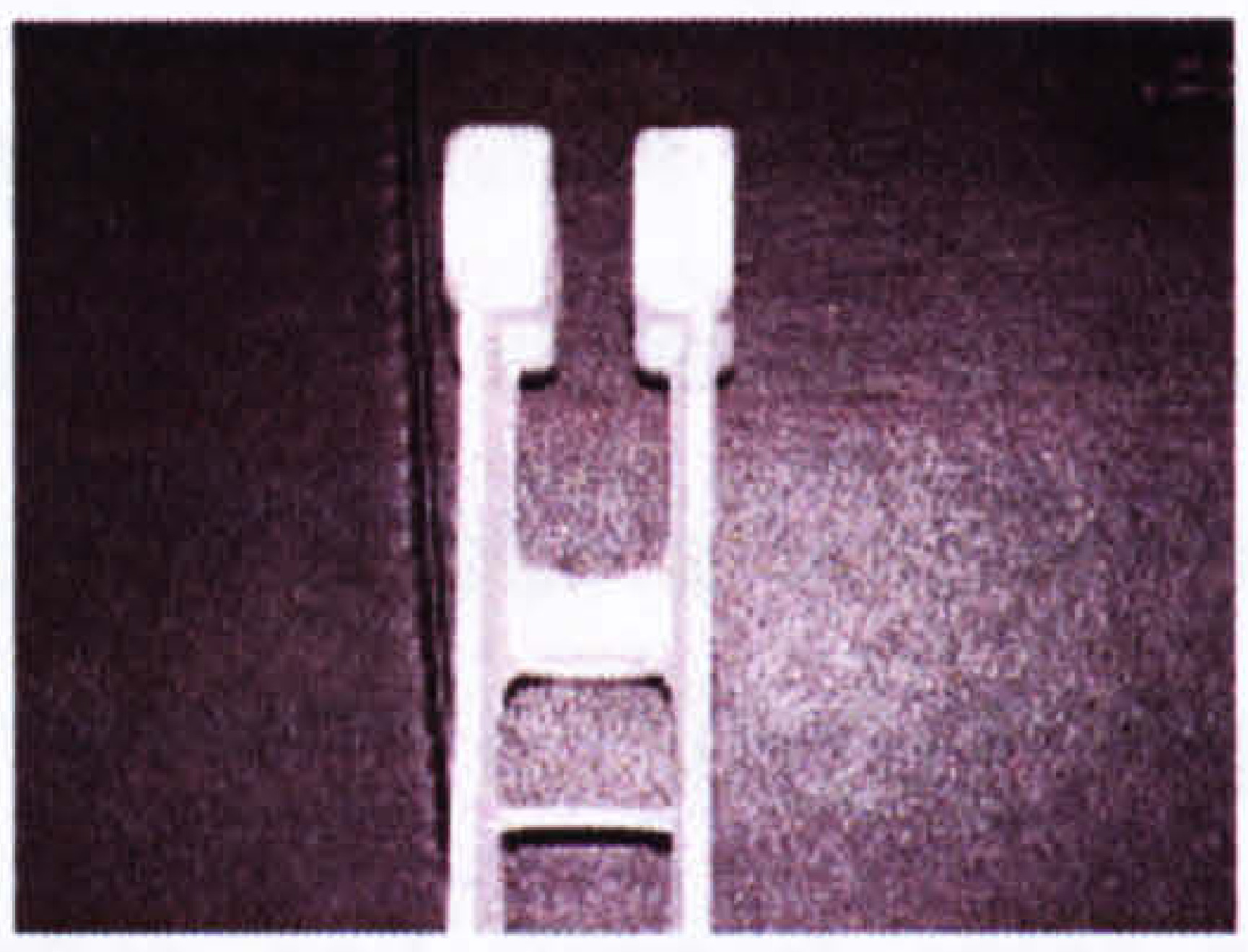
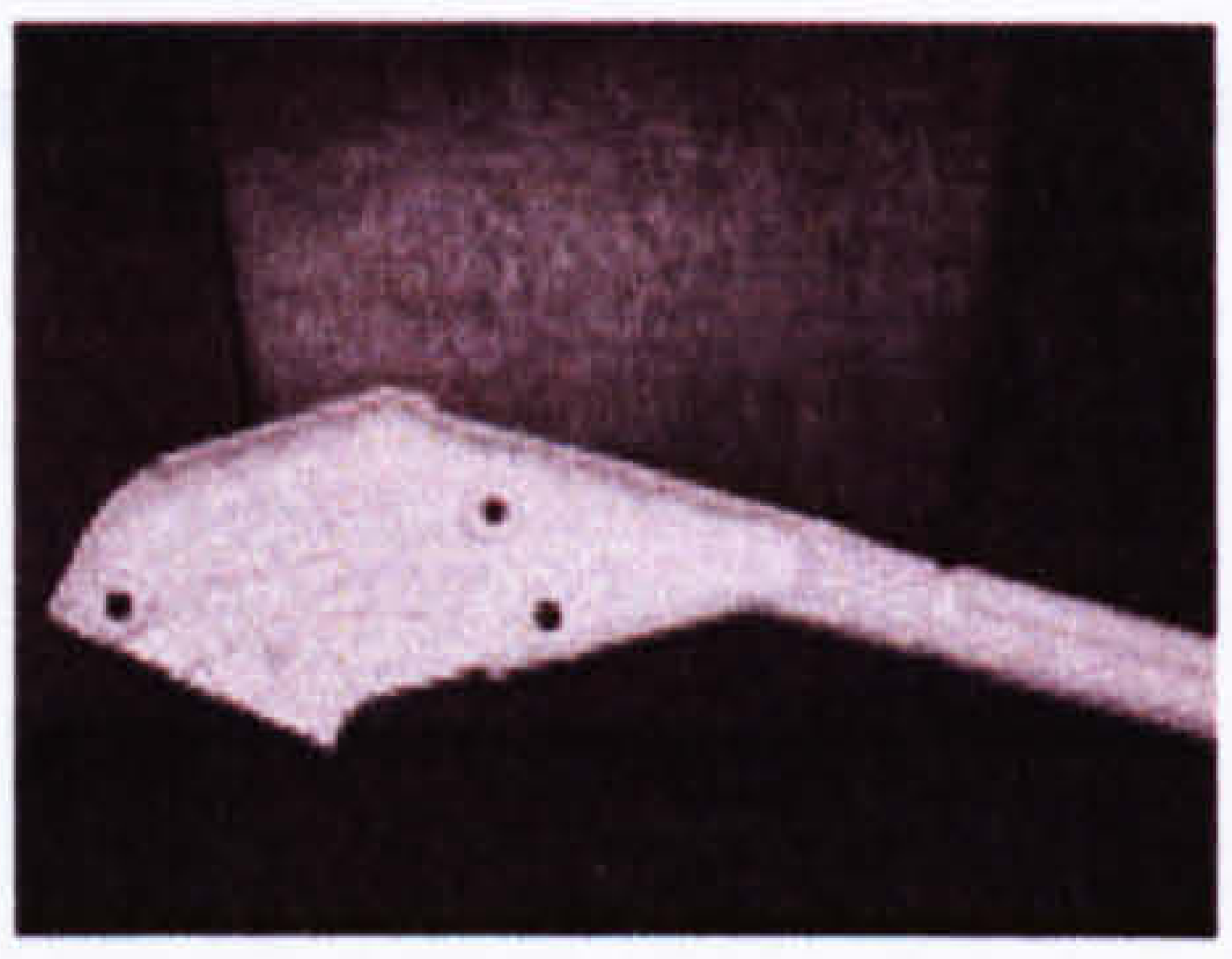
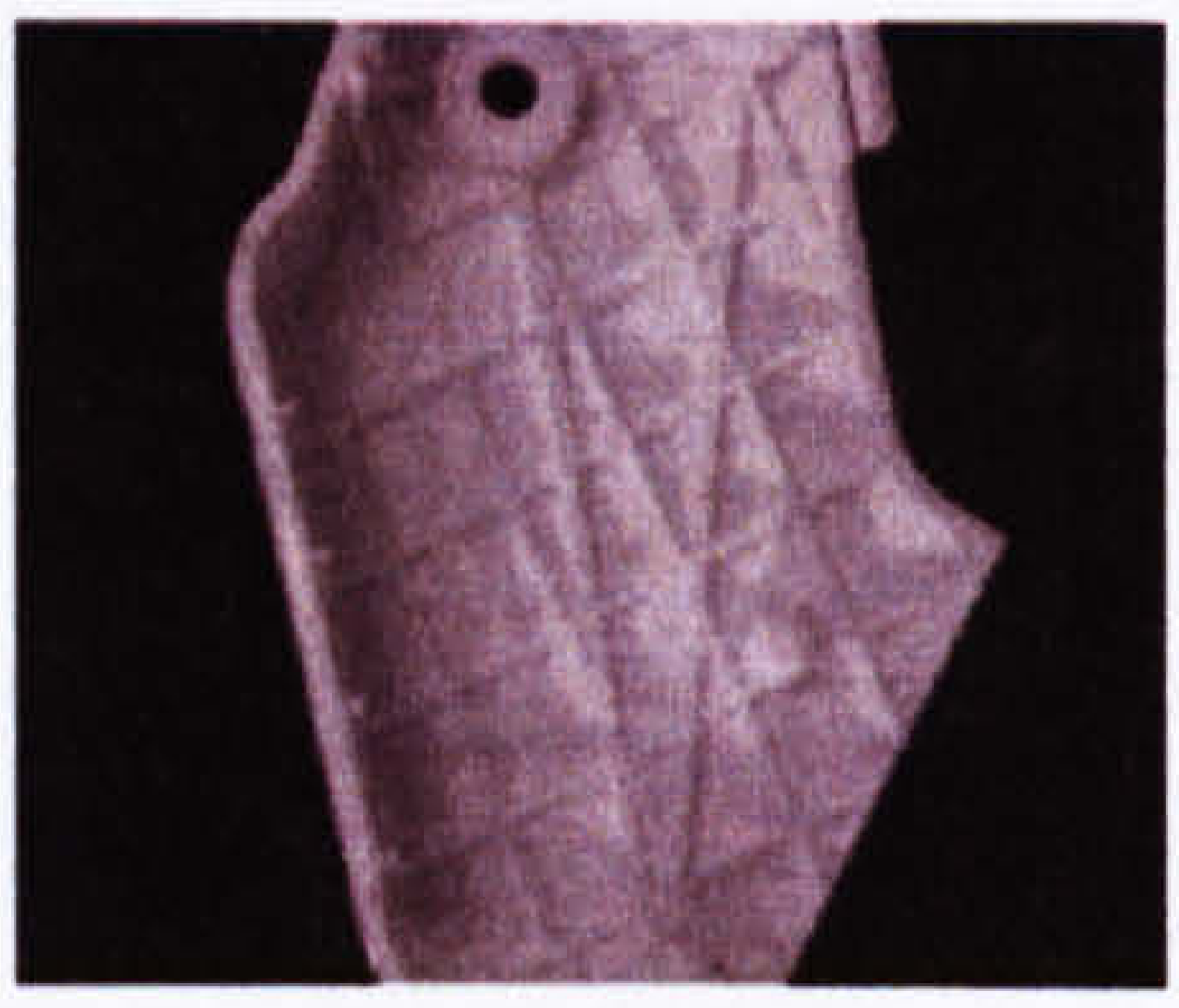
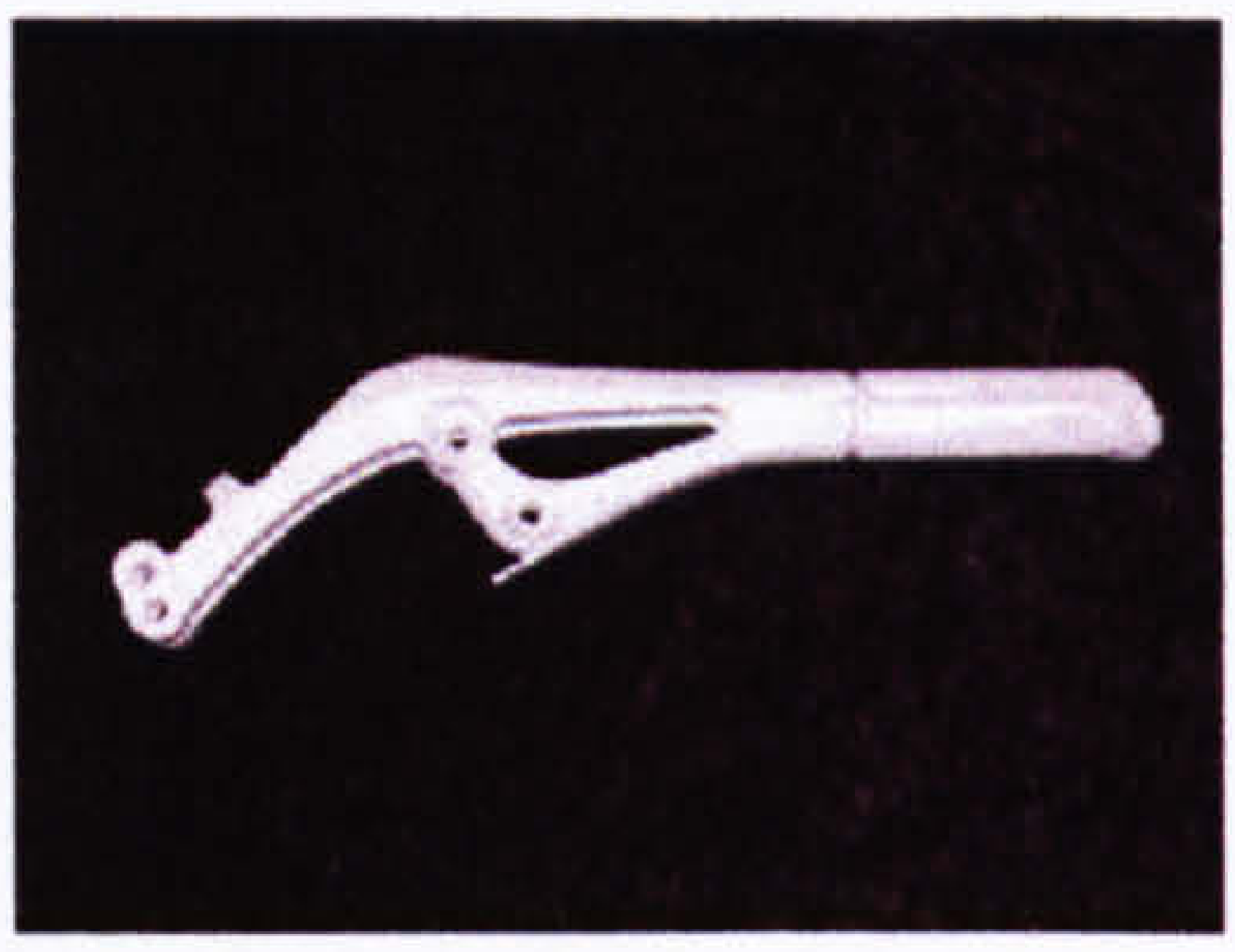
Design for Injection Moulding		**Design for Rapid Manufacture**	
Mainly flat surface		More complex stylised shape	
Constant wall thickness		Non uniform wall thickness	
Bulky design without any optimisation		12% weight reduction	
Heavily ribbed to strengthen flat surfaces		Selectively reinforced in areas of need	

Figure 6.32: Comparative table design for injection moulding RM

This case study highlights the ability of Rapid Manufacturing to produce a structurally optimised product that provides maximum mechanical performance with minimum use of material. Computer-based FEA tools enabled the generation of an approximate geometry through the calculated removal of material from a virtual 3D structure. The resulting form was stylised using traditional paper-based design approaches to achieve a more aesthetically pleasing concept. Paper-based sketches were then translated back into a 3D CAD model that was used to perform more detailed FE analysis and produce functional RP models that could be used to assess fit and assembly. With secondary testing and analysis complete, appropriate modifications were conducted to address the issues raised and a revised design was proposed.

The adoption of previously established Design For Rapid Manufacturing (DFRM) guidelines provided much freedom when generating appropriate product geometries. Design optimisation using FEA, and the evolution of form through removal of non-essential material, resulted in a complex "space frame" structure with a number of undercuts and re-entrant features. The design was also subject to varying wall thicknesses, where material was used to selectively strengthen and support areas of weakness and high stress. Whilst these geometric features would be a problem for more conventional processes, they are well lent to the additive systems used for Rapid Manufacturing.

6.5 Land Rover Dashboard Console

6.5.1 Project Background

Land Rover Special Vehicles is a branch of the main Land Rover Company based at the Solihull plant near Birmingham. This division is responsible for post-production customisation of the company's range of vehicles, including the Defender, Discovery, Freelander and Range Rover. It is the primary aim of this branch to provide low volume limited edition vehicles and augment specially requested features. Exemplar products include the customisation of standard production vehicles for use by the armed forces and emergency services.

As a collaborative industrial partner of Loughborough University's RMRG, an investigation was proposed to observe the effects of Rapid Manufacturing upon a typical Special Vehicles project. The focus of this project was to be the redesign and manufacture of the standard central console as fitted within all Land Rover Defender dashboards. This injection-moulded console usually accommodates the vehicles electrical control switches and audio entertainment system. Figure 6.33 shows the consoles prominent position alongside the steering wheel.

Figure 6.33: Land Rover Defender central dashboard console

Source: < http://www.landrover.com> 20/03/05

The project's specific objective was to redesign the console so that the audio system could be replaced with an electronic navigation system containing an LCD display. Figure 6.34 shows both console and navigation unit.

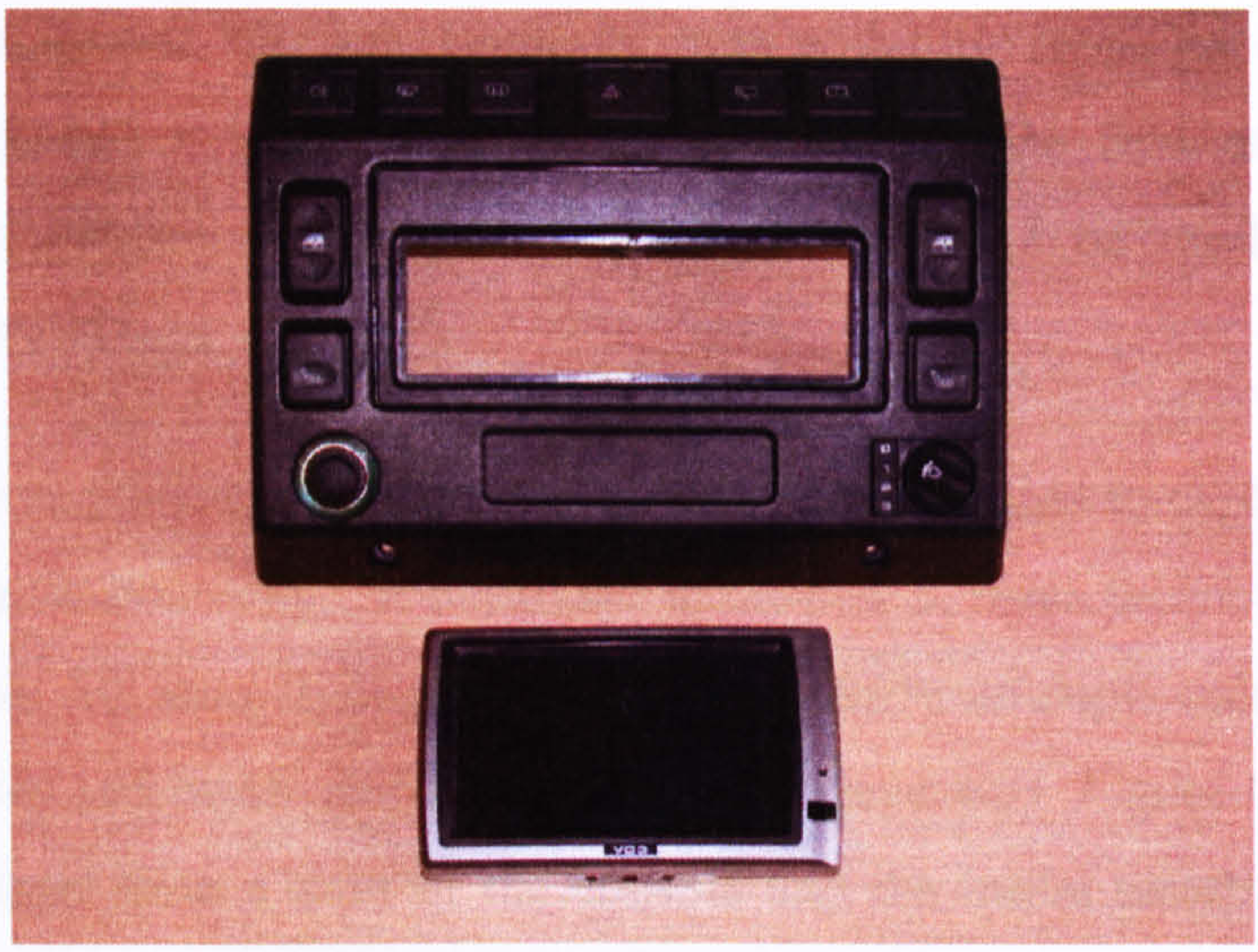


Figure 6.34: Current dashboard console and electronic navigation unit

The new electronic equipment, which was bought from an external supplier as a sealed unit, needed to be fitted intact so as not to invalidate the manufacturer's warranty. This was to be done in such a way that the driver and front seat passenger were able to view the screen and access the units control buttons. Whilst 2D schematics were provided for the navigation unit, there was no available CAD data or production drawings of any sort for the actual console. This meant it was necessary for Reverse Engineering techniques be used for the production of a suitably accurate CAD model. Hence, the overall objectives were identified as follows:

- Reverse Engineer the existing part and replicate generic part geometries
- Redesign the part so as to suitably house the new navigation equipment
- Exploit the design freedoms of Rapid Manufacturing
- Provide a product that is suitable for necessary vehicle testing

6.5.2 RM Concept Generation

Vehicle styling restrictions meant that any new console design would need to retain the same outward appearance as displayed by the original injection moulded part. In fact, the initial consensus was that the only noticeable change would be to the size and shape of the main audio system aperture. However, even with little scope for aesthetic change, the project presented a number of design challenges. The first of these was the generation of a suitably accurate CAD model that could be modified to include necessary design changes.

A suite of different Reverse Engineering technologies was used to capture and replicate the original console geometry. As discussed in chapter 3, these technologies enable the capture of virtual 3D data from physical objects. Early attempts using this approach looked favourable and much point cloud data was generated. Figure 6.35 shows point cloud data obtained from a scan of the console and the initial tessellated surface that was created from it.

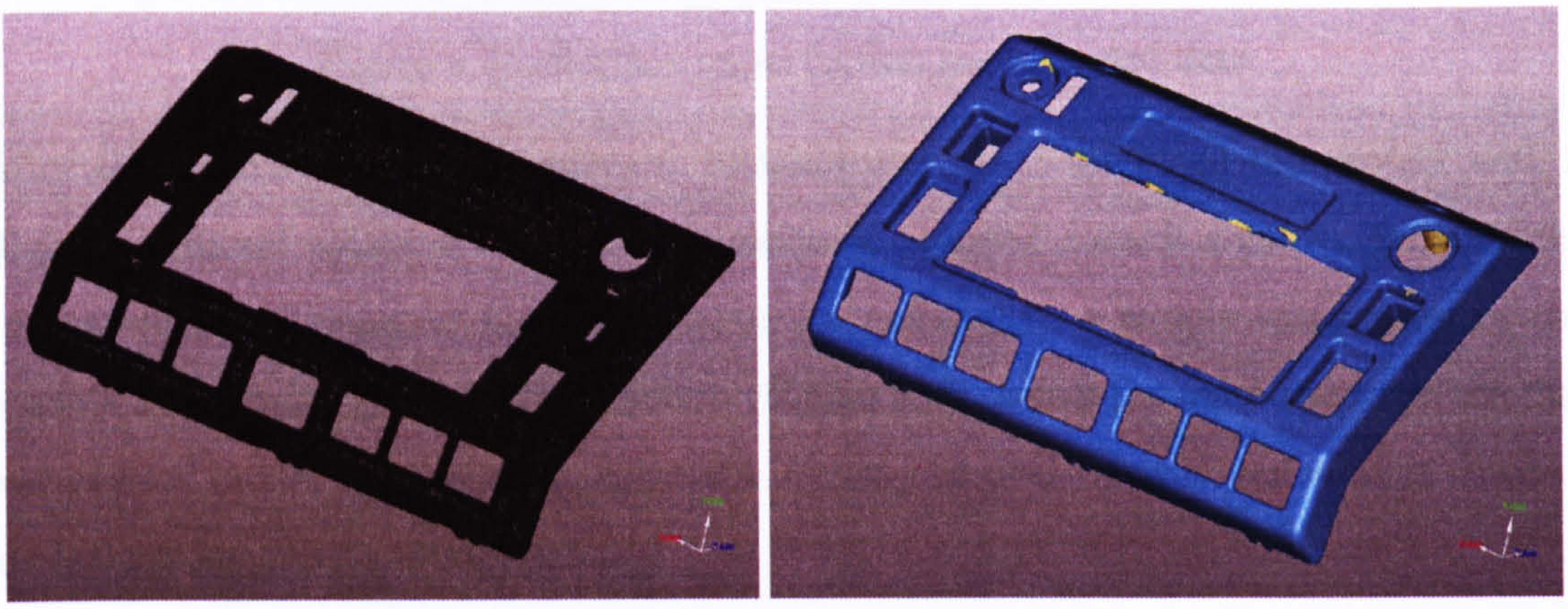


Figure 6.35: Point cloud and surface data from a 3D scan

Different sets of data were collected using both CGI and Modelmaker systems. The point clouds from these systems were then processed using Geomagics Studio, a specialised piece of Reverse Engineering software from the Raindrop Corporation. Initial attempts tried to process the whole console and all of its features. However, it soon became evident that scale of this was beyond the capability of both software and operator.

Whilst the scanned points clouds gave a true and accurate representation of all the necessary features, the huge scale and complexity of data made it extremely difficult to create a suitable surface for export to conventional CAD packages for editing. Figure 6.36 shows an example of the sort of surface imperfections experienced when attempting to generate a surface for export.

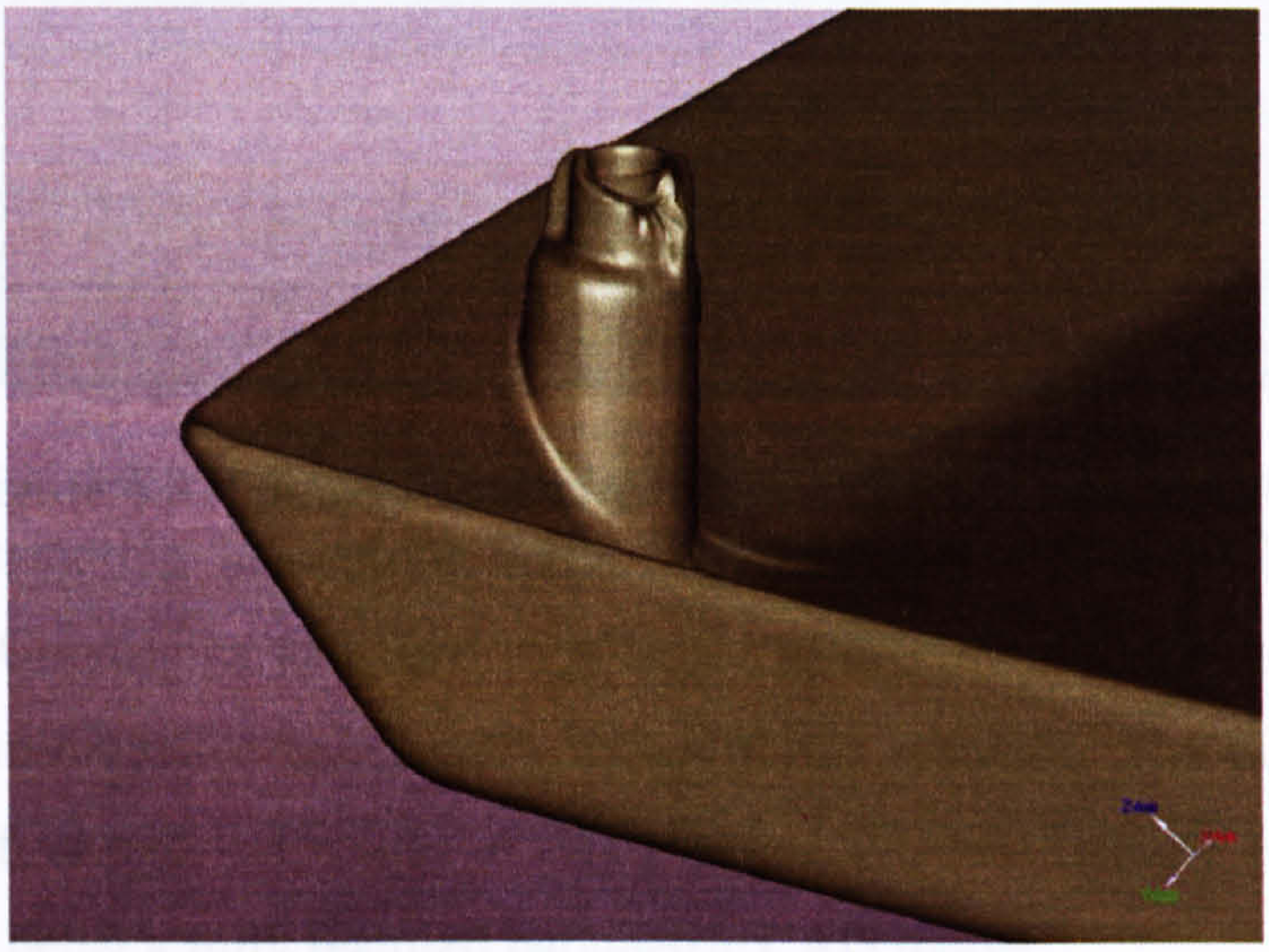


Figure 6.36: Surface imperfection in processed data

After several unsuccessful attempts a decision was made to revisit the project with a slightly different approach. Using the previously scanned data, it was decided that the amount of detail required for export could be reduced to a simple impression of the console's approximate top facing surface. Figure 6.37 shows the simplified surface that was created in line with this new approach. (It may be noted that all holes were filled in to create a completely blank surface.)

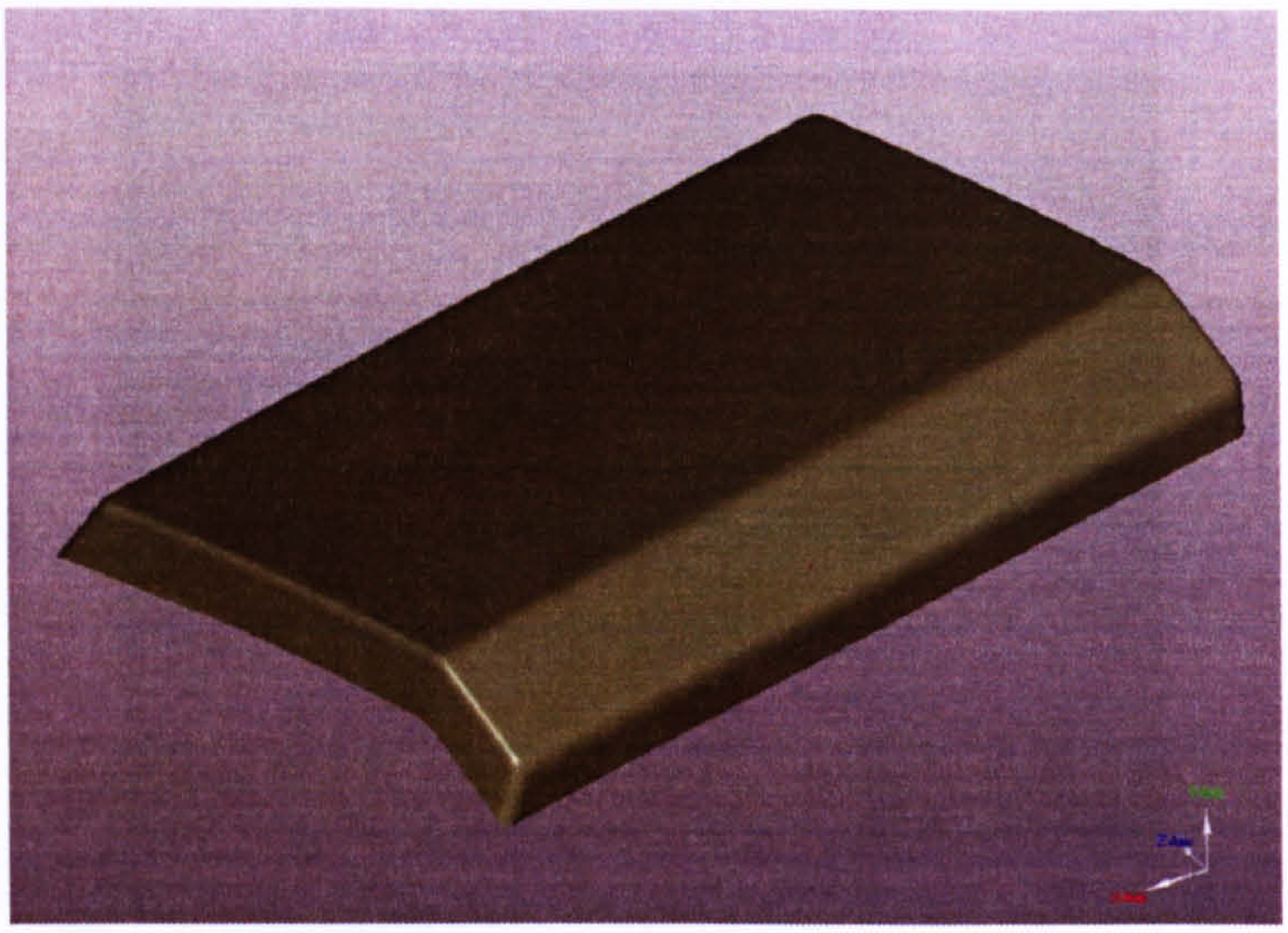


Figure 6.37: Simplified surface geometry for export to CAD

Rather than attempting to capture every single feature, the simplified surface was exported from Geomagics and used as a base feature upon which features could be parametrically re-modelled using conventional CAD software. The pictures in Figure 6.38 show the first and last stages of this process, the first being a blank "template" surface and last being a fully featured parametric CAD model.

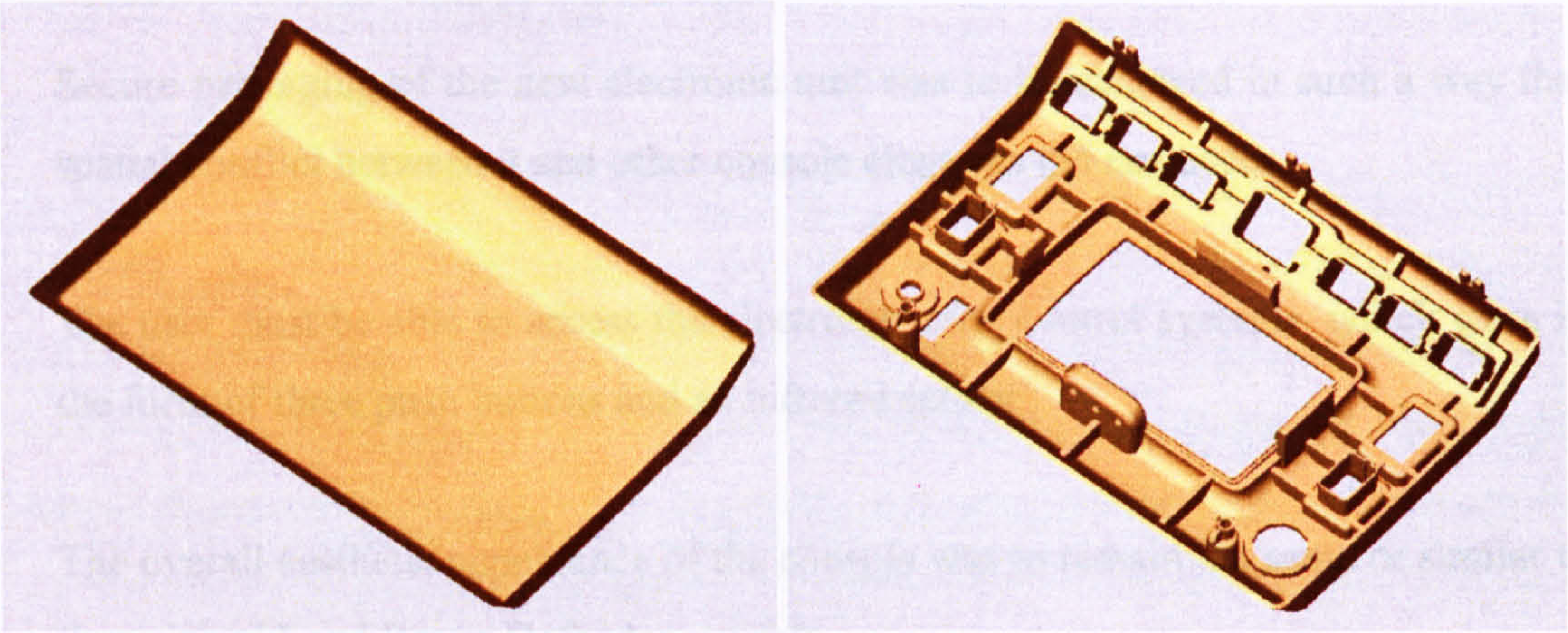


Figure 6.38: Initial surface and finished model complete with features

One advantage of using this approach is that it is relatively easy to alter the modelled features. For example, the new LCD screen aperture could be easily be altered to accommodate a different display, or even removed entirely to produce a blank sealed facia. The CAD generated using this approach was used to construct initial RP models to assess, accuracy and fit. Figure 6.39 shows one such part complete with switches and LCD screen.

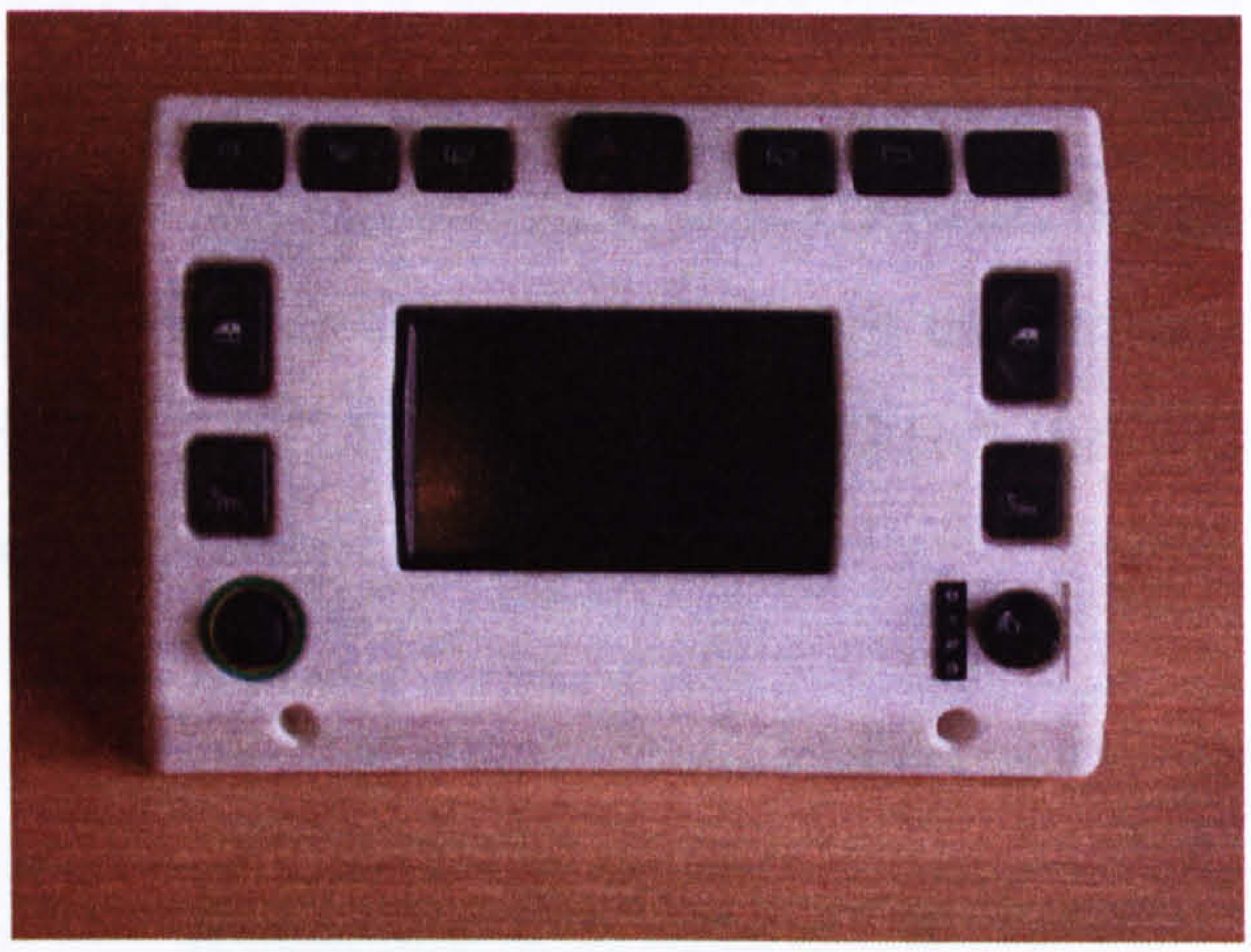


Figure 6.39: SLS part used to assess accuracy and fit

With a functional CAD model in place, concentration shifted back to design. The main criteria for this were as follows:

- The new console must accommodate all of the standard electrical controls and maintain the same instrumentation layout as used upon the regular console
- Secure packaging of the new electronic unit was to be achieved in such a way that spatial conflict between it and other console elements did not occur
- The user must be able to access the electronic units control systems, which were in the form of three push buttons and an infrared sensor
- The overall aesthetic appearance of the console was to remain the same or similar to the original Land Rover Defender console
- The design concept was to reflect the benefits afforded by Rapid Manufacture

During the project few paper-based drawings were made. Instead, use of parametric 3D CAD software enabled generation of a "fuzzy" model. Using this generic model it was relatively easy to apply conceptual features and design revisions in a format that could be physically reproduced and assessed as accurate RP parts. Whilst unseen by all but the designer, a number of paper-based sketches were made and used to roughly visualise and evaluate features prior to CAD modelling. Likened to "envelope" or "napkin" sketches, this is a common activity within such CAD based design methods. In addition to these methods, a digitising tablet and stylus were used to produce 2D presentation sketches. Figure 6.40 shows an image of the digital sketch that was used to represent the final chosen concept design.

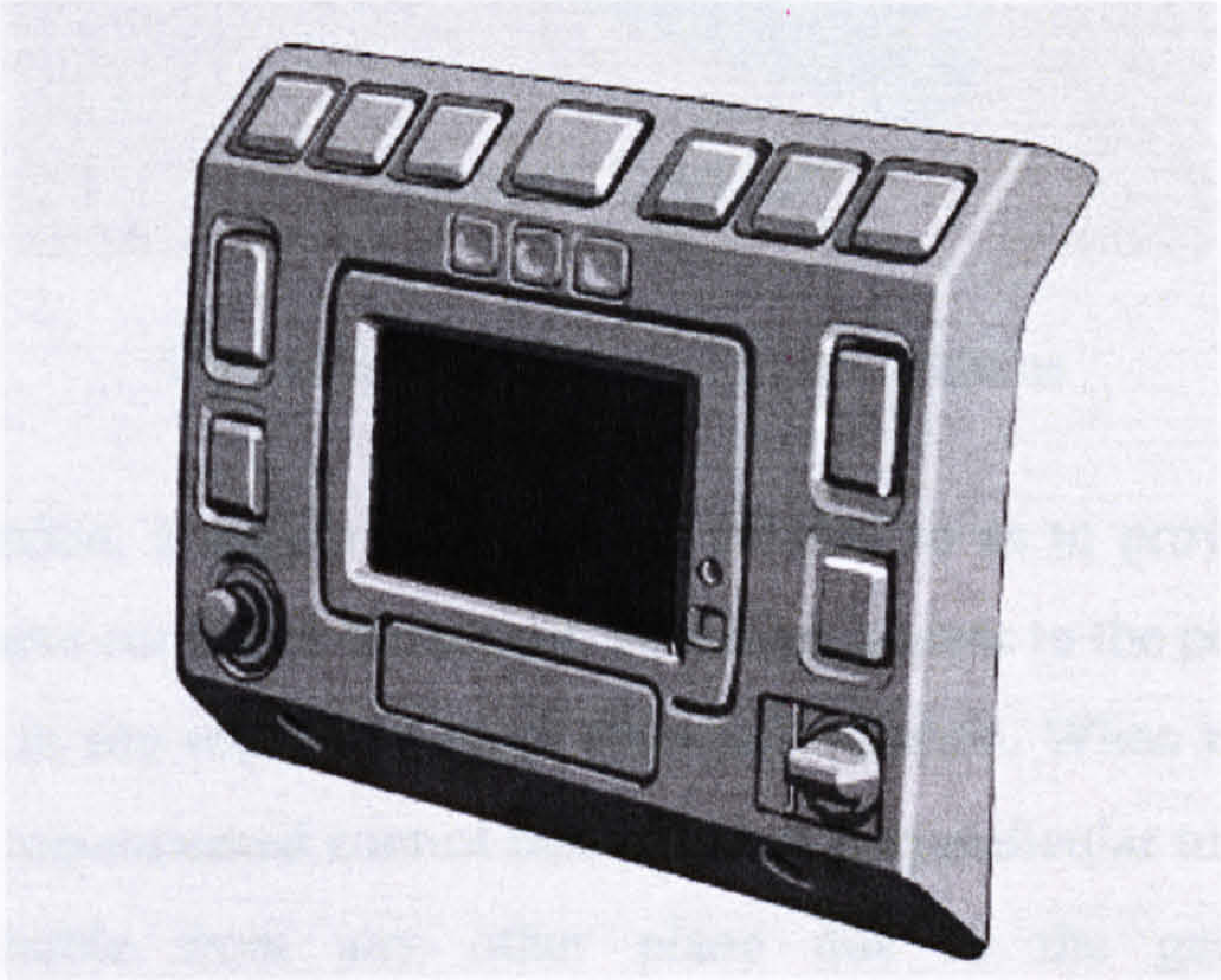


Figure 6.40: A digital sketch of the final RM console design

Secure mounting of the navigation unit was achieved in such a way as to provide ease of assembly, with the minimum number of components, whilst allowing simple non-destructive removal for replacement or repair. This was achieved with a "bounding box" that surrounds the unit and serves the dual function of locating the device and preventing any lateral movement. A raised boss provides the unit with underside support and houses the screw fittings that are used to attach it to the console. The actual unit was to be controlled via infrared remote control and direct physical contact with the three push buttons on top of the unit. Figure 6.41 shows a picture of the unit, which identifies the location of both control systems.

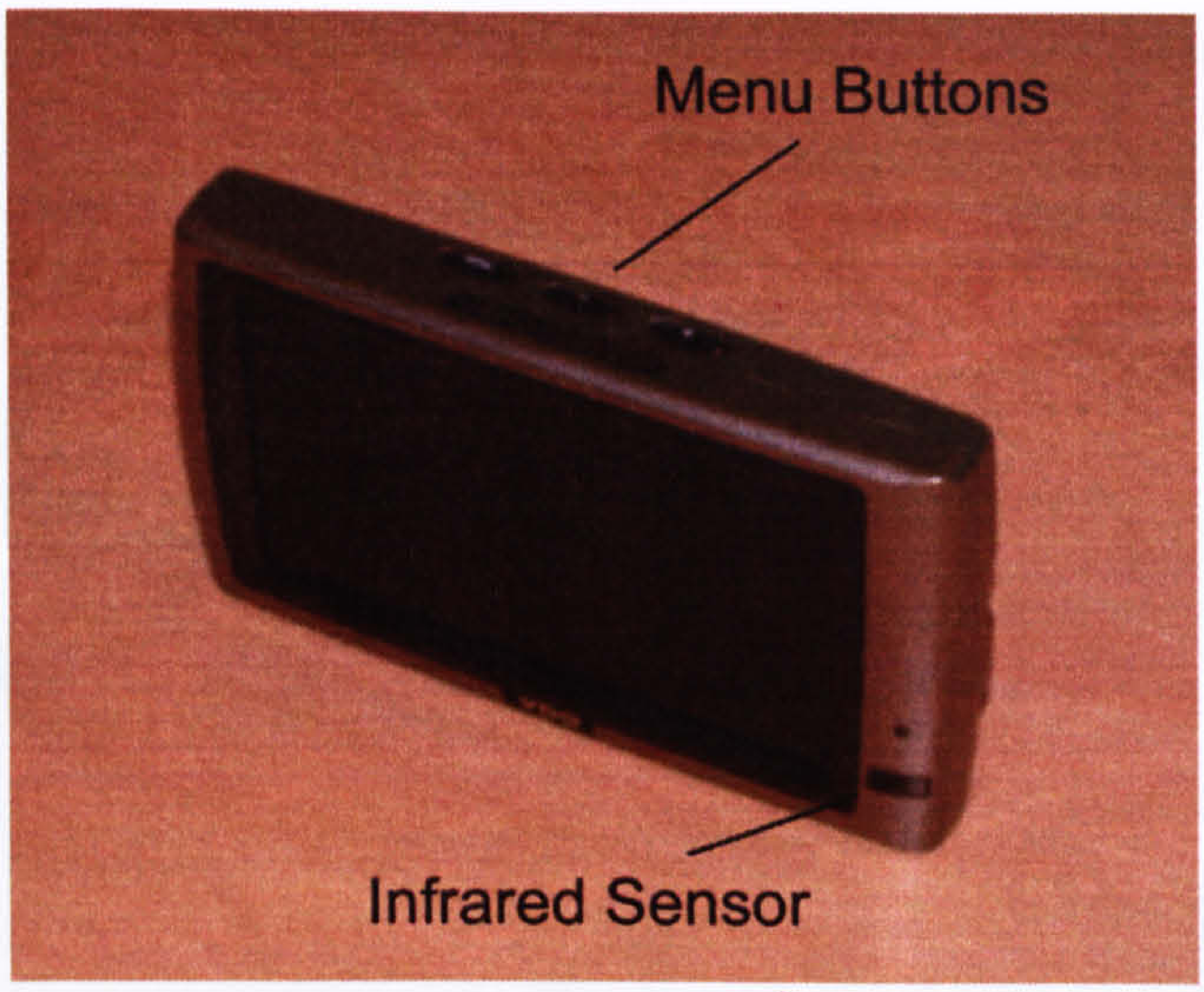


Figure 6.41: GPS unit control systems

For infrared activation, a simple aperture was created so as to provide a clear line of sight from the remote control to the sensor. However, access to the push button controls once the device is in situ required a more elaborate solution. When mounted within the console, the three top-mounted control buttons were perpendicular to the display screen area and inaccessible from any other plane due to the geography of other instrumentation.

In order to operate these controls it was necessary to devise a switch mechanism that allowed the transmission of force in a direction perpendicular to that which it was originally applied. To resolve this issue a purposely-designed cantilever switch was employed. Hinged from the unit's bounding box, the switch acts as a rocker type device through which force may be transferred. When downward force is applied to the exterior part of this switch, the mechanism flexes about its cantilever axis and transmits force through a push rod, which actuates the control button. Figure 6.42 shows a section view of this cantilever switch mechanism and how it transfers user-applied force to operate the navigation unit.

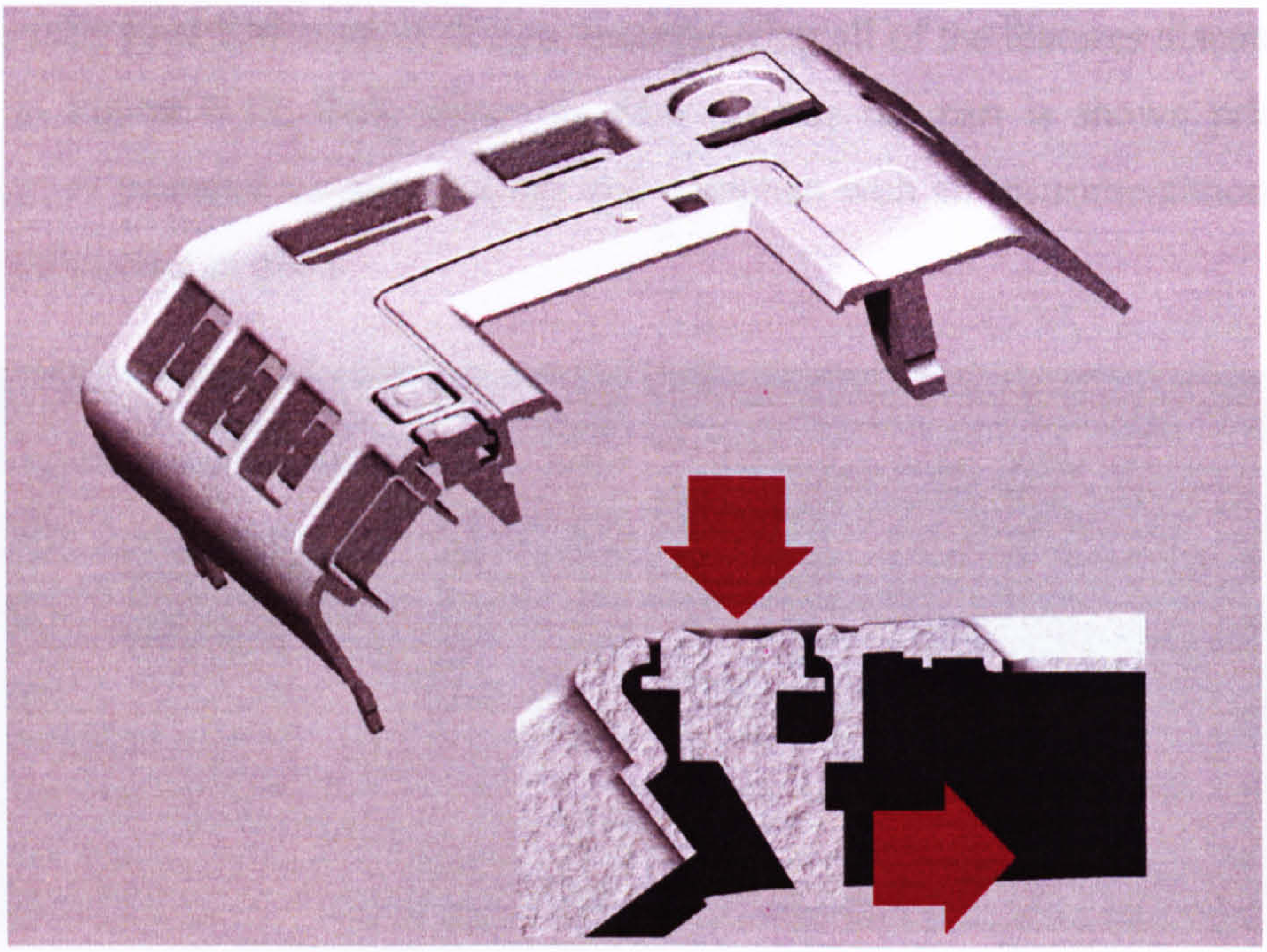


Figure 6.42: Integral cantilever switch mechanism

Designing this mechanism in a way that it remained an integral part of the console removed the need for any additional components and the issues commonly related to them, such as manufacture, assembly and their attached costs. The complexity of this feature and its geometry would make its production a near impossibility with conventional methods of manufacture. However undercut features and impossible lines of draw are of little consequence when producing parts via RM, which allows the inclusion of such features within components.

Exploiting this fact, it was also possible to create other features as integral parts of the design. For instance, the array block used to house the electrical instrumentation switches was previously manufactured as a separate part and mechanically attached to the console with screw fittings. Forming this block as part of the main console body would have made its production via injection moulding impossible because of the line of draw required to remove it from the mould tool. However, production via Rapid Manufacturing meant that no such restriction existed, enabling the two parts to be merged and built as one.

Pictures of the final RM console design, incorporating all of the features discussed, may be seen in Figure 6.43. Built using the SLS process the part is shown prior to the application of intended surface coatings and complete with all instrumentation controls and navigation unit in place.

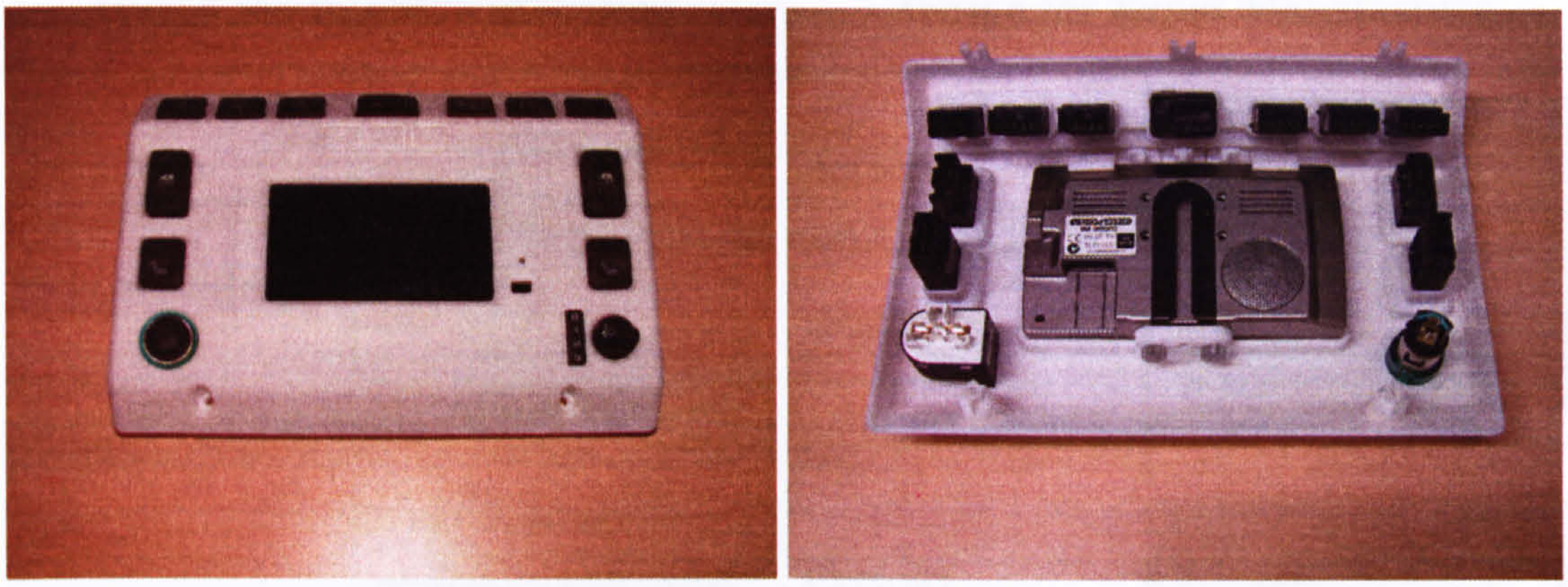


Figure 6.43: The final design for RM console

6.5.3 Discussion

Figure 6.44 shows a comparison of features associated with the injection-moulded dashboard console and re-designed RM concept.

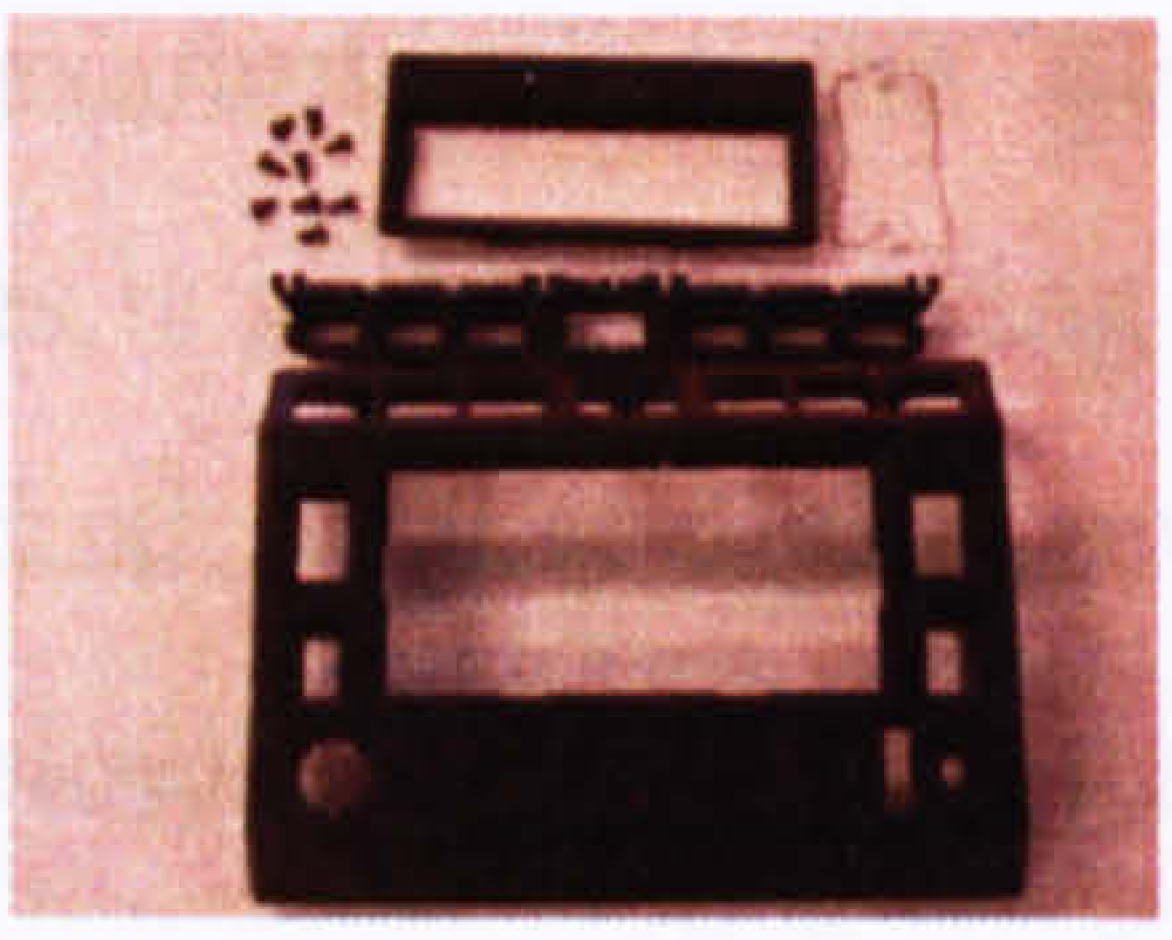
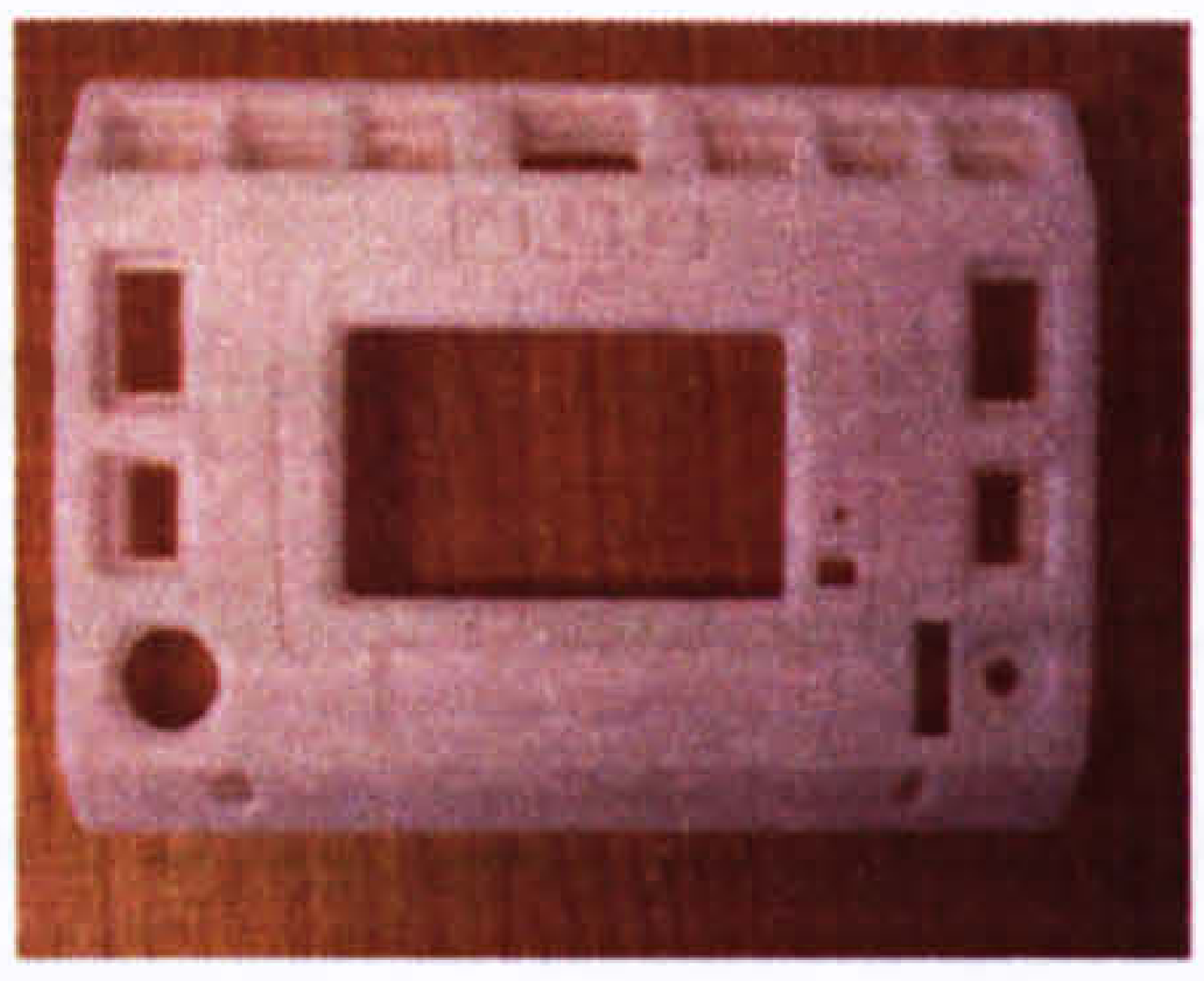
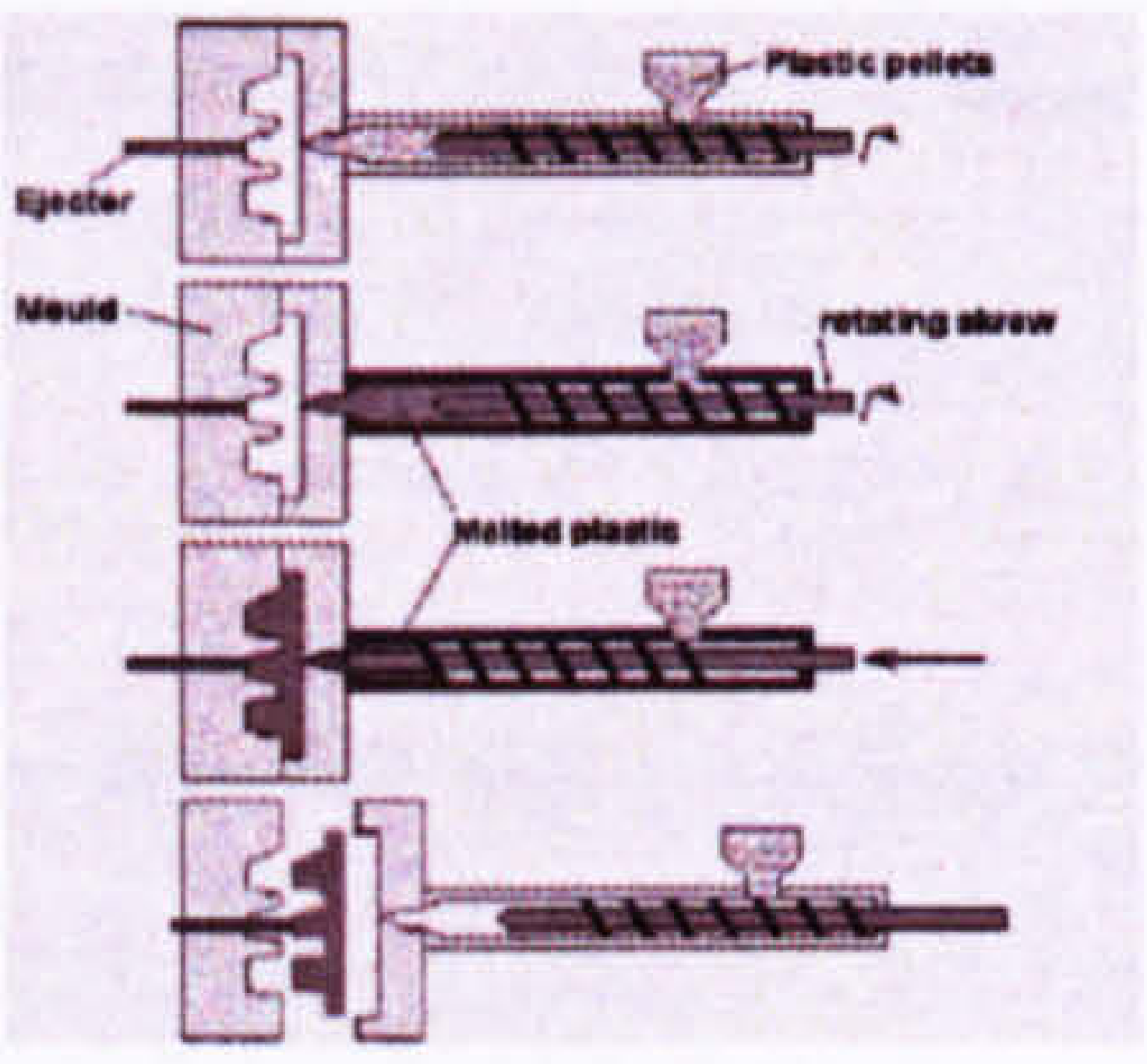
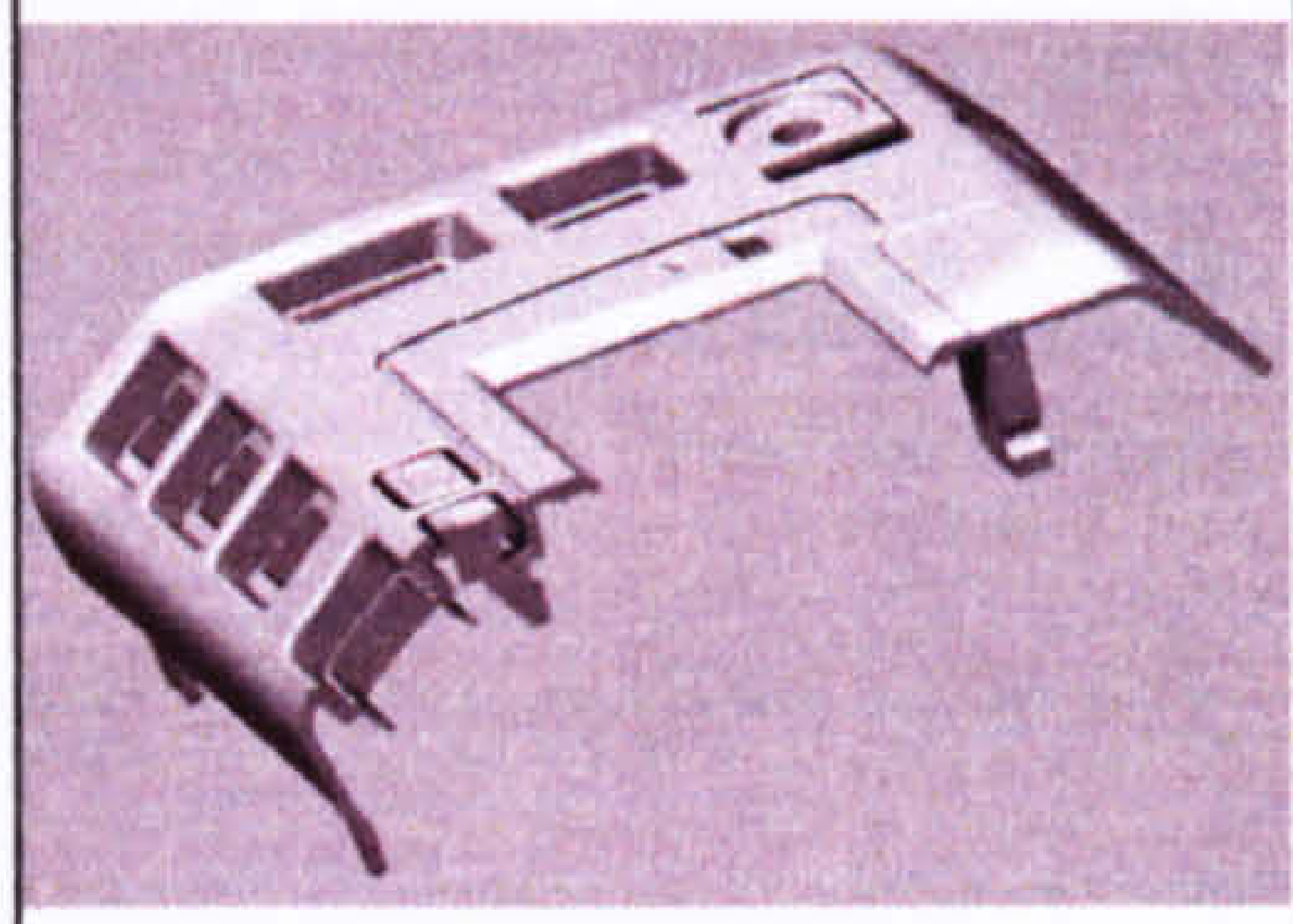
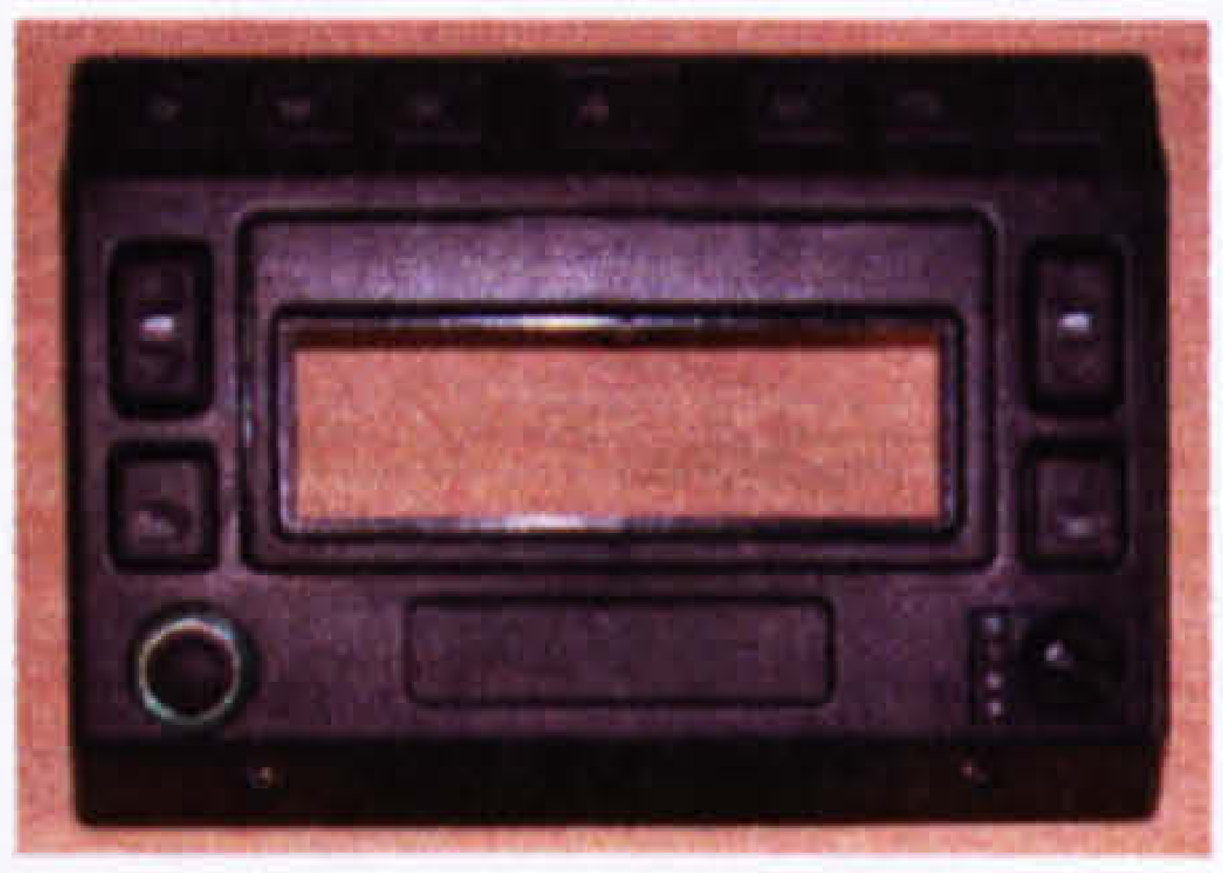
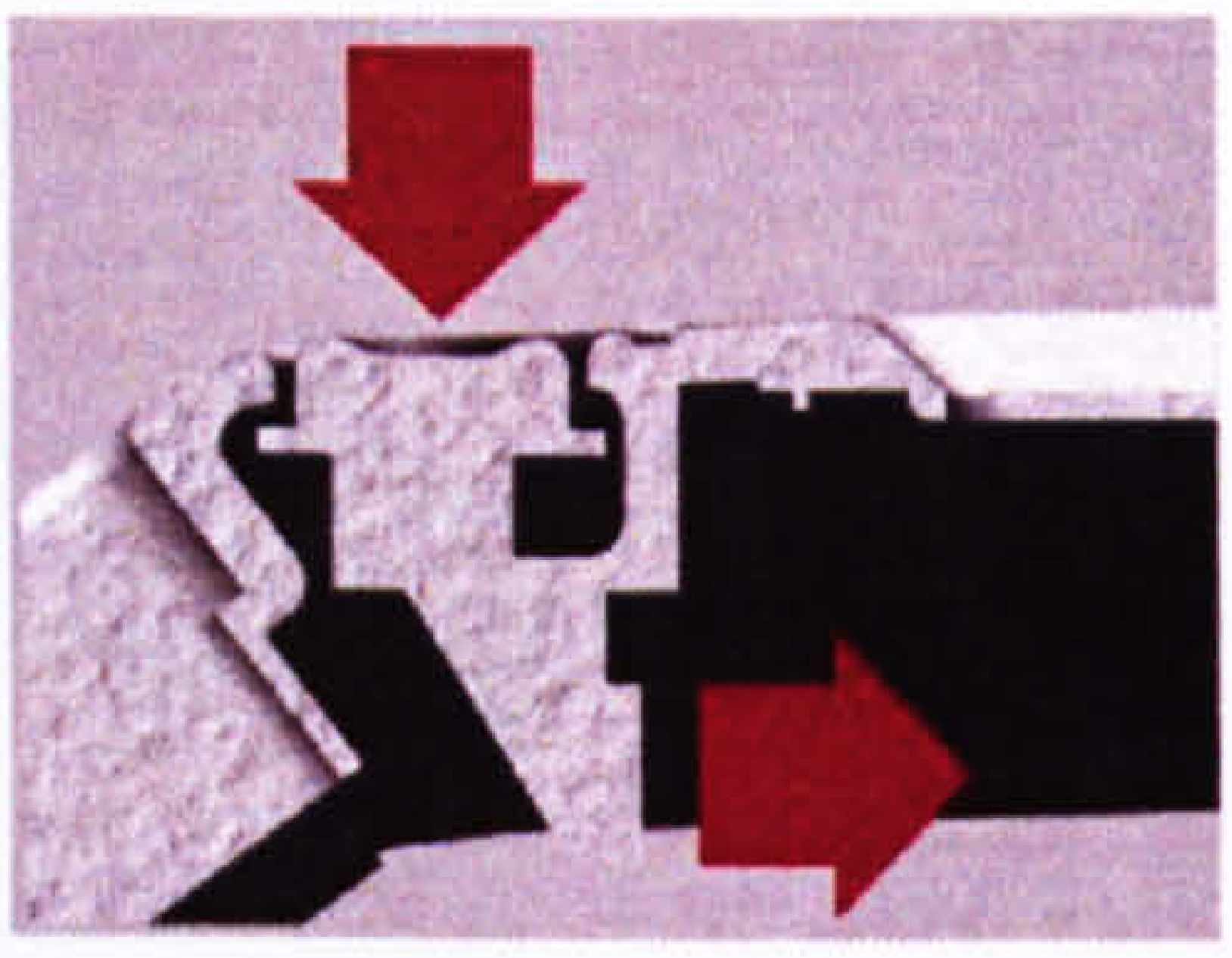
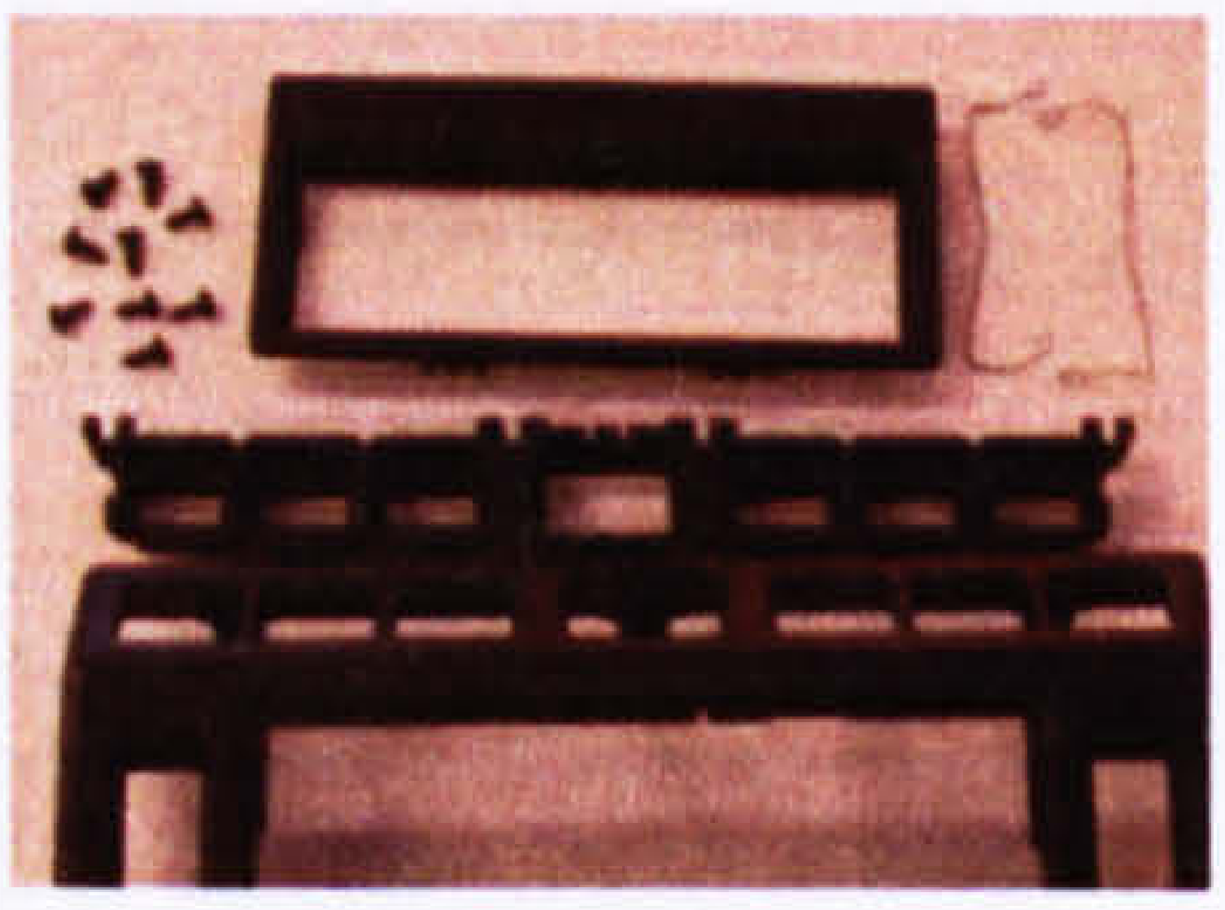
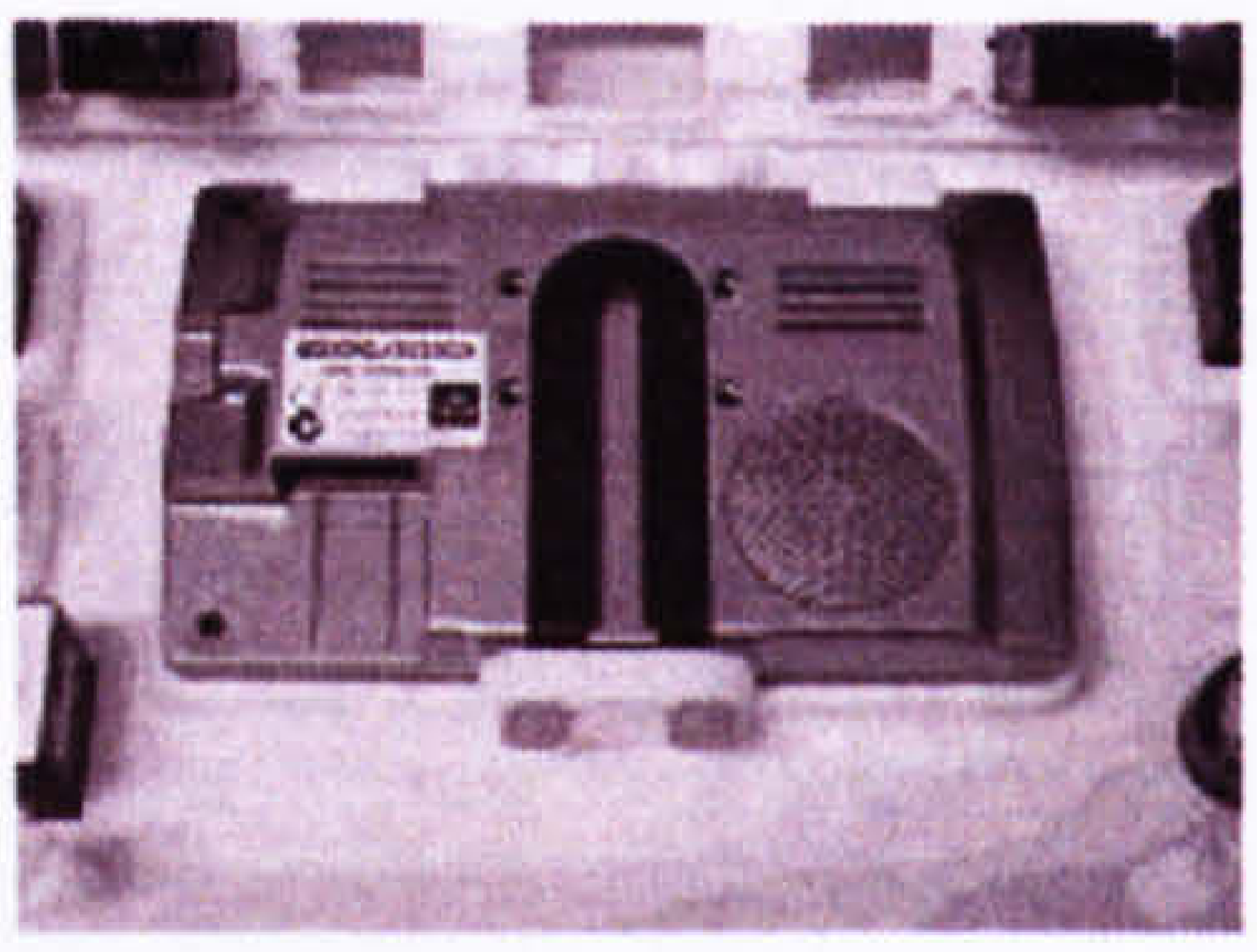
<table>
<tr><th colspan="2">Design for Injection Moulding</th><th colspan="2">Design for Rapid Manufacture</th></tr>
<tr><td>Many assembly parts and fittings</td><td></td><td>Assembly reduced to a single part</td><td></td></tr>
<tr><td>Tool dictates product form</td><td> </td><td>Exploits geometric freedom</td><td></td></tr>
<tr><td>Inert design simply holds instrumentation</td><td></td><td>Increased functionality with inbuilt actuator</td><td></td></tr>
<tr><td>Extra fittings required for mounting of equipment</td><td></td><td>Integral bounding boxes keep assembly parts secure</td><td></td></tr>
</table>

Figure 6.44: Comparative table design for injection moulding RM

In this study, Reverse Engineering technologies were applied to the capture of geometry from an existing product so that similar design variants could be produced using Rapid Manufacturing. The freedom of geometric creation associated with Rapid Manufacturing was exploited to increase product functionality and reduce the number of assembly parts. This included the consolidation of original "legacy" parts and the creation of new integrated features, like the cantilever switch mechanism and bounding box.

It is envisaged that a combination of Rapid Manufacturing and Reverse Engineering will enable the "three-dimensional photocopying" of products and parts. However, it is evident from this example that the generation and processing of scan data for downstream processes is still an involving task that requires a great deal of input from a highly skilled individual. Whilst digital reverse engineering has some obvious benefits, the associated technologies will need to go through changes before they can be used by industrial designers as automated "single button" systems.

6.6 JCB Control pod

6.6.1 Project Background

British company JC Bamford (JCB) are renowned for the manufacture and global distribution of earth moving and agricultural vehicles. The company has a workforce of over 4,000 people and produces over 160 different vehicles on 4 different continents, with bases in the UK, USA, India and South America.

JCB first entered the mini-excavator market in 1989 with the 801, and now produces 14 different mini excavator models that it sells in 130 countries worldwide. The Compact Products factory in Staffordshire is responsible for manufacturing the industry's largest range of compact machinery, which includes a variety of mini excavators, skid steer loaders, telescopic handlers, telescopic forklifts and backhoe loaders. The current mini excavator range includes the 8015, 8017 and 8018, along with numerous other models. Figure 6.45 shows a picture of 8018 mini-excavator in operation.

Figure 6.45: The 8018 mini-excavator

As a collaborative partner of Loughborough University's RMRG, JCB invited the group to investigate the effect that Rapid Manufacturing would have upon the redesign of one of it's products. The focus of this project was to be the control pod that is currently fitted to model 8018 mini excavators. The pod acts as an interface between the vehicle and it's user, incorporating a joystick and bank of switches that are used to control different electrical and hydraulic systems. The control pod is clearly visible in centre of Figure 6.34.

In addition to various control instrumentation, the pod contains a 12-volt cigarette lighter type port that may be used for the charging of battery-operated devices, such as mobile phones. An armrest is mounted on top of the pod that provides support for the user's forearm and elbow whist operating the vehicle. Each pod pivots about its rear, in a similar way to the armrests that may be found on aeroplane seating. This enables the user to mount and dismount the vehicle without obstruction. Electrical isolators contained within the pod are used to safely disable all systems when the pod is raised to the upright position.

An internal feature of each pod is a metal sub-frame that acts as a robust chassis upon which all other elements are attached. Figure 6.46 shows a picture of a pod that was taken on the JCB assembly line alongside a similar picture of the internal sub-frame structure.

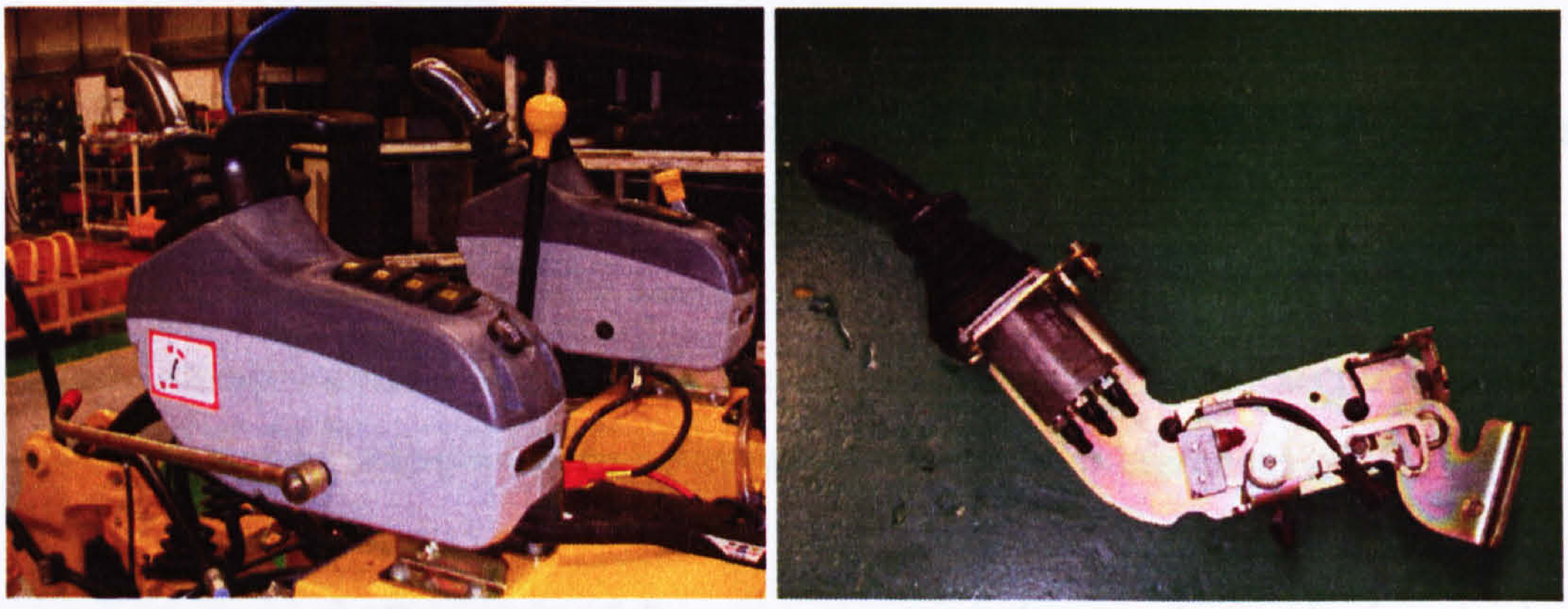


Figure 6.46: Control pod and steel sub-frame

The pod's exterior is comprised of an injection-moulded case that is made up of three main sections. These being a single top section and two lower halves. Each section is bolted in place with standard screw fittings and is removable so as to provide access for assembly, repair and maintenance. Similarly, a reaction injection moulded polyurethane armrest is attached to the sub-frame to provide the user with elbow support whilst operating the front mounted joystick servo control.

The pod is lifted about its pivot point using a handle that is constructed from tubular steel. As with the other components, this handle is bolted to the metal sub-frame. It protrudes through the side of the moulded plastic casing and projects forward to be within easy reach of the user. A rubberised sleeve on the end of this handle caps the tube and provides the user with an insulated tactile grip point.

Prior to the uptake of this project by the RMRG, an exercise was conducted by JCB to redesign the same pod and produce an improved concept to be manufactured using conventional processes. During a factory visit to the JCB production site, the team responsible for this redesign listed the main changes as follows:

- The lifting handle was moved from the side to the front of the pod.

- The internal structural assembly, which was previously welded together from several steel plates, was replaced with a single aluminium casting

- The armrest, which was previously attached via studs and bolted from underneath, is now bolted from the top to assist assembly and disassembly.

- Slight modifications were made to the case sections to accommodate the aforementioned changes and to better suit the aesthetic preferences of JCB

Figure 6.47 shows CAD images of the main structural changes that took place in the re-design exercise.

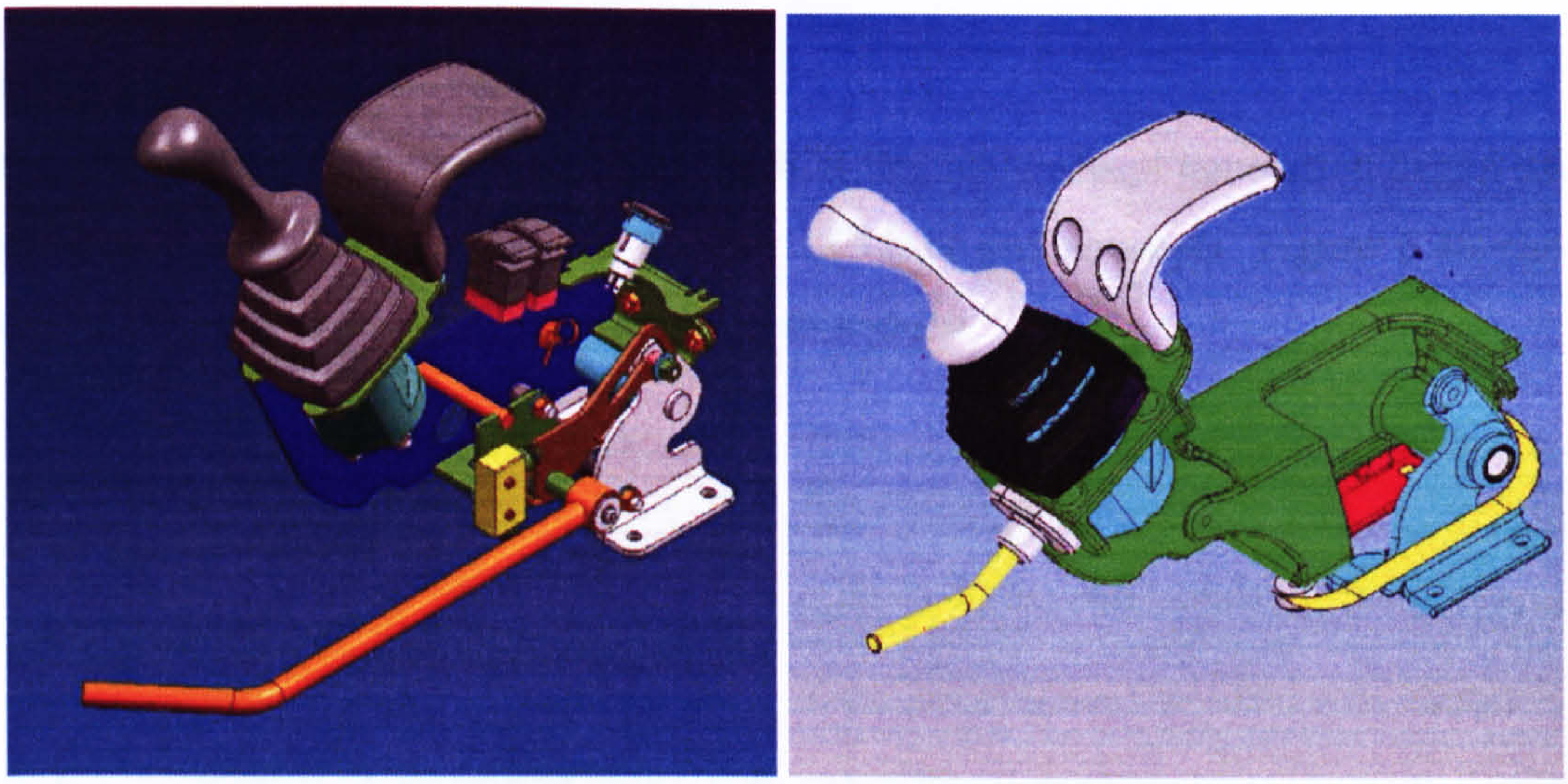


Figure 6.47: Comparative images of JCB pod designs

The new pod design is shortly set to replace its predecessor, although it was noted that vehicles are currently fitted with the original "side handle" design.

In redesigning the pod for Rapid Manufacture, a decision was made to concentrate upon developing the original side handle version. This was done to provide the project with same starting point and similar criteria as used in the prior JCB exercise. This also enabled direct comparison between a product redesigned for conventional methods of manufacture and the same product designed for Rapid Manufacture. The main objectives applied to the project were as follows:

- To redesign the part using design freedoms provided by Rapid Manufacture

- To make improvements on the existing product design wherever possible

- To address the perceived functional requirements of the user

- To provide a product that would comply with company styling preferences and functional expectations.

6.6.2 RM Concept Generation

Following an initial project meeting at the JCB factory, concept generation began using paper-based sketches to explore a number of ideas and concepts. Figure 6.48 shows some of the early sketches produced during this phase.

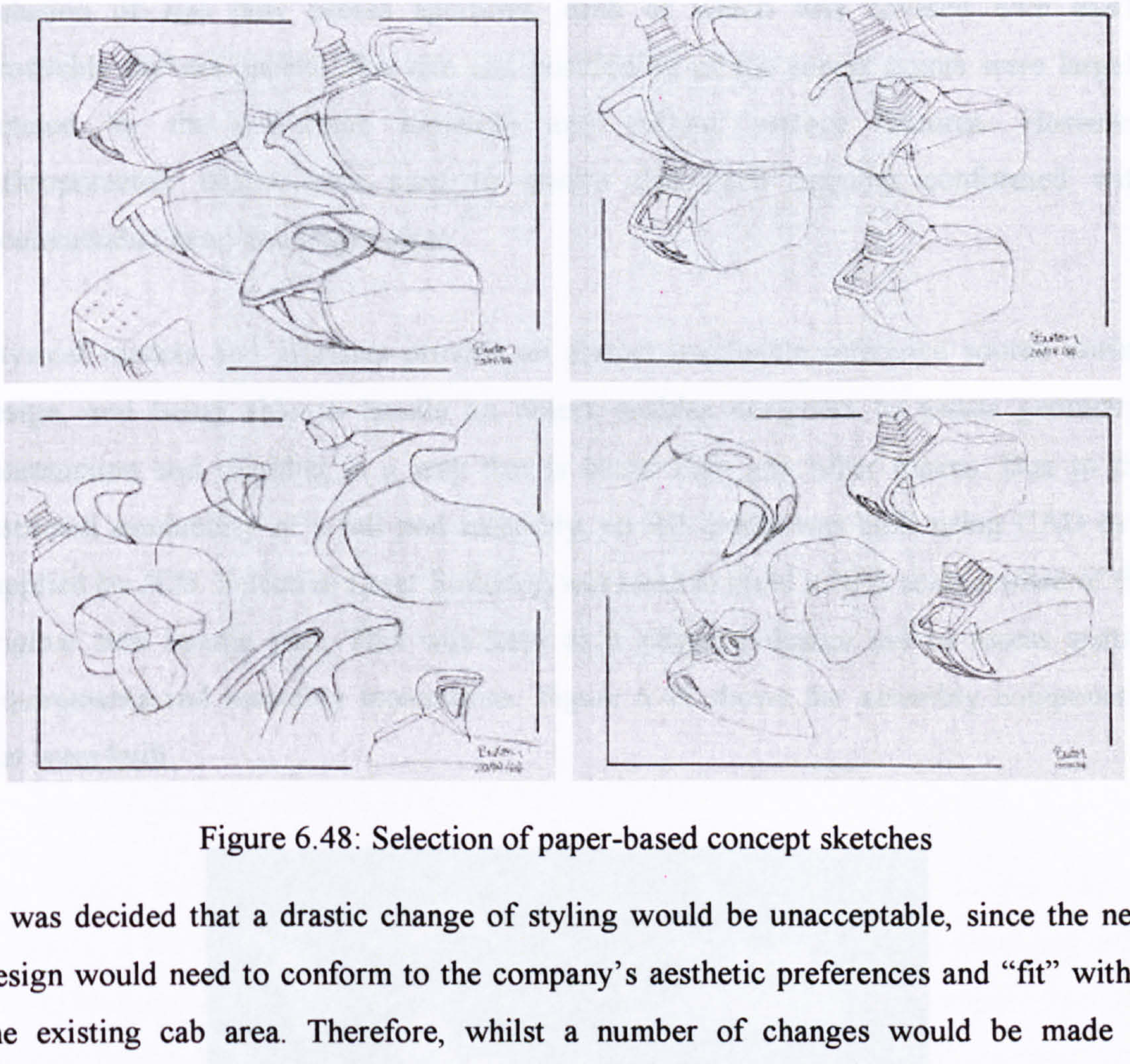


Figure 6.48: Selection of paper-based concept sketches

It was decided that a drastic change of styling would be unacceptable, since the new design would need to conform to the company's aesthetic preferences and "fit" within the existing cab area. Therefore, whilst a number of changes would be made to emphasise the abilities of the RM process, the overall product form would remain similar to that of the previous pod design. To assist this, images of the existing pod design were generated from CAD data supplied by JCB. These static images offered a number of different profiles and 3D views that could be placed under semi transparent sketch sheets and used as underlays to aid the sketching of similar forms.

An emphasis was placed upon the geometric freedoms of Rapid Manufacture and an attempt was made to consolidate as many of the pod's assembly parts as possible. The major reoccurring element within all of the concept designs was the consolidation of the pod's lift handle, armrest and outer casing. Variations of this theme were explored in some of the sketches that are shown in figure 6.37. Continuing the theme of part consolidation, the internal support structure was merged with the pods outer casing to form a single self-supporting shell structure. However, assembly and maintenance called for intermittent access to the structures internal cavity. This resulted in the inclusion of two new access apertures, each of which was covered with easily removable bolt-on panels. The size and positioning of the access points were largely dictated by the sub-frame structure and various surface features. However, anthropometric tables were used to ensure that each opening conformed with recommended hand and finger sizes.

Physical models and artefacts provide an almost invaluable reference source during design, and being able to handle an object enables designers to assess geometry; construction and working in a way that is better than any other means. Due to the restricted availability of a full pod assembly, an RP model was built using CAD data supplied by JCB. Selective Laser Sintering was used to build a 50% scale replica of the original side handle pod. This was used as a physical design aid to assess spatial requirements and assembly interactions. Figure 6.49 shows the assembly components that were built.

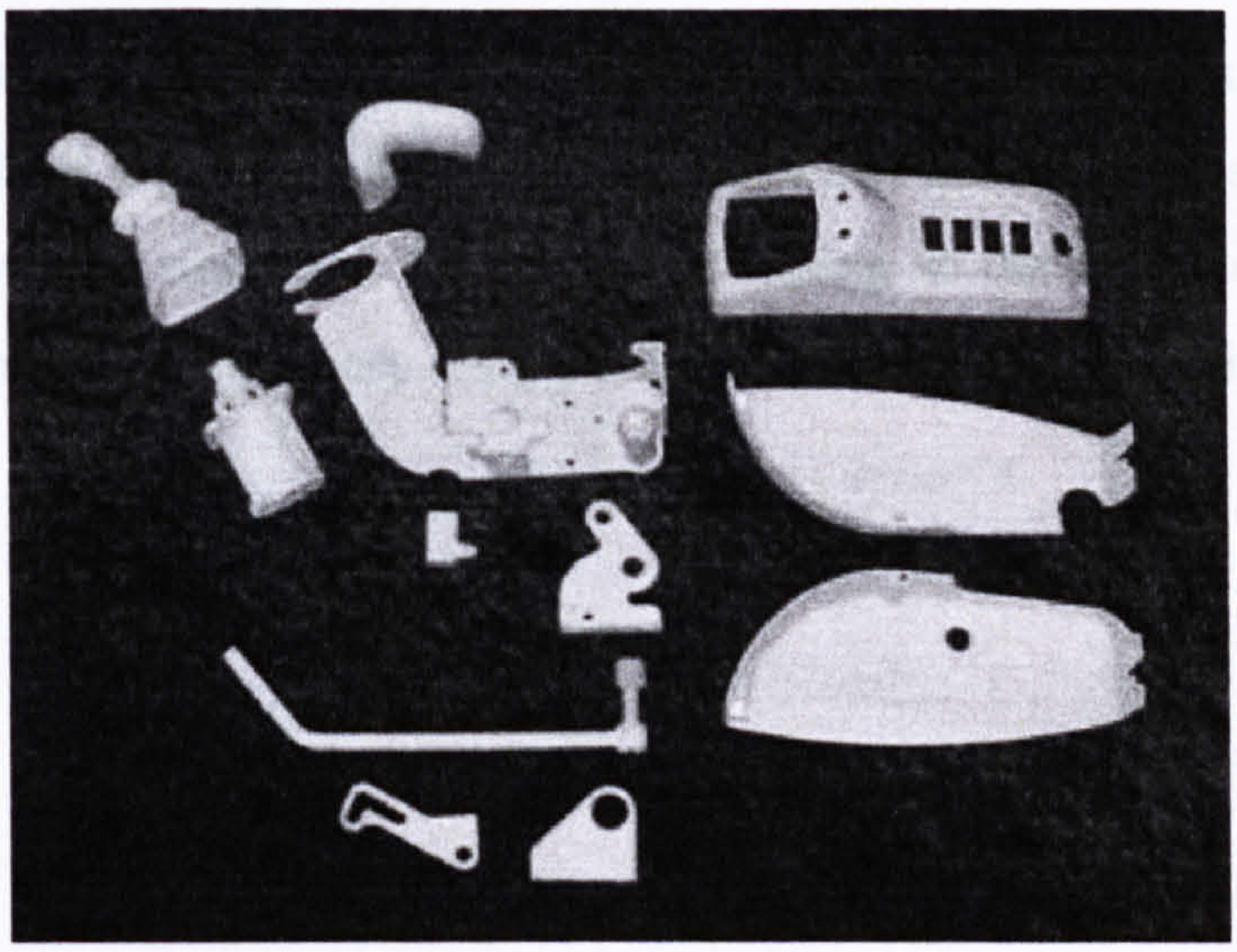


Figure 6.49: SLS reference model of original pod assembly

Later in the project a second SLS model was built for a meeting with JCB to demonstrate work in progress. The concept was built at the same 50% scale as the earlier reference model, which allowed the two designs to be displayed in a direct tabletop comparison that highlighted the changes made. A picture of this model may be seen below in Figure 6.50.

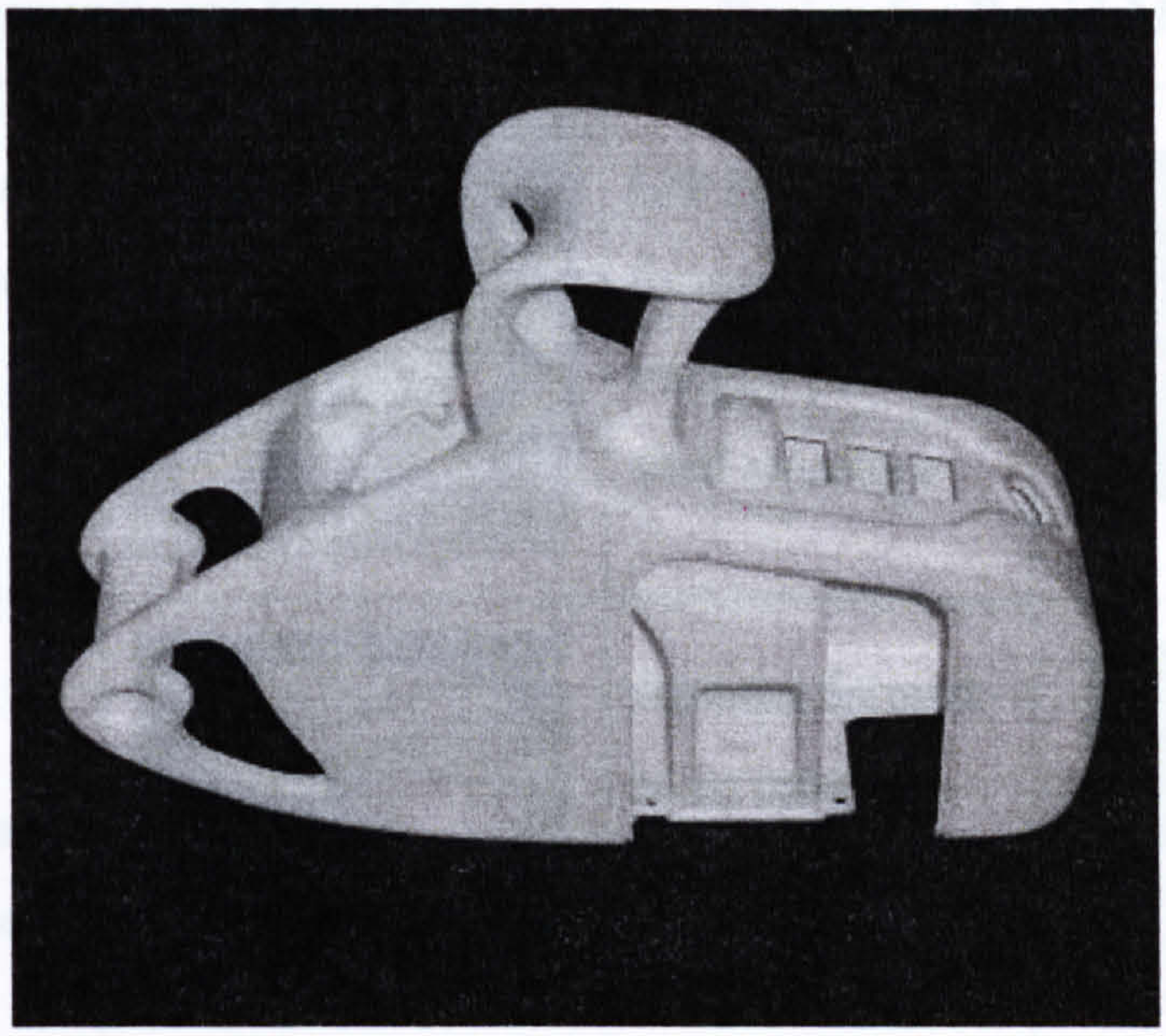


Figure 6.50: SLS model of proposed pod design

The model was well received, and following minor modifications to the internal structure, a finalised CAD model was produced. A full-scale part was produced using Stereolithography and submitted for functional testing at the JCB Compact Products factory. At the present time, these tests are reported to be ongoing with no conclusive results.

6.6.3 Discussion

Figure 6.51 compares the main notable features of the control pod designed by JCB for conventional methods of manufacture and the one that was designed for additive manufacturing.

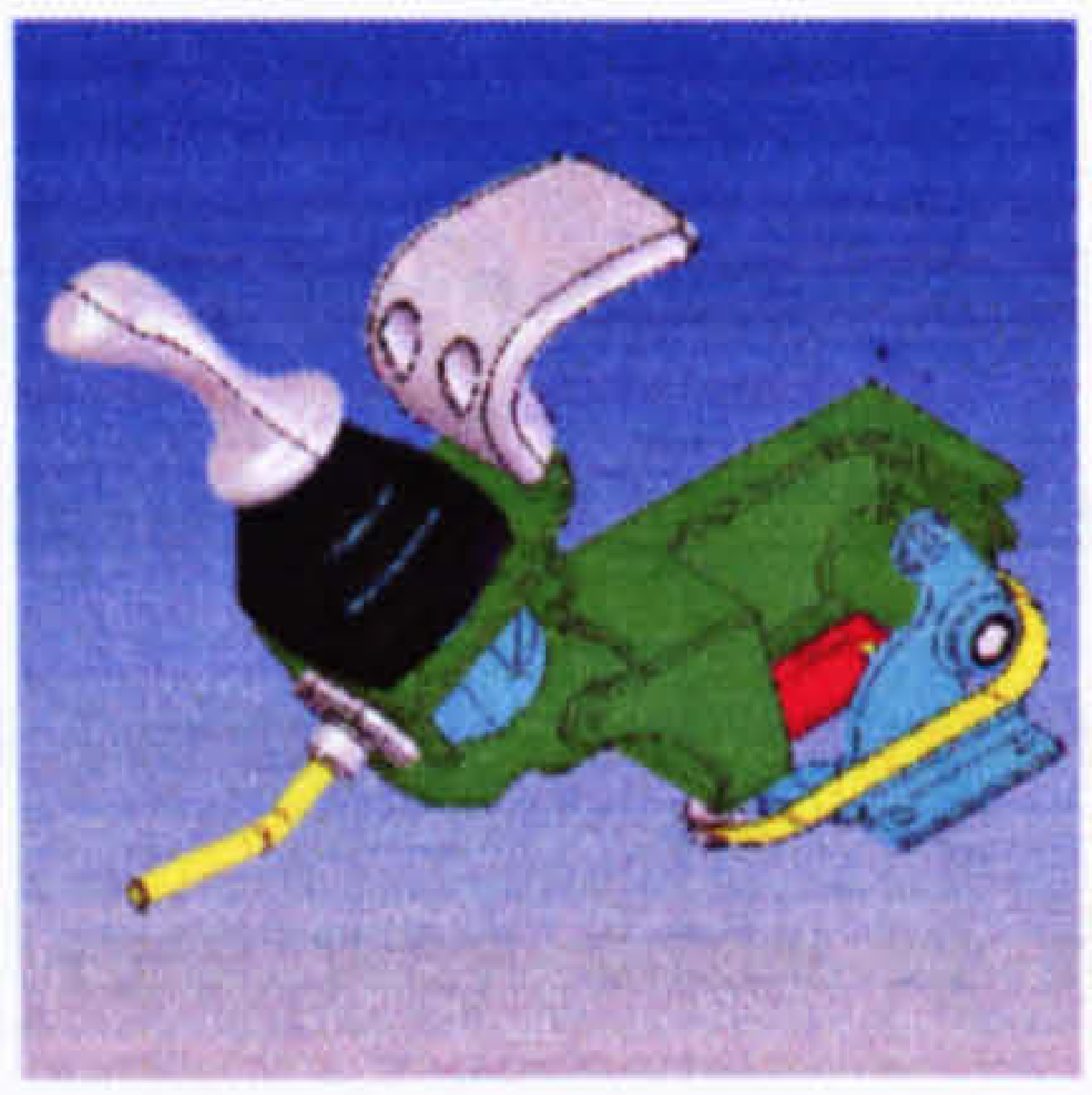
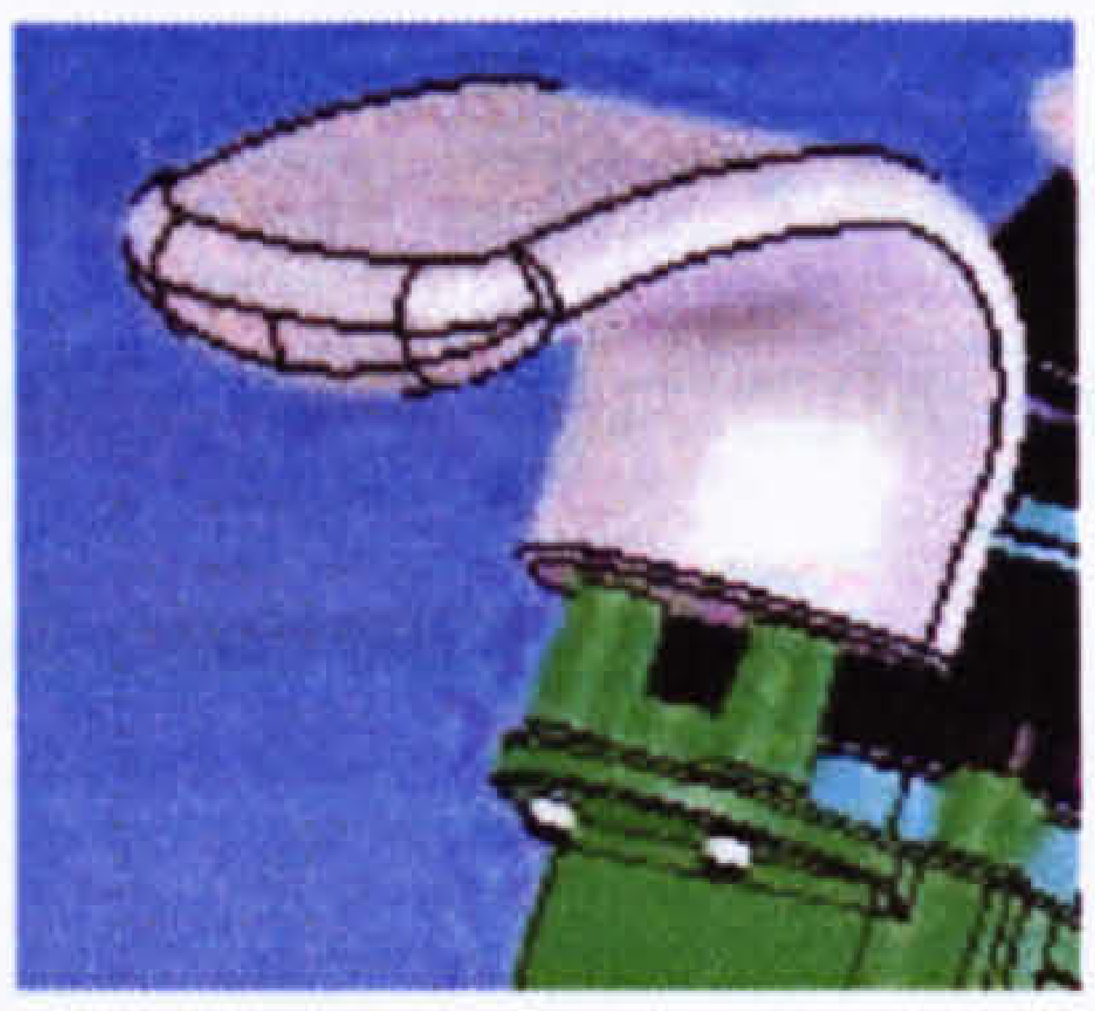
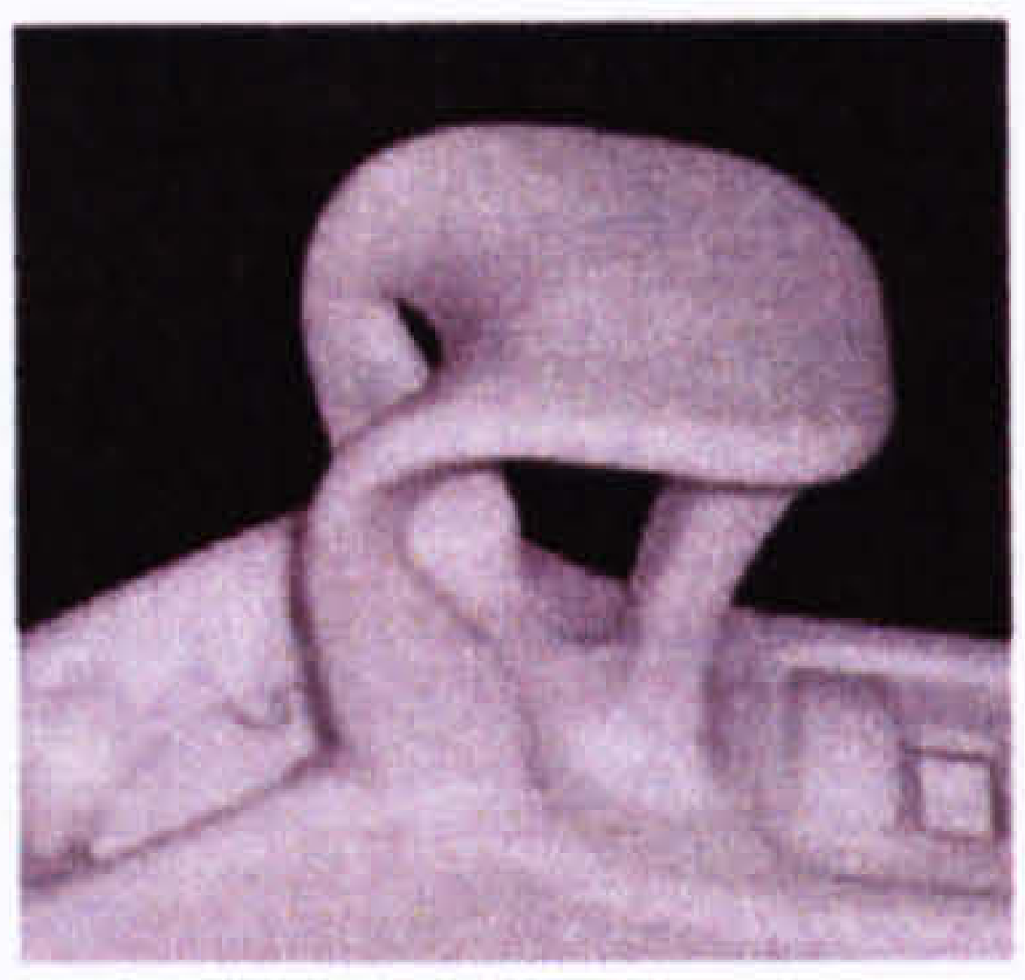
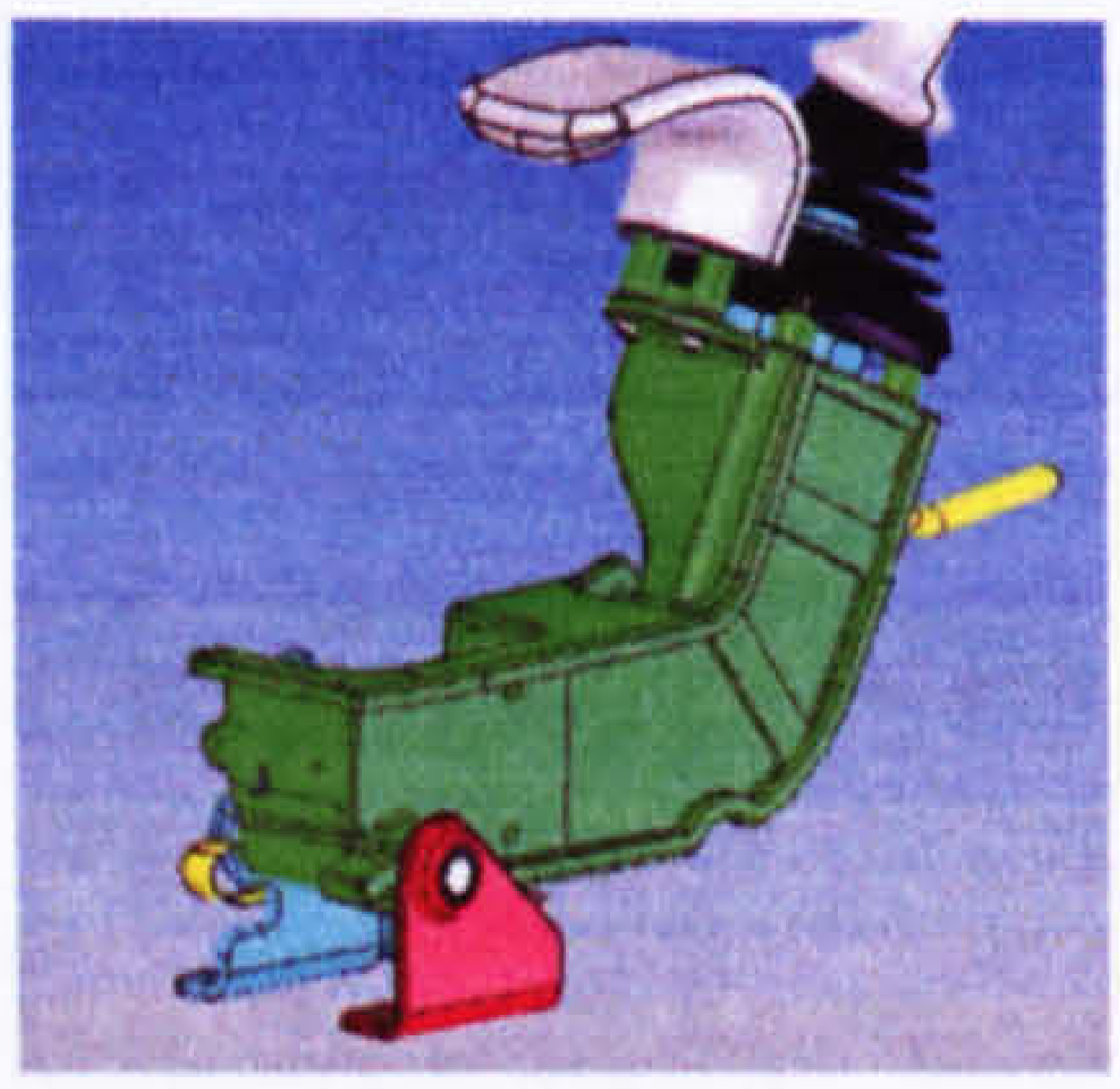
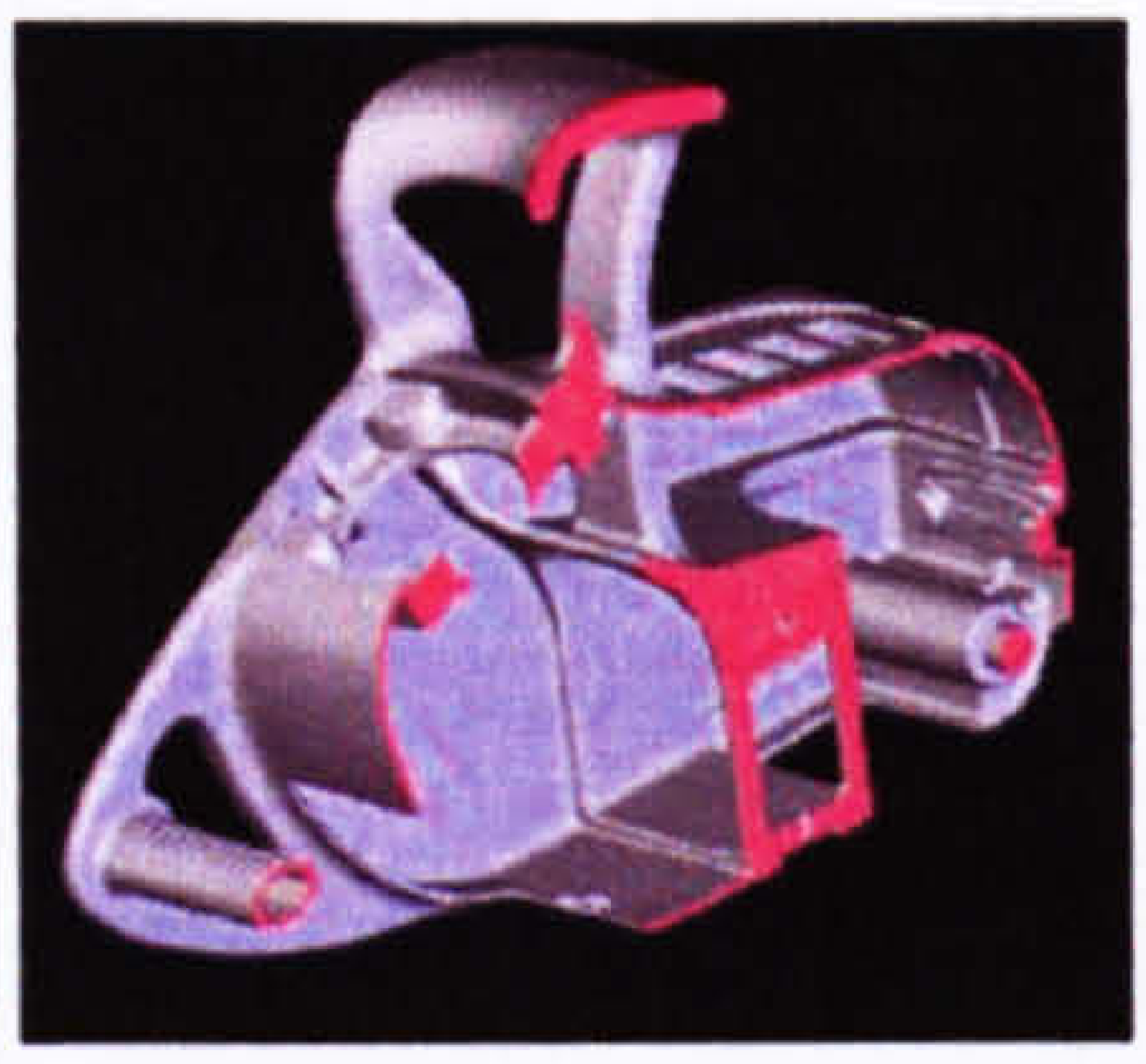
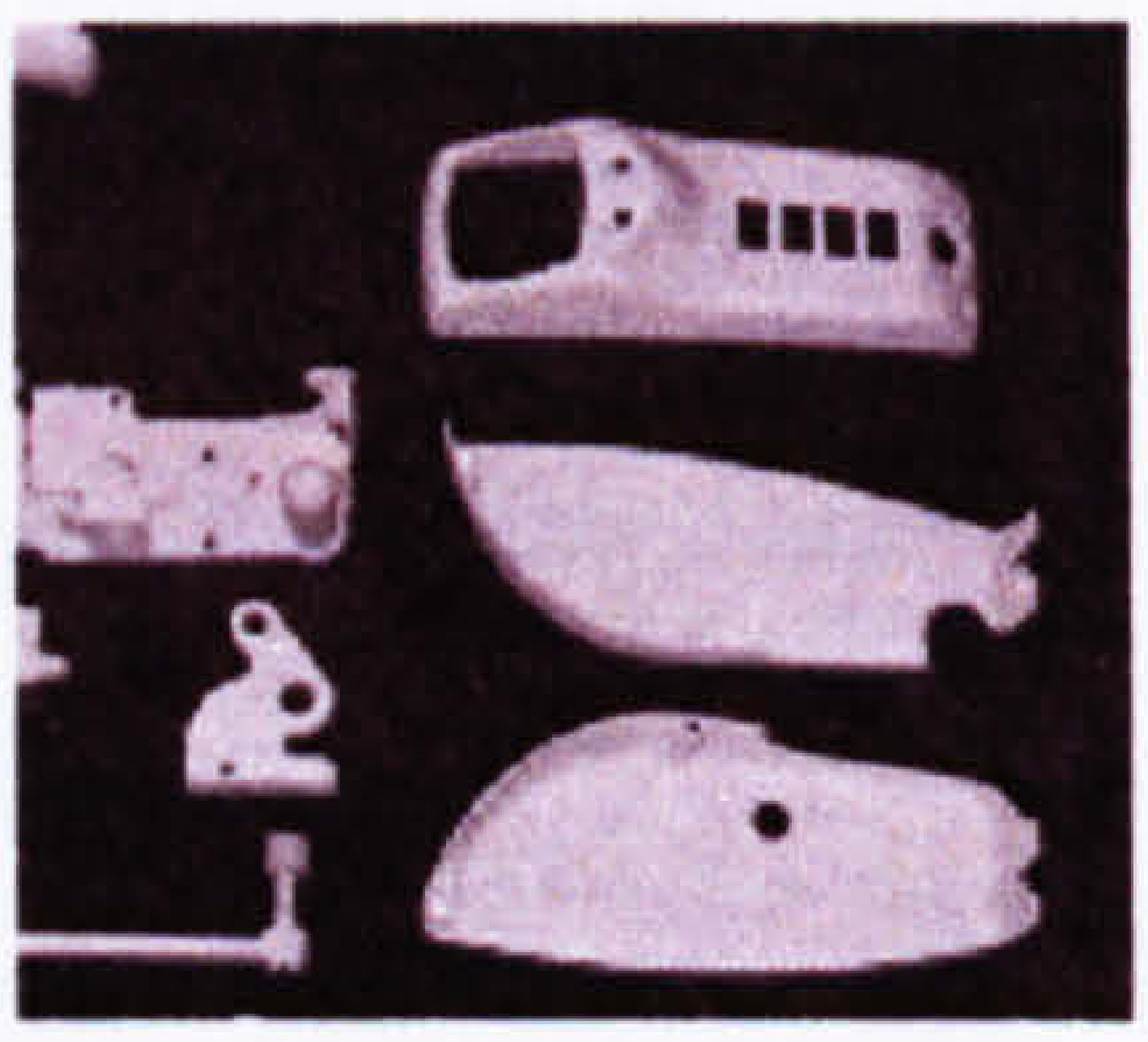
Design for Conventional Manufacture		**Design for Rapid Manufacture**	
Separate tubular steel lifting handle bolted to sub-frame		Lift handle formed as integral part of shell structure	
Separately moulded armrest bolted into place		Armrest formed as an integral part of pod structure	
Separately cast aluminium sub-frame		Self-supporting internal chassis (Section View)	
Removable outer casing sections		Access panels for assembly and maintenance	

Figure 6.51: Comparison of design features

The freedom of geometrical creation associated with Rapid Manufacturing has been used to great effect, consolidating parts and increasing functionality, in a structure that would be impossible to produce with conventional processes. Integrating the sub-frame chassis with the outer shell produced a substantial structure that enabled the merging of other parts, like the lifting handle and armrest. This resulted in greater aesthetic continuity and a handle design that looks like part of the structure, rather than a bolted on after thought.

Once aesthetic styling had been completed, structural design was conducted, applying user knowledge of materials and their performance. This resulted in a rather substantial structural form that is patently over-engineered through an excessive use of material. Overcompensating in this way adds to both weight and cost, neither of which is desirable. It is likely that the design optimisation techniques applied to the earlier handbrake example would generate a more efficient form. However, the complexity of geometry contained within this particular structure was beyond the current capability of available FEA tools and operator skill.

6.7 Custom Handgrip Study

6.7.1 Project Background

As part of wider research to investigate the potential role of users and their creative input during the design of products (Campbell et al, 2004 and Cain, 2005), a trial was conducted to observe how such "co-design" might be achieved. During the study, particular attention was given as to how various computer-based technologies might be used to capture user input.

A design exercise was constructed in which four separate users (non of whom had any previous design training) were asked to redesign a small hand-held gardening fork, producing customised handle concepts that were based upon their own specific requirements. Figure 6.52 shows a picture of the original fork that was used in the exercise.

Figure 6.52: Original gardening fork (Cain, 2005)

The redesign exercise was performed using the following process:

1. Discuss the handle requirements through a semi-structured interview
2. Evaluate the original handle design against pre-determined criteria such as grip, aesthetics, usability, etc
3. Generate a user-fit design, recording ideas in verbal, sketch and written format
4. Capture user-fit and other ergonomic requirements using modelling clay
5. Translate into a CAD model (using reverse engineering if necessary)
6. Capture and verify aesthetic requirements using CAD rendering
7. Verify functional requirements using an RP model

6.7.2 RM Concept Generation

During the design exercise, each of the users was shown the original fork design and then given the main metal element (shaft and prongs) together with some air-drying modelling clay. They were then asked to model a new handle to fit their own hand, including ergonomic aspects such as finger grips or wrist supports and other functional aspects such as hanging holes. Users were encouraged to attach the clay to the metal element during this process to give a representative feel of weight and balance. Figure 6.53 shows pictures of a "wrap-around" wrist supporting handle design being modelled in clay (**A**) and then attached to the metal element (**B**).

A B

Figure 6.53: Generating concept in clay (Cain, 2005)

Some of the resulting handle designs were relatively simple, making it easy to recreate them using direct observation and conventional CAD modelling techniques. However, other more complex designs (like the concept featured in Figure 6.53) required the use of reverse engineering technologies to accurately capture their geometry in a digital format.

Digitisation of these designs was performed using a 3D Scanners' ModelMaker and FARO arm system, as was discussed in chapter 3 (p58-59). However, the re-entrant sidewalls of the "wrap-around" design concept restricted the scanner's line of sight, making it impossible to capture geometry from the handle's inner surfaces. After a brief discussion, it was elected that this matter could be resolved by physically sectioning the hardened clay model with a blade so that it could be digitised in two separate pieces.

Figure 6.54 shows images of the two cut sections (**A**) and the subsequent digitisation process that was used to capture their geometries (**B**).

A **B**

Figure 6.54: Digitising the clay model (Cain, 2005)

Separate sets of point cloud data were created using scans that were taken from each of the handle sections. The images in Figure 6.55 show renderings of the two different data sets that were generated during this procedure. At this point the data remained in a raw point cloud state, visualised only as a graphic representation of the surfaces that would result from its subsequent processing.

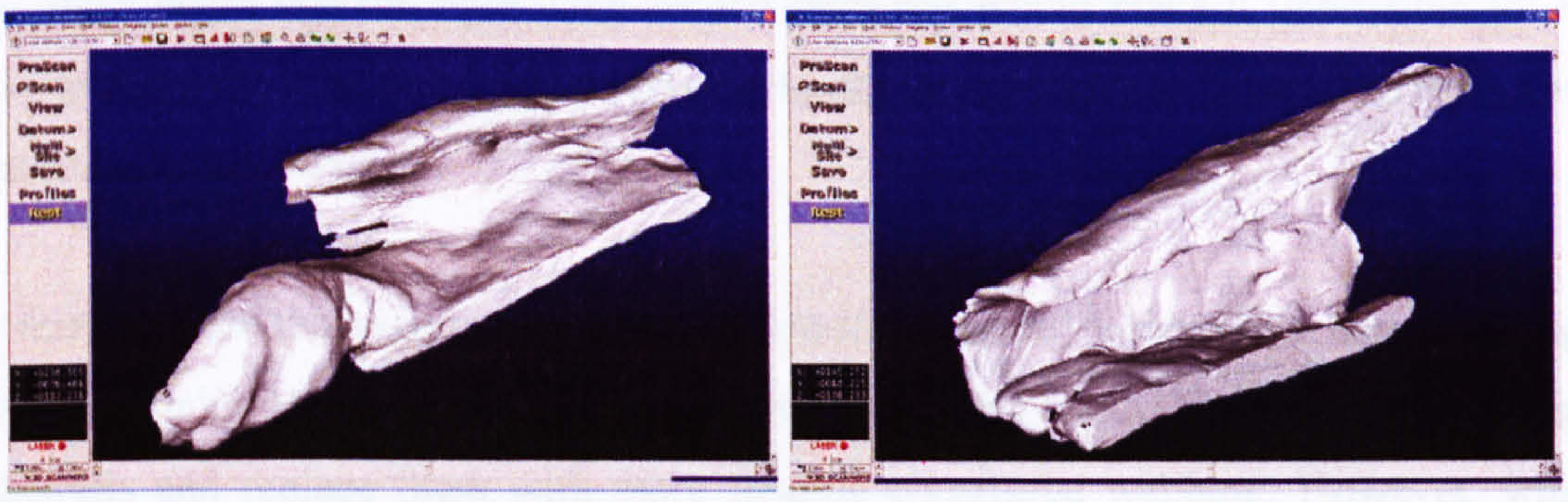


Figure 6.55: Scan files

Having created separate point clouds for each of the two handle sections, the data sets were imported into a specialised Reverse Engineering software package where they could be merged to form a single digital replica of the original clay model. Figure 6.56 shows an image of the reunited point cloud data.

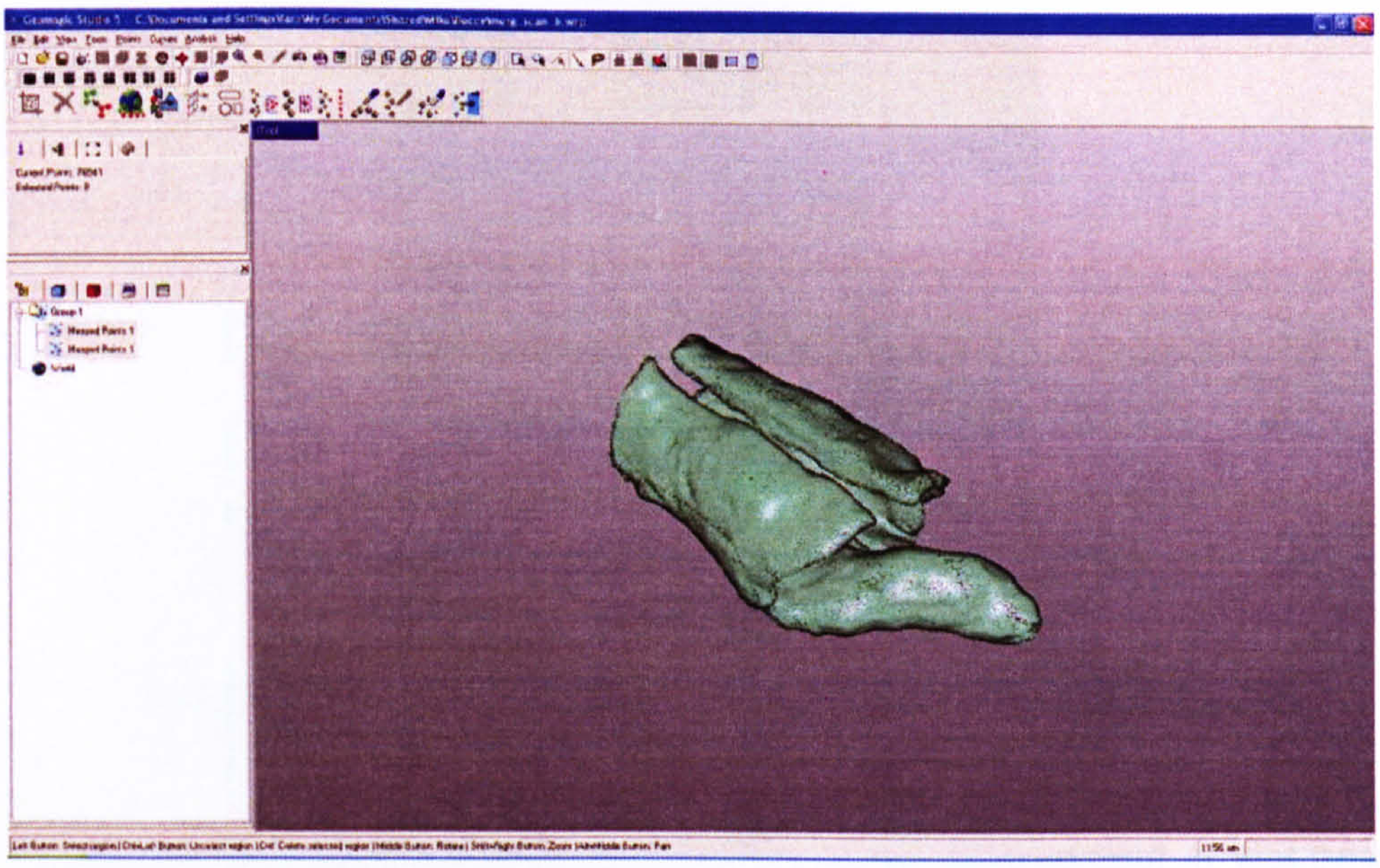


Figure 6.56: Reassembly of the scan files

With a single digital entity in place, the Reverse Engineering software was used to create a NURBS surface model that could be exported into any 3D CAD package for subsequent processing and manufacture. However, evaluation of the handle design at this stage noted that the rigid wrap-around sidewalls would make it impossible for the user to insert their hand and that a revision would be necessary to "open" the design and create easier user access.

It was felt that the easiest and most appropriate way to achieve this design change, whilst retaining the handle's wrap-around wrist support, would be to remove the rigid sidewalls and replace them with more flexible elasticated webbing. However, whilst conventional CAD packages would be able to "cut material" from the NURBS model, the amorphous nature of the geometry in question would make the operation very difficult to perform without leaving noticeable edges or witness marks. For this reason it was decided that a PHANToM haptic device would be used to "sculpt" the data within specialised haptic CAD software called Freeform. Figure 6.57 shows a picture of the virtual sculpting operation being performed.

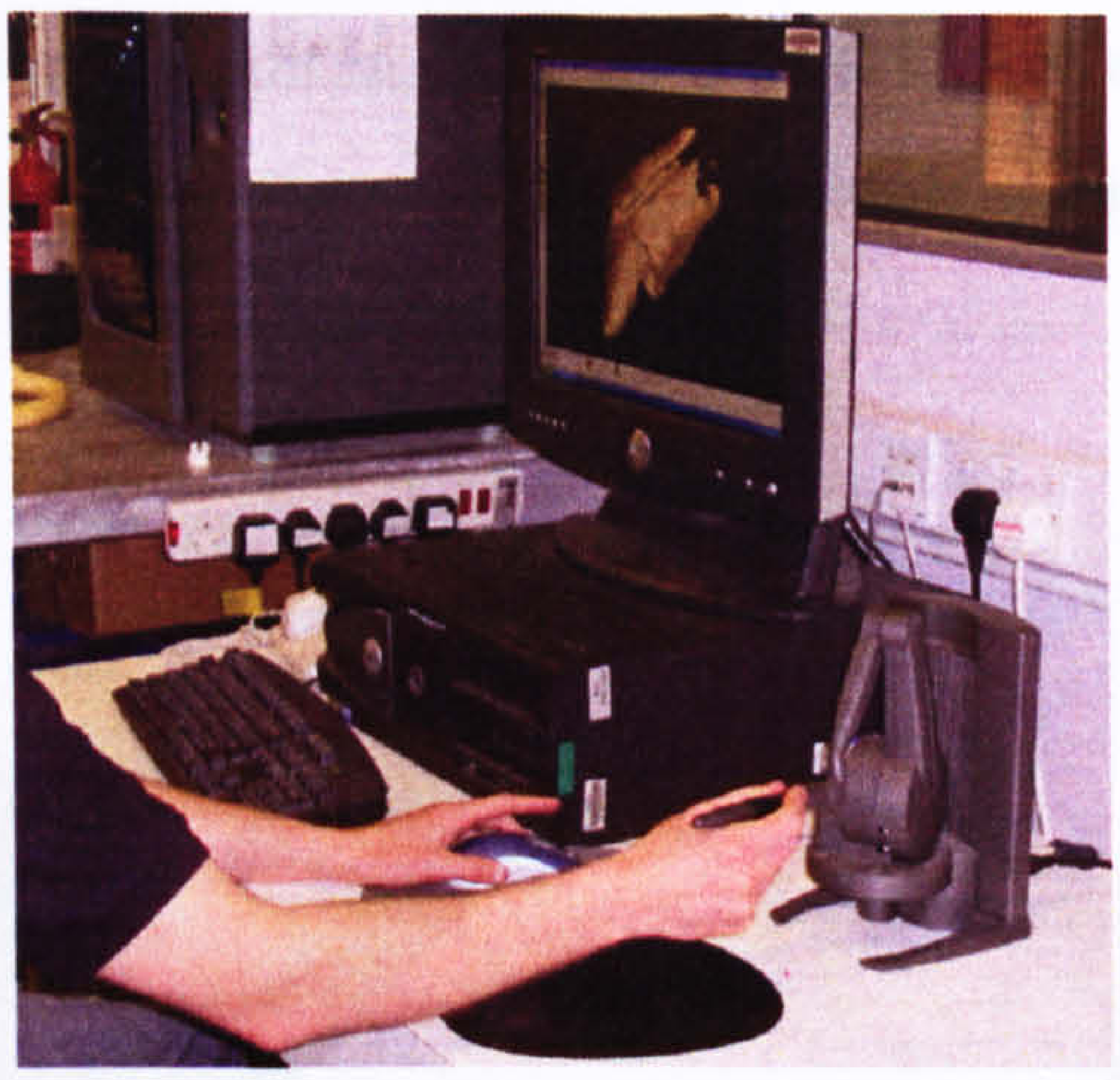


Figure 6.57: Using the PHANToM haptic device to sculpt the data

Using a PHANToM haptic device in the Freeform CAD environment, it was possible to treat the data as a piece of virtual clay, removing the unwanted sidewalls and blending the edges in a way that was sympathetic to the way the form was originally created. Figure 6.58 shows top (**A**) and side (**B**) views of the new "sculpted" handle data that was produced using this approach. It should be noted that the cut edges of the new digital model still retain the original clay model's "organic" texture.

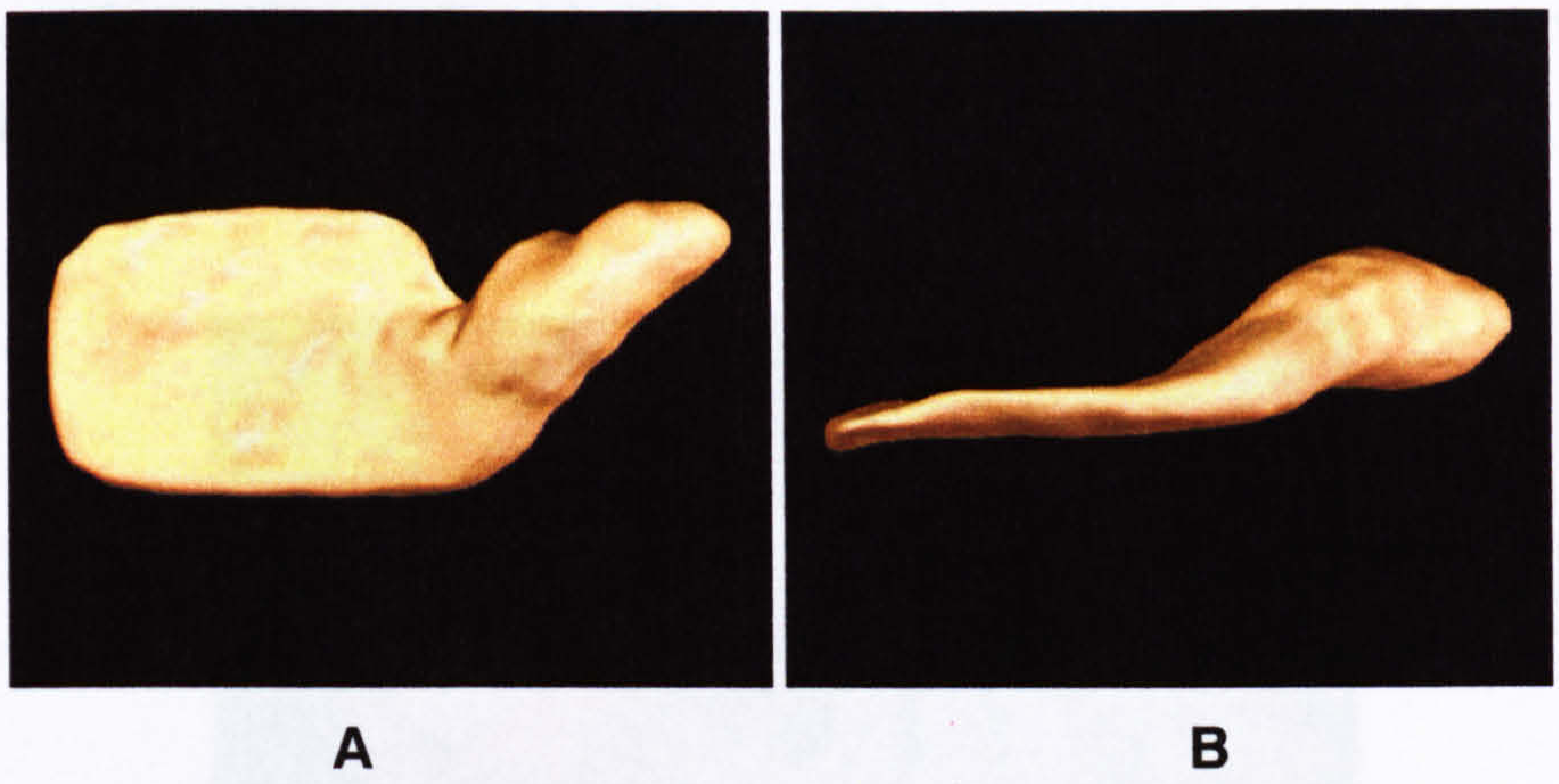


Figure 6.58: Revised design

Once the model was complete, it was exported as an IGES file that could be imported by any 3D CAD package. This file was then brought into a typical parametric CAD package as the base feature of a model so that holes could be made for the latter addition of elasticated webbing. In this format it was also possible to produce high quality rendered images that were used to convey the various colour and surface finishes that the final product might have. Figure 6.59 shows examples of these images showing the basic handle (**A**) and the same handle complete with metal prongs (**B**).

Figure 6.59: CAD renderings of revised design (Cain, 2005)

Finally, an STL file of the finished CAD model was generated and a Stratasys FDM 2000 machine was used to produce a physical Rapid Prototype (RP) part for verification purposes. The part was produced using a tough ABS-like material that enabled functional testing to be conducted. Figure 6.60 shows a picture of the part that was produced being tested in a user fit trial.

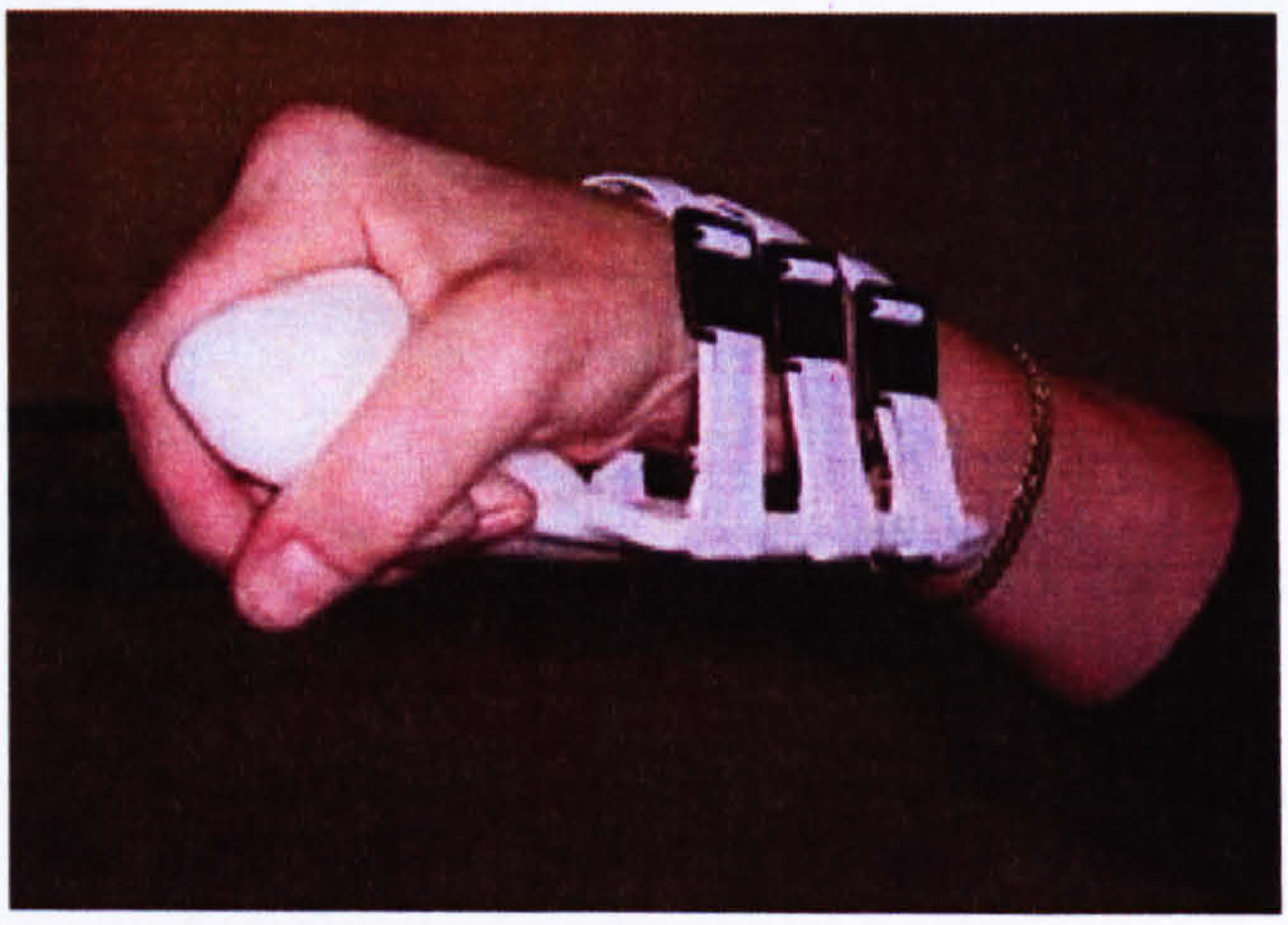


Figure 6.60: Testing the functional RP model (Cain, 2005)

6.7.3 Discussion

The table in Figure 6.61 shows a comparison of new and old handle designs.

Original Handle		**Customised RM Design**	
Ambiguous mass-market design		Crafted design that is unique	
Generic handle means user-fit is compromised		Individual custom fitting form	
"Economy" type product that is less desirable to demanding users		Value added product of greater worth to its user	
Generic design offers only basic functionality		Individual user requirements are better addressed	

Table 6.61: Comparative table of new and old designs

This case study has shown how the end users of products might become more directly involved in the design process, working in close proximity with designers to produce products that meet their individual requirements. This is a philosophy that is well suited to the capabilities of Rapid Manufacturing and the ancillary technologies that were discussed in chapter 3.

Highly amorphous product forms may be digitised with Reverse Engineering technologies to produce CAD geometries that would otherwise be difficult to achieve using conventional software packages and strategies. Haptic tools then allow these geometries to be manipulated in a way that is sympathetic to their original mode of creation. Hence if a form was created using modelling clay in the real world, it might then be manipulated as digital clay in a virtual environment to mimic the same type of surface finishes and textural qualities that were imprinted during its original creation. The resulting part geometries, which might be unsuitable for conventional tool-based production processes, may then be Rapid Manufactured using additive systems. This is an approach that would be ideal for the low volume production of individually customised or custom-fitting products.

In this study a relatively simple product was chosen to be the focus of the exercise, but the principles that have been applied would be valid for more complex products. As the end users of products become more discerning and selective (Campbell et al, 2004) designers must pay greater attention to their wants and needs, and it is likely that such practices will become commonplace. This sort of involvement of users in the design of products was mentioned in chapter 4, noting some of the implications pertaining to product liability and Intellectual Property Rights (IPR). However, in this study it is evident that whilst the end user of a product might have much input in its design within a co-design approach, they will remain to be a single member of a larger design team. As such it is unlikely that they will have complete responsibility for subsequent development or manufacturing, leaving these areas within the hands of more competently trained design professionals.

6.8 Chapter Summary

In this chapter a series of case study projects have been presented to compliment the earlier literature review chapters. In each project (with the exception of the first study) a comparison is made between an existing product that has been designed for conventional forms of manufacture and the same product redesigned for Rapid Manufacture. Rapid Manufacturing has been shown to provide designers with the freedom to create geometric forms that were previously impossible or unfeasible to produce. The absence of conventional tool-based manufacturing restrictions mean that design changes can occur at any point up to, or even after, the manufacture of end-use products. Tool-free manufacturing also means that production volumes are no longer governed or affected by amortised tool cost. This makes extremely low order numbers feasible and supports the generation of unique products that have been individually customised to the wants or needs of their user.

Consolidation of multiple assembly components has been demonstrated, exploiting the freedom of geometric creation to support a Design For Assembly (DFA) philosophy that minimises assembly operations. Parts with highly complex geometries and increased functionality have been shown to support innovative design solutions that would previously have been regarded as unfeasible. Finite Element Analysis (FEA) tools have been used for the optimisation of part geometries, which achieve maximum mechanical functionality with minimum use of material. The resulting "space frame" structures are often complex, with re-entrant features and varying wall thicknesses that would be impossible to produce using conventional processes. Similar to this is the construction of product housings as self-supporting shell structures that incorporate integral chassis forms as part of their internal makeup.

Reverse Engineering (RE) technologies were used to replicate physical surface geometries from existing real world bodies and it is envisaged that the amalgamation of RM and RE will eventually facilitate the "3D photocopying" of parts and products. Digitisation of concept models, which may be made from or clay, has been also shown as an approach that supports the generation of product forms that would be difficult to achieve using conventional CAD modelling techniques. In addition to this, haptic technologies have been demonstrated as a suitable means with which to manipulate the amorphous surface data that often results from this sculptural CAD modelling approach.

In conventional process chains, mechanical engineers and manufacturers often conduct knowledge-based design revisions to make initial concepts more manufacturable or mechanically stable. However, as process chains contract with the use of Rapid Manufacturing, designers are brought into direct contact with manufacturing and their role expands to encompass new activities and responsibilities. Designers of Rapid Manufactured products will have the status of "designer-maker" and, as such, it will be necessary for them to be versed in procedural knowledge so as to best exploit its capabilities.

This research project has so far identified Rapid Manufacturing as a new technology of increasing significance to the design and development of new products, for which no specific design aid exists. Numerous process capabilities have been highlighted in a review of literature and a series of practical case study projects, with a view to generating sufficient information to develop a procedural knowledge transfer tool. This is to be the topic of the next chapter, which observes the formulation and testing of a strategic Design For Rapid Manufacture (DFRM) tool that assists industrial designers in the generation and development of product concepts for Rapid Manufacture.

7 DEVELOPING A DFRM TOOL

7.1 Chapter Overview

Rapid Manufacturing has been introduced as a new method of production that will have a profound effect on the way that products are designed and made. A number of process capabilities and benefits have been highlighted, both in the literature review and the case study projects that were discussed in the previous chapter. The technology is shown to offer designers greater freedoms from the restrictions that are imposed by more conventional methods of manufacture. However, for industrial designers to fully capitalise upon the benefits that are afforded by Rapid Manufacturing, it has been proposed by the author that an appropriate design aid be implemented.

When using more conventional forms of manufacture, strategic approaches like Design for Manufacture and Assembly (DFM and DFA) are seen to aid efficiency by raising process awareness during early stages of design. However, whilst these tools are available for many forms of manufacturing, there is currently no obvious aid for the design of Rapid Manufactured products. Therefore, it was decided that this research project should identify a suitable Design For Rapid Manufacture (DFRM) tool that will assist industrial designers in the generation of concepts for Rapid Manufacturing.

In this chapter a strategic design tool is proposed that uses a questionnaire-based technique to validate the appropriateness of Rapid Manufacturing as a method of production. Linked to the questionnaire is a concept profiler that suggests applicable design features and an assessment matrix that is used to evaluate conceptual designs. A series of iterative tool developments are noted, along with user trials and testing. The chapter ends with a brief summary that notes a series of observations and conclusions.

7.2 DFRM Tool Objectives

In establishing how to best assist future design for Rapid Manufacture, a decision was made to develop a multi-faceted tool that would be capable of performing several different design related functions. From the knowledge gained through the literature review and case study projects, a number of criteria were identified as being appropriate to the formulation of such a tool. These were as follow:

- Needs to be generic and applicable to any given product or part
- Should assist decision-making within the product design process
- Needs to ascertain the appropriateness of Rapid Manufacturing
- Should suggest design features enabled by Rapid Manufacturing
- Needs to disseminate knowledge and raise procedural awareness

Decision-making is an important part of the product development process, and decision support tools are of much use to any designer. One area to which this is particularly applicable is in the selection and validation of the manufacturing process most suited to the product being designed. Establishing the most appropriate method of production at an early stage of development enables efficient process-based design and fewer downstream problems. Systematic validation of a specific manufacturing process ensures that the chosen method is suitable and also provides support if the decision is questioned by other project stakeholders.

Another area to benefit from decision support would be the evaluation and selection of design concepts. The "rapid-fire" concept generation methods favoured by industrial designers are synonymous with the production of many similar design concepts. Evaluation and selection of such concepts for subsequent development or manufacture represents a significant challenge that may greatly affect the final outcome of a project. However, the application of appropriate decision support tools at this key stage enables a logical and objective decision to be made.

The transfer or dissemination of procedural knowledge is crucial if inexperienced designers are to fully exploit the capabilities of any manufacturing process. As was established in Chapter 2, no two industrial design commissions are ever identical (Evans 2002, p44), although various commonalities may be found in all projects. Using this supposition, and on the basis that similar problems will often have similar solutions, it is possible to build a library of proven design features that may be applied to new design concepts. Hence, innovative product features from previous Rapid Manufacturing projects may provide designers with inspiration for similar solutions when faced with new design problems. This is a supposition that has been exploited in the development of the proposed tool.

7.3 Proposed Tool Structure

Using the above criteria, work began to develop a strategic design tool that includes the following elements:

- Process validation to assess the suitability of Rapid Manufacturing for the production of any given product

- A concept profiler to suggest applicable design features which are made possible with Rapid Manufacturing

- An assessment matrix for the objective evaluation of design concepts that are to be produced with Rapid Manufacturing technologies

The presence of similar elements in other DFM and DFA strategies suggested that they would probably be applicable to a new DFRM framework. An additional component, which facilitates all three aspects, is a product questionnaire that was chosen as an effective means with which to assess stakeholder perceptions of the new product's desired functions. This is completed at an early stage of the design project, and has much bearing upon subsequent actions and decisions.

The tool's various facets are intended to assist what were deemed to be key stages of the industrial design process. Using different design process models that were presented in Chapter 2, a single generic pattern was proposed to identify phases that appear to be present in practically all projects. Figure 7.1 shows a diagram of this pattern.

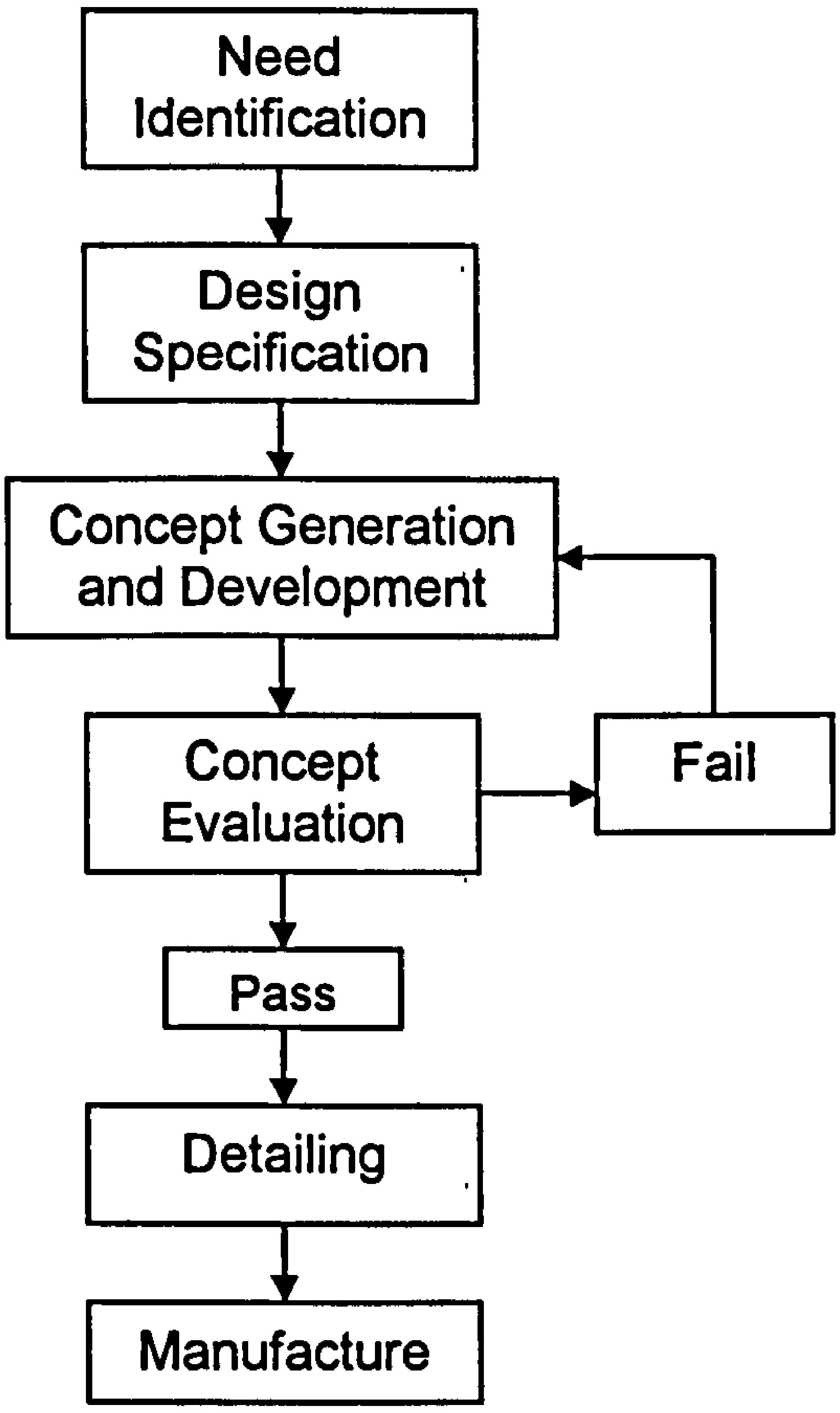


Figure 7.1: Generic product design phases

This model begins with identification of need, which is followed by a statement of solution requirements. These are commonly referred to as the design brief and specification. Having established necessary specification criteria, concept generation is conducted to produce a series of viable product concepts. Various design media may be applied to this phase, producing paper-based, digital or real-world physical models. The concepts that are produced undergo a process of evaluation, which may be either formal or informal. The purpose of this evaluation is to assess each concept's overall suitability and conformance to required specification criteria. If a concept is found to be unsuitable during evaluation, it will either be rejected outright or passed back to the earlier concept generation and development stage for alteration and refinement. This is often an iterative process that occurs a number of times before the concept finally passes evaluation. When a finalised concept is found to meet all of the necessary criteria, and deemed suitable by applicable stakeholders, it proceeds to final detailing that stage that precedes manufacture.

Using this model a similar framework was established, incorporating the previously identified DFRM components. Figure 7.2 shows a diagram of this altered design process.

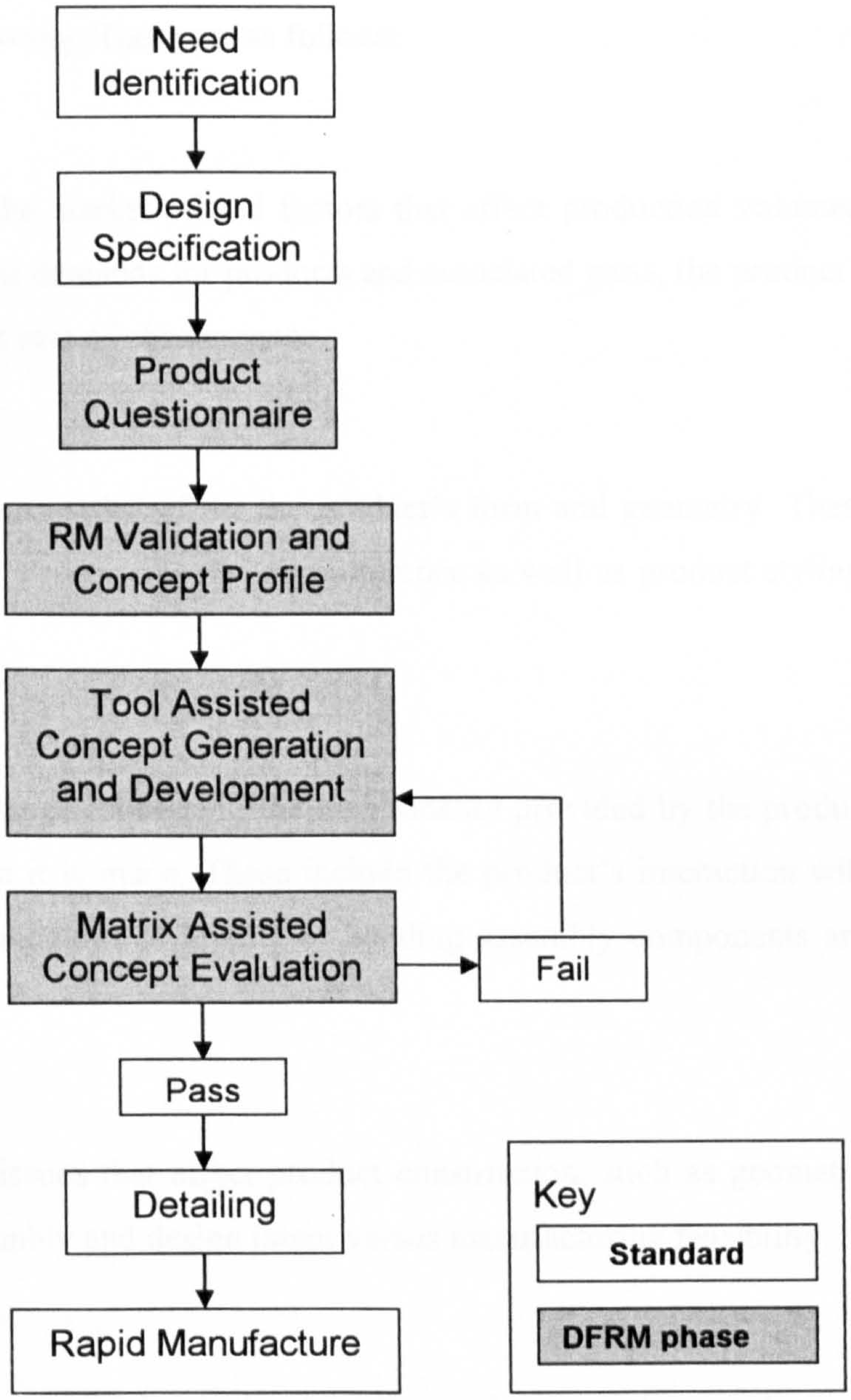


Figure 7.2: DFRM process

This model follows a pattern that is similar to the previous framework, but now includes DFRM support tools. The first of these tools is a product questionnaire, which is completed once the specification criteria have been identified and prior to the concept generation phase. A useful source in the formulation of this was Oppenheim (1992).

The proposed questionnaire is composed of a series of closed questions that are intended to elicit simple yes or no type responses. Questions are ordered using five categories that were observed from the case studies to best represent the areas most applicable to Rapid Manufacturing. These are as follows:

- **Volume**

  This section deals with the market related factors that affect production volumes. These include the different demands for products and associated parts, the product's expected life span and it's rate of obsolescence.

- **Form**

  This section deals with issues that affect the product's form and geometry. These include the intended user's requirements and preference as well as product styling, branding and range.

- **Function**

  This section deals with issues concerning the functionality provided by the product and the parts from which it is made. These include the product's interaction with other products or parts, methods of linking or bonding assembly components and user requirements.

- **Construction**

  This section deals with issues that affect product construction, such as geometric complexity, product assembly and design intent versus manufacturing feasibility.

- **Logistics**

  This section deals with matters concerning logistics such as supply and demand, along with the transportation and storage of products.

A positive response to the questions in any of the sections indicates the suitability of Rapid Manufacturing for that particular issue. The total number of positive answers is used to gauge the overall applicability of Rapid Manufacturing as a method of production.

Having established the validity of Rapid Manufacturing as a suitable method of production, designers must then begin the task of generating suitable product concepts. A "concept profiler" is used to assist this process by suggesting appropriate design features. All concept features are based upon the results of the questionnaire, with an appropriate suggestion made for each answer. This creates an overall profile that is made up from the features that are most likely to meet specified requirements and exploit the capabilities of Rapid Manufacturing. In each instance, examples are given using knowledge gained in previous Rapid Manufacturing projects. Using profile suggestions to guide their thoughts, designers are then able to generate appropriate concepts using their own favoured methods.

Once the profile-assisted designs reach a stage of development that warrants evaluation, a matrix is used to assess their performance in relation to specification criteria and profile suggestions. Like the concept profiler, this matrix is compiled from the questionnaire responses and differs in accordance with the responses given. After noting the prolific and successful use of matrices in other product development strategies that were observed in the literature review, it was felt that this would be an appropriate tool with which to perform concept evaluation.

7.4 Tool Development

The formulation of an appropriate DFRM tool took place over a period of several months, during which time a number of revisions and improvements were made. A series of pilot trials were performed to establish a suitable format and test procedure, before testing a finalised system in two separate sets of user trials with professional industrial designers and undergraduate students.

The subjects who took part in the pilot trials were all postgraduate students from Loughborough University's Design and Technology department, and as such were regarded as being highly competent industrial designers. An exercise was devised for the trials in which participants were asked to redesign an existing product for Rapid Manufacture using the DFRM tool to guide their actions. It was intended that the exercise should replicate a typical product design project, but on a slightly lesser scale. This was so the exercise could be completed under controlled conditions and in a relatively short timeframe. In each instance, trials were conducted in a room of the Design and Technology department.

7.4.1 DFRM Trial Exercise

A product was chosen for the controlled exercise that was felt to lend itself particularly well to redesign for Rapid Manufacturing. This was provided by the Bafbox Company, who were discussed in the earlier case study projects. Just like the previous example, the product that Bafbox supplied was a low volume custom designed enclosure for an electronic product that had been produced using the company's flat sheet fabrication process. As with the previous example, the product was bound by process restrictions that resulted in a flat angular form with poor ergonomics and a dated appearance. Figure 7.3 shows pictures of the enclosure and its various assembly components.

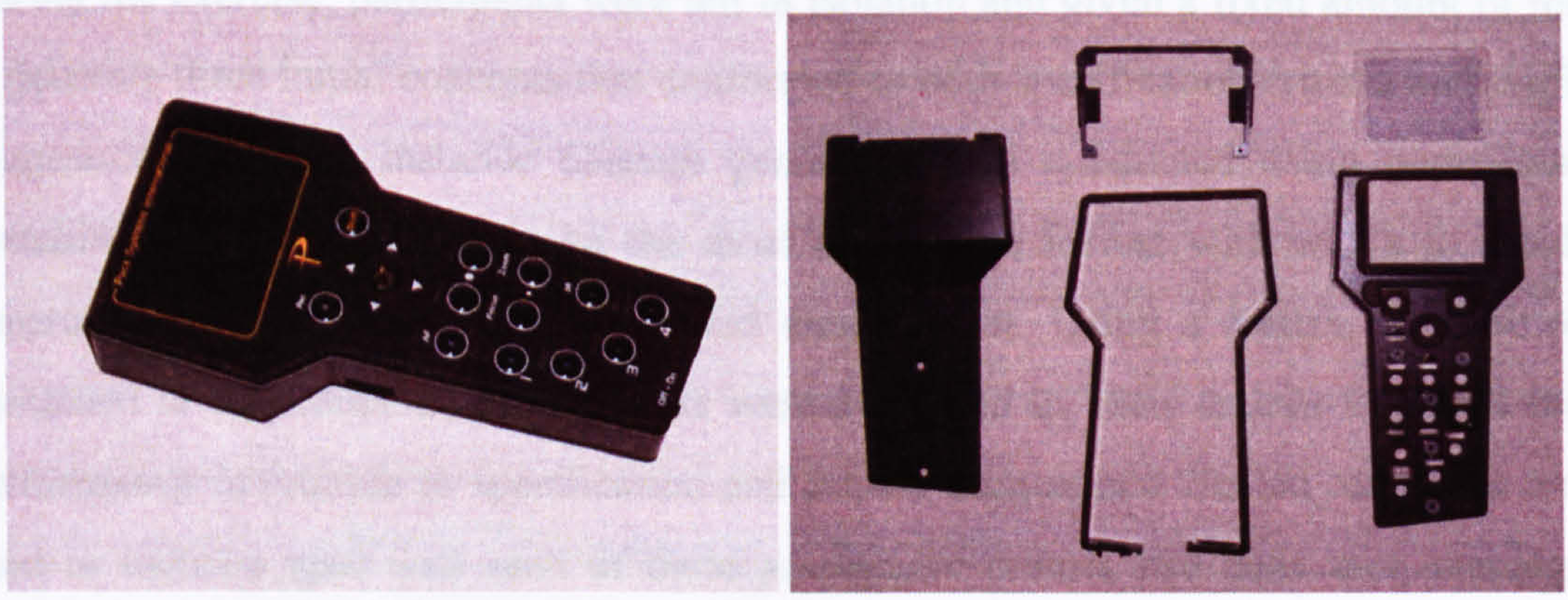


Figure 7.3: Focus product used in design trials

A meeting with the engineer responsible for the original design established the product's background and the market factors governing its various specification criteria. Following this meeting, and after deciding that the product was a suitable focus for the exercise, a booklet was produced for participants to use during subsequent trials. This contained the following sections:

- An explanation of the trial, its objectives, and running order
- A brief overview of the Rapid Manufacturing concept and its benefits
- A detailed synopsis of the focus product supplied by Bafbox
- A design brief and specification for the focus product's redesign*
- A DFRM questionnaire to be completed after reading the above sections

(*Specification criteria were noted as being either crucial or merely desired)

It was the aim of this document to brief each participant with trial objectives and introduce the DFRM tool in such a way as to reduce the need for additional instruction. A finalised version of the booklet is contained in Appendix A. Each participant was issued with a booklet and requested to return a completed DFRM questionnaire at least 24 hours before the design exercise. The responses from these questionnaires were used to generate appropriate concept profiles and evaluation matrices that were presented to participants immediately prior to the design exercise. Examples of these documents are contained in Appendix C and Appendix D.

During the exercise, participants were left in isolation and given a fixed amount of time to generate three initial concepts that conformed to both specification criteria and profile suggestions. In each instance concept generation was conducted using paper-based sketching, as this was seen to be the most appropriate format with which to rapidly generate conceptual ideas in a controlled environment. Using a matrix, like the one contained in Appendix D, the concepts were evaluated by their creator to assess their performance in relation to specification and profile suggestions. Scaled responses were used to indicate how well each of these assessment criteria had been met, making it possible to highlight the specific strengths and weaknesses of each design. After completing this task, participants were allowed to take a comfort break and the matrix results were assessed.

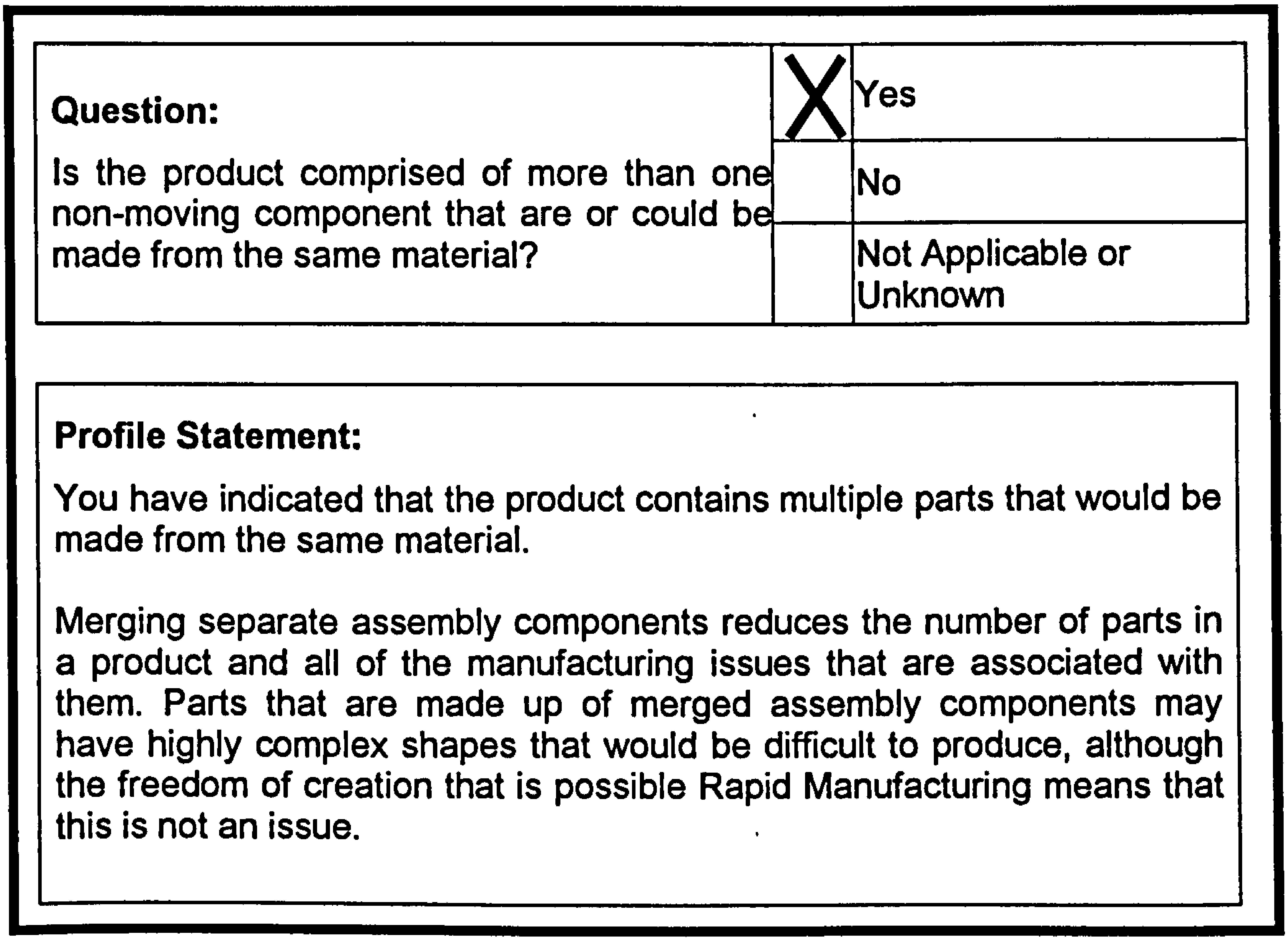
On returning to the test area, participants were offered an explanation as to matrix outcome and which of their concepts was deemed most suitable for development. Using this information, they were asked to develop the most appropriate concept, concentrating upon areas of weakness that were highlighted by the matrix. As with the initial concept generation phase, this was conducted in isolation. Finally, at the end of the time period allocated to this task, participants were asked to assess their revised design with the same matrix that was used for initial concept evaluation. The results of this were used to indicate changes and perceived improvements to the original concept.

At the end of each trial, participants were asked to complete a short feedback questionnaire, giving their opinions of trial format, documentation and DFRM tool usability. The comments and responses that this generated were used to make any necessary revisions or changes. This resulted in a finalised set of documentation and a trial format that was put in place for more conclusive testing to begin.

7.4.2 DFRM Tool Format

Prior to the pilot trials, much focus was placed upon the development of a single computer-based tool that would incorporate the previously identified elements. Using a web page format, the questionnaire was to be presented as a front-end interface. From this user-inputted data was to automatically generate validation figures, profile statements and an appropriate concept evaluation matrix. However, it soon became clear that use of digital technologies were unsuitable for early stages of tool development. The degree of interdependency between each element required complex programming that made frequent changes and refinements too difficult. For this reason a decision was made to concentrate upon the use of a more flexible paper-based format.

The first paper-based tool to be tested was based around a questionnaire that employed a checkbox framework, enabling users to indicate "yes", "no" and "not applicable or unknown" responses by marking the corresponding checkbox. A tally of these responses was used to calculate the applicability of Rapid Manufacturing, gauging validity upon the overall percentage of positive and negative answers. Profile statements were compiled from positive responses, with an individual written statement for each question. Figure 7.4 demonstrates a typical question and the corresponding profile statement that would be generated by a positive response.



Question: Is the product comprised of more than one non-moving component that are or could be made from the same material?	☒	Yes
	☐	No
	☐	Not Applicable or Unknown

Profile Statement:

You have indicated that the product contains multiple parts that would be made from the same material.

Merging separate assembly components reduces the number of parts in a product and all of the manufacturing issues that are associated with them. Parts that are made up of merged assembly components may have highly complex shapes that would be difficult to produce, although the freedom of creation that is possible Rapid Manufacturing means that this is not an issue.

Figure 7.4: An extract from the first generation questionnaire and profiler

However, as may be apparent from this example, initial concept profiles were quite lengthy and the cumulative result of twenty or more questions was many pages of text. This proved to be too much textural information for designers to interpret and retain, and initial feedback reported the format as being "too wordy".

To combat this, notarised bullet points containing a minimal amount of key information were implemented as an abbreviated alternative to the more wordy profile statements. The individual statements that were to have been provided for each question were also replaced with more generic suggestions that were applicable to multiple questions. The effect of this was to reduce the number of statements generated and the amount of text that designers would need to read. An example of this approach may be seen in the following sample questions:

Question:

Is the product comprised of more than one non-moving component, which are or could be made from the same material?

Question:

Are mechanical fasteners or chemical bonding agents used to join same material component parts?

Question:

Does the product need to house any specific bought in components or accommodate non-standard fixtures or fittings?

Question:

Is the recovery of construction materials at the end of the products life cycle an important consideration?

A positive response to all or any one of these questions would result in the following single concept suggestion:

Suggestion:

Consolidate parts by merging fixed assembly components

Using this approach, seven initial bullet point suggestions were proposed that were based upon findings of the literature review and case study projects. These include the following:

- **Utilise freedoms of geometric creation**

  This suggestion is intended to promote the exploitation of geometric freedoms and the ability of additive manufacturing systems to create practically any shape or form. Specific geometric features might include complex internal core sections; harsh undercuts and internal voids; blind or re-entrant holes; parts without draft angles and parts with variable wall thicknesses.

- **Part Consolidation**

  The merging or consolidation of fixed assembly components is suggested as a means to reduce overall part count. This is enabled by the freedom of creation associated with additive manufacture and supports a more conventional Design For Assembly (DFA) philosophy.

- **Size Variations**

  Here a suggestion is made to introduce a range of different sizes for improved ergonomics, instead of forcing compromise with a "one size fits all" product. The direct manufacturing of parts from CAD data makes this a possibility, where more conventional tool-based processes would prove cost prohibitive.

- **Conformal Geometry: User interface**

  This suggestion is linked to the ability of Rapid Manufacturing to produce products with custom fitting geometries that are shaped to fit individual users. This might be applied to a handgrip, armrest, seat or any other element that is subject to prolonged physical contact with a single user.

- **Conformal Geometry: History parts**

  This is similar to the previous suggestion, but relates to inanimate objects that a product will interact with, such as other products or component parts. The term "history" is used in reference to "legacy" parts that were identified by Clark (2003). The new wordage has been adopted from CAD terminology, where parametric features are dependent upon other features in the "history tree".

- **Range variation and styling**

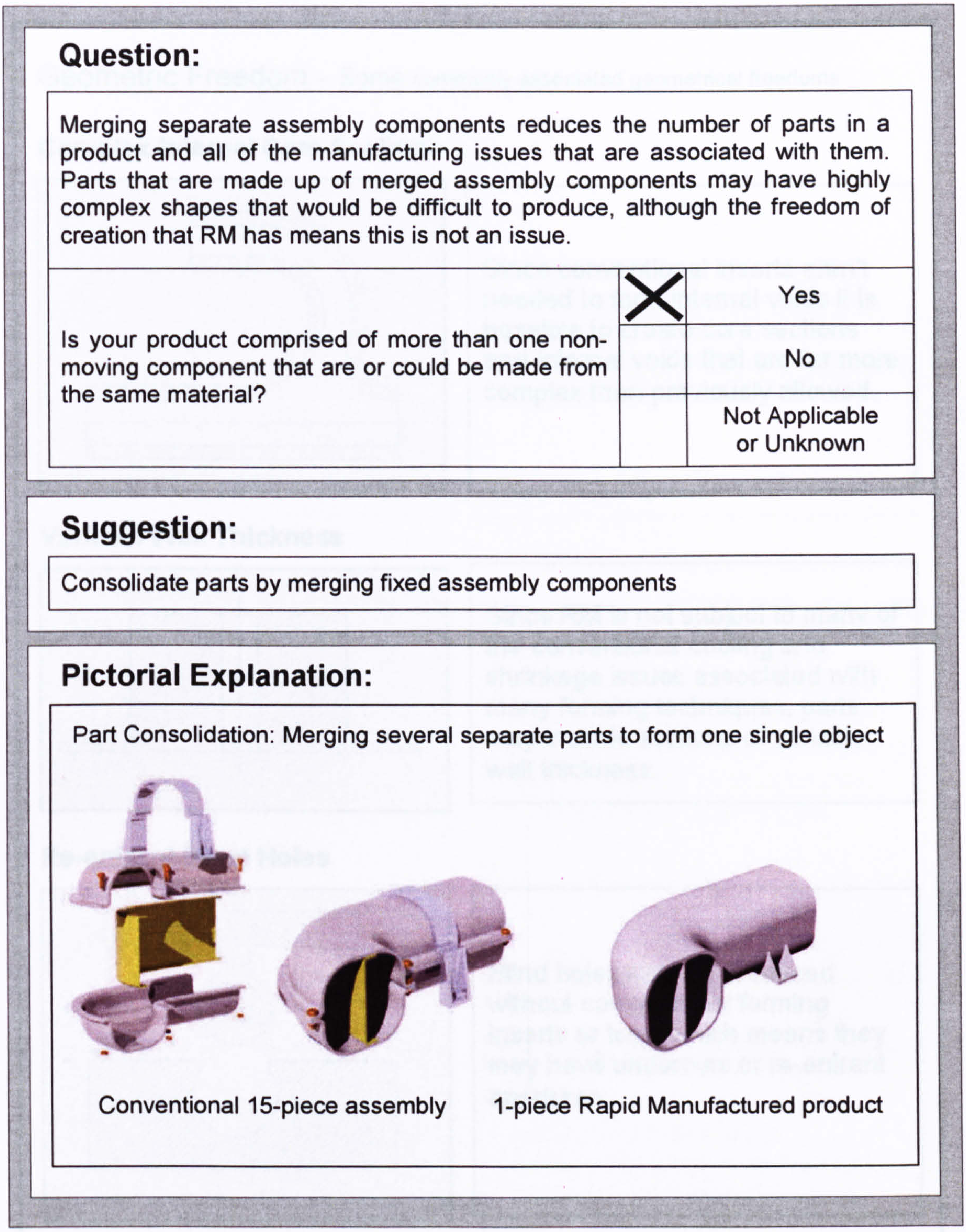
  Variations between "Budget" and "Executive" products could be used to alter perceived value of product or increase market acceptance of a single product by appealing to different user group tastes. The direct manufacture of products with additive technologies enables incorporation of multiple styling and aesthetic variations.

- **Integral fixings, mounts and actuators**
  The consolidation of assembly components creates individual structures with increased functionality. Exploiting the freedom of geometric creation, it is possible to integrate customised mechanisms and mounting devises within a structure's main geometry. Thick wall sections may be used to house sub-surface conduits, complex bosses and clip features may be formed as part of the product's structure and mechanisms may be formed whole, negating post-production assembly.

In the paper-based format, the facilitator applies a matrix to align positive questionnaire responses with applicable concept features. Suggestions are then presented alongside a set of bullet points that represent the various specification criteria. As previously mentioned, the criteria were categorised as being either crucial or desired components. It was intended that the specification and suggestions should together form a checklist of things that the user should consider when generating concept designs.

With the revised framework in place, pilot trials continued. However, results from the first few trials revealed that simplified textural bullet points on their own were too incoherent and that much explaining was required for the statements to be of any use. Hence it became necessary to alter the format to provide an interface that was more informative.

A new style of presentation was employed in which an informative opening statement is made prior to asking a related question. This presents the user with a detailed textural description of specific Rapid Manufacturing capabilities and provides a context for the subsequent question. The use of brief bullet point statements was continued in the concept profiler but was supplemented with additional pictorial examples. Given the highly visual nature and acuity of industrial designers it was felt that this would be the most appropriate medium through which to convey such information. Figure 7.5 shows an example of how questions and profile suggestions were presented in this revised framework.



Question:

Merging separate assembly components reduces the number of parts in a product and all of the manufacturing issues that are associated with them. Parts that are made up of merged assembly components may have highly complex shapes that would be difficult to produce, although the freedom of creation that RM has means this is not an issue.

Is your product comprised of more than one non-moving component that are or could be made from the same material?	☒	Yes
	☐	No
	☐	Not Applicable or Unknown

Suggestion:

Consolidate parts by merging fixed assembly components

Pictorial Explanation:

Part Consolidation: Merging several separate parts to form one single object

Conventional 15-piece assembly

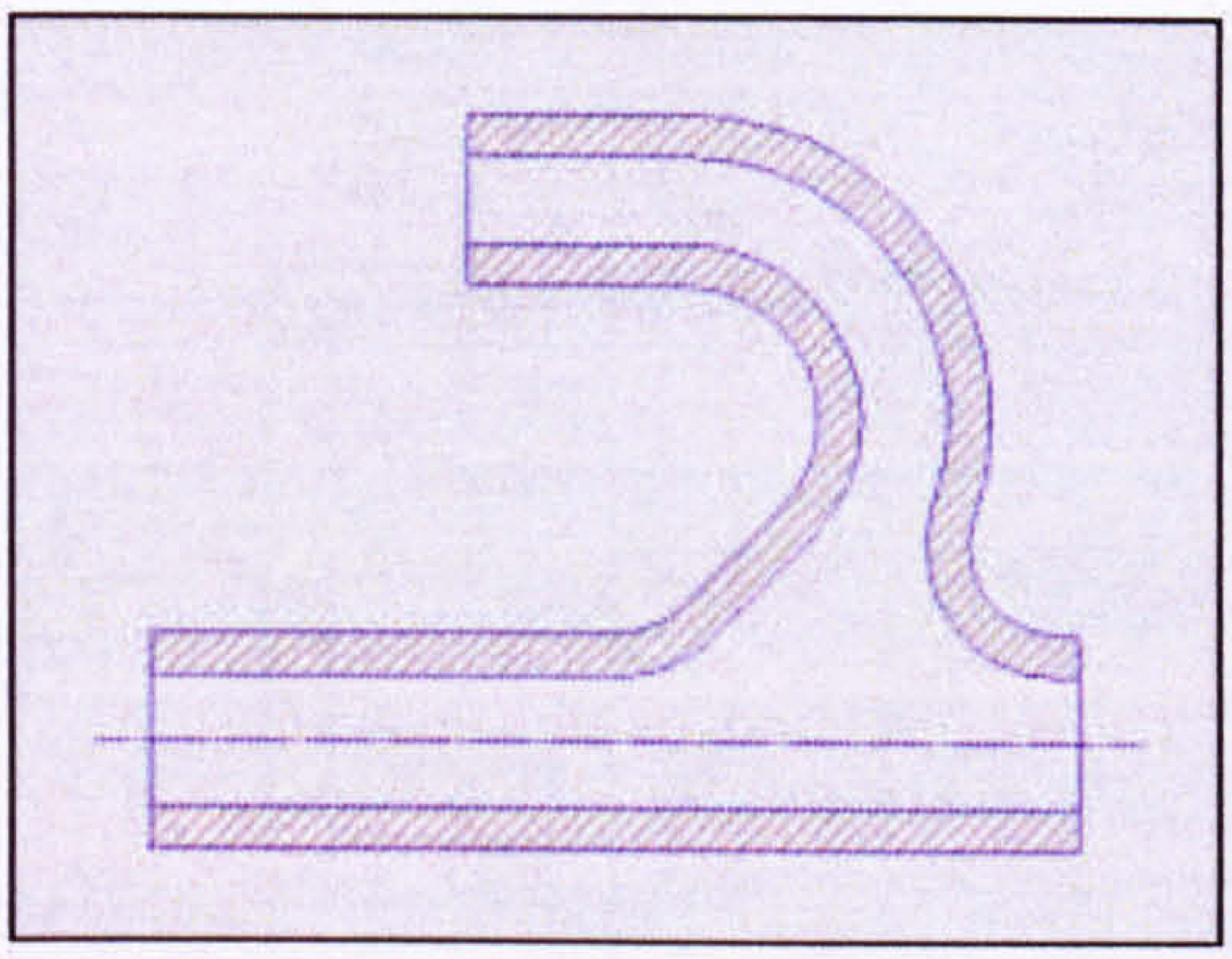
1-piece Rapid Manufactured product

Figure 7.5: Revised DFRM framework

Additional graphic examples that were used to illustrate the previously identified Rapid Manufacturing capabilities and concept suggestions are shown on the following pages.

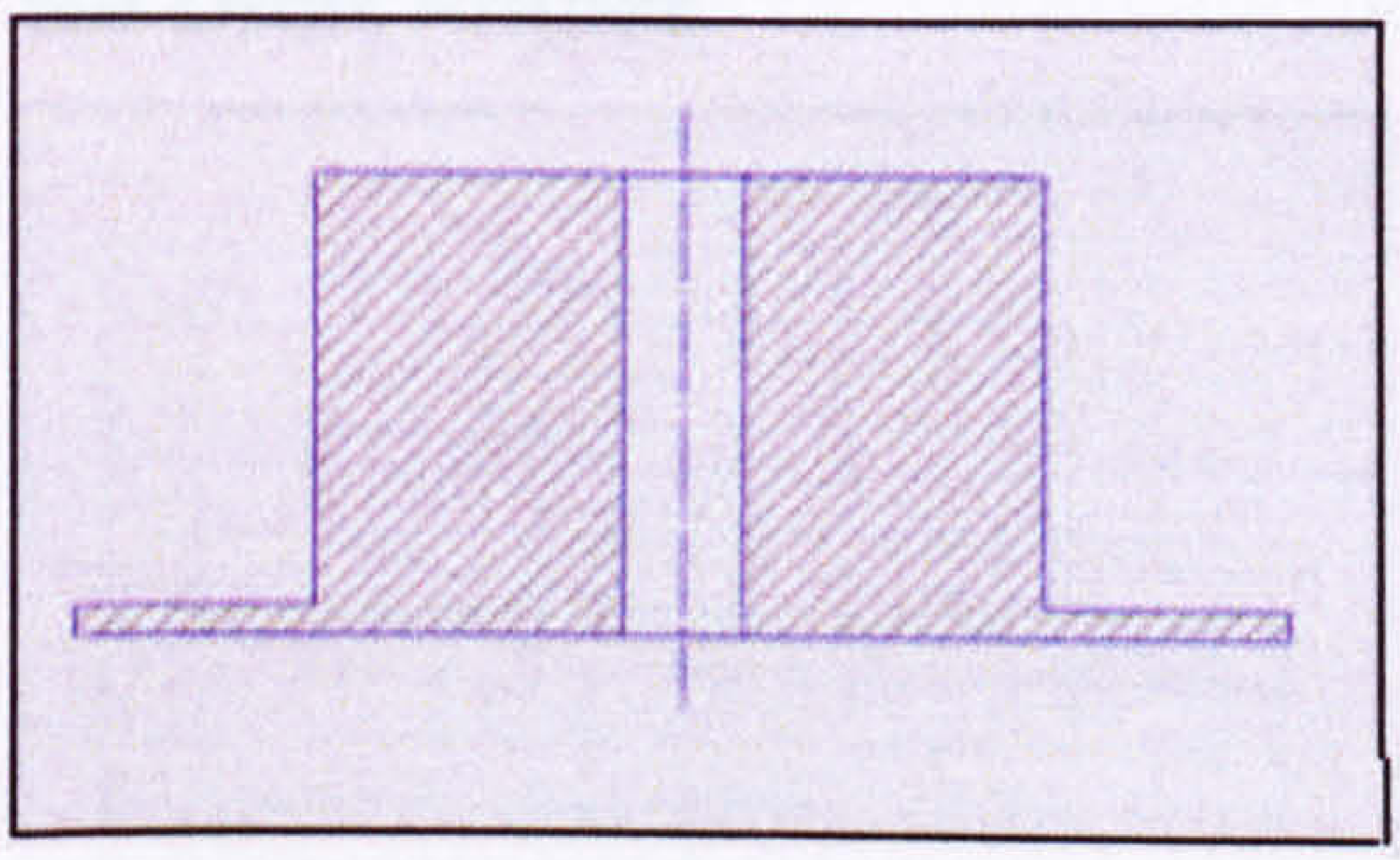
Geometric Freedom – Some commonly associated geometrical freedoms

Complex Internal Core Sections



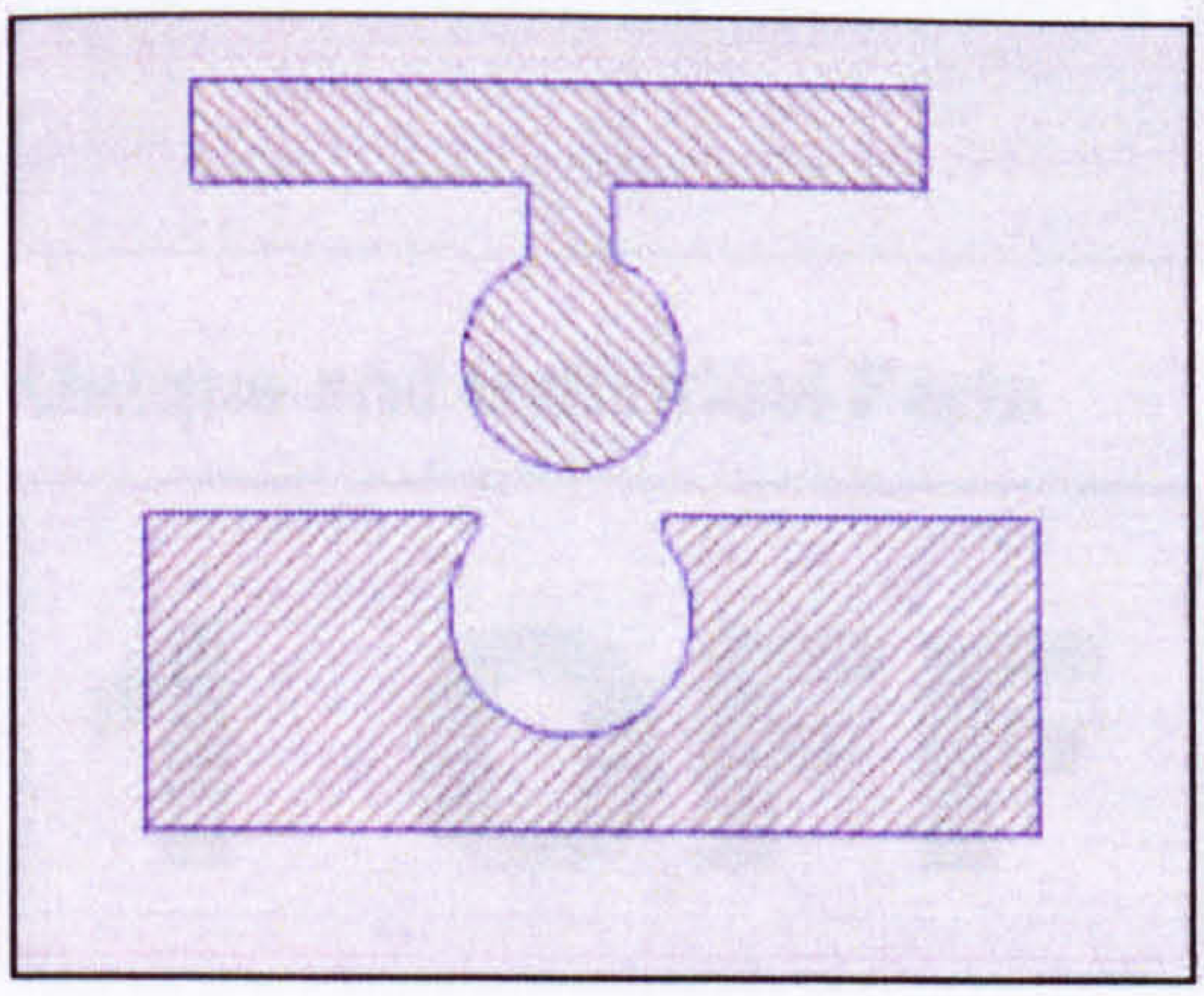
Since conventional inserts aren't needed to form internal voids it is possible to create core sections and internal voids that are far more complex than previously allowed.

Variable Wall Thickness

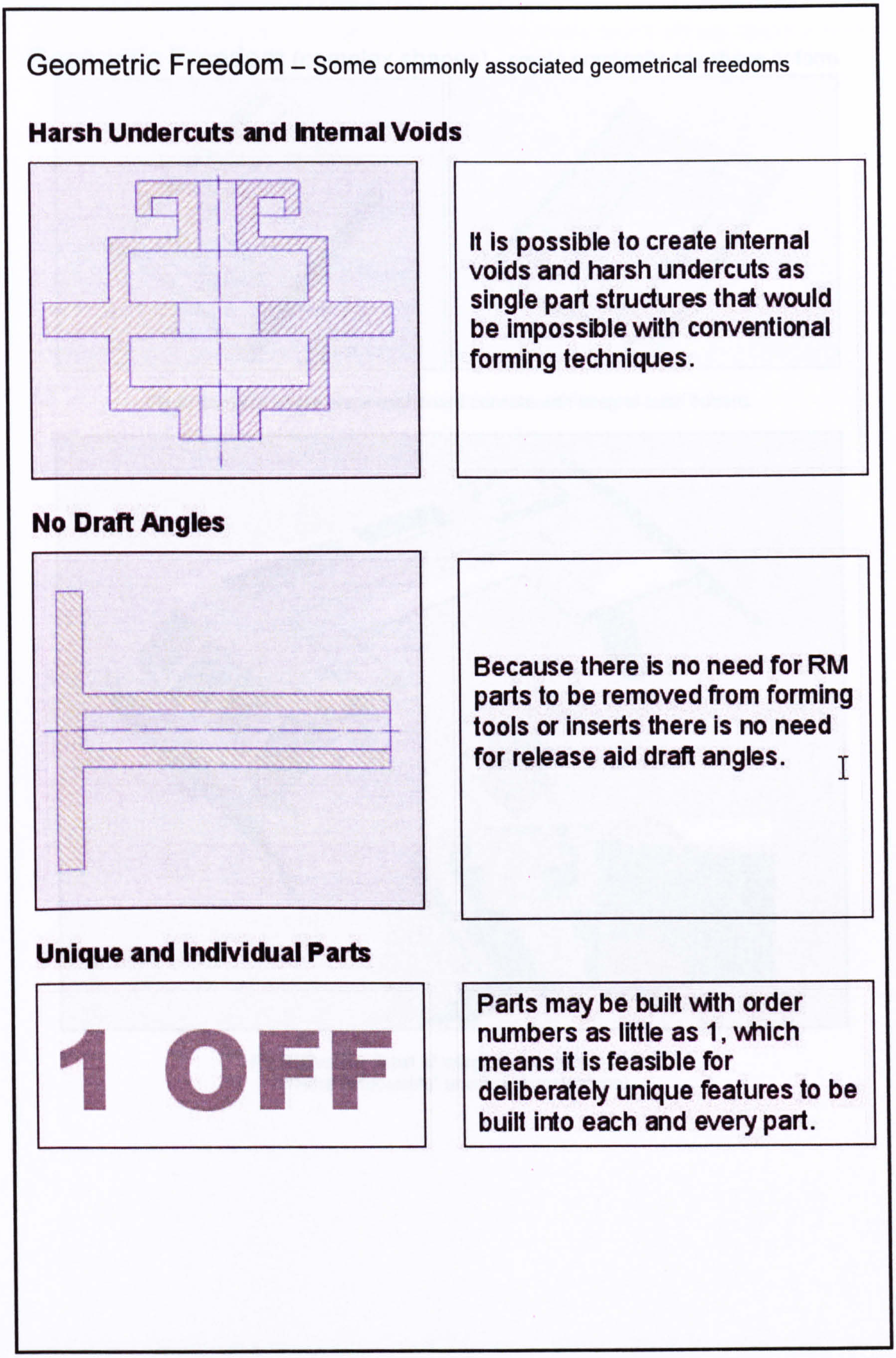


Since RM is not subject to many of the conventional cooling and shrinkage issues associated with many forming techniques, parts may include sections of variable wall thickness.

Re-entrant Blind Holes



Blind holes may be produced without conventional forming inserts or tools which means they may have undercuts or re-entrant apertures.



Geometric Freedom – Some commonly associated geometrical freedoms

Harsh Undercuts and Internal Voids

It is possible to create internal voids and harsh undercuts as single part structures that would be impossible with conventional forming techniques.

No Draft Angles

Because there is no need for RM parts to be removed from forming tools or inserts there is no need for release aid draft angles.

Unique and Individual Parts

1 OFF

Parts may be built with order numbers as little as 1, which means it is feasible for deliberately unique features to be built into each and every part.

Geometric Freedom (complex shapes) - create practically any shape or form

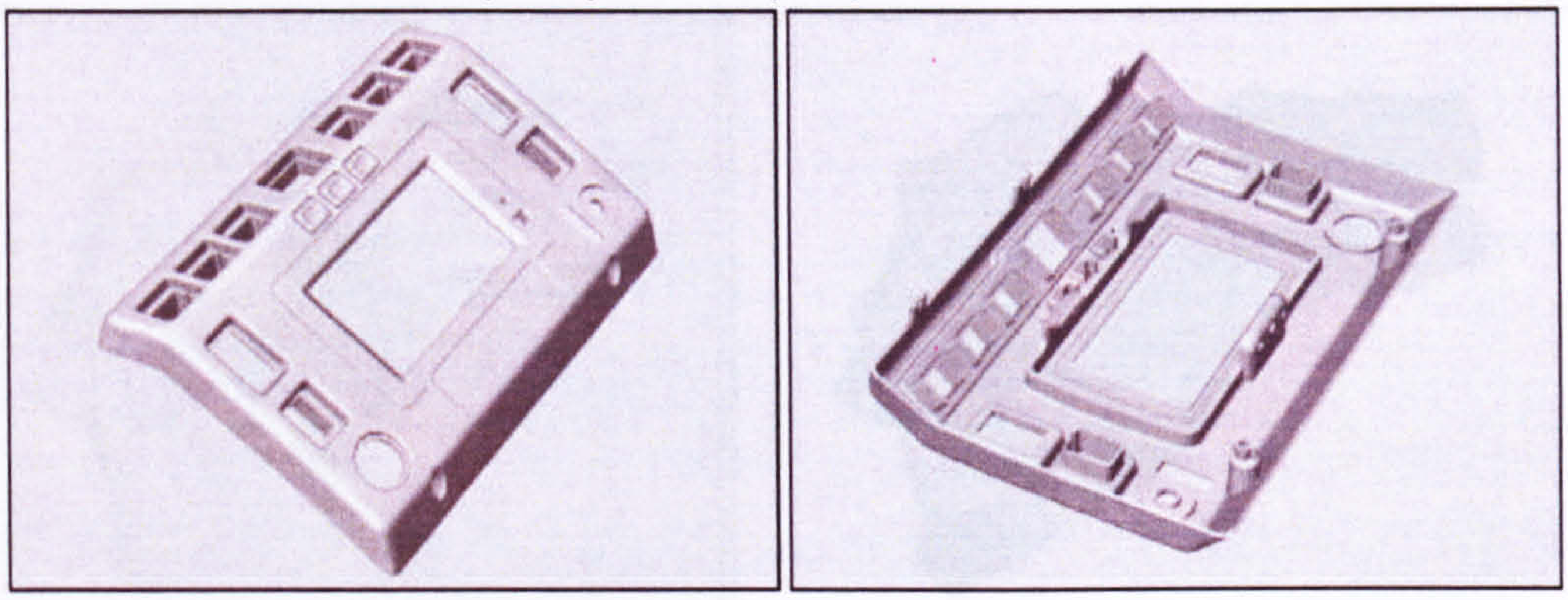


Fig A: complex single piece dashboard console with integral push buttons

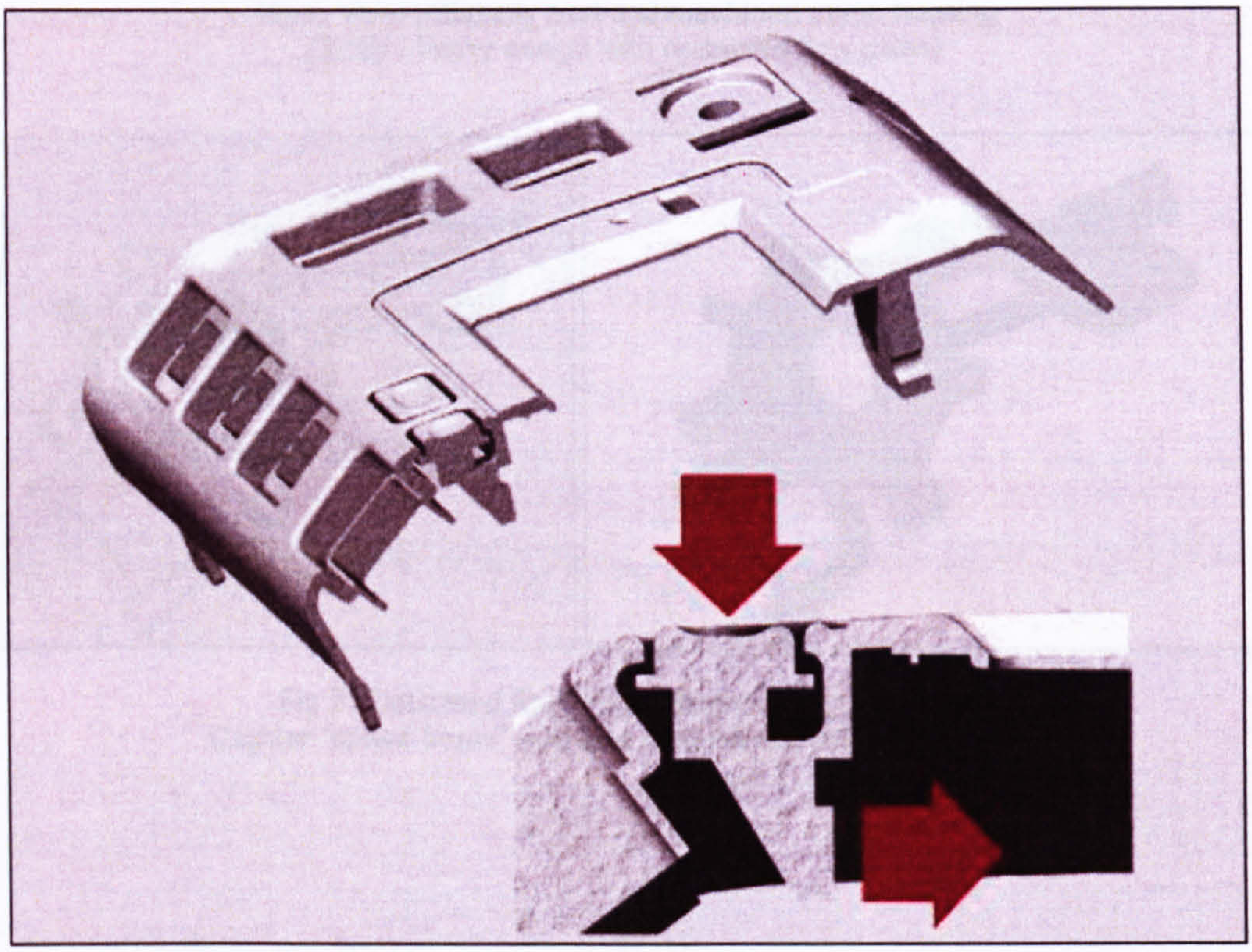


Fig B: Section detail of integral push button action
(*Note "impossible" undercut construction)

Geometric Freedom (Design Optimisation) - create practically any shape or form

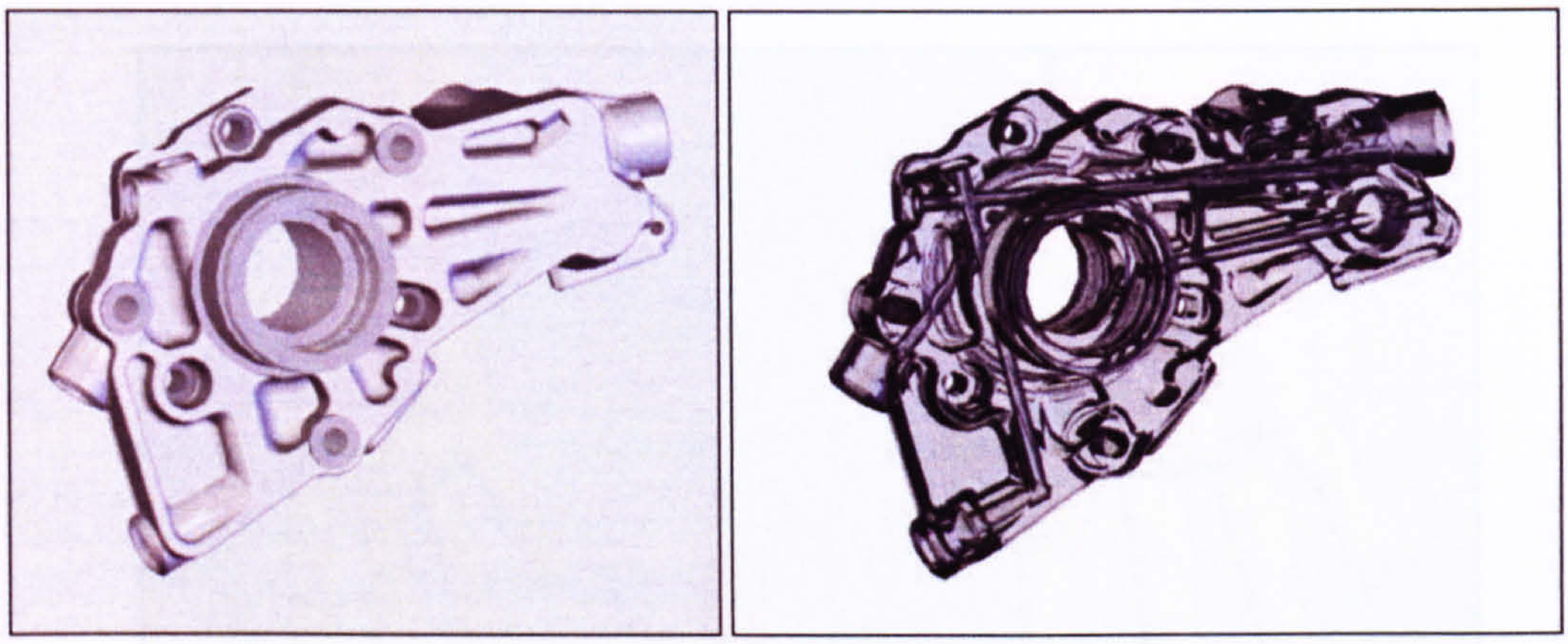


Fig A: Conventionally cast and machined pump housing
(Bulky / heavy design with restricted flow paths)

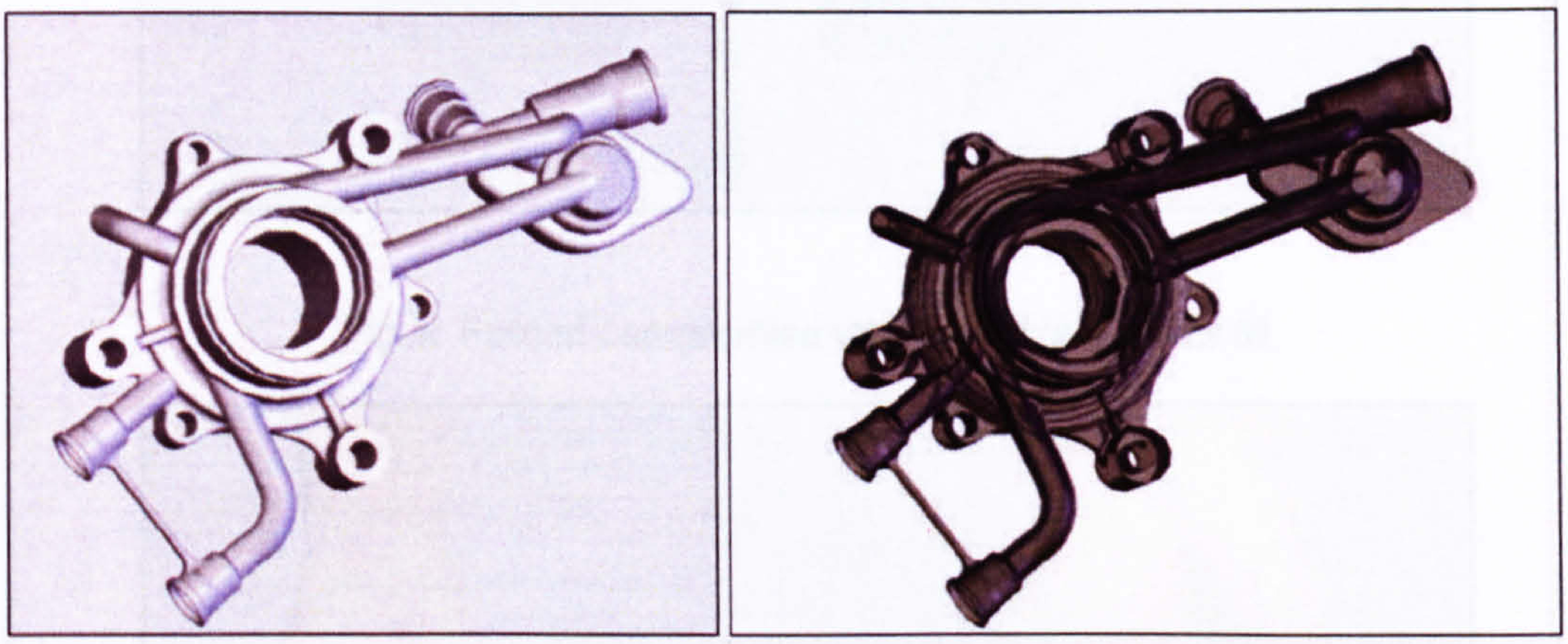


Fig B: Optimised Rapid Manufactured pump housing
(Lighter "space frame" with less material and better flow paths)

Size Variations – Using a range of different sizes to fit specific users

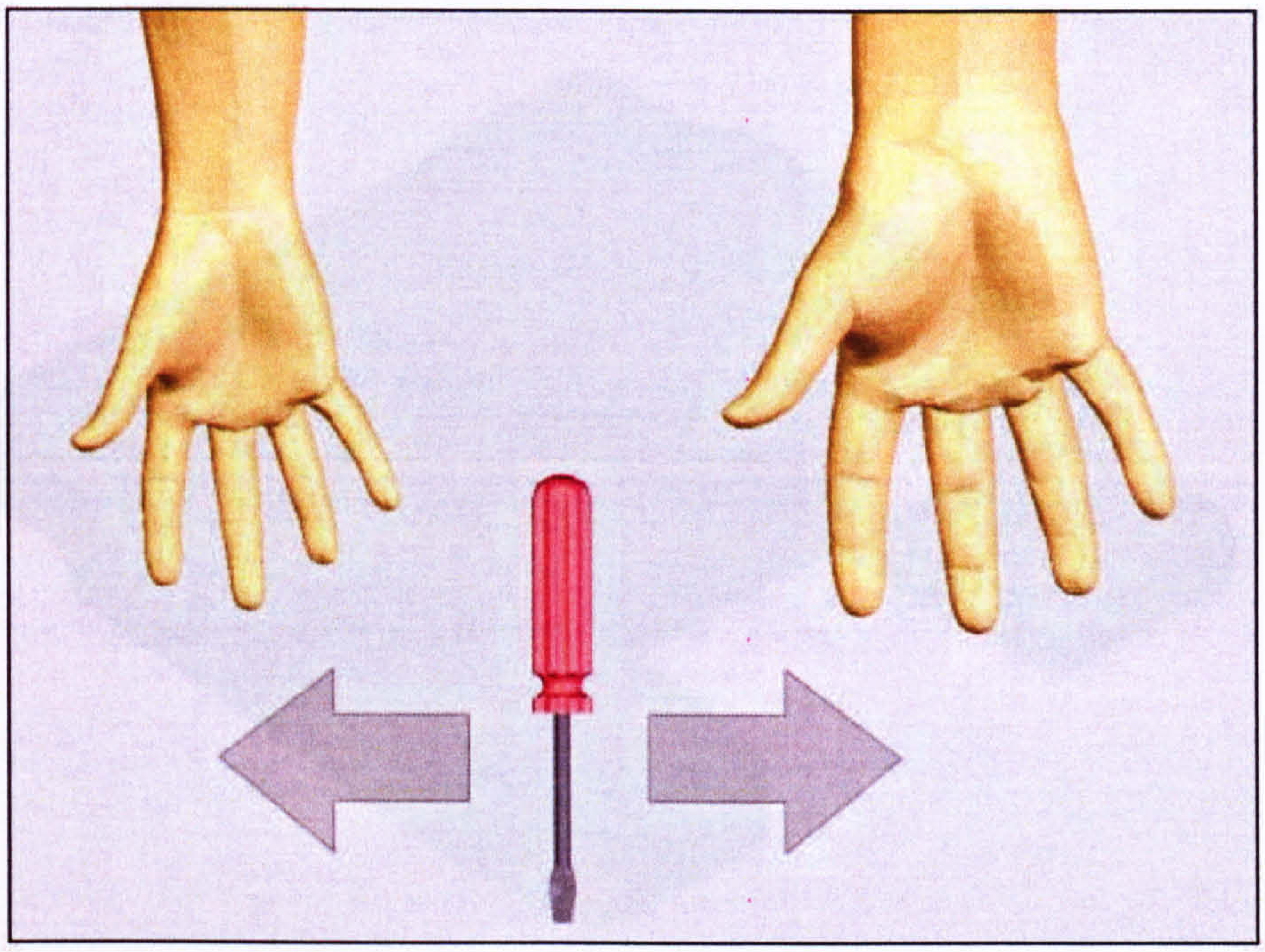


Fig A: Forced compromise with one size that fits all

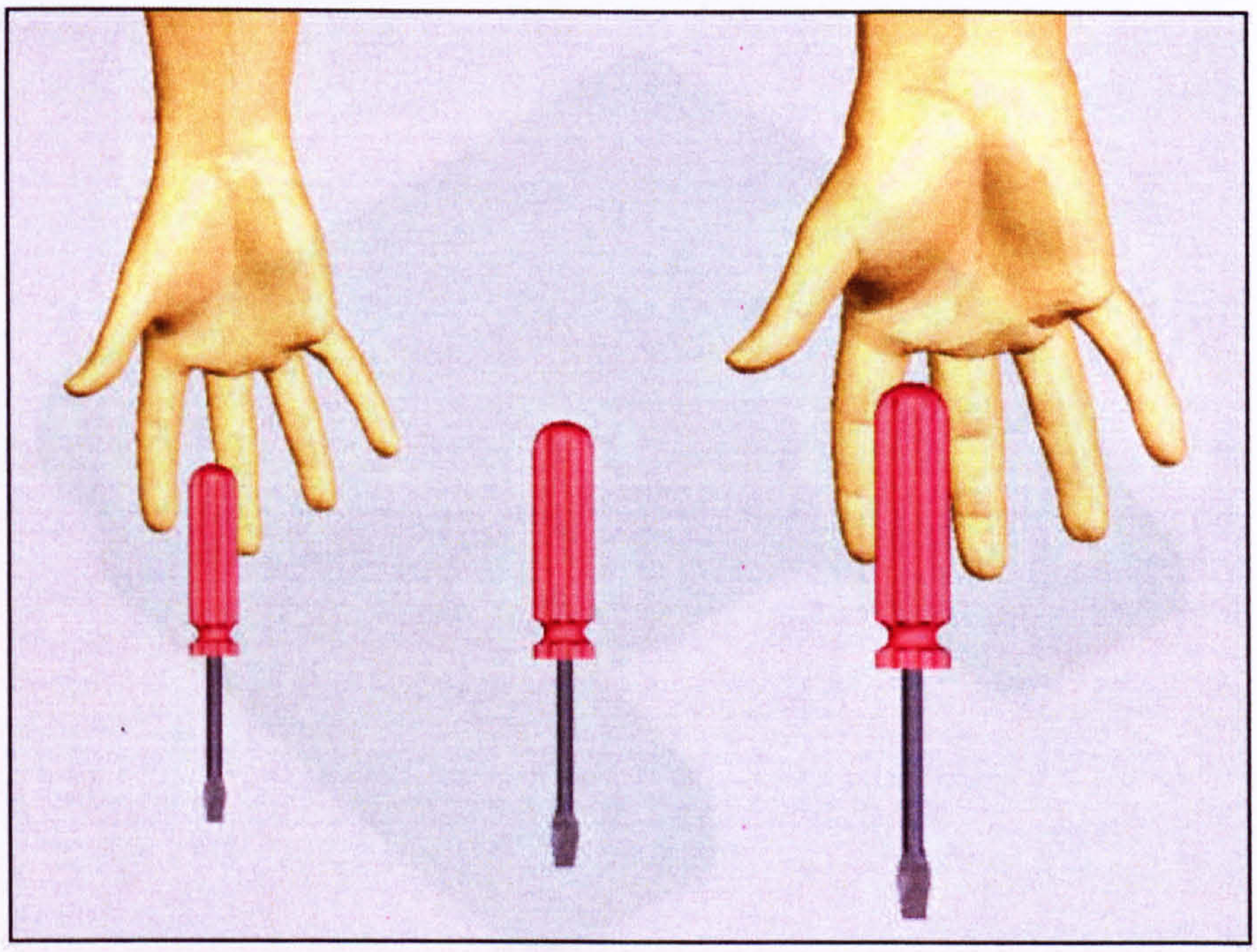


Fig B: Clothing type small, medium and large size options

Conformal Geometry (User Interface) - surface shaped to fit specific user

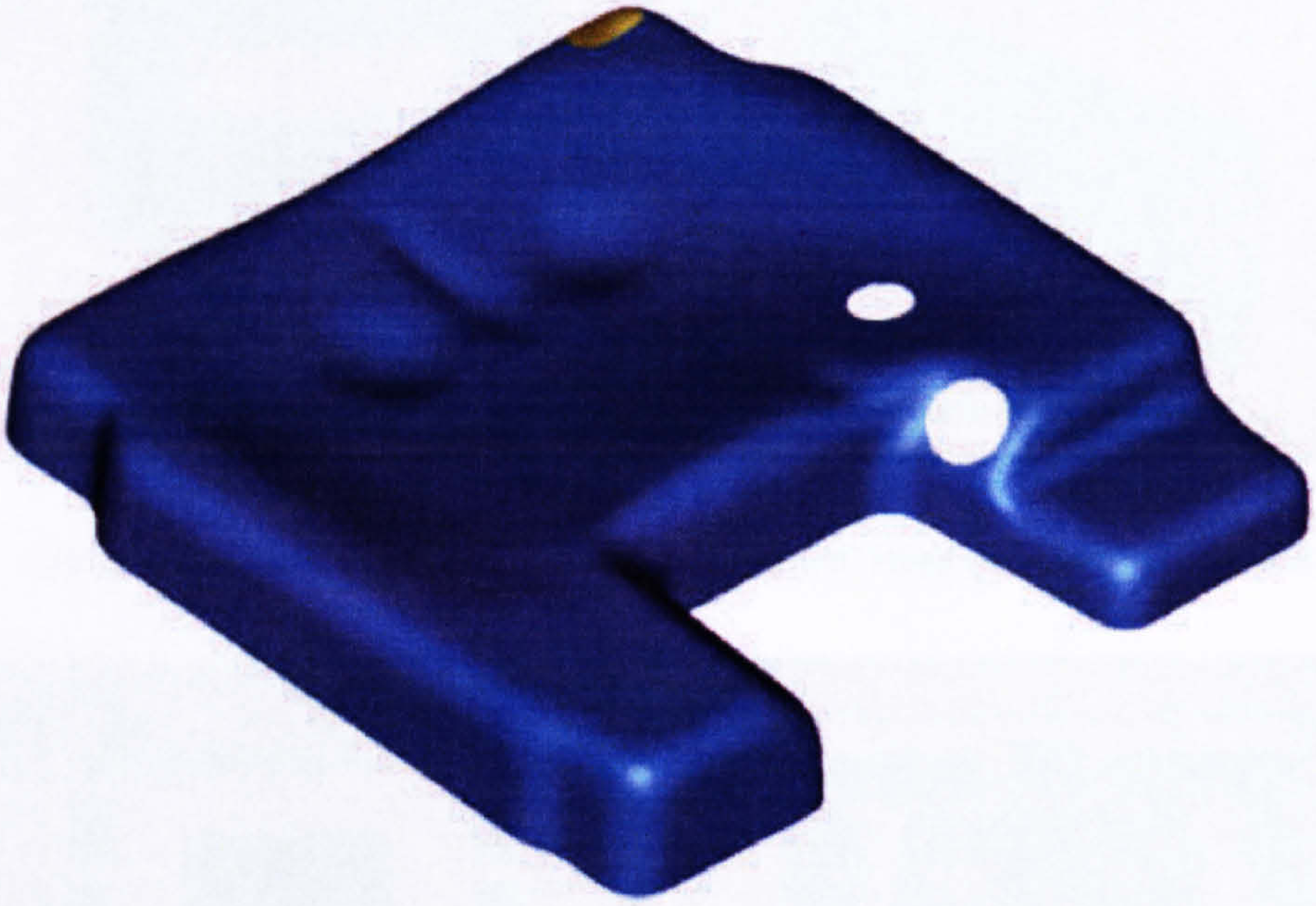


Fig A: Universal Seat Design (Made from rigid material)

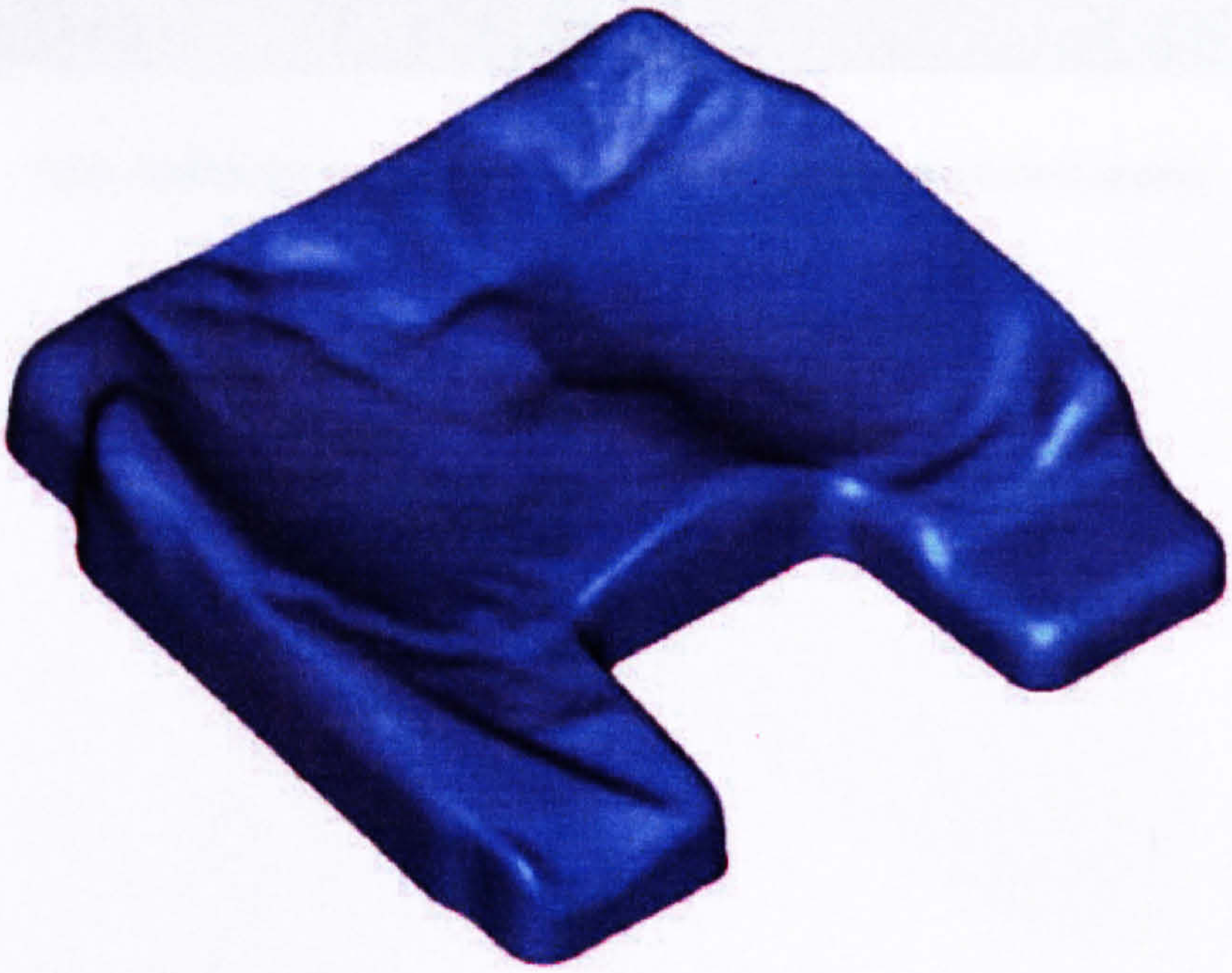


Fig B: Individually Customised Seat (Made from rigid material)

Conformal Geometry (History Parts) - fits an existing shape or form

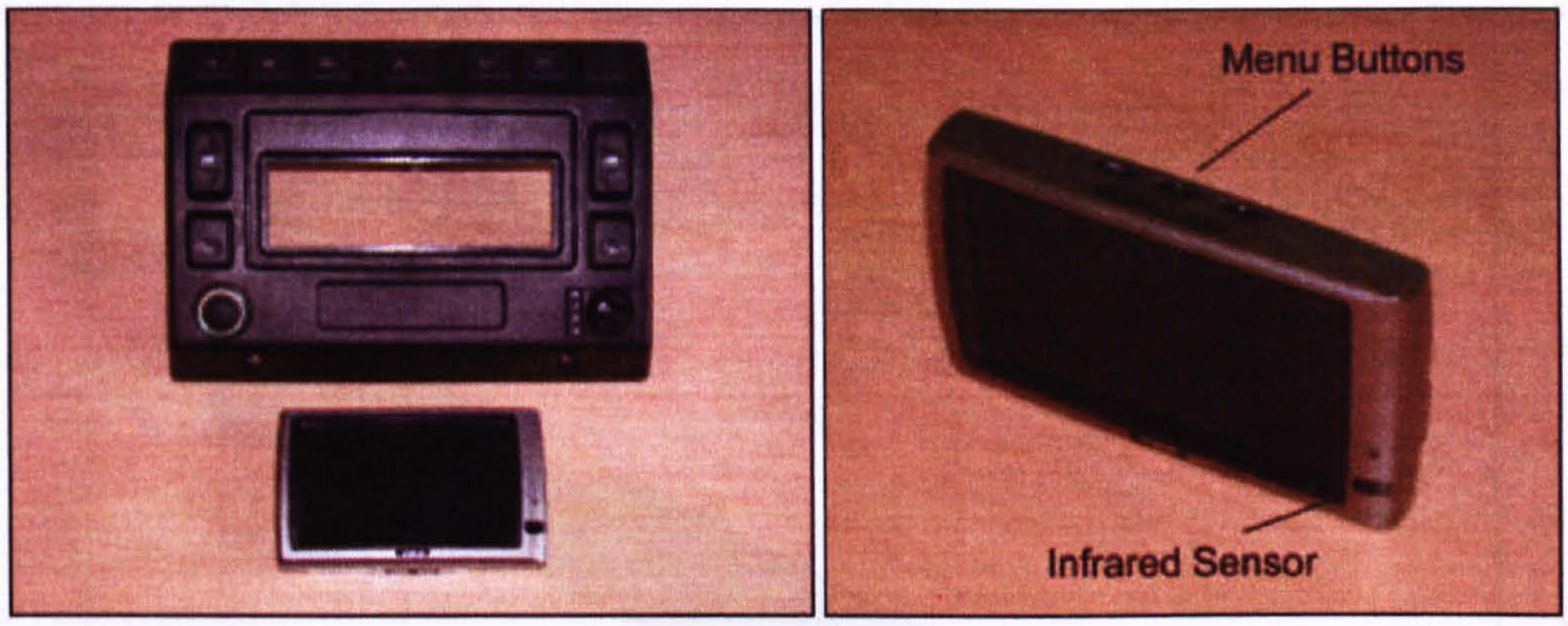


Fig A: Dashboard console needs to house "bought-in" Head Up Display (HUD) unit

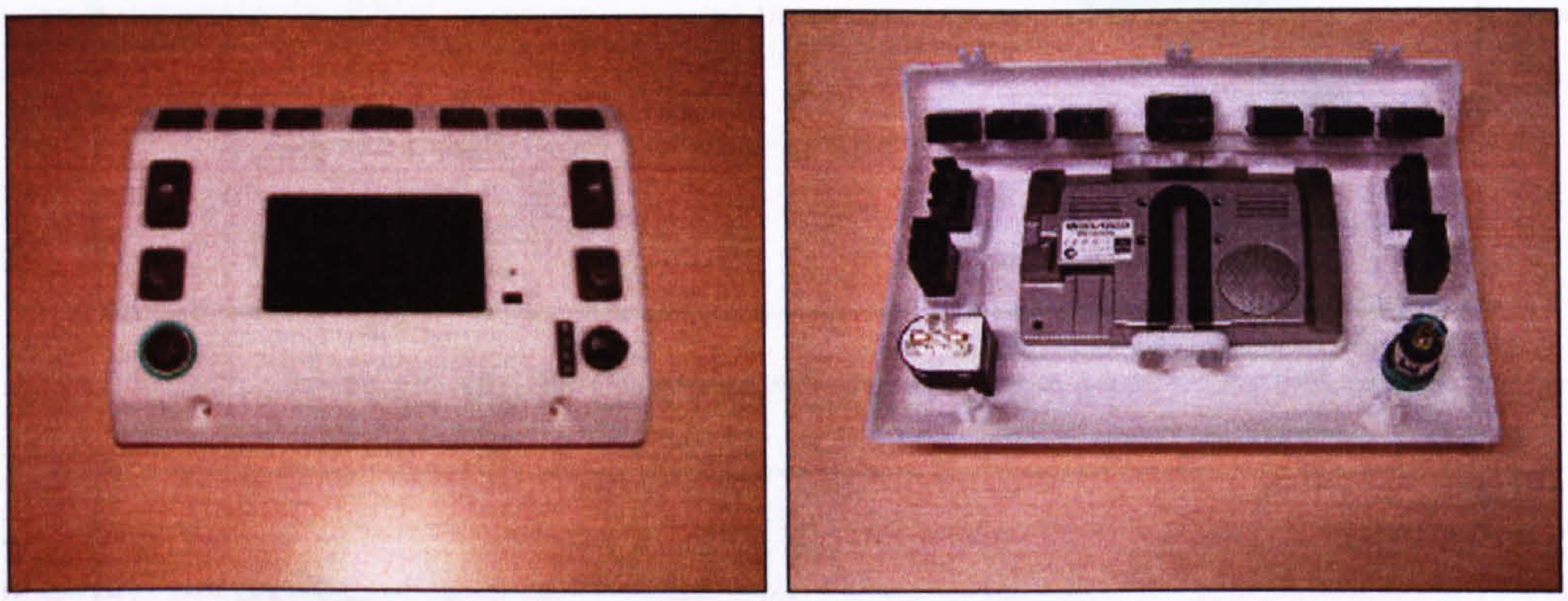


Fig B: Dashboard modified to house HUD without impeding control access

Range Variation Styling - Variations between "Budget" and "Executive" products

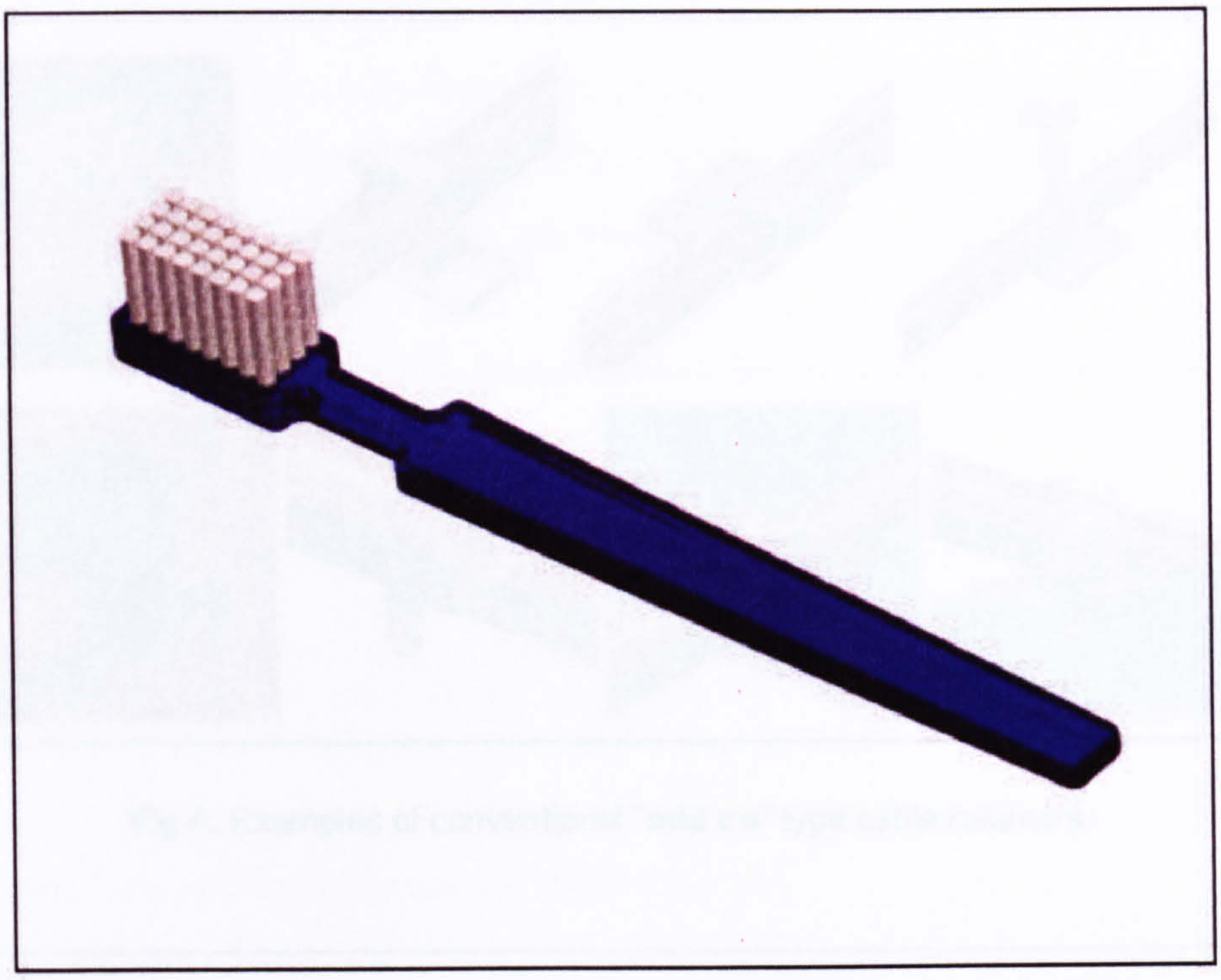


Fig A: Low end "Budget" product

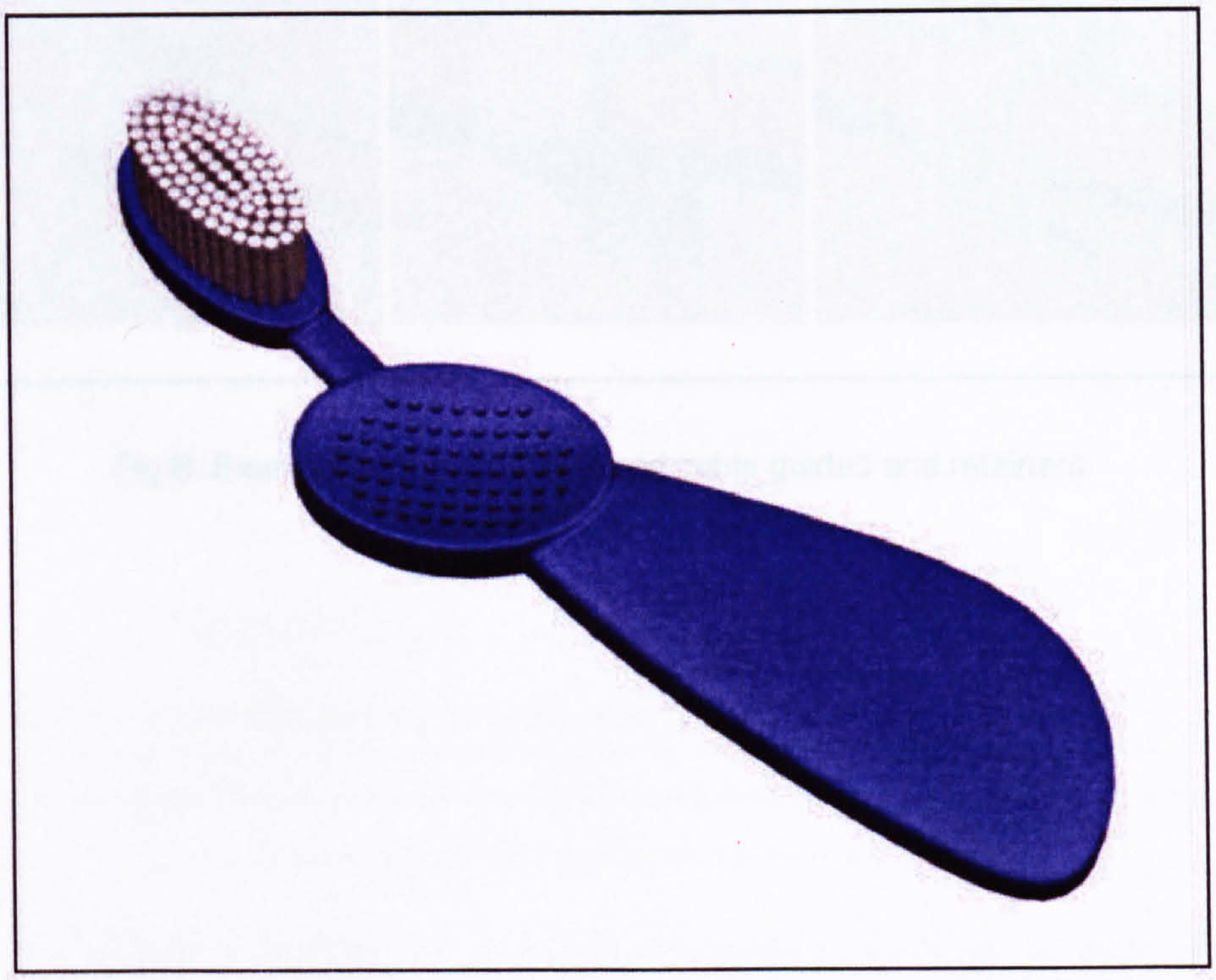


Fig B: High end "Executive" product

Custom Fixings and Mounts - Integral features for retaining product components

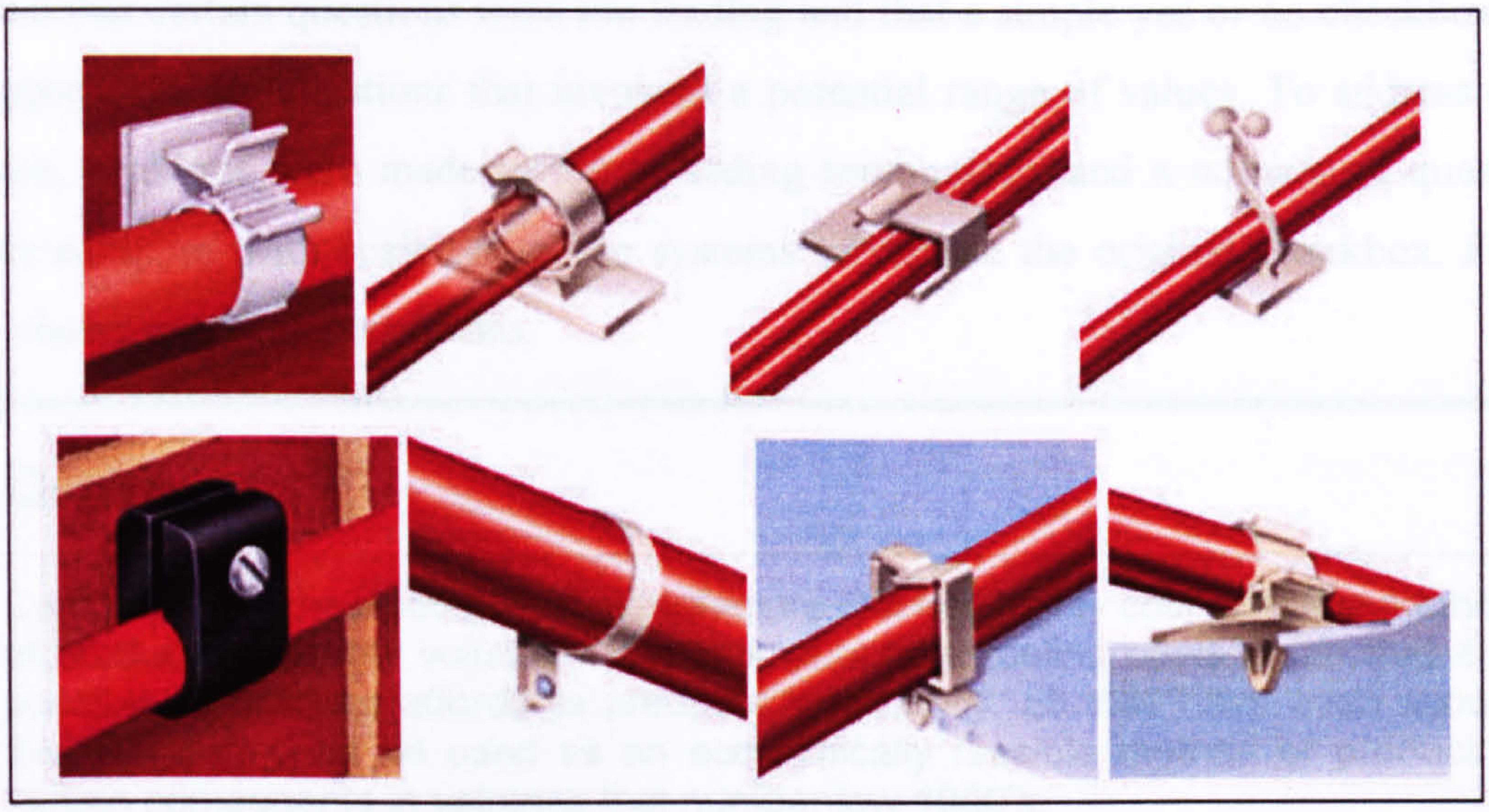


Fig A: Examples of conventional "**add on**" type cable retainers

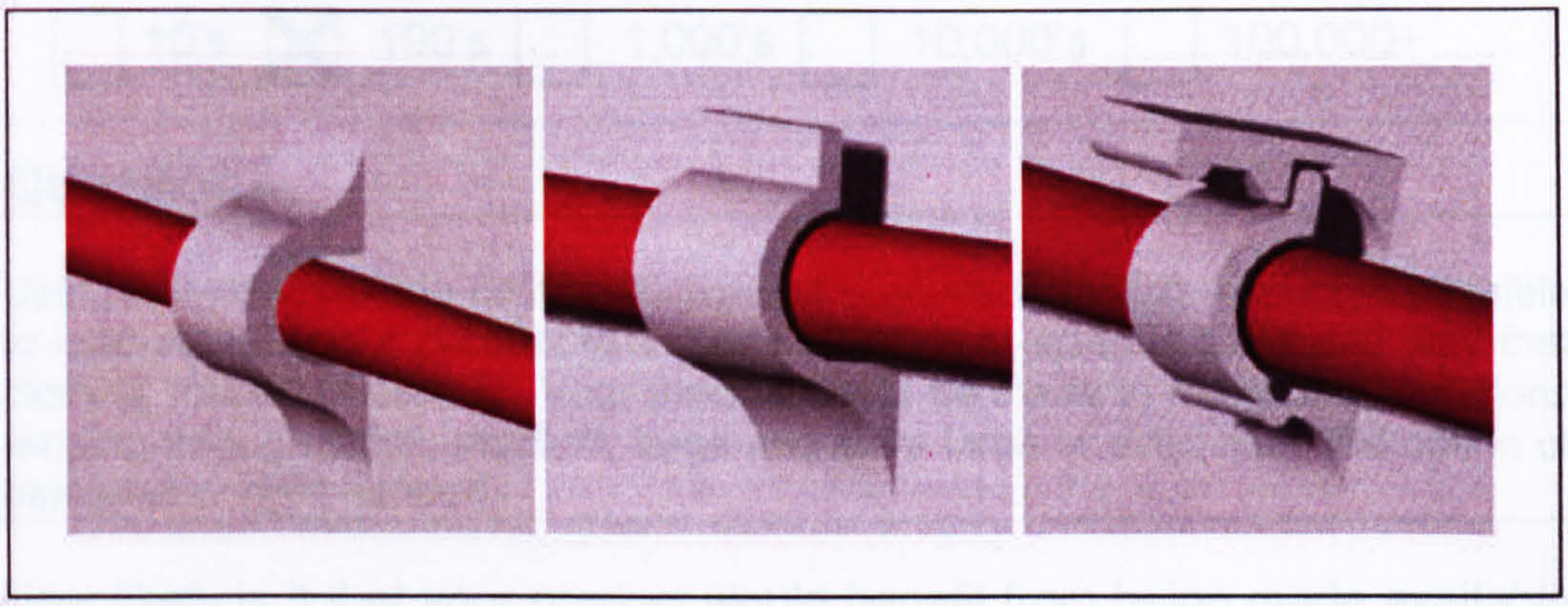
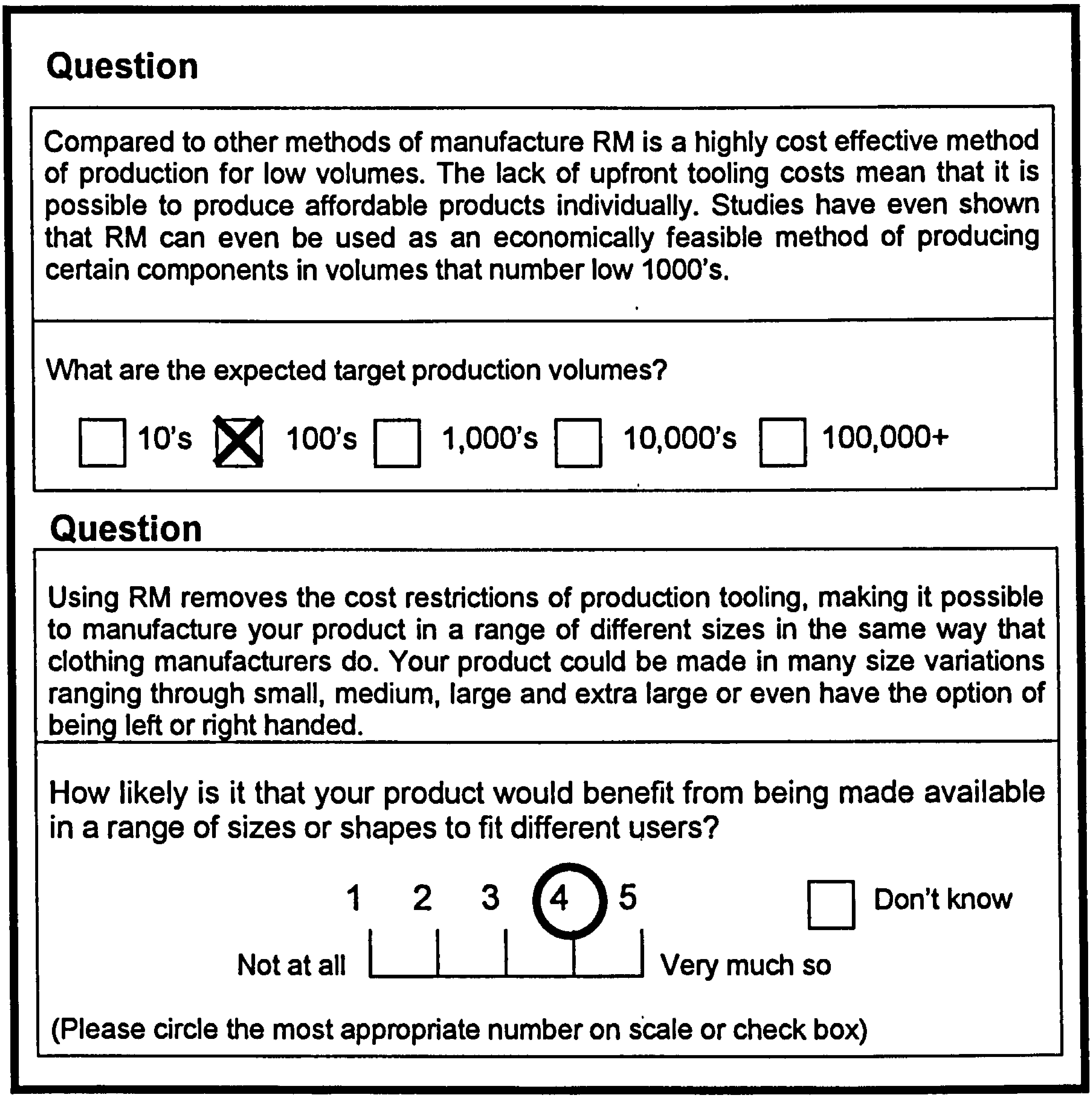


Fig B: Examples of integrally formed cable guides and retainers

Continued pilot trials showed this more graphic framework to be an effective format, although a need was highlighted for several grammatical changes to be made. It was stated that certain questions were too leading and that a simple yes or no checkbox was inappropriate for questions that involved a potential range of values. To address these issues, revisions were made to the offending terminology and a number of questions were equipped with scaled response systems to replace the original checkbox. Figure 7.6 shows two examples of this.



Question

Compared to other methods of manufacture RM is a highly cost effective method of production for low volumes. The lack of upfront tooling costs mean that it is possible to produce affordable products individually. Studies have even shown that RM can even be used as an economically feasible method of producing certain components in volumes that number low 1000's.

What are the expected target production volumes?

☐ 10's ☒ 100's ☐ 1,000's ☐ 10,000's ☐ 100,000+

Question

Using RM removes the cost restrictions of production tooling, making it possible to manufacture your product in a range of different sizes in the same way that clothing manufacturers do. Your product could be made in many size variations ranging through small, medium, large and extra large or even have the option of being left or right handed.

How likely is it that your product would benefit from being made available in a range of sizes or shapes to fit different users?

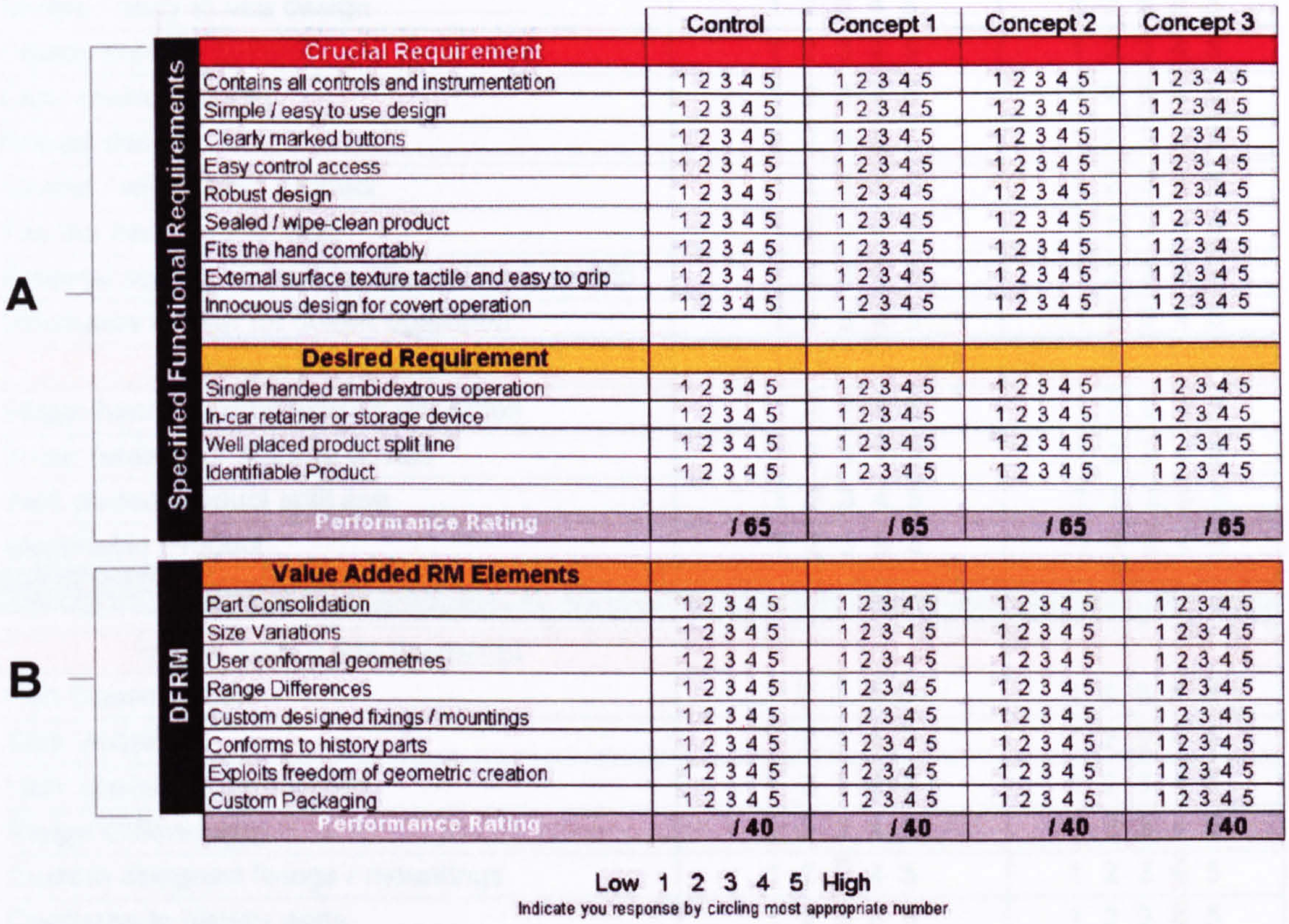
Not at all 1 2 3 [✓ 4] 5 Very much so ☐ Don't know

(Please circle the most appropriate number on scale or check box)

Figure 7.6: Two scaled response examples

Rather that asking a leading or ambiguous question, such as whether production volumes are likely to be low, the interviewee is asked to indicate their expectations by checking the most appropriate box. A mark in either 10's or 100's box would indicate low volumes and be interpreted as a positive response that supports the use of Rapid Manufacturing. Similarly, a question that relates to product size variations uses a 5-point scale to gauge how appropriate such a consideration might be in relation to the product being designed. In this instance, any response that is above the mid-point of the scale would be considered positive and generate an appropriate concept profile statement.

The matrix that was used to evaluate different design concepts remained relatively unchanged throughout the course of the pilot trials. Figure 7.7 shows a sample copy of the matrix, which is repeated again in Appendix D using a larger scale.



			Control	Concept 1	Concept 2	Concept 3
A	Specified Functional Requirements	**Crucial Requirement**				
		Contains all controls and instrumentation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Simple / easy to use design	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Clearly marked buttons	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Easy control access	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Robust design	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Sealed / wipe-clean product	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Fits the hand comfortably	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		External surface texture tactile and easy to grip	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Innocuous design for covert operation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Desired Requirement				
		Single handed ambidextrous operation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		In-car retainer or storage device	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Well placed product split line	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Identifiable Product	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Performance Rating	**/ 65**	**/ 65**	**/ 65**	**/ 65**
B	DFRM	**Value Added RM Elements**				
		Part Consolidation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Size Variations	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		User conformal geometries	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Range Differences	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Custom designed fixings / mountings	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Conforms to history parts	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Exploits freedom of geometric creation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Custom Packaging	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
		Performance Rating	**/ 40**	**/ 40**	**/ 40**	**/ 40**

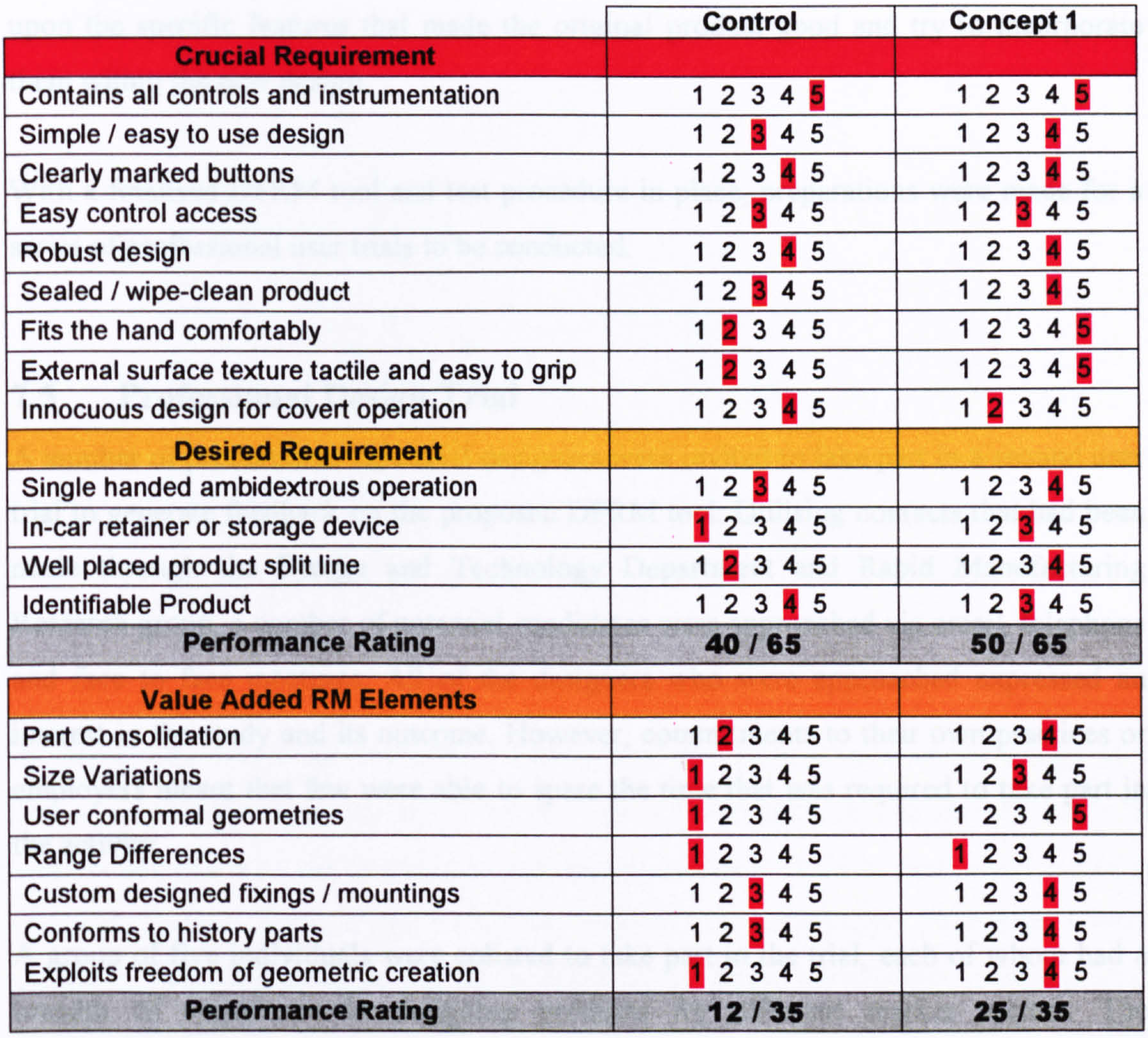
Low 1 2 3 4 5 High

Indicate you response by circling most appropriate number

Figure 7.7: DFRM evaluation matrix

The matrix is divided into two sections that deal with relevant product evaluation criteria. These are the product's specified functional requirements (**A**) and the suggested DFRM features (**B**), which result from completion of the DFRM questionnaire. Criteria in the first section are derived from a set of client approved factors that deal with issues such as product functionality and remain the same in each set of trial documentation. However, the second set of criteria is based upon the designer's individual interpretation of the product in relation to the DFRM questionnaire and may vary depending upon the answers that are given. For example, a designer may give a negative response to all of the questions relating to customised packaging, in which case this particular suggestion would be missing from both product specification and concept evaluation matrix.

Columns are used in the matrix to provide a benchmark evaluation of design concepts against an original "control" product and/or each other. Figure 7.8 shows a sample evaluation of the original Bafbox product and a new design concept.



	Control	**Concept 1**
Crucial Requirement		
Contains all controls and instrumentation	1 2 3 4 [✓ 5]	1 2 3 4 [✓ 5]
Simple / easy to use design	1 2 [✓ 3] 4 5	1 2 3 [✓ 4] 5
Clearly marked buttons	1 2 3 [✓ 4] 5	1 2 3 [✓ 4] 5
Easy control access	1 2 [✓ 3] 4 5	1 2 [✓ 3] 4 5
Robust design	1 2 3 [✓ 4] 5	1 2 3 [✓ 4] 5
Sealed / wipe-clean product	1 2 [✓ 3] 4 5	1 2 3 [✓ 4] 5
Fits the hand comfortably	1 [✓ 2] 3 4 5	1 2 3 4 [✓ 5]
External surface texture tactile and easy to grip	1 [✓ 2] 3 4 5	1 2 3 4 [✓ 5]
Innocuous design for covert operation	1 2 3 [✓ 4] 5	1 [✓ 2] 3 4 5
Desired Requirement		
Single handed ambidextrous operation	1 2 [✓ 3] 4 5	1 2 3 [✓ 4] 5
In-car retainer or storage device	[✓ 1] 2 3 4 5	1 2 [✓ 3] 4 5
Well placed product split line	1 [✓ 2] 3 4 5	1 2 3 [✓ 4] 5
Identifiable Product	1 2 3 [✓ 4] 5	1 2 [✓ 3] 4 5
Performance Rating	**40 / 65**	**50 / 65**

Value Added RM Elements		
Part Consolidation	1 [✓ 2] 3 4 5	1 2 3 [✓ 4] 5
Size Variations	[✓ 1] 2 3 4 5	1 2 [✓ 3] 4 5
User conformal geometries	[✓ 1] 2 3 4 5	1 2 3 4 [✓ 5]
Range Differences	[✓ 1] 2 3 4 5	[✓ 1] 2 3 4 5
Custom designed fixings / mountings	1 2 [✓ 3] 4 5	1 2 3 [✓ 4] 5
Conforms to history parts	1 2 [✓ 3] 4 5	1 2 3 [✓ 4] 5
Exploits freedom of geometric creation	[✓ 1] 2 3 4 5	1 2 3 [✓ 4] 5
Performance Rating	**12 / 35**	**25 / 35**

Figure 7.8: Matrix evaluation of design concepts

The matrix cells contain a five point numeric scale that is used to indicate how well each design performs in relation to the criteria that are outlined in the first column. On this scale, "1" indicates a poor or negative performance and "5" is used to express that the design performs as well as it possibly could.

A tally count is used to provide a series of overall scores for each concept, indicating the one that best meets the full set of specification criteria, and individual figures may also be used to highlight specific strengths and weaknesses within each concept. For example, in Figure 7.8, it is clear to see that the new design outperforms the original control and would make a suitable candidate for development. However, the "Innocuous design for covert operation" cell shows that the original control product was the best and that there is much room for improvement in the new design. During subsequent development phases, the designer would be able to use this knowledge to concentrate upon the specific features that made the original product good and try to incorporate them within the new design.

With a finalised DFRM tool and test procedure in place, preparations were made for a series of professional user trials to be conducted.

7.5 Professional Design Trial

A number of professional industrial designers were invited to take part in a second user trial to generate feedback on the proposed DFRM tool. Utilising contacts that had been made through the Design and Technology Department and Rapid Manufacturing Research group, a number of potential candidates were approached via email, telephone and face to face meetings. All of the designers who were approached expressed an interest in the study and its outcome. However, commitments to their own practices or employers meant that few were able to spare the time that was required to take part in the activity.

A group of five individuals were enlisted to take part in the trial, each of whom had a breadth of experience in designing products for different market sectors. The participants included an industrial designer from Bentley Cars; a freelance industrial designer with a long established design consultancy; the co-founder of a small design and build organisation that produces acoustic guitars from recycled polymers and two industrial design academics who were experienced in the professional design, development and styling of consumer products.

Using the design exercise and documentation that was established in earlier pilot studies, a series of individual user trials were conducted. These took place in the Design and Technology Department at Loughborough University using a private studio room to isolate the participants from distractions. In each instance, the design exercise was performed under the same controlled conditions using an identical set of documentation to maintain continuity. A3 paper and sketching materials were provided for participants to generate concepts. Figure 7.9 shows an example of the work produced, a full collection of which may be seen in Appendix E.

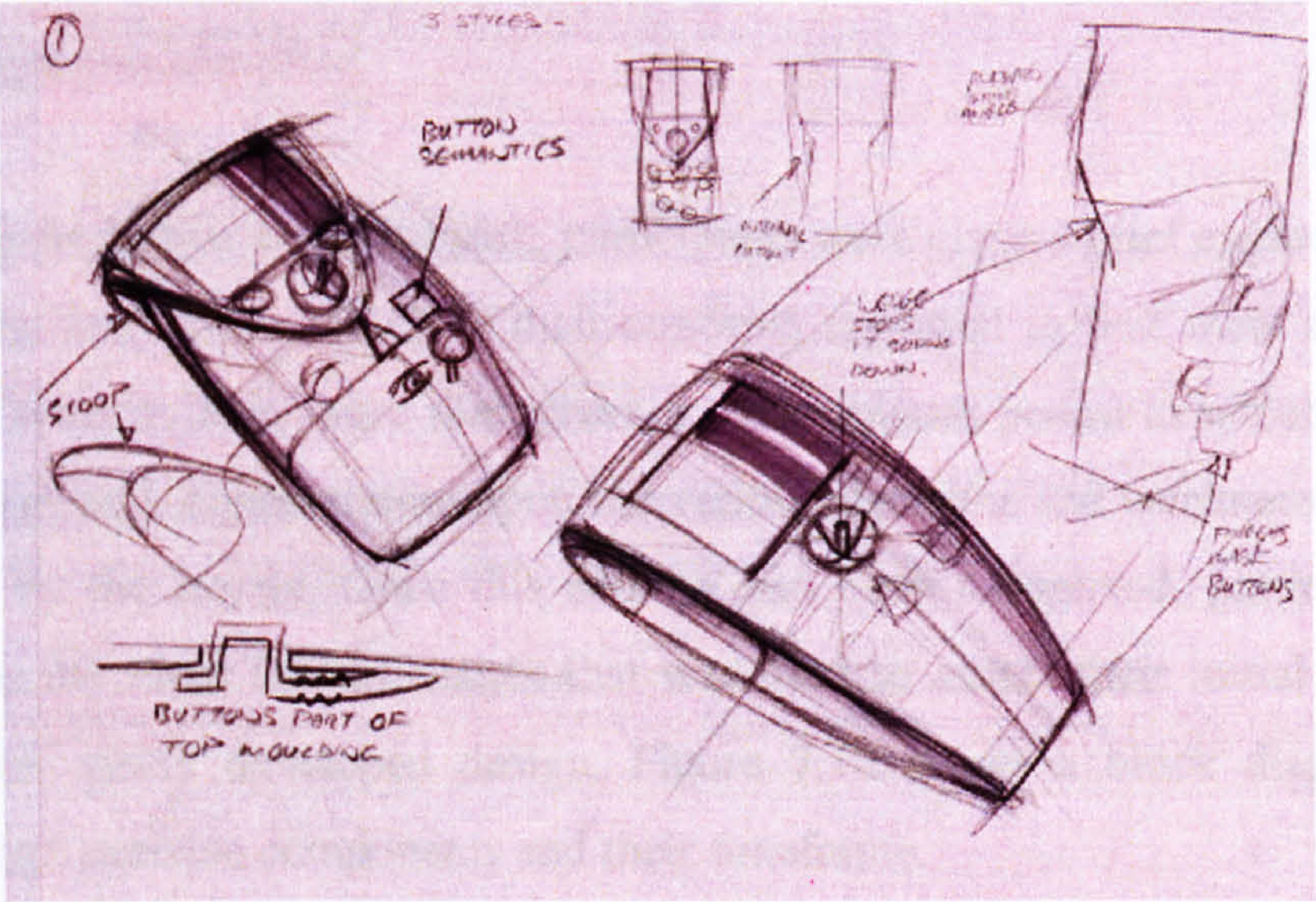


Figure 7.9: Example of DFRM concept sketches

As previously stated, the availability of free time in which to conduct the design trial was a problematic issue for all of the participants who were invited to take part. To combat this problem, the exercise was structured so that it could be completed within a relatively short time scale that would not encroach too much upon participant's own schedule. Tests conducted during the initial pilot trial phase were used to establish what would be a minimal, yet sufficient, amount of time for candidates to generate suitably communicative concept sketches and perform other test related actions. This resulted in a finalised trial format that was comprised of a single studio based design session of approximately two hours in duration, which was precluded with a pre-session trial booklet and set of preparatory documentation that participants were given to read and complete at their own leisure.

Each studio session began with a short briefing and a recap of the pre-session booklet before participants were given a sixty minute period in which to sketch a minimum of three design concepts that incorporated applicable DFRM features. During this session, time checks were given at twenty minute intervals to notify participants as to how much of the exercise had passed and how much remained. At the end of this first sketching session, participants were asked to assess their own concepts using the DFRM matrix before being given refreshments and a short comfort break. Whilst the participants were occupied with refreshments, the self assessment results were noted and a preferred design concept was identified.

On returning from their comfort break, participants were given a brief explanation of the matrix results and shown which of their concepts appeared to best meet specification and DFRM criteria. They were then given a thirty minute period in which to develop this design concept, concentrating upon the various strengths and weaknesses that were highlighted by the matrix. Once this activity had been completed, participants were asked to use the same DFRM matrix that was used to assess their initial concepts to evaluate their newly developed design. Figure 7.10 shows a block diagram of the specific design exercise components and their timeframe.

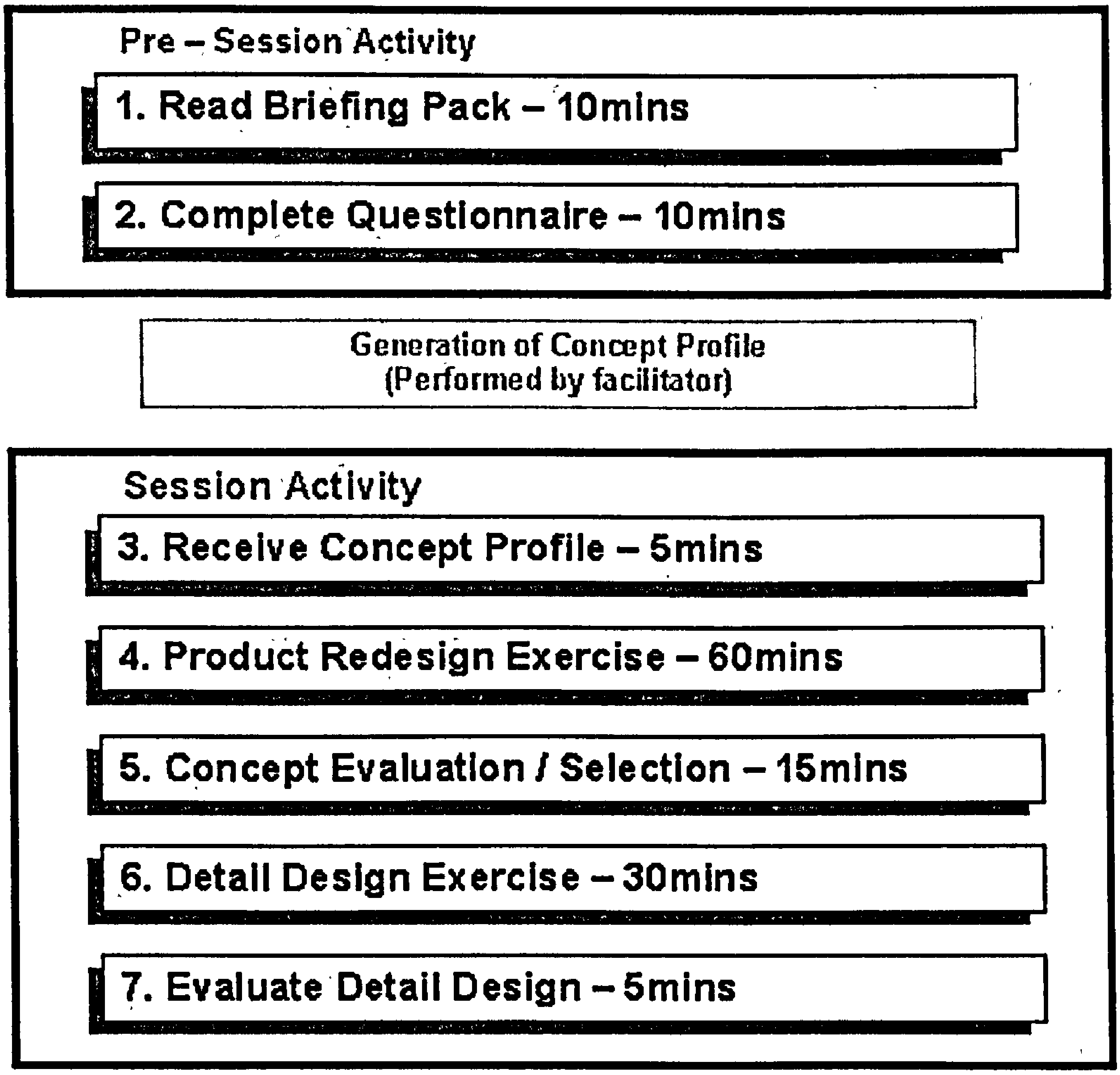


Figure 7.10: Timescale for DFRM exercise activities

At the end of each trial, participants were asked to complete a short feedback questionnaire that related to the DFRM tool. This contained ten questions that were intended to assess the DFRM tool's legibility and usability, as well as establishing the methods or approaches that participants normally use for concept generation and evaluation. A few lines were provided beneath each question for written comments and, where applicable, a numeric scale was presented for participants to quantify specific responses. Copies of the completed questionnaires are contained in Appendix F and key data is discussed in section 7.6.

7.6 Student Design Trial

In addition to the professional user trial, a second trial was conducted using undergraduate students from Loughborough University's Design Technology Department. Having observed DFRM tool usage in controlled conditions, the purpose of this second trial was to study its application in a more varied environment. Unlike the previous exercise, participants in this second trial were free to choose the product that they were to redesign. In addition to this, participants were able to perform concept generation using their own preferred design medium, in surrounds of their own choosing and in whatever time scale they deemed appropriate.

The exercise was incorporated as part of a taught module in which final year Design and Technology students were required to generate a 3D CAD model of a consumer product. Participants were selected using projected course grades to establish a group that had a range of varying design abilities. Grades were used to establish three ability ratings that were identified as top; middle and bottom, before selecting three closely matched students from each band.

A lecture theatre presentation was given to the whole student body, in which the concept of Rapid Manufacturing and its associated benefits were introduced. The presentation was supported with a printed handout that was given to each of the attendees and made available as an online resource. This contained the same illustrated

examples that are used in the DFRM concept profiler. At the end of the lecture presentation, the students were all instructed to select a readily available consumer product and redesign it for Rapid Manufacture.

As with the previous exercise, the students were all required to produce three initial concepts before selecting one to be refined and produced as a finalised 3D CAD model. Whilst the whole student group took part in this activity, and had access to the illustrated concept guide, use of other DFRM tool components was restricted to selected trial participants only. As with the first trial, a supporting booklet was produced for the participants that contained the following sections:

- An explanation of the trial and its objectives
- A design brief calling for the redesign of a product for Rapid Manufacture
- A blank specification chart to be completed by the participant
- A DFRM questionnaire to be completed and returned before concept generation

A copy of the booklet used in this trial is contained in Appendix B.

Unlike the earlier trial, in which attention was placed upon the redesign of a single focus product, participants of this second trial each worked upon different products of their own choosing. Having chosen the product that they were to redesign, participants were asked to identify the specification criteria they perceived to be most appropriate. This is supported in the booklet with a blank specification chart in which criteria are entered. When recording specifications in this chart, participants were asked to distinguish between crucial and desired criteria with the use of "must meet" and "should meet" statements. In addition to this, a numeric scale was used to indicate the relative importance or "weighting" of each of the criteria. This particular feature is discussed by Pugh (1990, p92), who recognised the need for certain factors, such as cost or reliability, to outweigh others.

Having recorded the necessary criteria, participants were presented with the same generic product questionnaire that was used in the first professional exercise. They were asked to complete and return both specification charts and questionnaires before generating any concepts. The information that this generated was used to create appropriate profile suggestions and evaluation matrices for the chosen product of each participant. Suggested profiles were then given to each of the students to assist the concept generation process, which occurred at a time and place of the students own choosing.

Once the initial concepts had been generated a group meeting was held to assess the designs and select a concept for development. Participants were asked to evaluate their designs using the matrices that had been created from their own specification criteria and questionnaire responses. As with the previous trial, the concept with the highest overall score was deemed to be the one most suited to both criteria and profile suggestions. The addition of weighted criteria made this scoring process more reliable, favouring important elements that may have ordinarily been out-numbered by less important components.

After selecting a concept for development, the completed matrices were used to highlight the strengths and weaknesses of each proposal. This was done to indicate areas of concern that required attention and to suggest desirable features that might be borrowed from otherwise unsuitable concepts. Once revisions had been made, a final group meeting was called for in which participants were asked to evaluate their final CAD model using the same matrix that was used to assess their initial concepts. The purpose of this exercise was to emphasise any changes or improvements that had been made to the initial conceptual design. At the end of the meeting, participants were asked to complete the same feedback questionnaire as used in the earlier professional user trial.

7.7 Data Analysis

It was the primary aim of both trials to establish usability of the proposed DFRM tool and its effectiveness in assisting product design for Rapid Manufacturing. In each instance, a practical design exercise was used to provide trial participants with a focus upon which to concentrate DFRM tool assisted design activities. This enabled participants to complete a feedback questionnaire, providing data that was deemed necessary to fulfil the stated research objectives. The same questionnaire was used in each trail, and it was structured to address the following four themes:

- Legibility and clarity of DFRM tool literature
- Whether or not the DFRM tool assisted the design process
- Approaches normally used for concept generation and evaluation
- Miscellaneous user comments and constructive criticism

Ten questions where used to address these issues, of which five where related to the key area of usability and functionality. The other five questions were used to gauge the tool's comprehensibility; methods or approaches that participants would normally use and to provide an opportunity for any miscellaneous comments. In each of the usability questions, a 5-point numeric scale was used for interviewees to indicate the magnitude of their responses. This was done to provide a clear and unmistakable means with which to gauge participant opinions. Fully completed copies of each questionnaire are contained in Appendix F. However, the following pages provide an overview of the five key questions, participant responses and a brief interpretation of collated data.

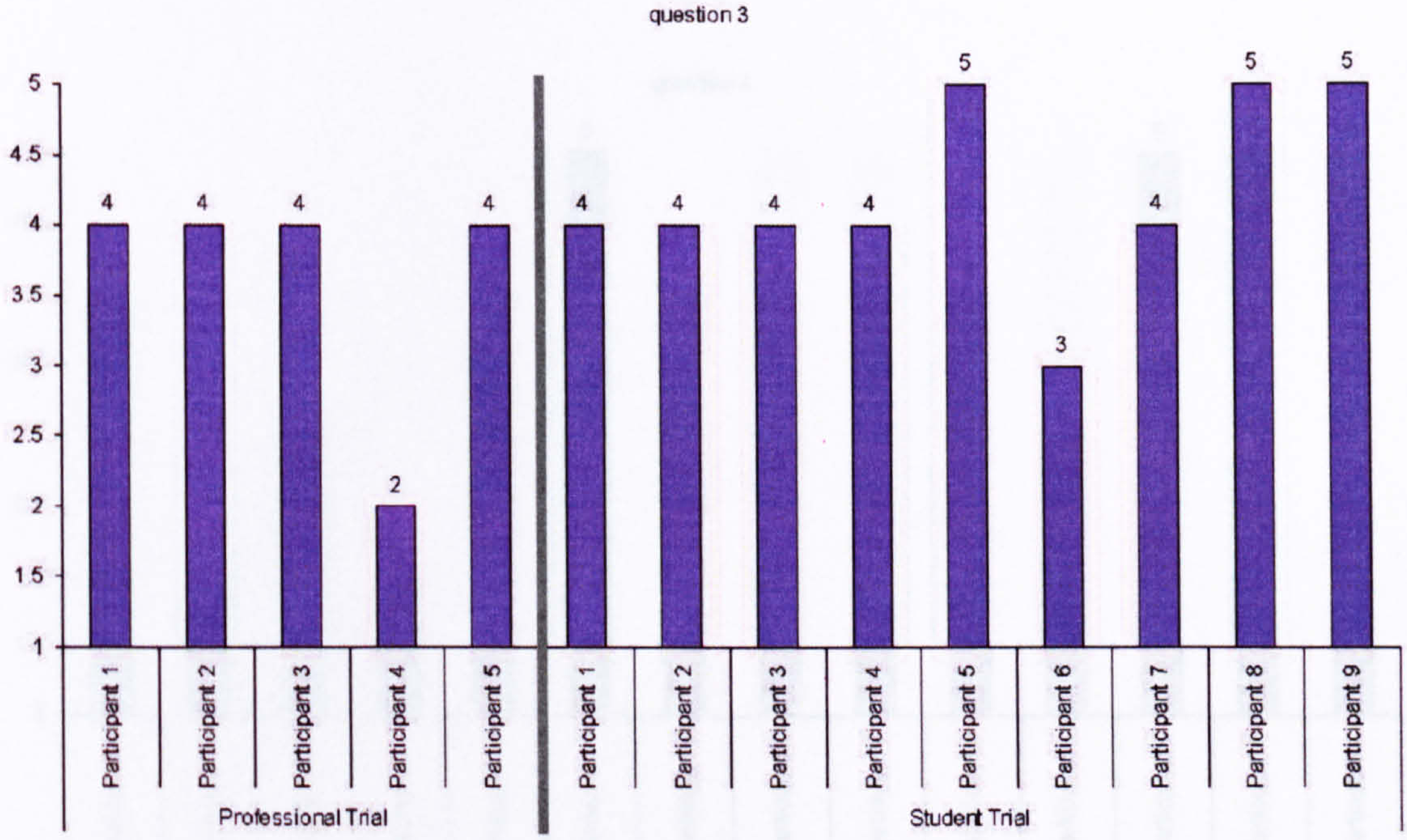
Question:

Were the concept suggestions useful when performing the design exercise?

1 2 3 4 5

(No, not at all) (Yes, very much so)

In this question an attempt is made to gauge how useful the concept suggestions where during the design exercise. The individual responses to this question were as follows:



With the exception of one participant, the professional users all found the suggestions to be of use. A similar result is reflected in the student trial, with eight positive answers and only one neutral response.

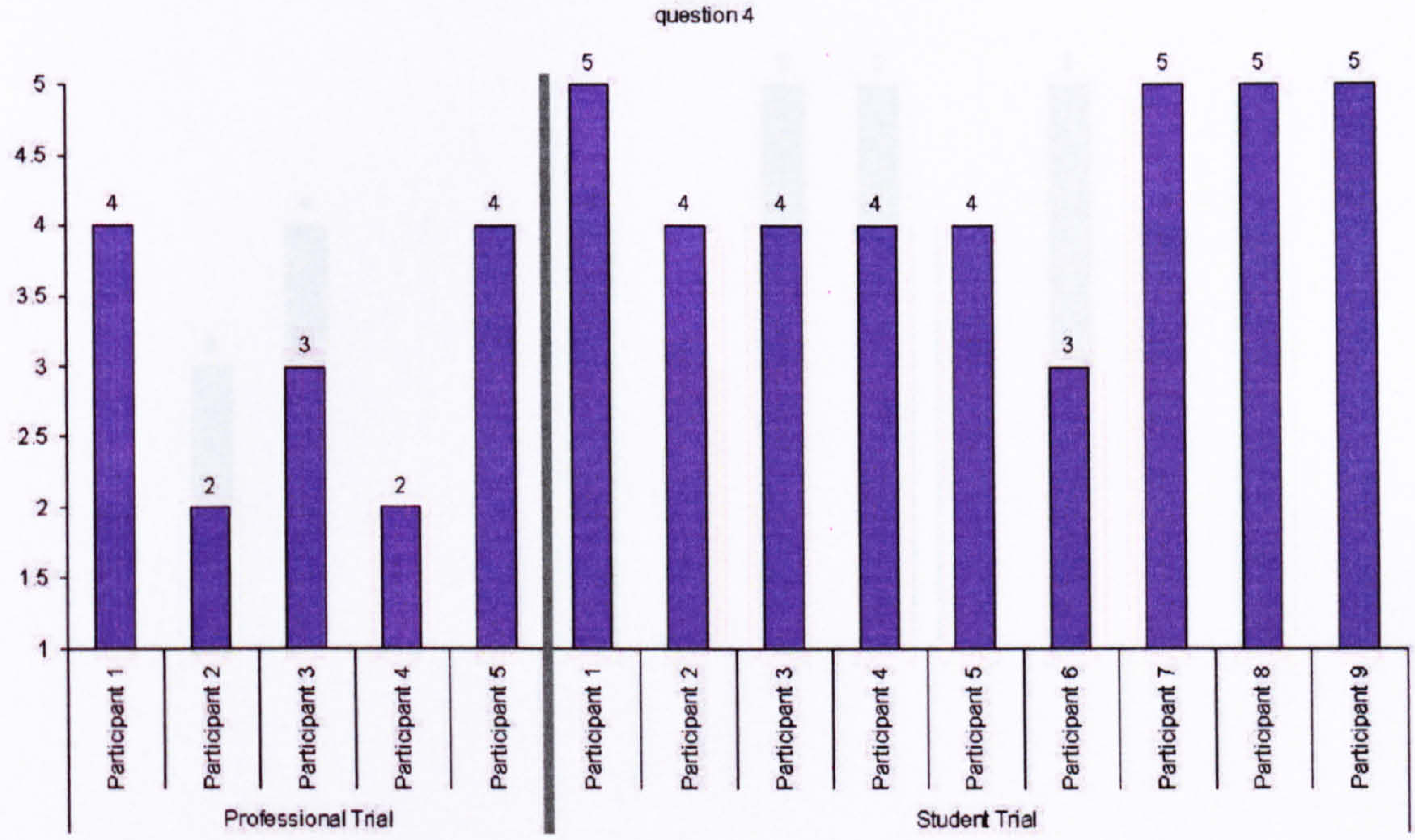
Question:

Do you feel your designs were influenced by the concept suggestions?

1 2 3 4 5

(No, not at all) (Yes, very much so)

This question was used to determine whether or not design concepts were influenced by the profile suggestions made, altering what might have otherwise been produced. The individual responses to this question were as follows:



Here professional opinions are divided between positive and negative, but are balanced to form an overall pattern of neutrality. The student samples are all positive with the exception of one neutral response, indicating that the DFRM concept suggestions were felt to be influential.

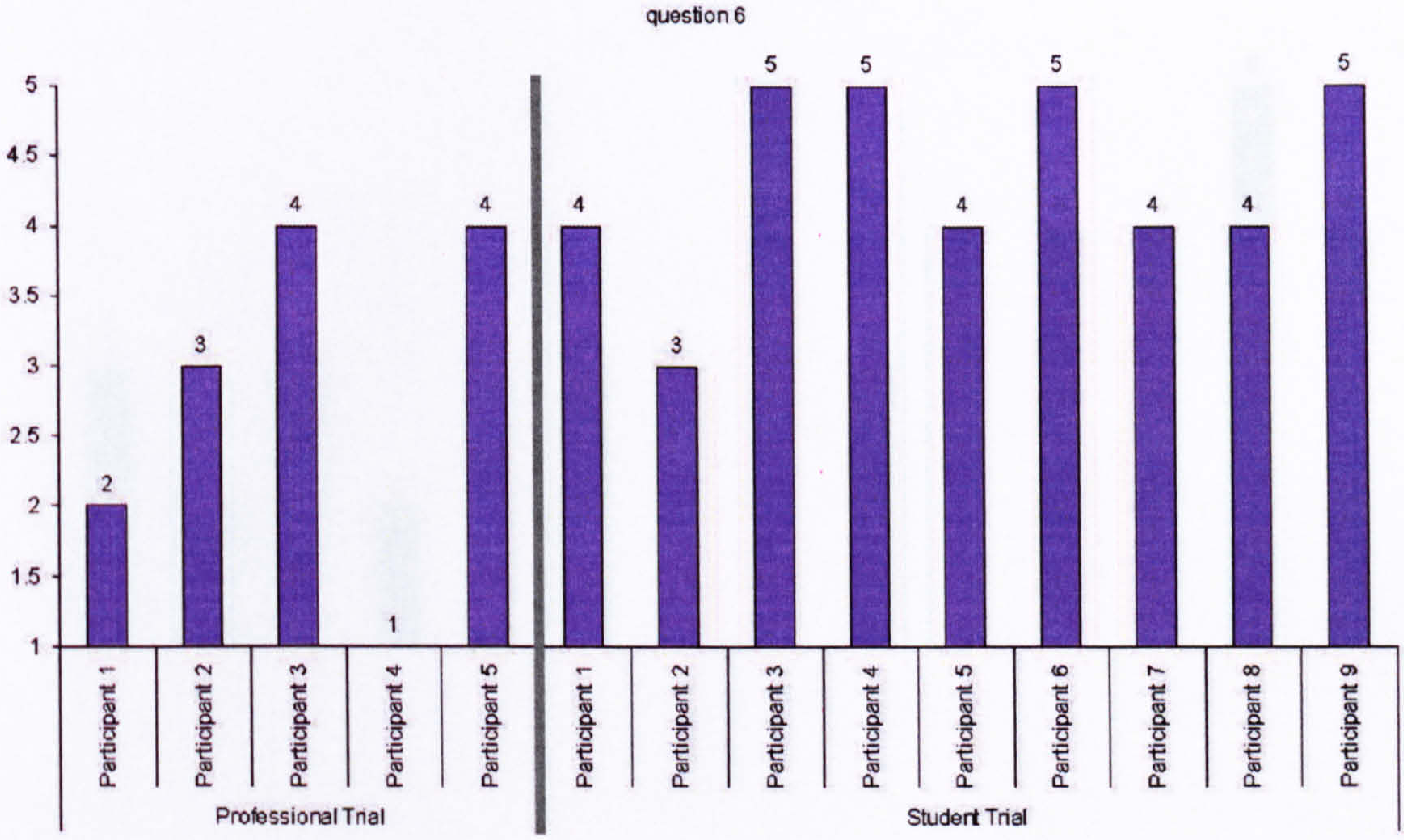
Question:

Do you think your design activities would benefit from using a systematic approach like the one you have just used?

1 2 3 4 5

(No, not at all) |____|____|____|____| (Yes, very much so)

With this question participants are asked to gauge how beneficial a systematic approach would be to their normal design activities. The individual responses to this question were as follows:



Once again the professional responses to this question were mixed. However the negative response of participant number 4 resulted in a mean result that was slightly below neutral. In contrast to this, the student responses were nearly all positive, and with the exception of one neutral response, they all felt that their work would benefit from a systematic approach as used in the DFRM tool.

Question:

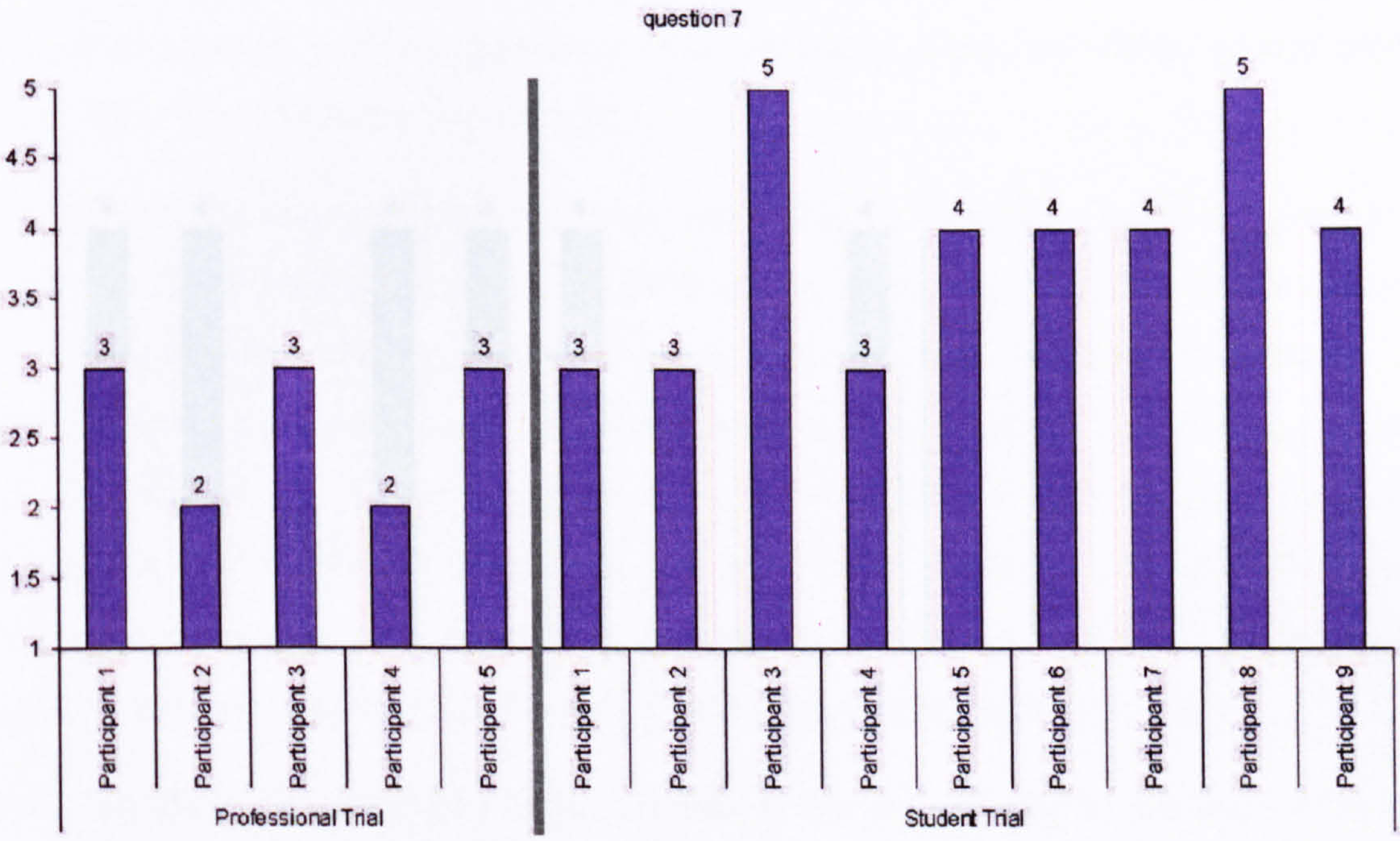
How effective would you say this systematic approach is in comparison with any other design methods that you use?

1 2 3 4 5

(Less effective) |___|___|___|___| (More Effective)

(Same)

Here participants were asked to compare the DFRM tool with other methods or approaches that they would ordinarily use to design products. The individual responses to this question were as follows:



The professional feedback for this question comprised three neutral responses and two negative. The negative responses resulted in an overall average that is slightly below neutral. However, student feedback was more favourable with three neutral responses and six positive, suggesting that the tool assisted approach was more effective than the methods that they would normally apply.

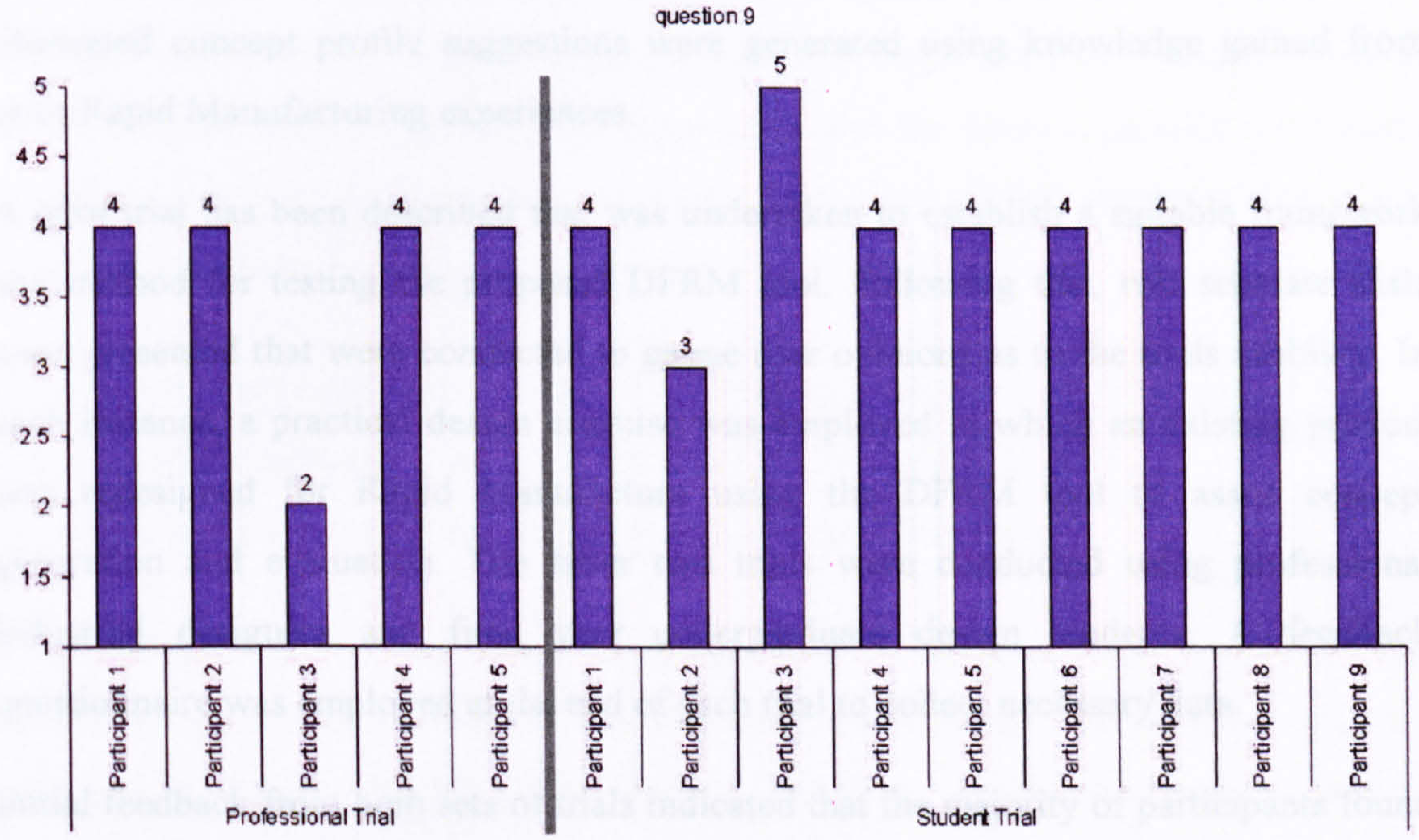
Question:

Did you find the assessment matrix helpful in selecting a preferred design?

1 2 3 4 5

(No, not at all) (Yes, very much so)

This question asked participants to determine whether the matrix approach assisted the evaluation and selection of design concepts. The individual responses to this question were as follows:



The question was met with an almost unanimous response from all participants. With the exception of one negative response, the professional users all agreed that the matrix system assisted their concept evaluation. This sentiment was reflected in the student feedback, which was comprised of eight positive responses and one neutral.

7.8 Chapter Summary

In this chapter a framework has been put forward to assist the design of products for Rapid Manufacturing. The proposed DFRM tool incorporates process validation to assess the suitability of Rapid Manufacturing for the production of any given product. A concept profiler is used to suggest applicable design features that are made possible with Rapid Manufacturing and an assessment matrix is used for the objective evaluation of design concepts. A pivotal element to each of the three tool components is a generic product questionnaire that is used at the onset of a design project to gauge stakeholder perceptions of the focus product.

Product questions are ordered into groups that were felt by the author to represent the areas most applicable to Rapid Manufacturing. These groups were established using observations from the prior literature review and case study projects. Similarly, the illustrated concept profile suggestions were generated using knowledge gained from prior Rapid Manufacturing experiences.

A pilot trial has been described that was undertaken to establish a suitable framework and method for testing the proposed DFRM tool. Following this, two separate trials were presented that were conducted to gauge user opinions as to the tools usability. In each instance, a practical design exercise was employed in which an existing product was redesigned for Rapid Manufacture using the DFRM tool to assist concept generation and evaluation. The latter two trials were conducted using professional industrial designers and final year undergraduate design students. A feedback questionnaire was employed at the end of each trial to collect necessary data.

Initial feedback from both sets of trials indicated that the majority of participants found the DFRM concept suggestions to be of use and that their design concepts were influenced by the suggestions made. Likewise, the DFRM tool's concept evaluation matrix was found to be of assistance to almost all of the participants. However, user opinions of the DFRM tool's systematic approach in relation to typical design approaches were mixed. Whilst the student group generally indicated a preference toward the use of such a system, professional designers seemed to be less positive, favouring their own "tried and tested" methods.

8 DISCUSSION

8.1 Overview

In previous chapters a study was made of Rapid Manufacturing and its predicted effect upon the design of products from an industrial design perspective. Using abstract elements from existing design strategies, a systematic approach was developed to assist industrial designers in exploiting the capabilities and freedoms associated with Rapid Manufacturing. This suggested framework was composed of three sections that perform the following functions:

- Assess user perceptions of product requirements and the appropriateness of RM
- Suggests applicable conceptual features that are enabled by RM
- Assists the evaluation and selection of RM design concepts

Two separate sets of user trials were described in which a design exercise was conducted to establish usability of the proposed DFRM system and its effect upon the concept generation process. The results of these trials indicated a general acknowledgement from participants that the DFRM tool was of use to the design process and that it influenced the generation of design concepts.

This chapter discusses the overall research objectives that were identified at the start of the project and how they have been met during the course of work. The research questions that were posed in Chapter 5 to direct the formulation of a suitable DFRM tool are reiterated, along with answers that have since been derived. Finally a summary discussion is presented that deals with the DFRM tool and its use.

8.2 Research Objectives Achieved

A number of objectives were identified at the beginning of this research project. The following section recounts these objectives and discusses how the various issues have been addressed.

- *To identify the methods, tools and strategies that have been formulated and applied to the New Product Development process*

- The NPD process was first defined and industrial designers were identified as key stakeholders. A literature review was then conducted to study the practice of industrial design, distinguishing it from that of engineering design and charting typical procedural events. Product "Newness" and "Status" were identified as factors affecting the scale and complexity of NPD projects, before identifying a number of systematic methods and approaches that have been formed to assist the design and development of new products. Specific strategies included Knowledge Management, Value Analysis and Design for Manufacture. The "Total Design" approach was also introduced as a holistic ideology in which design is seen to encompass all aspects associated with NPD, from the initial identification of a market need to the manufacture and marketing of a saleable product. In each instance, a reoccurring theme was that of various matrices as effective decision support tools.

- *To determine the key technologies that are commonly applied within the practice of industrial design and concept generation*

- During an expansive literature review, various product design media were identified that ranged from paper-based drawing and sketching to advanced digital technologies. Drawing was established as a key skill for industrial designers and physical 3D models of different sorts were noted as playing an important role in the design and communication of product concepts. Recent advances in Computer Aided Design (CAD) were accredited with making the technology an integral part of product design and development. An introduction was made to a variety of different input devises that facilitate the generation and manipulation of geometries within virtual CAD environments. Haptic devices were discussed as responsive interfaces that enable intuitive creation of the sort of organic part geometries that are a common trait of many industrial design concepts. Reverse Engineering technologies were also introduced as a means with which to capture surface geometries from real world objects. This latter technology enables the generation of data that would be impossible to replicate by other means and supports the use of traditional physical models in form creation. Various output devices were discussed before giving an overview of Rapid Prototyping, which uses additive manufacturing to produce physical objects from virtual CAD data.

In addition to the literature review, direct involvement with case study work provided a practical opportunity with which to observe the described media forms in the context of live product design projects. This afforded a much greater depth of procedural knowledge than could have been attained through pure literary sources.

- *To track the development of Rapid Manufacturing and access the impact that it has upon product design and development*

- Rapid Manufacturing was introduced and defined as the use of additive manufacturing systems for the direct production of finished goods from digital data. Whilst it was stated that no true Rapid Manufacturing systems exist at the present time, numerous examples of work have been observed using current Rapid Prototyping technologies. The negative effects associated with these improvised technologies were noted as being high operating costs; slow build times; an absence of many true engineering materials; relatively low accuracy and poor surface finish. However, the continued improvement of both systems and materials has led toward a greater functionality of parts and an increase in the number of RM applications and practitioners.

It was noted that powder-based systems are the most prevalent machine format to be applied to current Rapid Manufacturing applications. The mechanical advantages associated with powder deposition processes include the elimination of inbuilt supporting structures, a greater range of build materials and the ability to consolidate multiple build materials within a single part.

A number of procedural benefits and constraints were noted before discussing the effect of Rapid Manufacturing upon designing. Direct production of end use parts from digital sources is seen to shorten conventional process chains to an extent in which industrial designers are brought into direct contact with manufacturing. Effectively, this expands the designer's remit and creates a "hybrid" individual who is versed with cross-disciplinary knowledge and capable of performing actions that would be traditionally associated with mechanical and manufacturing engineers. Other specific implications of Rapid Manufacturing upon the design of products included Manufacture for Design (Using process flexibility to reverse the conventional DFM ethos); the ability to produce parts of greater geometrical complexity than was previously possible; the individual customisation of parts and the elimination of part shipping and storage.

- *To recommend and test a strategic tool or approach that would assist industrial designers in the generation of product concepts to be produced by Rapid Manufacturing*

- Using procedural knowledge gained from the literature review and case study projects, a multi-faceted tool was put forward to assist industrial designers in the design of products for production by Rapid Manufacturing. Based around a central questionnaire, it was the aim of this DFRM tool to establish the appropriateness of use of RM for any given product; to suggest applicable concept features enabled by RM and to assist the evaluation and selection of design concepts.

  A series of pilot trials were conducted to establish an appropriate tool format and suitable test procedure with which to obtain feedback upon the tool's usability. With a finalised tool framework and test procedure in place, two separate sets of user trials were conducted using undergraduate design students and practicing industrial design professionals. Results from these trials showed the majority of participants to be in favour of the tool's concept profiler and evaluation matrix elements. However, opinions as to the likelihood of tool uptake were mixed, with a positive response from the student group and the professional designers favouring their own "tried and tested" methods.

- *To identify future research and development that would be required to transform the recommended approach into a commercial package*

- Suggestions are made to address this issue in a later section of this chapter and amongst the thesis' final conclusions.

8.3 Research Questions Answered

Formulation of the proposed DFRM tool was conducted inline with a set of questions that were posed in Chapter 5 to ascertain procedural knowledge and establish a suitable system for its dissemination. An outline of these research questions and their answers is given below.

- *What are the capabilities of Rapid Manufacturing as a method of end-use part production?*

- The primary process capabilities were noted as being:
  - Provides an almost unbound freedom of geometric creation
  - Enables the consolidation of fixed assembly parts and components
  - Economically feasible low volume production (order numbers as low as one)
  - Versatile manufacturing centres (product range and geographic location)
  - Composite fabrication of individual parts using multiple materials

- *What impact will the process have upon the design of products from an industrial design perspective?*

- Industrial design concepts are often compromised to comply with production issues, something that is well illustrated by the Remploy case study that was discussed in chapter 6. However, the ability of Rapid Manufacturing to produce parts of almost any geometry and with low order numbers provides industrial designers with a freedom to realise product designs that are without compromise. Table 8.1 highlights some of the features that might have been incorporated in the Remploy Caresse™ Hip protector had it been designed for Rapid Manufacturing. This alternate design would be unrestrained by many of the issues that shaped the current product and would provide a much more user-focused solution, as was originally intended.

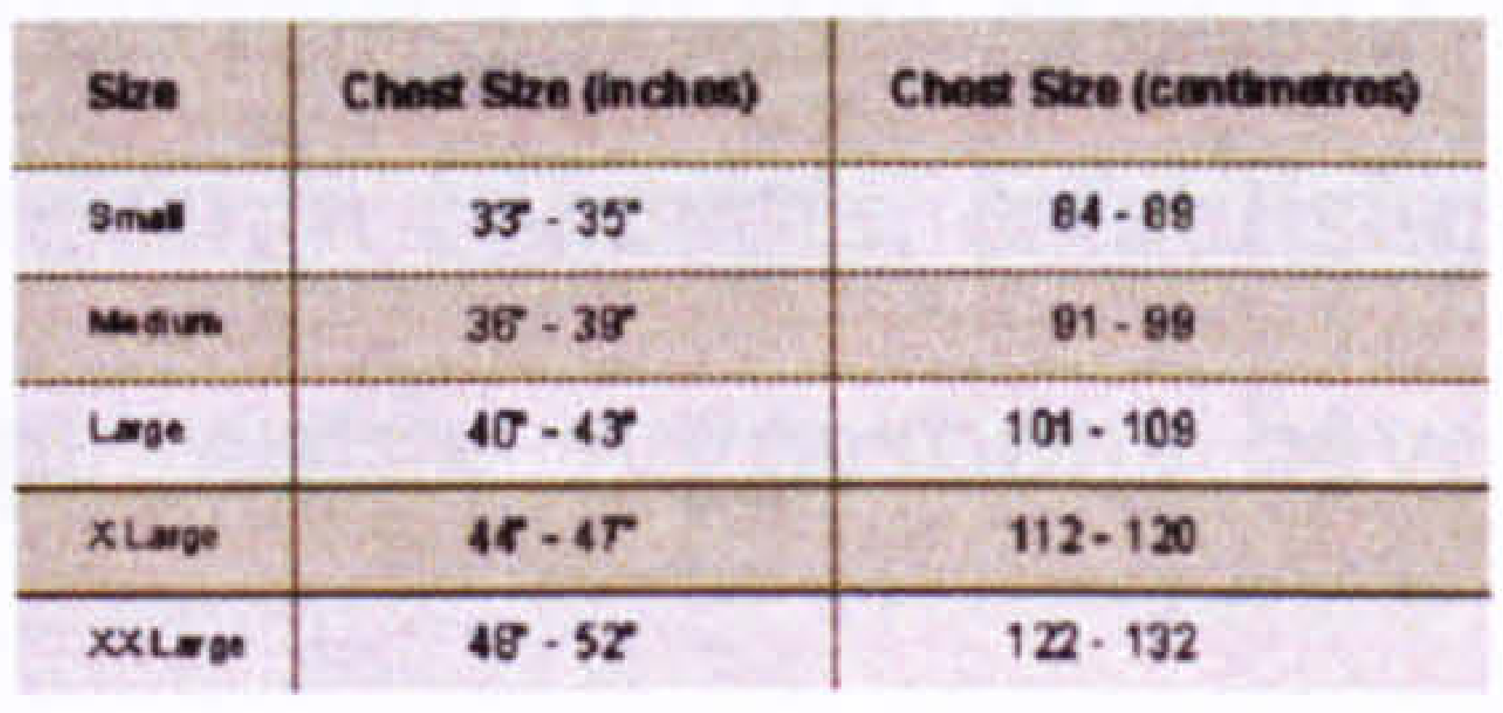
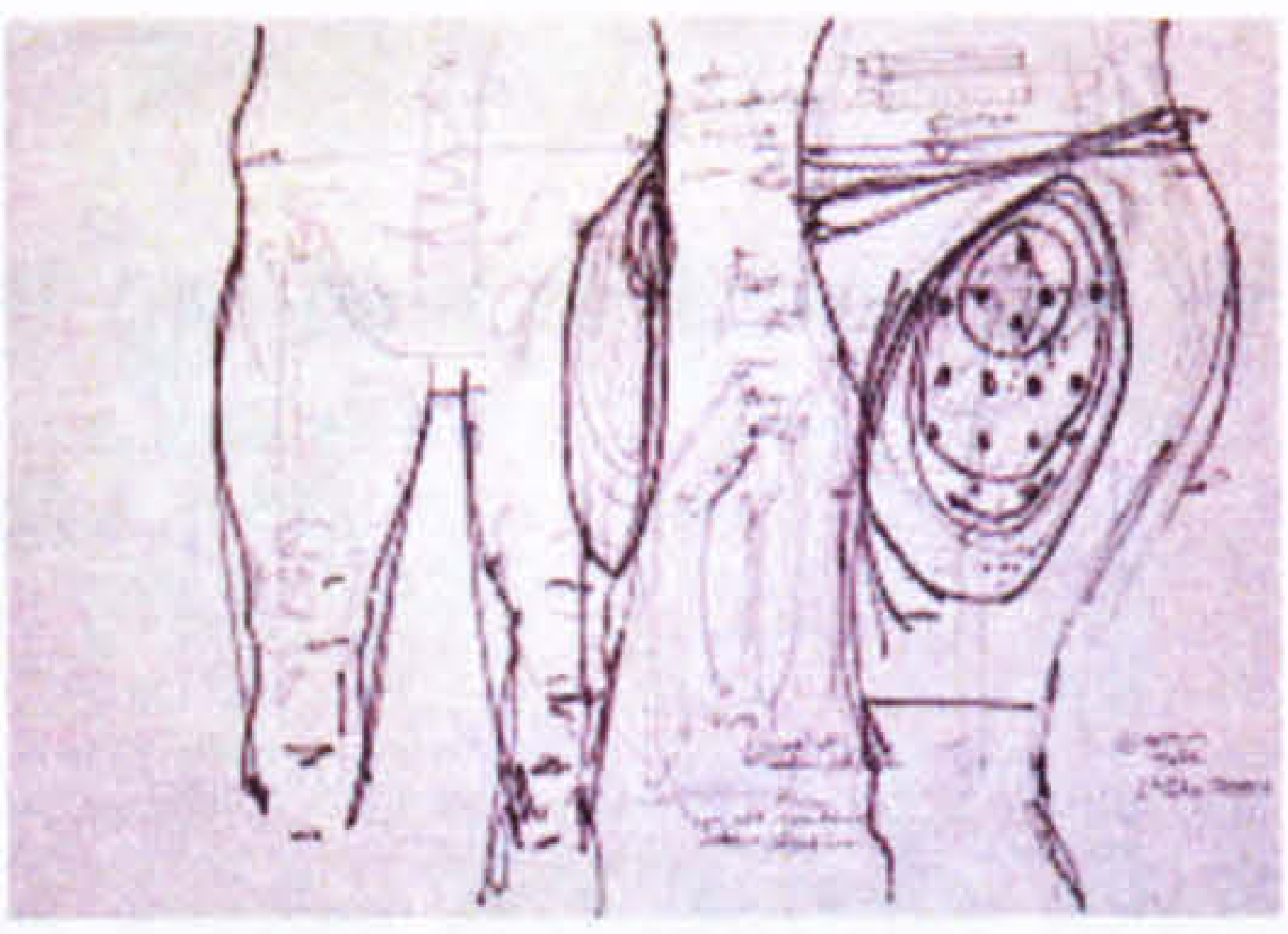
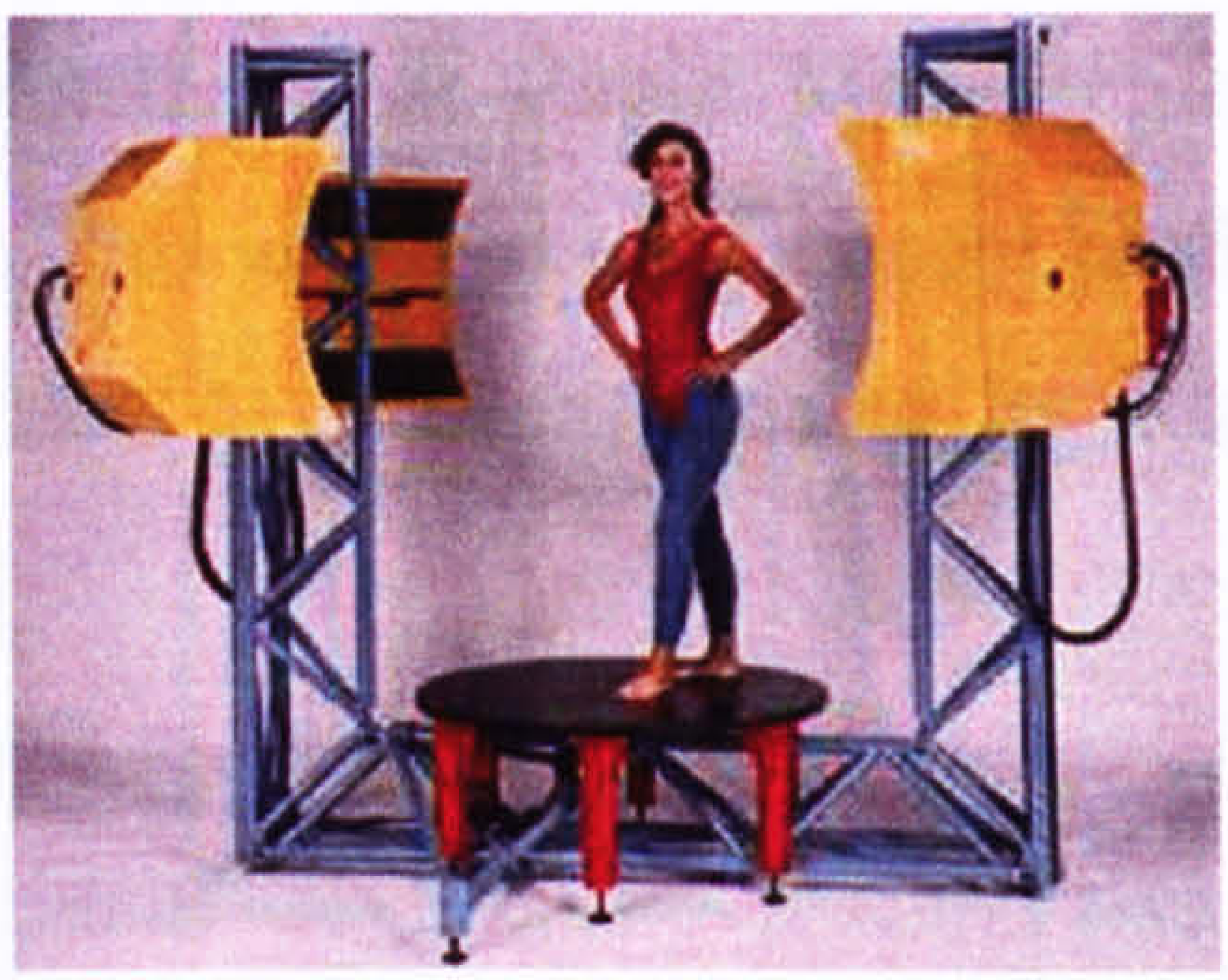
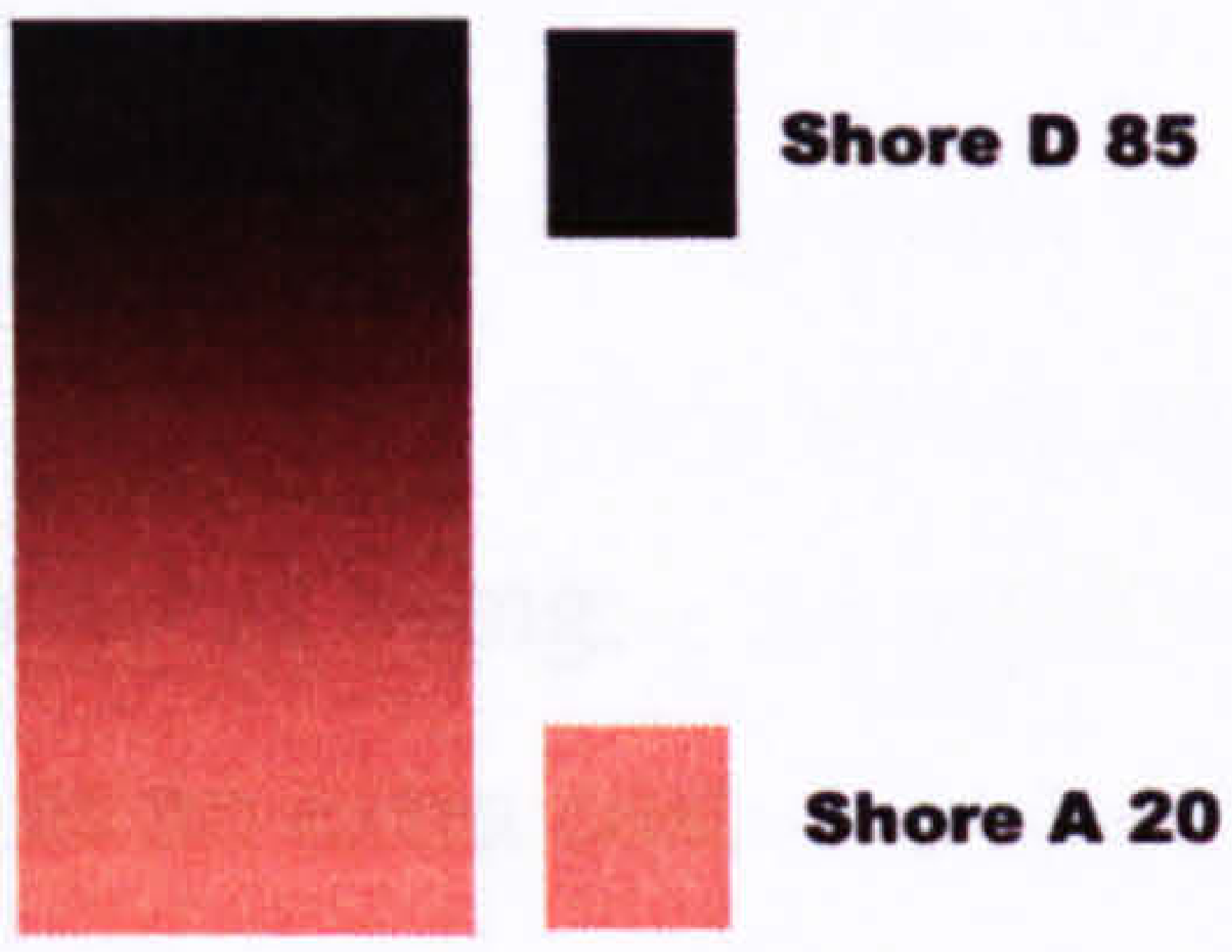
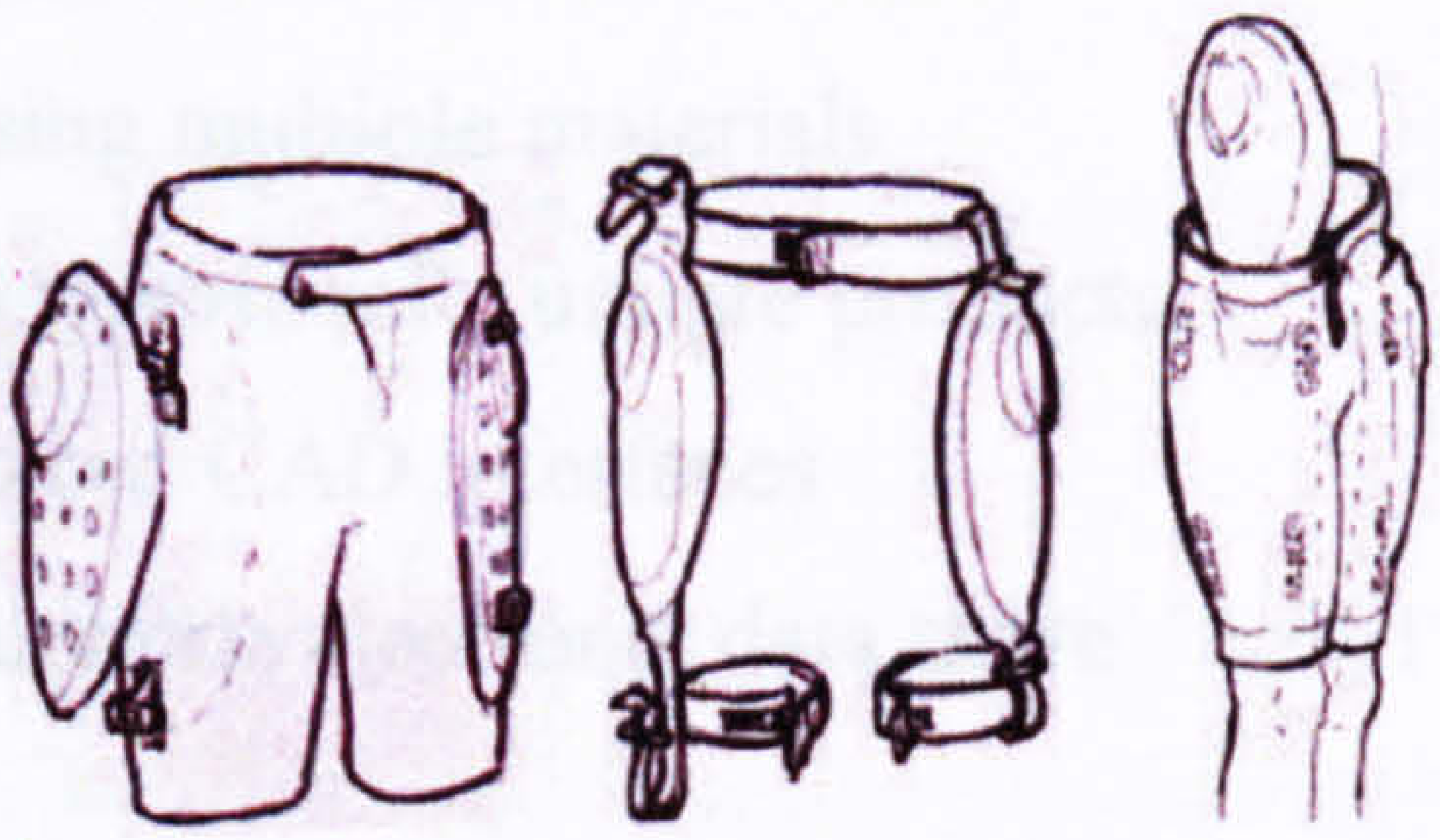
<table>
<tr><th colspan="2">Remploy Caresse™ Hip Protector redesigned for Rapid Manufacture</th></tr>
<tr><th>What an RM concept might include:</th><th>Illustration:</th></tr>
<tr><td>Different sizes to account for percentile range</td><td><table><tr><th>Size</th><th>Chest Size (inches)</th><th>Chest Size (centimetres)</th></tr><tr><td>Small</td><td>33" - 35"</td><td>84 - 89</td></tr><tr><td>Medium</td><td>36" - 39"</td><td>91 - 99</td></tr><tr><td>Large</td><td>40" - 43"</td><td>101 - 109</td></tr><tr><td>X Large</td><td>44" - 47"</td><td>112 - 120</td></tr><tr><td>XX Large</td><td>48" - 52"</td><td>122 - 132</td></tr></table></td></tr>
<tr><td>Separate asymmetric pads for left and right hand sides instead of single symmetrical form.</td><td></td></tr>
<tr><td>A customised body-fitting design using RE technologies to scan the body geometries of individual users. This would provide a more comfortable and better fitting product that was contoured to fit individual users (like the Amfit Footfax in chapter 3, p62). This would also allow the edges to be blended with the user to create a less obvious protrusion.</td><td></td></tr>
<tr><td>More subtle transition gradient used to vary the protective pad's composition, from a hard rigid outer facing plate to a soft and flexible inner facing foam.</td><td> </td></tr>
<tr><td>Integration of appropriate garment or body fixation method such as belt, strap, button, catches or eye holes etc. for better positioning and more effective protection.</td><td></td></tr>
</table>

Table 8.1: Impact of RM on a previously compromised design concept

- *How may industrial designers best exploit Rapid Manufacturing technologies to create optimum product design concepts?*

- The evaluation matrix that is contained within the proposed DFRM system enables users to perform an objective analysis of multiple design concepts, establishing the degree to which specification criteria and concept profile suggestions have been addressed.

- *How may formal design strategies be used to assist the best practice use of Rapid Manufacturing technologies by industrial designers?*

- The proposed DFRM system uses a questionnaire to assess stakeholder perceptions of a product's requirements and determine exactly what Rapid Manufacturing features are applicable to that particular product. This is linked to a concept profiler that suggests appropriate conceptual features that have been enabled by Rapid Manufacturing.

Additional questions in this area included:

- *What are the tangible benefits of Rapid Manufacturing?*

- The main benefits of Rapid Manufacture were noted as being:
  - Geometry for free: Any complexity of geometry at no extra cost
  - Design freedom: Unrestricted by conventional considerations
  - Materials: Composite fabrication of parts using multiple materials
  - Custom parts: Order number of one enables individually unique products
  - Innovative Interfaces: Supports use of advanced CAD interfaces
  - Collaborative design: Digital process that supports electronic data share

- *What are the criteria that make a product particularly suitable for production by current rapid manufacturing technologies?*

- The following points were identified as making a product suitable for RM:
  - Complex or demanding part geometries: Exploits freedom of creation
  - Low production volumes: Output restricted by slow build speeds
  - Customised product: Exploits freedom of creation and low order number
  - Immediate product demand: RM enables short NPD cycle time
  - High value product application: Resulting from high production cost
  - Relaxed surface requirements: Laminate production gives poor surface finish

- *What are the restrictions of current CAD technologies upon Rapid Manufacturing?*

- Whilst CAD is a key enabler of the Rapid Manufacturing process, current CAD technologies are a bottleneck that restricts process capabilities. A high degree of user skill is required to operate most systems, which often limits form creation. Insufficient bridging technologies also mean that design intent is often compromised when translating part geometries from other forms of design media, such as paper-based sketches. The ability of RM to produce practically any part geometry stretches the modelling capability of the most proficient CAD operators and places considerable demands on processing hardware. Specialised equipment, such as haptic interfaces and Reverse Engineering technology, provide a means with which to create geometries that would be impossible using other methods. However, with current professional systems and software costing the equivalent of ten or more CAD workstations, their uptake is limited to larger and more affluent organisations.

- *To what extent are current design strategies applicable to the formulation of a specific Design For Rapid Manufacturing (DFRM) tool?*

- Matrices were noted as frequently occurring elements of many formalised design strategies and were proven to be an effective tool for the objective evaluation of design concepts during the DFRM user trials. Similarly, the concept profile suggestions, which are a common trait of other established DFM and knowledge-based systems, were found to be of use by practically all of the trial participants.

- *How may a DFRM strategic tool be applied and what form might it take? (i.e. handbook, log table, matrix, computer software, etc)*

- The proposed DFRM tool used a set of paper-based literature that included a questionnaire, an illustrated guide booklet (concept profiler) and a tabular matrix for the evaluation of design concepts. These were all proven effective when tested in the user trials. However, the paper-based format was labour intensive and it is felt that a computer-based DFRM tool would require less manual interaction when correlating questionnaire results with applicable profile suggestions and evaluating different matrix variables.

8.4 Summary Discussion

Conventional Value Engineering balances functional cost against manufacturing cost with the aim of equipping products with as much functionality as is economically viable. However, one of the main procedural benefits of Rapid Manufacturing is that of "geometry for free", in which any complexity of part geometry can be produced at no extra cost. This makes it feasible to instil design concepts with any number of functional features, whether they are appropriate to the product or not.

Presenting industrial designers with a simple list of RM capabilities provides them with numerous design possibilities, although it does not identify which features are most appropriate to the product that they are designing. This issue is addressed by the DFRM questionnaire, which assesses stakeholder perceptions of a product's requirements to determine exactly what sort of RM enabled features are most appropriate for that particular product. These are then graphically illustrated with the suggestive concept profiler, in a manner that is appropriate to the designer's visual acuity, using examples from a database of previous DFRM projects. Ideally, the database would be frequently updated to include exemplar RM features from new projects to provide a rich supply of inspirational source material.

Having generated an initial set of design concepts, the DFRM matrix provides an objective means of evaluation, enabling the benchmarking of multiple concepts to highlight the specific strengths and weaknesses of each one. The primary function of this is to identify which design is most suitable for development or production in relation to the project's original specification criteria and DFRM suggestions. However, it is possible that certain favourable points may be identified within rejected designs that may be incorporated or built upon when developing the concept that is actually chosen.

Initial feedback from both sets of user trials indicated that the majority of participants found the DFRM concept suggestions to be of use and that their design concepts were influenced by the suggestions made. Likewise, the DFRM concept evaluation matrix was found to be of assistance to almost all of the participants. However, opinions as to the tool's systematic approach in relation to typical design activities were mixed. Whilst the student group generally indicated a preference toward the use of such a system, the professional designers seemed less positive, favouring their own "tried and tested" methods. It could be argued that these differences reflect the "glass box" and "black box" mindsets that were identified by Jones (1992), with the more experienced designers representing "black boxes" and the students "glass boxes". However, in this instance it is likely that the design students were simply prone to a more open-minded adoption of new methods as a result of their fledgling status.

As recent products of an educational process, the design students were well used to the adoption of new methods and approaches, making them highly receptive to new ideas and concepts like the DFRM tool. In contrast, the professional designers would have amassed a greater wealth of personal experience and established their own fixed working practices, so it is understandable that they would show a degree of hesitancy in adopting a new and unknown approach. The fact that each of the test groups both recognised the benefits of the DFRM is good. However, the professional group's reticence toward tool uptake is indicative of what would probably occur when attempting to promote the DFRM tool on a larger scale.

It is likely that the initial doubts and suspicions of professional designers could be dispelled with sufficient proof of the tool's positive application, showing the value it could add to products and time savings it might make. This might overcome negative user perceptions that the approach restricted creativity. However, an obvious paradox is that the majority of supporting evidence would be dependent upon the tool's initial uptake by the same peer group that needed to be convinced of its effectiveness.

An interim solution to this problem would be to collaborate with other Rapid Manufacturing research organisations, like the ones that were identified in Chapter 4. Since many of these groups are already engaged in live commercial projects, they would provide an ideal testing ground for the proposed DFRM tool (and its inevitable variants) by professional designers. Also, with prior experience of RM projects, these groups would be in a position to greatly increase the range and number of "Case-Based" examples and suggested features that are contained in the tool's database.

It is likely that this suggestion would require translation of the currently paper-based DFRM tool into a more versatile and easy-to-use format, like the self-contained computer-based program that was originally envisaged. One potential route for this translation would be for the tool to be built into an existing DFM tool as a new procedural aid that could be presented to an established user group in a format that they recognised and were familiar with using. In this guise, the tool would almost certainly take on the form of an Internet web-page type interface, with a front-end questionnaire that automatically generates profile statements and concept evaluation matrices.

As was previously stated in Chapter 7, an attempt was made to do this during the early stages of the project, but the task proved itself beyond the programming capabilities of the author due to the complex cross-linking of constantly changing program elements. This resulted in the use of a more flexible paper-based system that could be easily amended. Having since established a workable tool, with a relatively fixed content, it would be now more feasible to return toward the development of a computer-based tool. However, whilst this suggestion falls within the broad original remit of this research project, the intended scale of work that would be involved in its complete execution is beyond the reasonable scope of activity that might be included in this single PhD.

9 CONCLUSIONS AND FUTURE WORK

9.1 Overview

This final thesis chapter concludes the research project, stating contributions that have been made toward new knowledge, offering a summary conclusion and making some recommendations for future work.

9.2 Contributions to new knowledge

This PhD has resulted in the following contributions to knowledge:

- A new strategic design tool has been devised that was proven to assist industrial designers in the generation of product concepts that are to be produced by Rapid Manufacturing.

- It has been shown that existing design strategies can be incorporated within an effective DFRM tool and applied to the design of Rapid Manufactured products.

- The newly proposed DFRM tool has been shown to support conventional design media, such as paper-based sketching, that would be used by industrial designers during the generation of concepts.

- Graphic representation of process-enabled capabilities has been demonstrated as an effective means of knowledge transfer amongst industrial design practitioners.

- Decision support matrices were proven to be an effective means of evaluating RM concepts and acknowledged by users as a helpful aid to the selection of designs.

- The case study work demonstrates a cumulative gain in procedural knowledge, starting with the early Bafbox example and progressing to more process exploitive work that is featured in the JCB and user customised handle studies.

- Ancillary computer-based technologies, like Reverse Engineering and haptics, have been introduced along with practical demonstrations as to how they might be used to support future DFRM projects.

- Rapid Manufacturing has been shown to support collaborative design strategies and user-centred design, which enables greater involvement of end users within the design of new products.

9.3 Summary Conclusion

In summary, it may be concluded that this research project has been a success, having addressed all of the objectives that were identified at its outset. Rapid Manufacturing was noted as an emerging production technology that is in need of a supporting mechanism with which to assist industrial designers in the generation of suitable product concepts. Utilizing elements from existing design strategies, a systematic framework was first proposed and then tested, showing itself to be an effective means with which to guide the generation and development of Rapid Manufactured products.

From initial trial results, it is clear to see that the proposed formal design strategy will suit some users better than others, with more spontaneous designers perceiving the regimented and methodical framework as a hindrance to their fluid creativity. As Rapid Manufacturing becomes more established as a commonplace production process it is likely that experienced designers, who are familiar with process capabilities, will begin to apply intuitive "black-box" strategies. However, until that time, application of the proposed DFRM tool (either in part or whole) represents an interim solution that has been proven effective as an aid to inexperienced designers of Rapid Manufactured products.

9.4 Recommendations for Future Work

Whilst this PhD has been successful in achieving numerous research objectives, there are several recommendations for future work that could be made to expand upon the outcomes that have so far been achieved. These are as follows:

- Expansive long-term user trials to establish more comprehensive feedback and suggestions for improvement. This might include the uptake and testing of a refined DFRM tool by other RM research bodies from the various sectors that were noted in the literature review.

- Transition of the DFRM tool from a series of paper-based forms to an automated computer-based format that is less labour intensive. It is likely that this would take the form of an Internet web-page type interface, with a front-end questionnaire that automatically generated digital profile statements and concept evaluation matrices.

- Collaboration with the producers of commercial DFM and DFA systems to develop a viable DFRM support package. Corporate styles could be used to present the DFRM tool to an established user-base in a format they are used to working with.

- Expansion of the concept profile database to include more RM feature examples. This might be achieved through the formulation of a central repository of innovative RM enabled features. Standardised data collection forms could be issued to an RM user group or collective to obtain database entries from various case study projects. Collective feedback and database updates could be returned to users in the same way that computer software updates are currently issued, using update CD's or downloads from an online Website.

REFERENCES

Alexander C., 'The determination of components for an Indian village', in Jones, J.C. and Thornley, D.G. (Eds.): 'Conference on design methods' Pergamon Press, 1963

Anon, "Ta-ta to tooling", Design Engineering, London, (n APR.), p 21-22, 2002, ISSN 0308-8448

Archer L B., "*Systematic Method for Designers*", in Jones, J.C. and Thornley, D.G. (Eds.): 'Conference on design methods' Pergamon Press, 1963

Archer L B., "*Systematic Method for Designers*", The Design Council, London, 1964, ISBN w7316999.

Bak D., "Rapid prototyping or rapid production? 3D printing processes move industry towards the latter", Assembly Automation, Volume 23, Issue 4, p340-345, 2003, ISSN 0144-5154

Barclay I., Dann. Z., Holroyd. P., "New product development: a practical workbook for improving performance", Boca Raton, FL: CRC Press Boston: Butterworth-Heinemann, 2000, ISBN: 0849323851.

Battersby D., "DSM and N^2 methods", Researcher Website, Systems Engineering Innovation Centre, Loughborough University, Available at: <http://www-staff.lboro.ac.uk/~oudjb/DSM/n2_and_dsm_methods.htm> 07.01.2005

Baxter M., "Product design: a practical guide to systematic methods of new product development", London, Chapman & Hall, 1995, ISBN: 0412632306

Beaman J J., Atwood C., Bergman T L., Bourell D., Hollister S. and Rosen D., "Additive / Subtractive Manufacturing Research and Development in Europe", WTEC Panel Report, World Technology Evaluation Center Inc., Baltimore, US, 2004

Boothroyd G., Dewhurst. P. and Knight. W., "Product Design for Manufacture and Assembly", Marcel Dekker, New York, 2001, ISBN: 082470584x

Boothroyd G., "Why DFM?", Design Engineering, London, p15-16, September, 2001, ISSN 0308-8448

Boothroyd, G. and Dewhurst, P., "DFMA - Design For Manufacture and Assembly", Internet Web-page of Boothroyd Dewhurst Inc., available at: <http://www.dfma.com/dfma.htm> 07.01.2005

Broek J J., Sleijffers W., Horváth I. and Lennings A F., "Using Physical Models in Design", Conference Paper, CAID & CACD 2000, Hong Kong, 2000

Buggie F D., "New product development strategies", New York, AMACOM, 1981, ISBN 081445626x

Burdea G C., "Haptic Feedback for Virtual Reality", Proceedings of International Workshop on Virtual Prototyping, p87-96, Laval, France, 1999

Cain R.E., "Involving users in the design process: the role of product representations in co-designing", Thesis (Ph.D.), Loughborough University, 2005

Campbell R I., Martorelli M. and **Lee, H.S.**, "Surface roughness visualisation for rapid prototyping models", CAD Computer Aided Design, 34(10), 2002, pp 717-725, ISSN 0010-4485

Campbell. R I., Hague R J., Senner B and Wormald P W., "The potential for the bespoke industrial designer", The Design Journal, Volume 6, Issue 3, pp24-33, 2003, ISBN 0754609103

Campbell R.I., Cain R. and Gyi D.E., "The Role of Customer Input within The Design Process", Computing and Solutions in Manufacturing Engineering, Brasov, Romania, 16-18 September 2004

Carrascosa M., Eppinger, S. D., Whitney D. E., "Using the Design Structure Matrix to Estimate Product Development time", Proceedings of the Design Engineering Technical Conferences, Atlanta, USA, September 13-16, 1998

Clark, J., "Implementing non-contact digitization techniques within the mechanical design process", Sensor Review, Volume 20, Issue3, p195-202, 2000, ISSN 0260-2288

Chua C K., Teh S H. and Gay RKL. "Rapid Prototyping Versus Virtual Prototyping in Product Design and Manufacturing", The International Journal of Advanced Manufacturing Technology, Volume 15, Issue 8, p597-603, 1999, ISSN: 0268-3768

Chua C K., Leong K F. and Lim C S., "Rapid Prototyping: Principles and Applications" (2nd Edition), World Scientific Pub Co., Singapore, 2003, ISBN: 9812381171

Cohen L., Manion L. and Morrison K., "Research methods in education", London, Routledge Falmer, 2000, ISBN 0415195411

Cooper R., "Proceedings of the European Academy of Design Inaugural Conference", 11 – 13 April 1995, Salford, The European Academy of Design, p213, 1995

Cross N., "Engineering Design Methods: Strategies for Product Design", John Wiley & Sons Ltd, UK, 1994, ISBN 0-471-94228-6

De Beer D J. and Campbell R I., "Concept Development Through Functional RP", Society of Manufacturing Engineers, 14 PP, May 2005, SME Product ID: TP05PUB47

De Beer D J, Barnard L J. and Booysen G J., "Three-dimensional plotting as a visualization aid for architectural use", Rapid Prototyping Journal, Volume 10, Issue 2, p146-151, 2004, ISSN 1355-2546

Dean A., "Direct Manufacturing", Prototype: The dedicated journal for prototyping and direct manufacture, Issue 1, p8-15, 2003

Dickens P. and **Hague, R.** "Design for Rapid Manufacture", EPSRC Grant Reference GR/R13517/01, 2001

Dickens P., Hague R., Hopkinson N., Tuck C J., Dekker C and Wohlers T., "Rapid Manufacturing", In "Wohlers Report: Rapid Prototyping, Tooling and state of the art", Annual Worldwide Progress Report 2004, Part 7, p169-188, 2004, ISBN 0975442902

Dieter G E., "Engineering design: a materials and processing approach", New York; London: McGraw-Hill, 1983, ISBN: 0070168962.

Dhillon B S., "Advanced Design Concepts for Engineers", Technomic Publishing Company, Pennsylvania US, 1988, ISSN 1566766265

Dove R., "Rapid Manufacturing: Delivering on the promise of those 'impossible' aims", Metal Powder Report, Volume 59, Issue 1, p28-32, 2004

DSM Somos (Anon), "Functional testing in a snap" Case Study, Prototype: the dedicated journal for prototyping and direct manufacturing, Issue 3, Q2, 2004

Emori R I., "Scale models in Engineering", (In Evans 1992, Pergamon Press, 1977, p 3-5

Evans M A., "The Potential of Computer Aided Industrial Design to Act as a Catalyst for Greater Professional Collaboration", ASIS Midyear '98 Proceedings, Orlando, Florida, 1998

Evans M A., Cheshire D. and Dean C., "An investigation into the use of haptic modeling during industrial design activity", IDATER 2000, p188-193, Loughborough University, 2000

Evans M A., "Model or prototype which, when and why?", IDATER92, Loughborough University, 1992

Evans, M A., "The integration of rapid prototyping within industrial design practice", Doctoral Dissertation, Loughborough University, 2002.

Finlay P. N., "Introducing decision support systems", 2nd Edition, Oxford, NCC Blackwell, 1994, ISBN 1855543141

Frost R. A., "Introduction to Knowledge Base Systems", London: William Collins Sons & Co. Ltd., 1986, ISBN 0-00-383114-0

Freeman L. A., "Information Systems Knowledge: Foundations, Definitions and Applications", Information Systems Frontiers, Issue 3 Volume 2, p249-266, 2001

Gebhardt A., "Rapid Prototyping", Hanser Gardner Publications; 1st ed., 2003; (Originally published in German, 1995); ISBN: 156990281X.

Griffiths A., "Rapid manufacturing - The next industrial revolution", Materials World, Volume 10 Issue 12, p34-35, 2002, ISSN 0967-8638

Grimm T., "User's guide to rapid prototyping", Dearborn, Michigan, Society of Manufacturing Engineers, 2004, ISBN: 0872636976.

Hague R., Campbell R I. and Dickens P., "Implications on design of rapid manufacturing", Proceedings of the Institute of Mechanical Engineers Part C Journal of Mechanical Engineering Science, Volume 217, Issue 1, p25-30, 2003

Hague R., Mansour S. and Saleh N., "Design opportunities with rapid manufacturing", Assembly Automation, Volume 23, Issue 4, p346-356, 2003a

Halfpenny, P., "The Analysis of qualitative data", Sociological Review, Volume 27, Issue 4, pp799-825, 1979

Hänninen J., "DMLS moves from rapid tooling to rapid manufacturing", Metal Powder Report, Volume 56, Issue 9, p24-29, 2001

Harryson O L A., Cormier, D.R., Marcellin-little, D.F. and Fajal, K., "Rapid prototyping for treatment of canine limb deformities", Rapid Prototyping Journal, 9(1), 2003, pp 37-42, ISSN 1355-2546

Hieu L C., Bohez E, Sloten J V, Phien H.N., Vatcharaporn E., Binh P.H., An P.V. and Oris P., "Design for medical rapid prototyping of cranioplasty implants", Rapid Prototyping Journal, Volume 9, Issue 3, p175-186, 2003

Hill P H., "The science of engineering design" New York; London: Holt, Rinehart & Winston, 1970, ISBN: 0030813905.

Hinckley K., Pausch R, Proffitt D and Kassekk N F, "Two-Handed Virtual Manipulation", ACM Transactions on Computer-Human Interaction, Volume 5, Issue 3, p260-302, 1998

Hollins B. and Pugh S., "Successful product design: what to do and when", London, Butterworth, 1990, ISBN: 0408038616.

Hollins G. and Hollins B., "Total design: managing the design process in the service sector", London, Pitman, 1991, ISBN: 0273033387

Holmes W P. and Azam M. A., "A Preliminary Study of the Relationship Between Industrial Design and Engineering Design", Symposium on Designing Interactive Systems 1995, Michigan, US, 1995, ISBN 0897916735

Hopkinson N. and Dickens P., "Rapid prototyping for direct manufacture", Rapid Prototyping Journal, Volume 7, Issue 4, p197-202, 2001, ISSN 1355-2546

Hopkinson N. and Dickens P., "Analysis of rapid manufacturing - Using layer manufacturing processes for production", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Volume 217, Issue 1, p31-40, 2003, ISSN 0954-4062

Hsiao Shih-Wen and Chuang Jiun-Chau, "A reverse engineering based approach for product form design", Design Studies, Elsevier Science Ltd., Volume 24, Issue 2, 2003

ICSID - The International Council of Societies of Industrial Design, "Industrial design definition" ICSID Internet Website, 2004 <http://www.icsid.org> (27/11/04)

Ingle K A., "Reverse Engineering", 1994, New York: McGraw-Hill Inc, ISSN 0070316937

Jones T., "New product development: an introduction to a multifunctional process", Oxford, Butterworth-Heinemann, 1997, ISBN: 0750624272

Jones J C. and Thornley D G. (Eds.): 'Conference on design methods'. Papers presented at the conference on systematic and intuitive methods in engineering, industrial design, architecture and communications. London Sept. 1963, (Pergamon Press).

Jones J C., "A Method of Systematic Design", Conference on Design Methods, Pergamon Press, London, 1963, pp 53-73, ISSN 63018671.

Jones J C., "Design Methods", 2nd edition, John Wiley & Sons Inc, New York, 1992, ISSN 0471279587.

Kasik D J., "Viewing the future of CAD", IEEE Computer Graphics and Applications, Volume 20, Issue 1, p34-35, 2000

Kawai T., "3D displays and applications", Displays, 23(n 1-2), 2002, pp 49-56, ISSN 0141-9382.

Kermode G R., Sivaloganathan S. and Shahin, T.M.M., "Value Analysis - the technique: state of the art and future directions", 2000, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Professional Engineering Publishing Ltd., London, ISSN 0954-4054.

Klein B H., "Dynamic Economics", Harvard University Press, Cambridge, MA, 1977, ISBN 0674218663

Knoppers R. and Hague R., "CAD for Rapid Manufacturing", in: "Rapid Manufacturing: An Industrial Revolution For The Digital Age" Edited: Hopkinson N., Hague R. and Dickens P., to be published August 2005

Kochan A., "Rapid prototyping helps Renault F1 Team UK improve championship prospects", Assembly Automation, Volume 23, Issue 4, p336-339, 2003

Kojima T., et al, "Models and Prototypes", Graphic-sha Publishing, Tokyo, p6, 1991, ISBN 4-7661-0617-2, (In **Evans M.,** "The Potential of Computer Aided Industrial Design to Act as a Catalyst for Greater Professional Collaboration", ASIS Midyear '98 Proceedings, Orlando, Florida, 1998)

Kowalik J. S., "Knowledge based problem solving", Englewood Cliffs, London, Prentice-Hall, 1986, ISBN: 0135165768

Krishnan V. and Ulrich K.T., "Product Development Decisions: A Review of the Literature", Management Science, Volume 47 Issue: 1 pp 1 –21, January 2001, ISSN: 0025-1909

Kruth J P., Mercelis P., Van Vaerenbergh J, Froyen L. and Rombouts M., "Binding mechanisms in selective laser sintering and selective laser melting", Rapid Prototyping Journal Volume 11, Issue 1, p26-36, 2005

Lan Po-Ting, Chou Shuo-Yan, Chen Lin-Lin and Gemmill Douglas, "Determining fabrication orientations for rapid prototyping with stereolithography apparatus", Computer Aided Design, Volume 29, Issue 1, p53-62, 1996

Landers R., Pfister A., Hubner U., JOHN H., Schmelzeisen R. and Mulhaupt R., "Fabrication of soft tissue engineering scaffolds by means of rapid prototyping techniques", Journal of Materials Science, Volume 37, Issue 15, p3107-3116, 2002

Lawson B., "How designers think", Oxford: Butterworth Architecture, 1990, ISBN 0750602686

Li, L., Schemenauer, N., Peng, X., Zeng, Y. and Gu, P., "A reverse engineering system for rapid manufacturing of complex objects", Robotics and Computer-Integrated Manufacturing, 18(1), 2002, pp 53-67, ISSN 0736-5845

Lipson H. and Shpitalni M., "Conceptual design and analysis by sketching", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Volume 14, p391-401, 2002

Lu D., "Kanban just-in-time at Toyota: management begins at the workplace", Translation of: "Toyota no genba kanri", edited by the Japan Management Association, Stamford, Productivity Press, 1986, ISBN: 0915299089

Lorenz. C., "The design dimension: product strategy and the challenge of global marketing", Oxford, Basil Blackwell, 1986, ISBN: 0631137475.

Lowe A J. and Ridgway K., "Quality Function Deployment: 'House of Quality' illustration", website, The Ibberson Centre, University of Sheffield, Available at: <http://www.shef.ac.uk/~ibberson/Images/QFD/Example-HOQ.GIF > 07.01.2005

Luzadder W J., "Innovative Design", (In Evans 1992), Prentice-Hall, p29, 1975, ISBN: 0134656415.

MacKenzie, I S., "Input devices and interaction techniques for advanced computing", In W. Barfield, & T. A. Furness III (Eds.), Virtual environments and advanced interface design, p. 437-470. Oxford, UK: Oxford University Press, 1995, ISBN: 0195075552

Mackinlay J D., Card S K. and Robertson G G ., "Rapid Controlled Movement Through a Virtual 3D Workspace", Computer Graphics, Volume 24, Number 4, August 1990

Mansour S. and Hague R., "Impact of Rapid Manufacturing on Design for Manufacture for Injection Moulding", Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, Volume 2174, Issue 4, p453-461, 2003

McMahon C. and Browne J., "CADCAM: Principles, practice and manufacturing management", 2nd Edition, Addison Wesley Longman Ltd, England, 1998, ISBN 0-201-17819-2

Mayall W H., "The principles of design", The Design Council, London p 117, 1979, (In: **Evans M.**, "Model or prototype which, when and why?", IDATER92, Loughborough University, 1992)

Miles B L. and Swift, K., "Design for manufacture and assembly", Manufacturing Engineer, 77(5), pp. p 221-224, 1989, ISSN 0956-9944

Miles L D., "Techniques of Value Analysis and Engineering", New York, McGraw-Hill, 1972, ISBN: 0070419264.

Neap H S. and Celik T., "Value of a Product: A Definition", International Journal of Value-Based Management, Volume 12 issue 2 p181-191, 1999 ISSN 0167-4544

O'Driscoll M. "Design for manufacture", March 2002, Journal of Materials Processing Technology, v 122, n 2-3, pp 318-321, ISSN 0924-0136.

Oppenheim A N., " Questionnaire design, interviewing and attitude measurement", New York, Basic Books, 1992 (Previous ed. 1966), ISBN: 0826451764.

Pahl G. and Beitz W., "Engineering Design", translated by Ken Wallace, Luciënne Blessing and Frank Bauert ; edited by Ken Wallace, London, Springer, 1996, ISBN: 3540199179

Pandey P M., Reddy N V. and Dhande S G., "Improvement of surface finish by staircase machining in fused deposition modeling", Journal of Materials Processing Technology, Volume 132, Issues 1-3, 2003, p323-331

Pham D. and Dimov S., "Rapid Prototyping: a time compression tool", Ingenia, Number 17, p43-48, 2003, ISSN 14729768

Pham D. and Dimov S., "Rapid Prototyping and Rapid Tooling – the key enablers for Rapid Manufacture", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Volume 217, Issue 1, p1-23, 2003a, ISSN 0954-4062

Powell D., "Presentation Techniques", Macdonald & Co, London, 1991, ISBN 0-356-17584-7

Price L A, "Studying the Mouse for Cad Systems", Proceedings of the 21st conference on Design automation, p288-293, 1984

Pugh S. and Smith D G., "CAD in the context of engineering design: the designer's viewpoint", CAD 76, pp193–198, 1976

Pugh S., "The application of CAD in relation to Dynamic / Static Product Concepts", ICED83 Conference, Copenhagen 15-18 August, 1983

Pugh S., "Total Design: Integrated Methods for Successful Product Engineering", Addison-Wesley Publishing Company, Pennsylvania US, 1990, ISBN 0-201-41639-5

Purcell A T. and Gero J S., "Drawings and the design process", Design Studies, Issue 19, p389-430, 1998

Rodgers P A. and Clarkson P J., "Knowledge usage in new product design", IDATER 98 International Conference on Design and Technology Educational Research and Curriculum Development, 1998, p252 – 258

Rooks B., "Rapid Manufacturing advances at Loughborough", Assembly Automation, Volume 22, Issue 4, p333-336, 2002

Sener B., and Wormald P., "The Future of Computer Use in Product Design", Proceedings of CADE 2001 – Computers in Art and Design Education: "Digital Creativity Crossing the Border", p358-363, Glasgow, Scotland, 2001

Sener B., Wormald P. and Campbell R I., "Towards 'Virtual Clay' Modelling – Challenges and Recommendations: A Brief Summary of the Literature", Proceedings of the Design 2002 - International Design Conference, p545-550, Dubrovnik, Croatia, 2002a

Sener B., Wormald P. and Campbell R I., "Evaluating a Haptic Modelling System with Industrial Designers", Proceedings of the EuroHaptics-2002 International Conference, p165-169, Edinburgh, Scotland, 2002b

Sener B., "Enhancing the form of creation capabilities of digital industrial design tools", Thesis (Ph.D.), Loughborough University, 2004

Silverman D., "Doing Qualitative Research", Sage Publications Ltd., London, 2000, ISBN 0 7619 5822 3

Sivadas E., Dwyer. R. F., "A Comparison of Organizational Factors Influencing New Product Success in Internal and Alliance Based Products", ISBM Report 4, Pennsylvania State University, 1998
(http://www.ebusiness.xerox.com/isbm/dscgi/ds.py/Get/File-75/4-1998.pdf)

Smith D G. and Burgess E M., "The use of CAD/CAM technology in prosthetics and orthotics – Current clinical models and a view to the future", Journal of Rehabilitation Research and Development, Volume 38, Issue 3, p327-334, 2001

Sprague R H. and Watson H. J., "Decision support systems: putting theory into practice", London, Prentice-Hall, 1993, ISBN: 0130422355.

Stoll H W., "Design for Manufacture: An Overview", Article 3.1, Design for Manufacture: Strategies, Principles and Techniques, Edited by J. Corbett, et al, Addison-Wesley Publishing Company, 1991. ISSN 0201416948.

Stoll H W., "Product design methods and practices", New York, Marcel Dekker, 1999, ISBN: 0824775651

Stratasys (Anon), "Turning the screw with FDM" Case Study, Prototype: the dedicated journal for prototyping and direct manufacturing, Issue 1, 2003

Strickland M T., Mckay S. and Scanlon T J., "The development of a three-dimensional imaging system and its application in computer aided design workstations", Mechatronics, 13(5), pp. p 521-532, 2003, ISSN 0957-4158

Sturman D J. and Zeltzer D., "A Design Method for 'Whole-Hand' Human-Computer Interaction", ACM Transactions on Information Systems, Volume 11, Issue 3, p219-238, 1993

Suh N P., "The Principles of Design", Oxford University Press Inc, New York US, 1990, ISBN 0-19-504345-6

Taminger K M B., Hafley R A. and Dicus DL, "Solid Freeform Fabrication: An Enabling Technology for Future Space Missions", Invited Keynote Lecture, International Conference on Metal Powder Deposition for Rapid Manufacturing, Texas, 2002

Taminger K M B. and Hafley R A., "Electron Beam Freeform Fabrication: A Rapid Metal Deposition Process", Proceedings of the 3rd Annual Automotive Composites Conference, Society of Plastics Engineers, 2003

Taylor A J. and Taylor V M., "The use of social representation in product design", 2002, In: McDonagh D., et al., "Design and emotion: the experience of everyday things", Proceedings of 3rd Design and Emotion Conference held at Loughborough University (2002) p267-271, London: Taylor & Francis, 2004, ISBN: 041530363x.

TCT, "RM in F1 Racing: Case Studies", Time Compression Technologies Magazine, Volume 13, Issue 2, p23-26, 2005

Thurfjell L., McLauglin J., Mattsson J. and Lammertse P., "Haptic interaction with virtual objects: the technology and some applications", Industrial Robot, Volume 29, Issue 3, p210-215, 2002, ISSN 0143-991x

Turban E.," Decision support systems and intelligent systems", Upper Saddle River, NJ, Prentice Hall, 2001, ISBN: 0130894656.

Ullman D G., Wood S. and Craig D., "The Importance of Drawing in the Mechanical Design Process", Computer & Graphics, Volume 14, Issue 2, p263-274, 1990

Ulrich K T. and Eppinger S.D., "Product Design and Development", Boston, Irwin McGraw-Hill, 2003, ISBN: 0071232737

Wang C L., Wang, Y, and Yuen M F., "Design automation for customised apparel products", Computer Aided Design, Volume 37, Issue 7, pp 675-691, 2005

Westin S H., "Computer-Aided Industrial Design", Computer Graphics, Volume 32, Issue 1, p49-52, 1998

Wohlers T., "Wohlers Report: Rapid Prototyping, Tooling and state of the art", Annual Worldwide Progress Report 2002, Wohlers Associates, USA, 2002, ISBN 001055405

Wohlers T., "Wohlers Report: Rapid Prototyping, Tooling and state of the art", Annual Worldwide Progress Report 2004, Wohlers Associates, USA, 2004, ISBN 0975442902

Wright I C., "Design methods in engineering and product design", London, McGraw-Hill, 1998, ISBN 0077093763

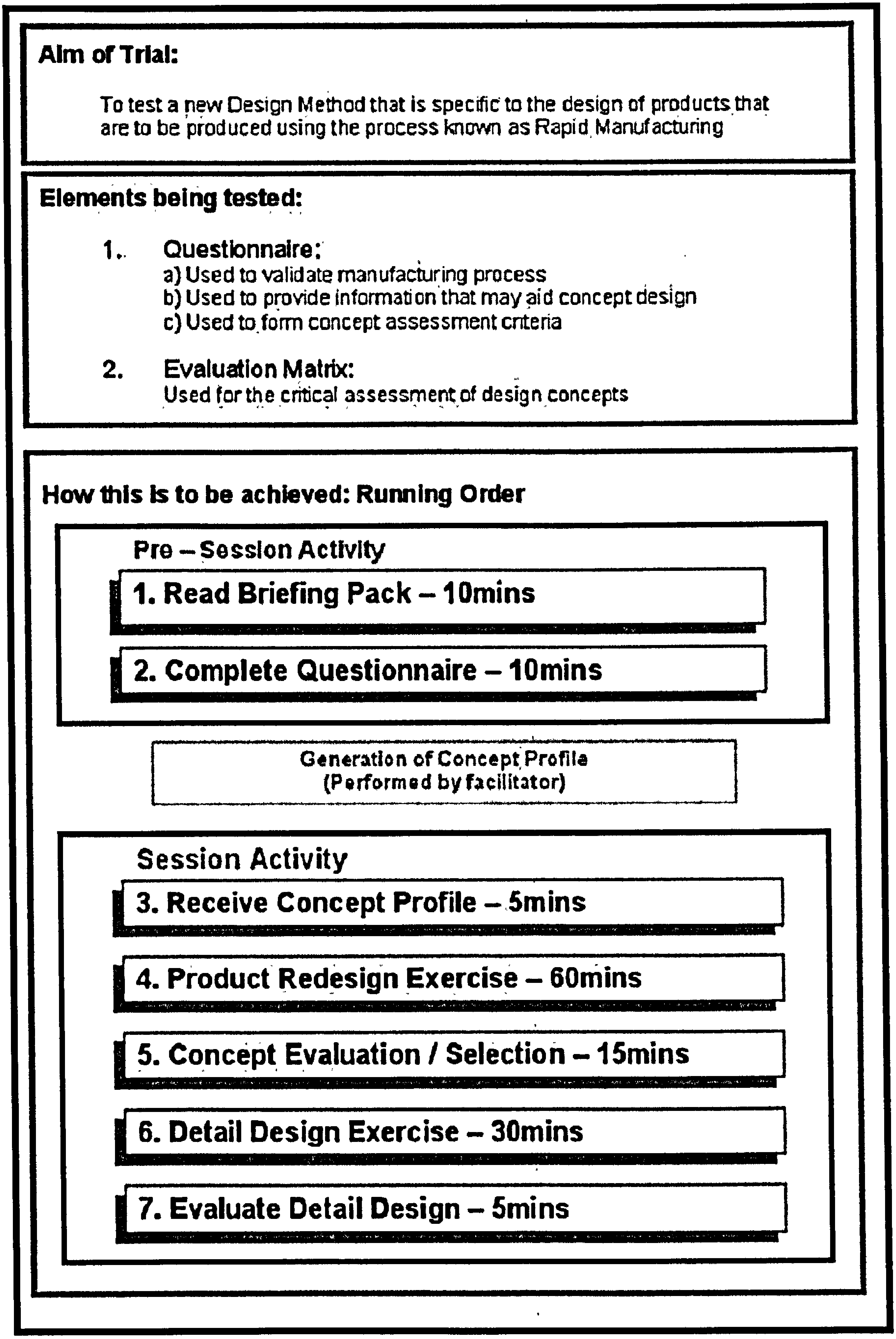
Vervis M., "The Importance of the use of physical engineering models in design", IDATER94, Loughborough University, 1994

Yan Y., Wu, R., Zhang R., Xiong Z. and Lin F., "Biomaterial forming research using RP technology", Rapid Prototyping Journal, Volume 9, Issue 3, p142-149, 2003, ISSN 1355-2546

Yaxiong L., Dichen L., Bingheng L., Sanhu H., and Gang L., "The customized mandible substitute based on rapid prototyping", Rapid Prototyping Journal, Volume 9, Issue 3, p167-174, 2003, ISSN 1355-2546

Zhengying W, Yiping T., Bingheng L., and Wei Z., "A Rapid Manufacturing Method for Water-Saving Emitters for Crop Irrigation Based on Rapid Prototyping and Manufacturing", The International Journal of Advanced Manufacturing Technology, Volume 21, Issue 9, p644-648, 2003, ISSN: 0268-3768

Appendix A Professional Trial Booklet



Aim of Trial:

To test a new Design Method that is specific to the design of products that are to be produced using the process known as Rapid Manufacturing

Elements being tested:

1. **Questionnaire:**
   a) Used to validate manufacturing process
   b) Used to provide information that may aid concept design
   c) Used to form concept assessment criteria

2. **Evaluation Matrix:**
   Used for the critical assessment of design concepts

How this is to be achieved: Running Order

Pre – Session Activity

1. Read Briefing Pack – 10mins

2. Complete Questionnaire – 10mins

Generation of Concept Profile
(Performed by facilitator)

Session Activity

3. Receive Concept Profile – 5mins

4. Product Redesign Exercise – 60mins

5. Concept Evaluation / Selection – 15mins

6. Detail Design Exercise – 30mins

7. Evaluate Detail Design – 5mins

What is Rapid Manufacturing?

Rapid Manufacturing is a relatively new manufacturing process that uses additive manufacturing technologies to produce final end use products.

Rapid Prototyping (RP) is the collective name given to a group of technologies that are used to fabricate physical objects directly from 3D CAD data. These technologies differ from conventional manufacturing methods in that they generate objects through the successive addition and bonding of material layers, a process known as additive manufacture.

Unlike more conventional subtractive processes, such as milling and lathing that generate forms by removing material from a stock billet, additive manufactured parts are built from nothing using the controlled addition of build material in predefined layers. Additive manufacturing requires no forming tools, is unrestricted by many conventional manufacturing considerations and is capable of producing practically any part geometry.

Objects created in this way start with a 3D CAD model, which may be generated using almost any of the software packages that are available in today's market place. The native CAD model is converted into a process standard format known as an STL or Stereolithography file before being sliced into a series of sections that describe the object as a set of consecutive layers. These layers are deposited in succession, one on top of the other, to create a solid three-dimensional part. A diagram of the key stages involved in this process may be seen in figure 1.

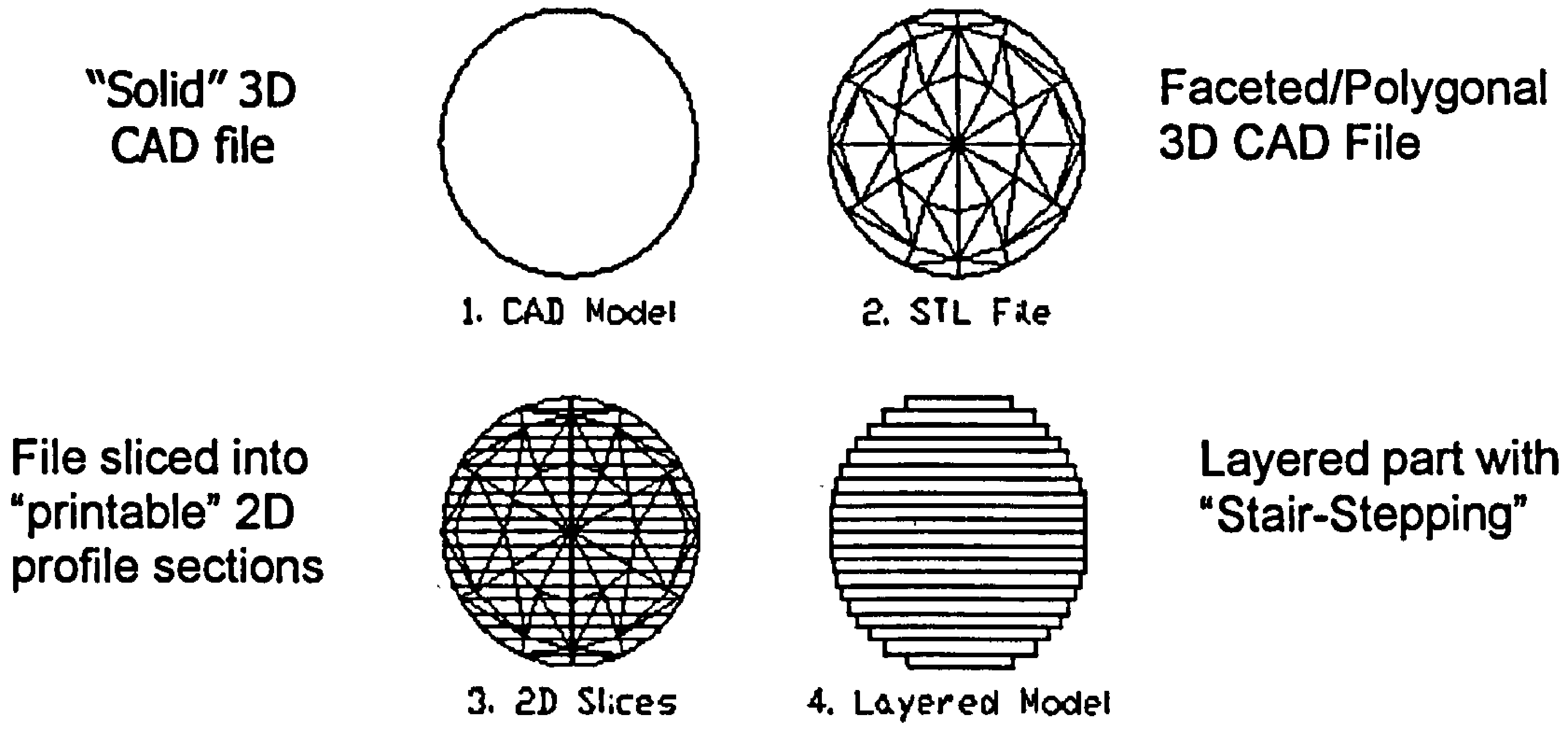


Figure 1: The Additive Manufacturing Process

There have been many advances in the field of Rapid Prototyping since it's initial appearance in the late 1980's and much speculation has been made regarding its future uses as the applicable technologies evolve. One area of much interest is that of **Rapid Manufacturing (RM)**, a process that uses additive manufacturing systems for the production of final end-use parts.

The relative infancy of these technologies mean that current examples of their application for the manufacture of end use components are limited. However, a number of Rapid Manufacturing projects, both commercial and academic, have been undertaken using currently available RP systems. One well-documented example of commercial work is the production of custom design hearing aids by Siemens Hearing Solutions and Phonak Hearing Systems.

Key benefits to arise from Rapid Manufacturing studies include:

- **Manufacture For Design instead of Design For Manufacture**
  RM offers a freedom of creation that enables the design and manufacture of products that are uninhibited by the restraints of conventional production processes.

- **Greater Part Complexity**
  The freedom of creation offered by additive manufacturing removes the constraints of conventional production methods and allows the manufacture of much more complex part geometries.

- **Part Consolidation**
  The ability to produce parts of increased complexity provides greater scope for the merging of multiple assembly components.

- **Design Customisation**
  With no production tooling or associated cost restraints it is economically feasible to produce single "one off" items that are unique to individual user specifications.

- **Elimination of Part Shipping and Storage**
  Building parts on site using electronic data removes the need to physically ship components from supplier to user. This also removes the need to predict what spare parts require storage, as they may be made on demand.

The disadvantages in using current RP systems for Rapid Manufacturing include:

- **Relatively poor accuracy and tolerances**
- **Limited surface finish**
- **Course resolution**
- **Few Engineering grade materials**
- **High perceived costs**

It is important to note that all these disadvantages are the result of using a young technology that is still being developed. As technologies evolve at an exponential rate, the arrival of true Rapid Manufacturing machines can only be a few years away from the present. Placing focus upon the more positive aspects mentioned, there can be little doubt that these future systems will greatly affect how products are both designed and made.

Focus Product: Synopsis

The focus of the redesign part of this study is a hand held unit for controlling video surveillance equipment as used by police, military and various security organisations.

The ambidextrous unit may be held and operated using a single hand and is physically attached to recording equipment via a cable that protrudes from the controller. The device contains 12 push buttons, a thumb actuated joystick, a single on/off slide switch and a display screen that is approximately 12 cm^2 in size. A picture of the unit may be seen in figure 2.

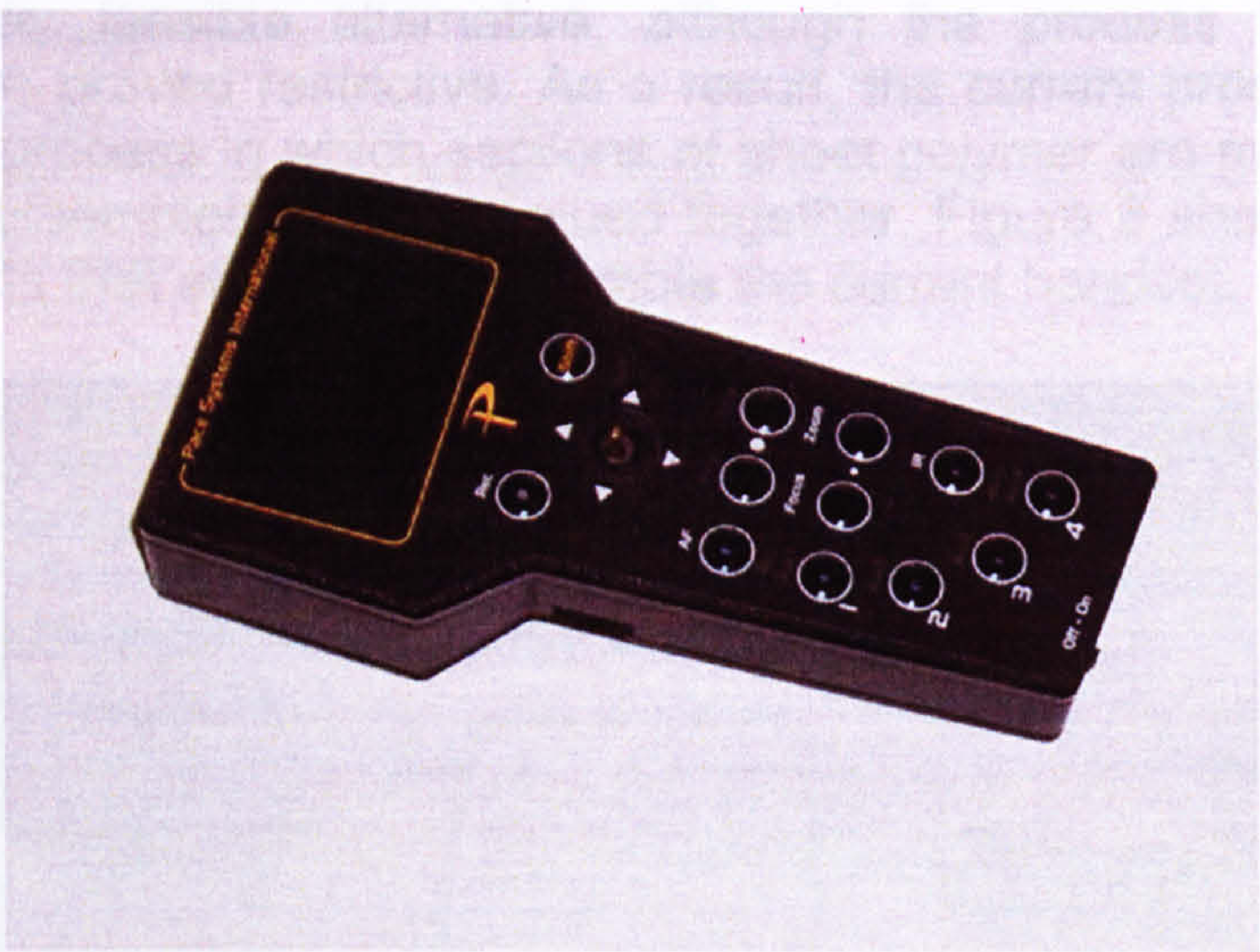


Figure 2: Current hand held control unit

Used predominantly in road vehicles, the unit is not directly exposed to any exterior elements, however a requirement for gloved operation during wintertime does suggest a periodic exposure to the cold. As an "interior" product the device does not need to be weatherproof, however a sealed wipe-clean exterior is used to prevent the ingress of hand-borne dirt and contaminants. For this reason the current unit is fitted with a sealed membrane keypad that is flush with the unit's main facia.

As the product is used for covert surveillance, it is necessary that its design is as discrete and innocuous as possible. Often used by people with limited technical experience, the device's controls and instrumentation need to be clearly marked, easy to interpret and easy to use. A partially illuminated keypad is used to define the unit's controls in the dark or when light levels are low. Occasional heavy-handed use also calls for a design that is robust and capable of withstanding a reasonable amount of abuse and neglect. Finally, it is essential that the equipment is reliable, as the events it is used to record may be of great importance, such as prosecution evidence for example.

Following terrorist attacks in September 2001 and the ensuing conflicts, there has been an overall growth in demand for products within the security and defence sectors. The volumes in which this particular product is required is relatively low, numbering 200 units in the first year of sales and growing to an estimated 500 units in the second year. No figures were given for subsequent years, although it is predicted that the product's life expectancy will be relatively short, with obsolescence and replacement taking place in next few years. The company's current warranty period is 12 months, although there are plans to offer an additional maintenance contract on all units sold.

At present the low product volumes do not warrant the initial high cost of injection moulding. Reaction Injection Moulding (RIM) has been considered as an economically feasible alternative, although the process limitations and tolerances have proved restrictive. As a result, the current production method employed is a process in which sections of sheet polymer are machined before being folded, assembled and then glued together. Figure 3 shows a picture of the various parts that are used to assemble the current handset.

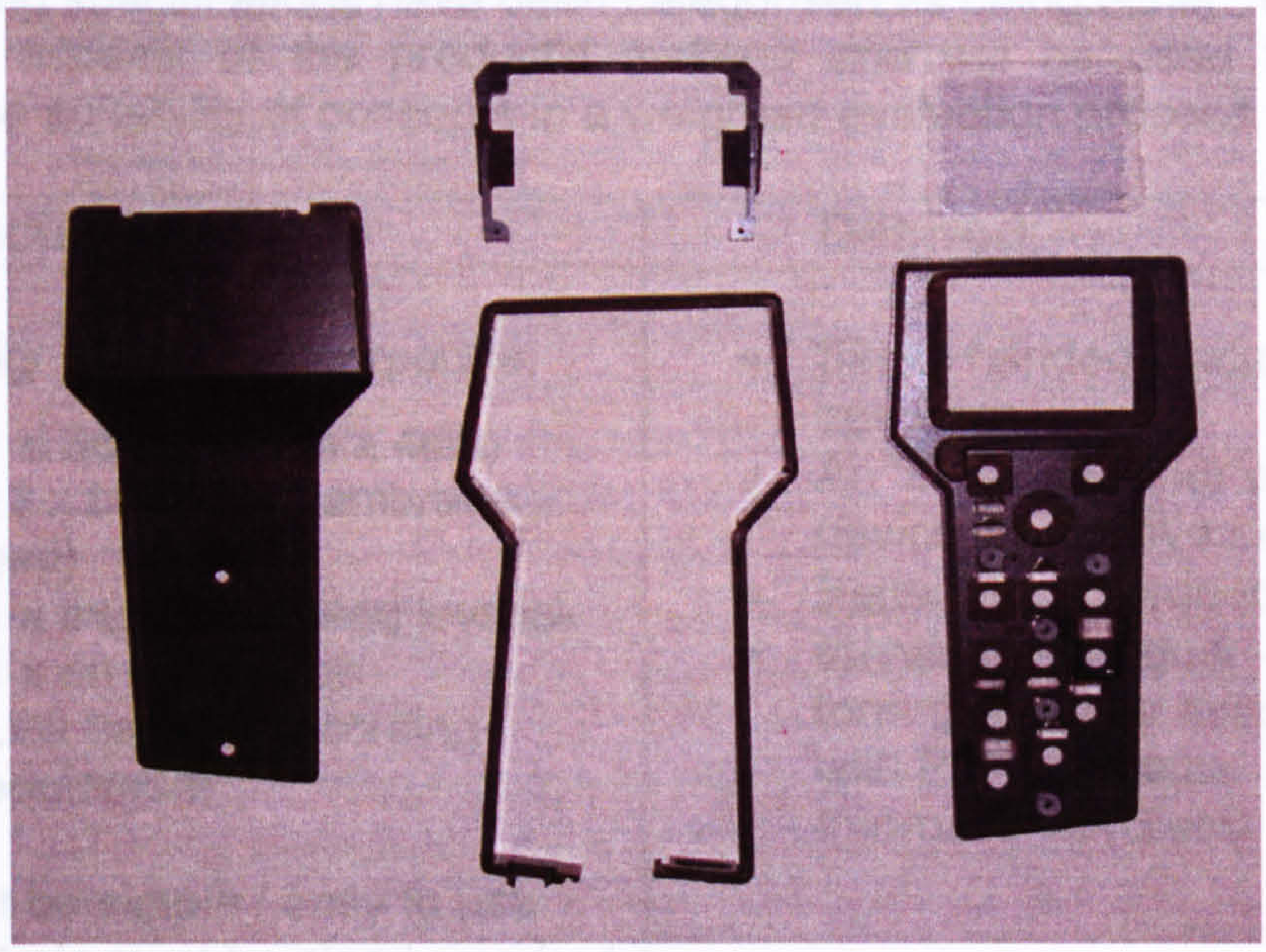


Figure 3: Current assembly fabrication
(Total 21 pieces excluding membrane keypad)

It is claimed that Pace Systems were the first company in their sector to provide control units of this sort with custom-built housings. This is felt to have given the company a commercial sales advantage over their competitors who used less desirable "off the shelf" project box type enclosures. In addition it is believed that the unit's unique "hammer head" shape is now recognised and associated with Pace Systems, allowing customers to clearly differentiate products.

Design Brief

You are to redesign the previously described handset for production via Rapid Manufacturing.

You will be given approximately 60 minutes to produce 3 concept designs as paper based sketches. Each concept should meet the criteria outlined below as well as reflecting the benefits associated with Rapid Manufacturing. Following the initial concept generation, and using a prescribed method, you are to assess your own designs and select one for further development. You will then be allowed an additional 30 minutes in which to conduct more detailed design revisions.

Design Specification

For any concept to be considered as a viable solution to the brief it is necessary that it meets with a specific set of criteria.

The following specifications have been categorised as being either **"Crucial"** or **"Desired"** aspects of the product's makeup and will be used to critically compare the suitability of concepts in a weighted evaluation process.

Crucial:	**Desired:**
• Design needs to incorporate: 1 x Screen (3cm x 4cm) 12 x buttons (membrane pad) 1 x thumb actuated joystick 1 x on / off switch Link cable to recording equipment • Must be simple / easy to use • Controls must be clearly marked • Controls must be easily accessible • Design must be Robust • Needs to be sealed / wipe-clean • Needs to fit the hand comfortably • External surface texture to be tactile and easy to grip • Innocuous design for covert operation	• Single handed ambidextrous operation • An "in-car" retainer or storage device for inactive moments • Better placed product split lines • Identifiable product - Unique form that will be associated with Pace Systems International (client)

Concept Profile Questionnaire

The following questionnaire contains a series of questions that are intended to provide assistance in designing any given product for production via Rapid Manufacturing (RM).

Using the design brief and specification, along with your own understanding of the project that you have been asked to design, you are to provide an answer for each question. The answers you give will be collated and used to generate a profile that can be used as an aid to guide subsequent design activity and provide criteria for assessing the concepts you produce.

The five areas of concern that the questionnaire deals with are:

(1) Volume

(2) Form

(3) Function

(4) Construction

(5) Logistics

Section 1: Volume

This section deals with the market related factors that affect production volumes. These include the different demands for products and associated parts, the product's expected life span and it's rate of obsolescence.

1.1

Compared to other methods of manufacture RM is a highly cost effective method of production for low volumes. The lack of upfront tooling costs mean that it is possible to produce affordable products individually. Studies have even shown that RM can even be used as an economically feasible method of producing certain components in volumes that number low 1000's.

What are the expected target production volumes?

☐ **10's** ☐ **100's** ☐ **1,000's** ☐ **10,000's** ☐ **100,000+**

1.2

In order to restrict potential losses RM may be used as a relatively low cost method of manufacturing "tester" products. These could be used to test the market place and assess the acceptance of your product before committing yourself to high volume production methods and costs

What level of confidence is there that the product will sell well in its market place?

Low **1 2 3 4 5** High ☐ Don't know

(Please circle the most appropriate number on scale or check box)

1.3

RM products may be built without the need for minimum order numbers or high volume production runs.

Will there be an after sales support commitment to supply replacement parts after production has ceased and stock is depleted?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

1.4

With no capital investment required for production tooling there are far fewer financial restraints that would otherwise hinder design changes or the launching of new product lines to stay ahead of competition technologies and products.

What is the predicted life expectancy of your product in the market place before it becomes obsolete and requires change?

☐ **1 year or less** ☐ **1 - 5 years** ☐ **5 - 10 years** ☐ **10 years +**

1.5

Using RM as a method of manufacture would make iterative post-production design changes easy, low cost and enable your product to be kept up-to-date with market trends.

Is the product a fashion item or is having up-to-date aesthetic styling an important factor in maintaining market popularity?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

Section 2: Form

This section deals with issues that affect the products form and geometry. These include the intended user's requirements and preference as well as product styling, branding and range.

2.1

Using RM removes the cost restrictions of production tooling, making it possible to manufacture your product in a range of different sizes in the same way that clothing manufacturers do. Your product could be made in many size variations ranging through small, medium, large and extra large or even have the option of being left or right handed.

How likely is it that your product would benefit from being made available in a range of sizes or shapes to fit different users?

1 2 3 4 5

Not at all |___|___|___|___| Very much so

☐ Don't know

(Please circle the most appropriate number on scale or check box)

2.2

User customized products often include areas of conformal geometry that are shaped to provide better fit and interaction between user and product. Since RM is not restricted by conventional tooling restrictions it is perfectly suited to producing complex and unique custom fit products that conform to individual users.

During use, will there be a high degree of interaction between the product and its user, such as prolonged or repeated physical contact?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

2.3

RM is the ideal way of producing a fully customized product that can be made so that it is unique to an individual user. The absence of production tooling means that one off designs are cost effective, and because the process is digital the user may re-order any number of identical personalized products.

During its life, will the product be used by a single person and no other?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

2.4

RM provides a cost effective method of producing any number of different product permeations as single part items. This removes the need to produce and assemble different component parts.

Is the product modular or does it use trim features and extra components to define different levels within a product range (e.g. Budget or economy versions to more exclusive or executive options)	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

Section 3: Function

This section deals with issues concerning the functionality provided by the product and the parts from which it is made. These include the product's interaction with other products or parts, methods of linking or bonding assembly components and user requirements.

3.1

Merging separate assembly components reduces the number of parts in a product and all of the manufacturing issues that are associated with them. Parts that are made up of merged assembly components may have highly complex shapes that would be difficult to produce, although the freedom of creation that RM has means this is not an issue.

Is your product comprised of more than one non-moving component that are or could be made from the same material?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

3.2

The flexibility of RM to generate practically any form makes it easy to reverse engineer new conformal geometries around existing parts.

Does your product interact with other products or parts? (E.g. Is the product attached to another part or parts, or will it need to fit inside, around or between other predefined forms?)	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

3.3

Any fixed assembly pieces that require permanent fixing could be merged and built as a single part with RM. Alternately any assembly components requiring semi-permanent fixing could be designed to incorporate integral fixing features. These may include moving parts and linkages such as chains or hinges, which may be built intact.

Does your product use mechanical fasteners or chemical bonding agents used to join same material component parts?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

3.4

Users have a better understanding than designers as to the functions they want a product to achieve, but their design concepts are unlikely to reach manufacturing without having to make process related compromises. The flexibility of RM to produce almost any geometry make it ideal for the realization of "un-producible" products that have been conceived by those who are either unversed in conventional methods of manufacturing or would like to avoid their restrictions.

Will the product's intended user have any suggestive or creative input during design or development?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

Section 4: Construction

This section deals with issues that affect product construction, such as geometric complexity, product assembly and design intent versus manufacturing feasibility.

4.1

RM is an additive manufacturing process capable of producing virtually any 3D form, and as such the restrictions of many other conventional manufacturing process do not apply. This means it is possible to produce parts that include features such as undercuts and variable wall sections that are free of draft angles.

Is the product's shape or geometry compromised in any way for conventional manufacturing methods?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

4.2

The freedom of geometrical creation that is offered by RM makes it possible to build integral mounting features such as bosses or fixing plates into any design. It is possible for thick wall sections to contain cooling channels or sealed conduits for the routing of electrical cables.

Does the product need to house any specific bought in components or accommodate non-standard fixtures or fittings?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

4.3

The design optimisation of products often results in "space-frame" structures that use optimum amounts of material. The degree of freedom that is offered by RM makes it possible to produce lightweight space frame designs that would be impossible with other forms of manufacturing.

How important is it that your product is lightweight? (E.g. consider portable products etc)

Low 1 2 3 4 5 High ☐ Don't know

(Please circle the most appropriate number on scale or check box)

4.4

RM enables the merging of a product's assembly components, which may reduce the number of different construction materials and also the amount of mechanical or chemical bonding agents that often hinder post life-cycle separation and recovery of construction materials.

How important is the recovery of construction materials at the end of the products life cycle?

Low 1 2 3 4 5 High ☐ Don't know

(Please circle the most appropriate number on scale or check box)

Section 5: Logistics

This section deals with matters concerning logistics such as supply and demand, and also the transportation and storage of products.

5.1

RM offers the direct manufacture of parts without the need for tools, and without production tools there is no tooling lead-time. This means RM products can be produced and released for marketing as soon as the design work is complete.

Do the lead-times of conventional manufacturing cause undesirable delays in getting the product to market?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

5.2

RM is particularly suited to the JIT strategy. Since it is economically feasible to produce low part volumes the process it is ideal for supply on demand manufacturing when even just a few of the product are required.

Are you considering the use of Just In Time (JIT) strategies for the manufacture of this product?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

5.3

Stocking raw materials for the production of RM parts on demand will require less storage space, provide greater versatility and prove more cost effective than attempting to maintain a stock of pre-built products.

Is the product likely to be stored as a replacement or stock item?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

5.4

Any outfit that is engaged in a relatively long-term venture and operating in an area that is difficult to access via conventional means of transport may use on-site RM to resolve problematic part storage and delivery issues. With an on-site RM system and a supply of build material, users may build parts directly and on demand from a digital product catalogue.

Is there a requirement to transport the product or any replacement parts to a location that is difficult to reach? (E.g. military combat zones, oil rigs, exploration, etc)	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

5.5

If the user has an RM system the product could be transmitted electronically and built onsite, to avoid any transportation issues. Alternately, support structures that are built during the additive manufacturing process could be left intact to support the product in transit and then removed by the user on receipt of the product, much like the plastic sprues that are attached to model air-fix kits.

Is the product fragile and require specialist packaging or transport?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

Appendix B Student Trial Booklet

Aim of Trial:

To test a new Design Tool that is specific to the design of products that are to be produced using the process known as Rapid Manufacturing

Elements being tested:

1. **Questionnaire:**
   a) Used to validate manufacturing process
   b) Used to provide information that may aid concept design
   c) Used to form concept assessment criteria

2. **Evaluation Matrix:**
   Used for the critical assessment of design concepts

Design Trial:

- You are asked to redesign a small and familiar product of your own choosing, developing a concept that lends itself to production via Rapid Manufacturing.
- You are to consider some specification criteria that would be applicable to your chosen product and complete a generic project questionnaire. (Responses from the questionnaire will be used to make suggestions as to what RM specific features you should consider incorporating within your design concepts.)
- Adhering to specification criteria and RM suggestions, you must produce a minimum of 3 initial concept designs using any method you are comfortable with (i.e. paper based sketches; physical models; CAD; etc).
- You are to assess your own designs using a matrix that contains your own specification criteria and suggested RM features.
- After choosing a single concept design you are to develop the design and produce a detailed 3D CAD model.
- You are to assess your final CAD model using the same evaluation matrix as previously used to select a development concept before completing a feedback questionnaire.

Design Specification

For any concept to be considered as a viable solution it is necessary that it meets with a specific set of criteria. Please list what you feel would be the necessary specification criteria for your chosen product (e.g. should have tactile surface finish; must be water resistant; must operate in sub-zero conditions, etc). Please try to distinguish between **"must meet"** and **"should meet"** criteria. You may use the following scale to indicate the relative importance you feel should be attached each specification (Circle appropriate number).

1 2 3 4 5

Little Importance | | | | | | Crucial to product

Desirable

Specification Criteria	Importance
	1 2 3 4 5
	1 2 3 4 5
	1 2 3 4 5
	1 2 3 4 5
	1 2 3 4 5
	1 2 3 4 5
	1 2 3 4 5

DFRM Questionnaire: Section 1 - Volume

This section deals with the market related factors that affect production volumes. These include the different demands for products and associated parts, the product's expected life span and it's rate of obsolescence.

1.1

Compared to other methods of manufacture RM is a highly cost effective method of production for low volumes. The lack of upfront tooling costs mean that it is possible to produce affordable products individually. Studies have even shown that RM can even be used as an economically feasible method of producing certain components in volumes that number low 1000's.

What are the expected target production volumes?

☐ **10's** ☐ **100's** ☐ **1,000's** ☐ **10,000's** ☐ **100,000+**

1.2

In order to restrict potential losses RM may be used as a relatively low cost method of manufacturing "tester" products. These could be used to test the market place and assess the acceptance of your product before committing yourself to high volume production methods and costs

What level of confidence is there that the product will sell well in its market place?

1 2 3 4 5 ☐ Don't know

Low |_|_|_|_| High

(Please circle the most appropriate number on scale or check box)

1.3

RM products may be built without the need for minimum order numbers or high volume production runs.

Will there be an after sales support commitment to supply replacement parts after production has ceased and stock is depleted?

☐ Yes

☐ No

☐ Not Applicable or Unknown

1.4

With no capital investment required for production tooling there are far fewer financial restraints that would otherwise hinder design changes or the launching of new product lines to stay ahead of competition technologies and products.

What is the predicted life expectancy of your product in the market place before it becomes obsolete and requires change?

☐ 1 year or less ☐ 1 - 5 years ☐ 5 - 10 years ☐ 10 years +

1.5

Using RM as a method of manufacture would make iterative post-production design changes easy, low cost and enable your product to be kept up-to-date with market trends.

Is the product a fashion item or is having up-to-date aesthetic styling an important factor in maintaining market popularity?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

DFRM Questionnaire: Section 2 - Form

This section deals with issues that affect the products form and geometry. These include the intended user's requirements and preference as well as product styling, branding and range.

2.1

Using RM removes the cost restrictions of production tooling, making it possible to manufacture your product in a range of different sizes in the same way that clothing manufacturers do. Your product could be made in many size variations ranging through small, medium, large and extra large or even have the option of being left or right handed.

How likely is it that your product would benefit from being made available in a range of sizes or shapes to fit different users?

Not at all 1 2 3 4 5 Very much so ☐ Don't know

(Please circle the most appropriate number on scale or check box)

2.2

User customized products often include areas of conformal geometry that are shaped to provide better fit and interaction between user and product. Since RM is not restricted by conventional tooling restrictions it is perfectly suited to producing complex and unique custom fit products that conform to individual users.

During use, will there be a high degree of interaction between the product and its user, such as prolonged or repeated physical contact?		Yes
		No
		Not Applicable or Unknown

2.3

RM is the ideal way of producing a fully customized product that can be made so that it is unique to an individual user. The absence of production tooling means that one off designs are cost effective, and because the process is digital the user may re-order any number of identical personalized products.

During its life, will the product be used by a single person and no other?		Yes
		No
		Not Applicable or Unknown

2.4

RM provides a cost effective method of producing any number of different product permeations as single part items. This removes the need to produce and assemble different component parts.

Is the product modular or does it use trim features and extra components to define different levels within a product range (e.g. Budget or economy versions to more exclusive or executive options)		Yes
		No
		Not Applicable or Unknown

DFRM Questionnaire: Section 3 - Function

This section deals with issues concerning the functionality provided by the product and the parts from which it is made. These include the product's interaction with other products or parts, methods of linking or bonding assembly components and user requirements.

3.1

Merging separate assembly components reduces the number of parts in a product and all of the manufacturing issues that are associated with them. Parts that are made up of merged assembly components may have highly complex shapes that would be difficult to produce, although the freedom of creation that RM has means this is not an issue.

Is your product comprised of more than one non-moving component that are or could be made from the same material?		Yes
		No
		Not Applicable or Unknown

3.2

The flexibility of RM to generate practically any form makes it easy to reverse engineer new conformal geometries around existing parts.

Does your product interact with other products or parts? (E.g. is the product attached to another part or parts, or will it need to fit inside, around or between other predefined forms?)		Yes
		No
		Not Applicable or Unknown

3.3

Any fixed assembly pieces that require permanent fixing could be merged and built as a single part with RM. Alternately any assembly components requiring semi-permanent fixing could be designed to incorporate integral fixing features. These may include moving parts and linkages such as chains or hinges, which may be built intact.

Does your product use mechanical fasteners or chemical bonding agents used to join same material component parts?		Yes
		No
		Not Applicable or Unknown

3.4

Users have a better understanding than designers as to the functions they want a product to achieve, but their design concepts are unlikely to reach manufacturing without having to make process related compromises. The flexibility of RM to produce almost any geometry make it ideal for the realization of "un-producible" products that have been conceived by those who are either unversed in conventional methods of manufacturing or would like to avoid their restrictions.

Will the product's intended user have any suggestive or creative input during design or development?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

DFRM Questionnaire: Section 4 - Construction

This section deals with issues that affect product construction, such as geometric complexity, product assembly and design intent versus manufacturing feasibility.

4.1

RM is an additive manufacturing process capable of producing virtually any 3D form, and as such the restrictions of many other conventional manufacturing process do not apply. This means it is possible to produce parts that include features such as undercuts and variable wall sections that are free of draft angles.

Is the product's shape or geometry compromised in any way for conventional manufacturing methods?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

4.2

The freedom of geometrical creation that is offered by RM makes it possible to build integral mounting features such as bosses or fixing plates into any design. It is possible for thick wall sections to contain cooling channels or sealed conduits for the routing of electrical cables.

Does the product need to house any specific bought in components or accommodate non-standard fixtures or fittings?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

4.3

The design optimisation of products often results in "space-frame" structures that use optimum amounts of material. The degree of freedom that is offered by RM makes it possible to produce lightweight space frame designs that would be impossible with other forms of manufacturing.

How important is it that your product is lightweight? (E.g. consider portable products etc)

1 2 3 4 5 ☐ Don't know

Low High

(Please circle the most appropriate number on scale or check box)

4.4

RM enables the merging of a product's assembly components, which may reduce the number of different construction materials and also the amount of mechanical or chemical bonding agents that often hinder post life-cycle separation and recovery of construction materials.

How important is the recovery of construction materials at the end of the products life cycle?

1 2 3 4 5 ☐ Don't know

Low High

(Please circle the most appropriate number on scale or check box)

DFRM Questionnaire: Section 5 - Logistics

This section deals with matters concerning logistics such as supply and demand, and also the transportation and storage of products.

5.1

RM offers the direct manufacture of parts without the need for tools, and without production tools there is no tooling lead-time. This means RM products can be produced and released for marketing as soon as the design work is complete.

Do the lead-times of conventional manufacturing cause undesirable delays in getting the product to market?	☐	Yes
	☐	No
	☐	Not Applicable or Unknown

5.2

RM is particularly suited to the JIT strategy. Since it is economically feasible to produce low part volumes the process it is ideal for supply on demand manufacturing when even just a few of the product are required.

Are you considering the use of Just In Time (JIT) strategies for the manufacture of this product?		Yes
		No
		Not Applicable or Unknown

5.3

Stocking raw materials for the production of RM parts on demand will require less storage space, provide greater versatility and prove more cost effective than attempting to maintain a stock of pre-built products.

Is the product likely to be stored as a replacement or stock item?		Yes
		No
		Not Applicable or Unknown

5.4

Any outfit that is engaged in a relatively long-term venture and operating in an area that is difficult to access via conventional means of transport may use on-site RM to resolve problematic part storage and delivery issues. With an on-site RM system and a supply of build material, users may build parts directly and on demand from a digital product catalogue.

Is there a requirement to transport the product or any replacement parts to a location that is difficult to reach? (E.g. military combat zones, oil rigs, exploration, etc)		Yes
		No
		Not Applicable or Unknown

5.5

If the user has an RM system the product could be transmitted electronically and built onsite, to avoid any transportation issues. Alternately, support structures that are built during the additive manufacturing process could be left intact to support the product in transit and then removed by the user on receipt of the product, much like the plastic sprues that are attached to model air-fix kits.

Is the product fragile and require specialist packaging or transport?		Yes
		No
		Not Applicable or Unknown

Appendix C Concept Profile

Specification Criteria

Crucial:	**Desired:**
• Design needs to incorporate: 1 x Screen (3cm x 4cm) 12 x buttons (membrane pad) 1 x thumb joystick 1 x on / off switch Link cable to recording equipment • Must be simple / easy to use • Controls must be clearly marked • Controls must be easily accessible • Design must be Robust • Needs to be sealed / wipe-clean • Needs to fit the hand comfortably • External surface texture to be tactile and easy to grip • Innocuous design for covert operation	• Single handed ambidextrous operation • An "in car" retainer or storage device for inactive moments • Better placed product split lines • Identifiable product – Unique form that will be associated with Pace Systems International (Client)

Concept Profile Suggestions: Results of Questionnaire

1. Consolidate parts by merging fixed assembly components
2. Introduce a range of sizes to cater for all users
3. Use conformal geometries for user interface surfaces
4. Emphasize differences in product range with styling variations
5. Consider using customised integral fixing or mounting elements
6. Use conformal geometries to accommodate history parts
7. Exploit benefits of geometric freedom (e.g. under cuts, variable wall sections, sheer geometries, irregular blind holes...)

Appendix D Evaluation Matrix

Design For Rapid Manufacture

Concept Evaluation Matrix

		Control	Concept 1	Concept 2	Concept 3
Specified Functional Requirements	**Crucial Requirement**				
	Contains all controls and instrumentation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Simple / easy to use design	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Clearly marked buttons	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Easy control access	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Robust design	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Sealed / wipe-clean product	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Fits the hand comfortably	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	External surface texture tactile and easy to grip	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Innocuous design for covert operation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Desired Requirement				
	Single handed ambidextrous operation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	In-car retainer or storage device	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Well placed product split line	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Identifiable Product	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Performance Rating	**/ 65**	**/ 65**	**/ 65**	**/ 65**

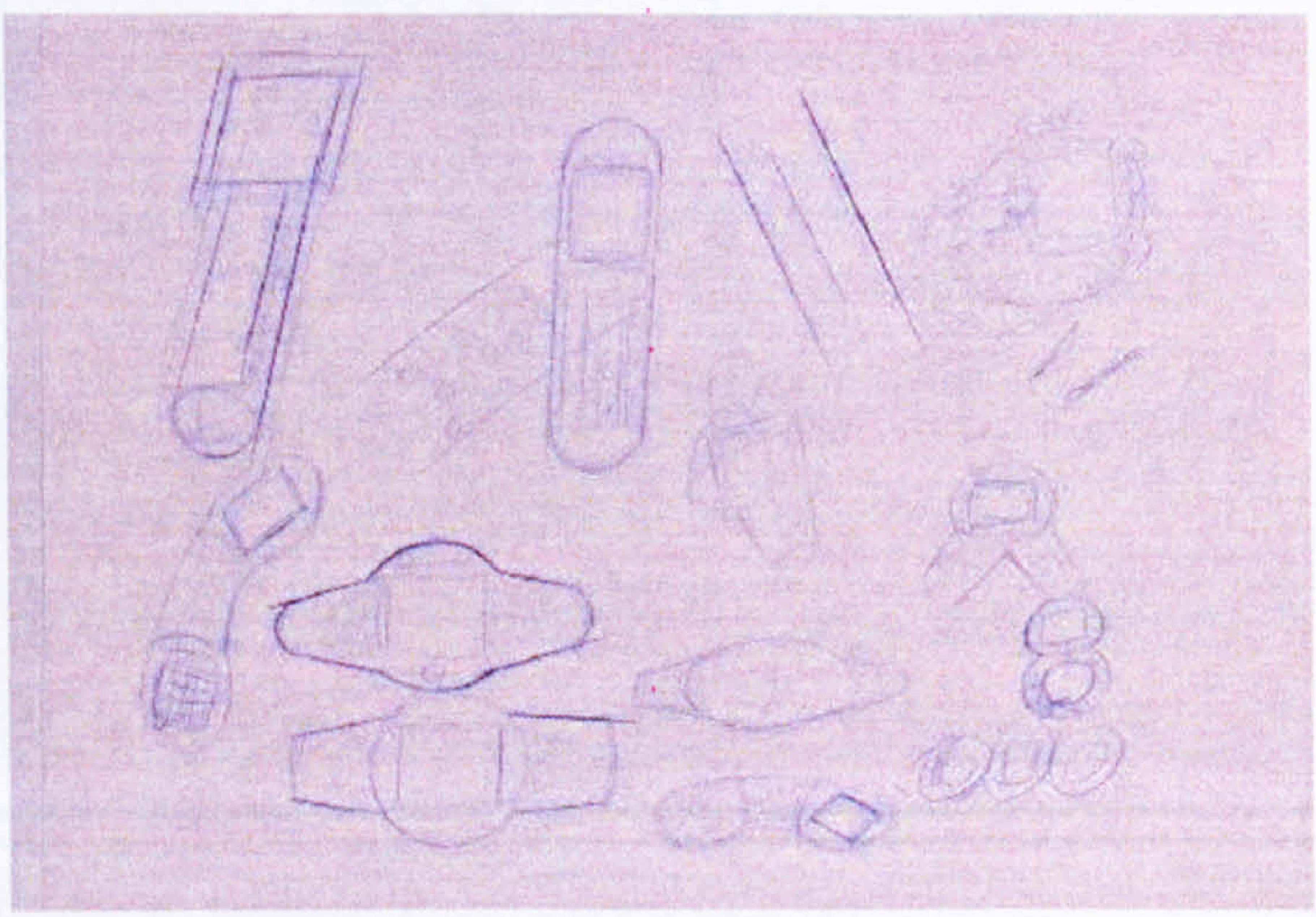
DFRM	**Value Added RM Elements**				
	Part Consolidation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Size Variations	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	User conformal geometries	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Range Differences	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Custom designed fixings / mountings	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Conforms to history parts	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Exploits freedom of geometric creation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	Performance Rating	**/ 35**	**/ 35**	**/ 35**	**/ 35**

Low 1 2 3 4 5 High

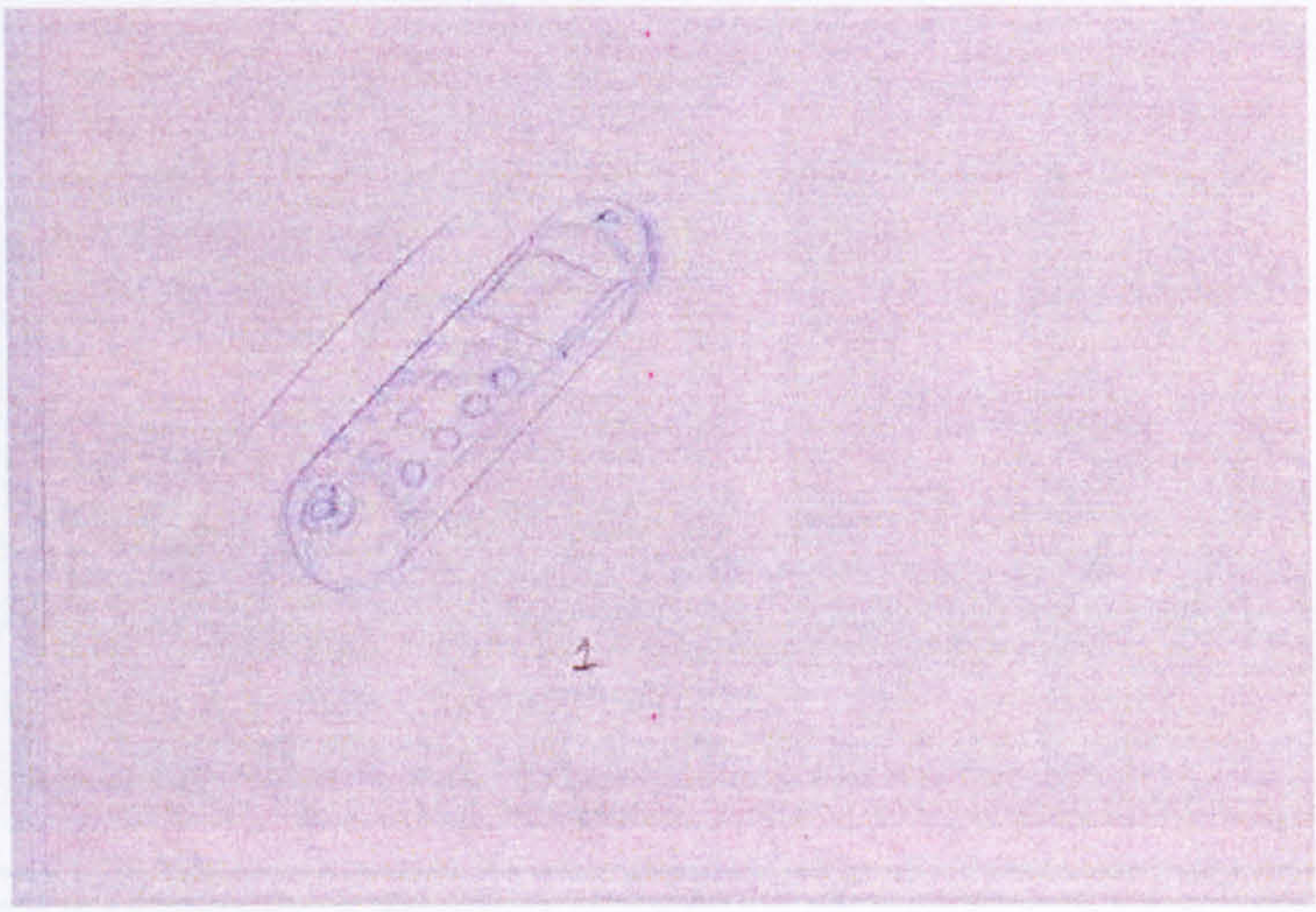
Indicate your response by circling most appropriate number

Appendix E Professional Trial Sketches

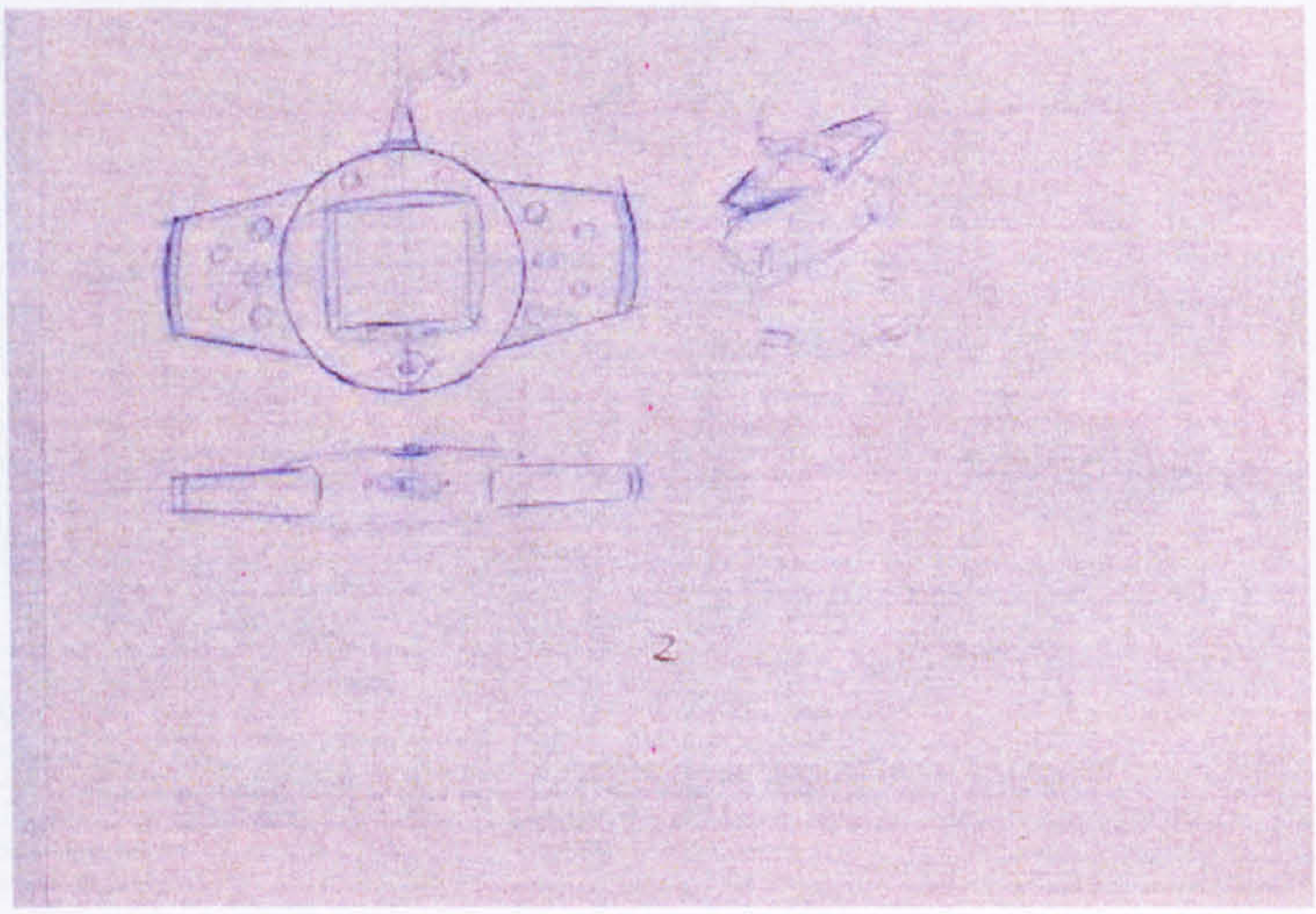
Participant Number 1



Sheet 1

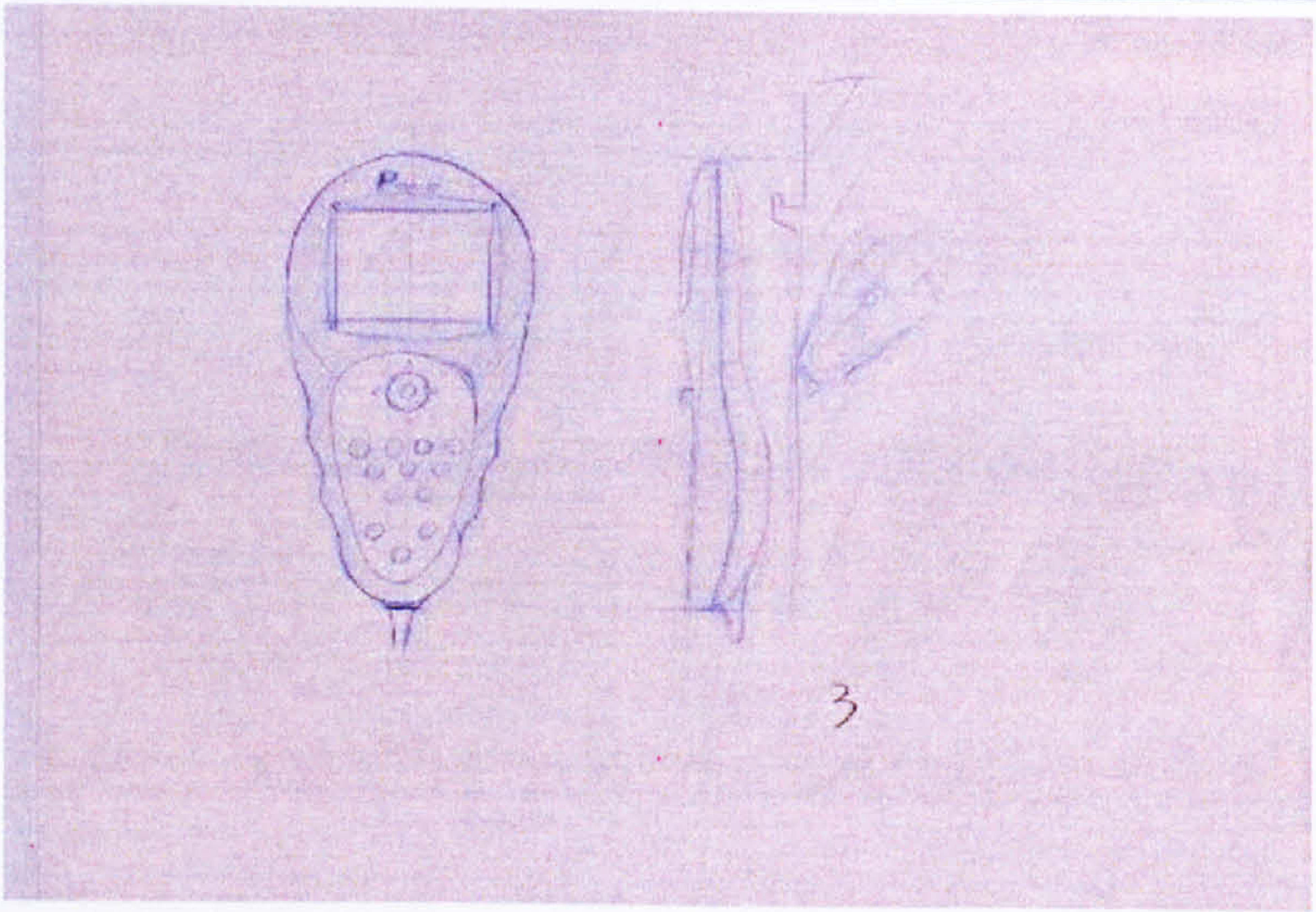


Sheet 2

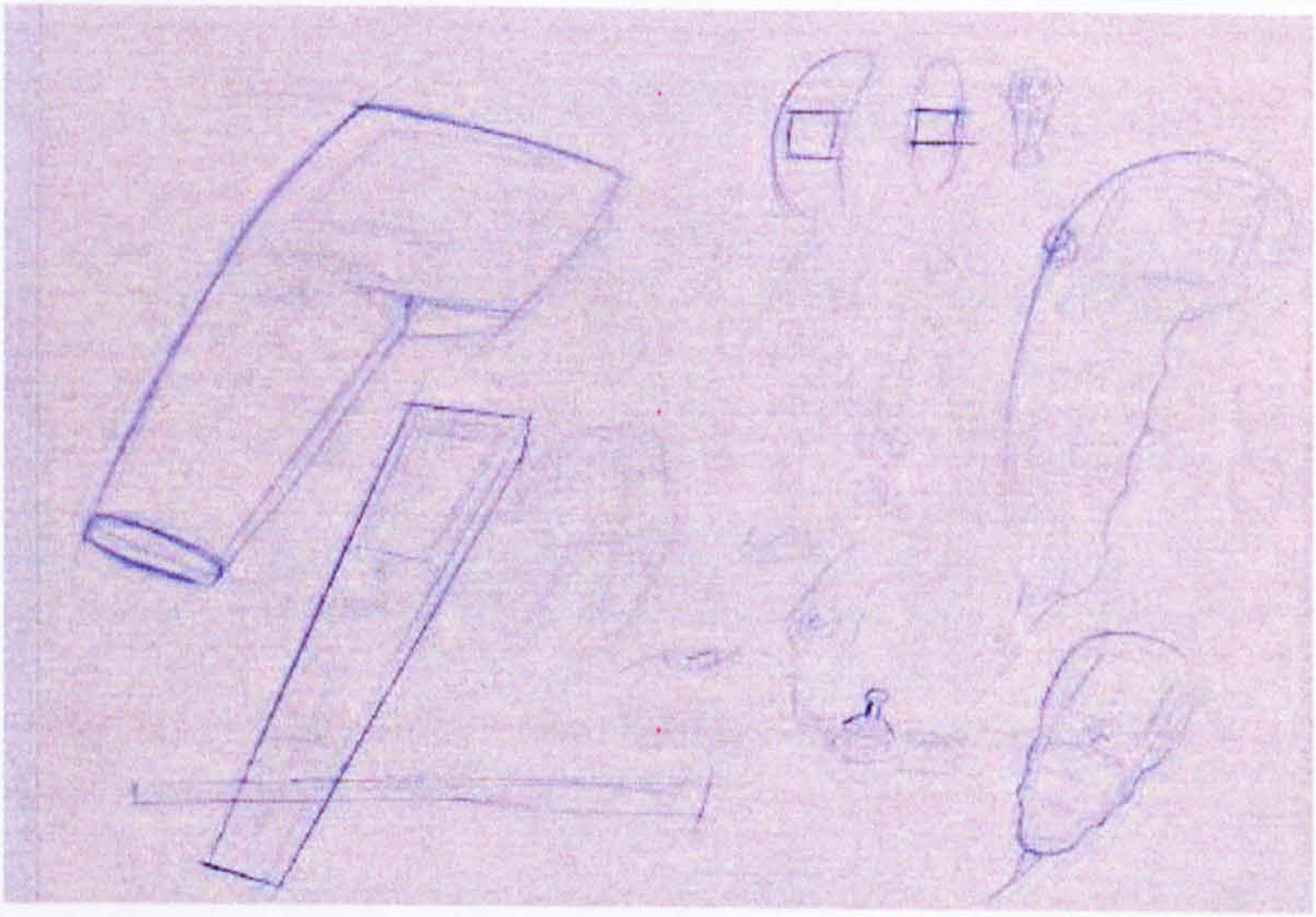


Sheet 3

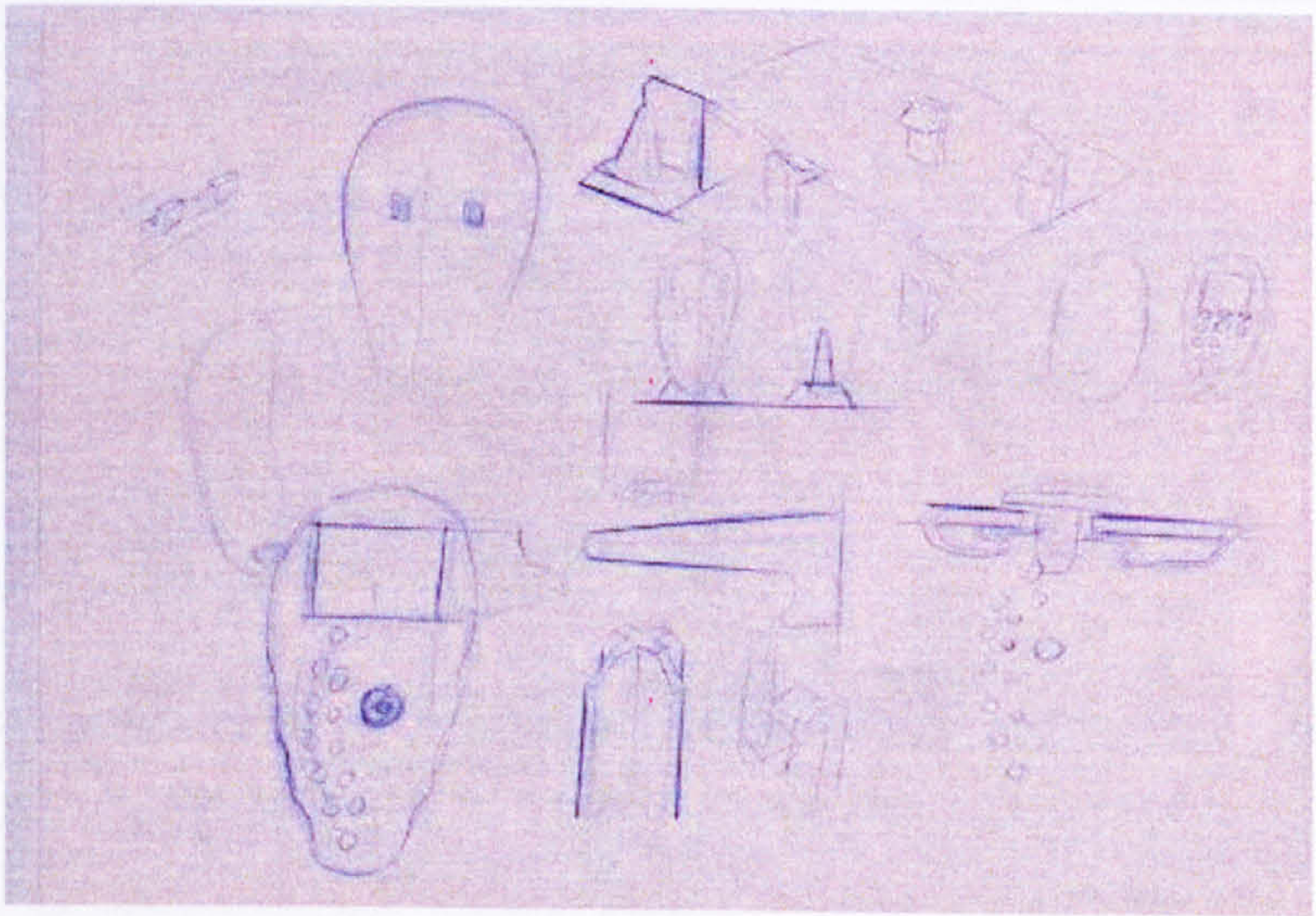
Participant Number 1



Sheet 4

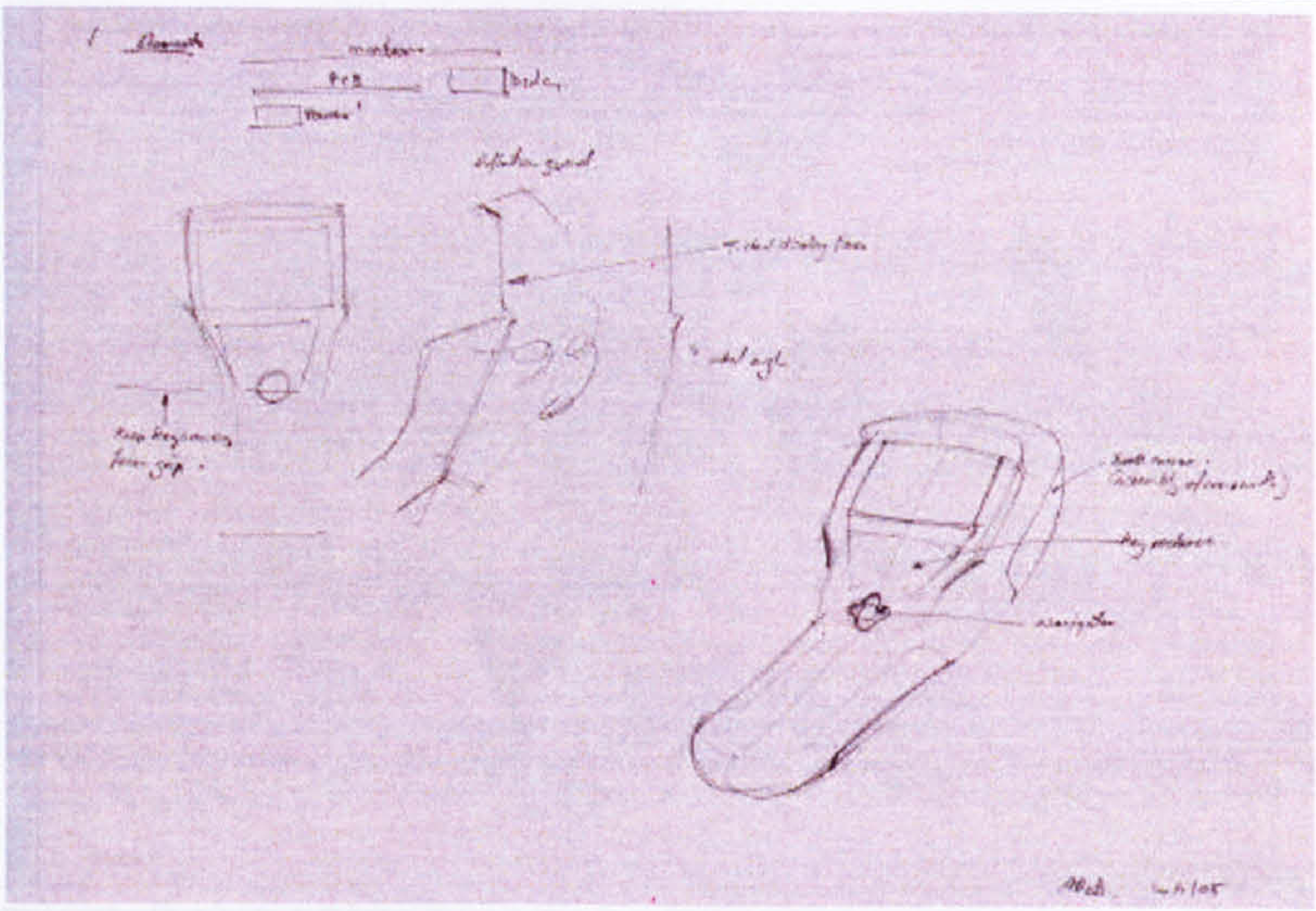


Sheet 5

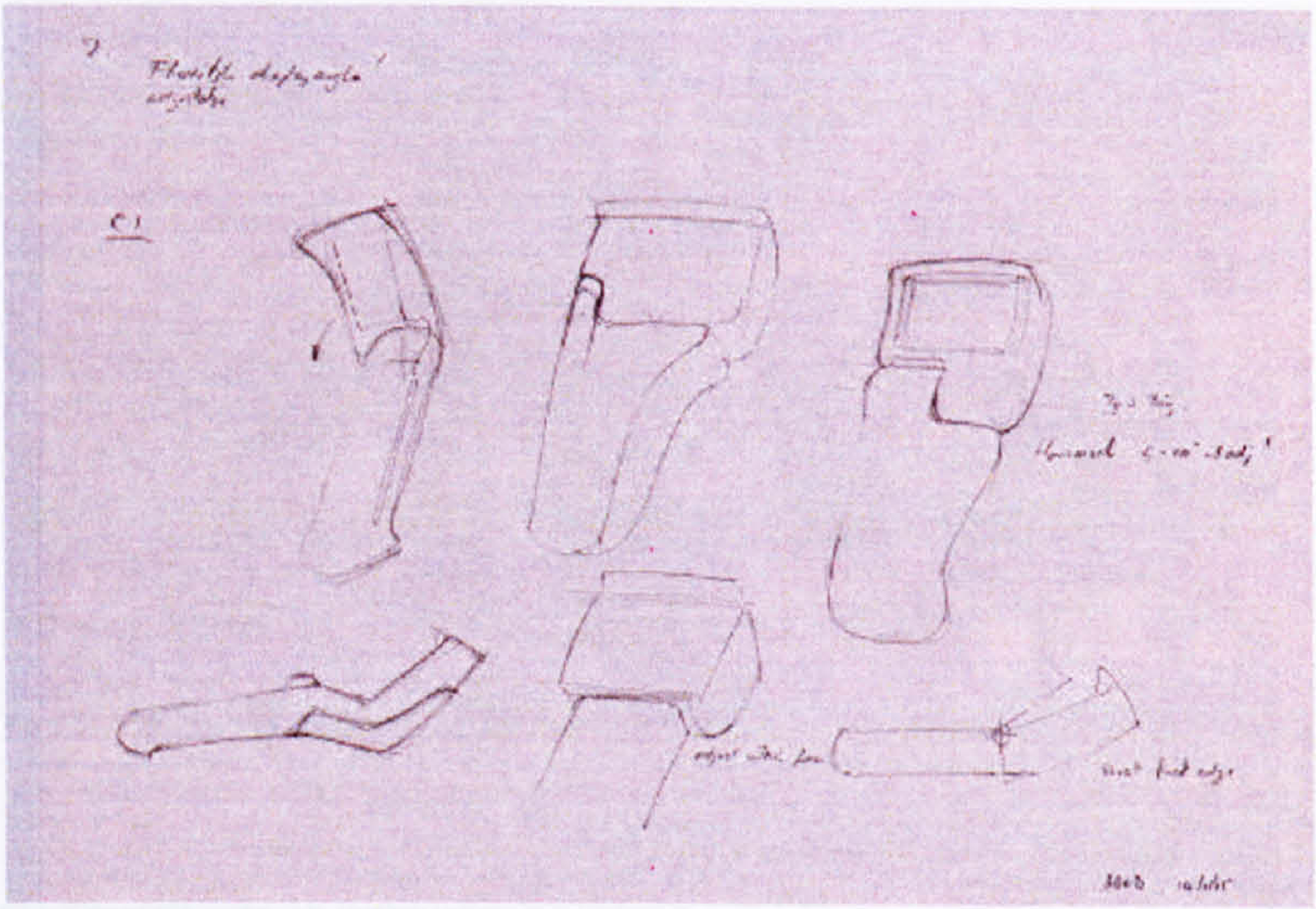


Sheet 6

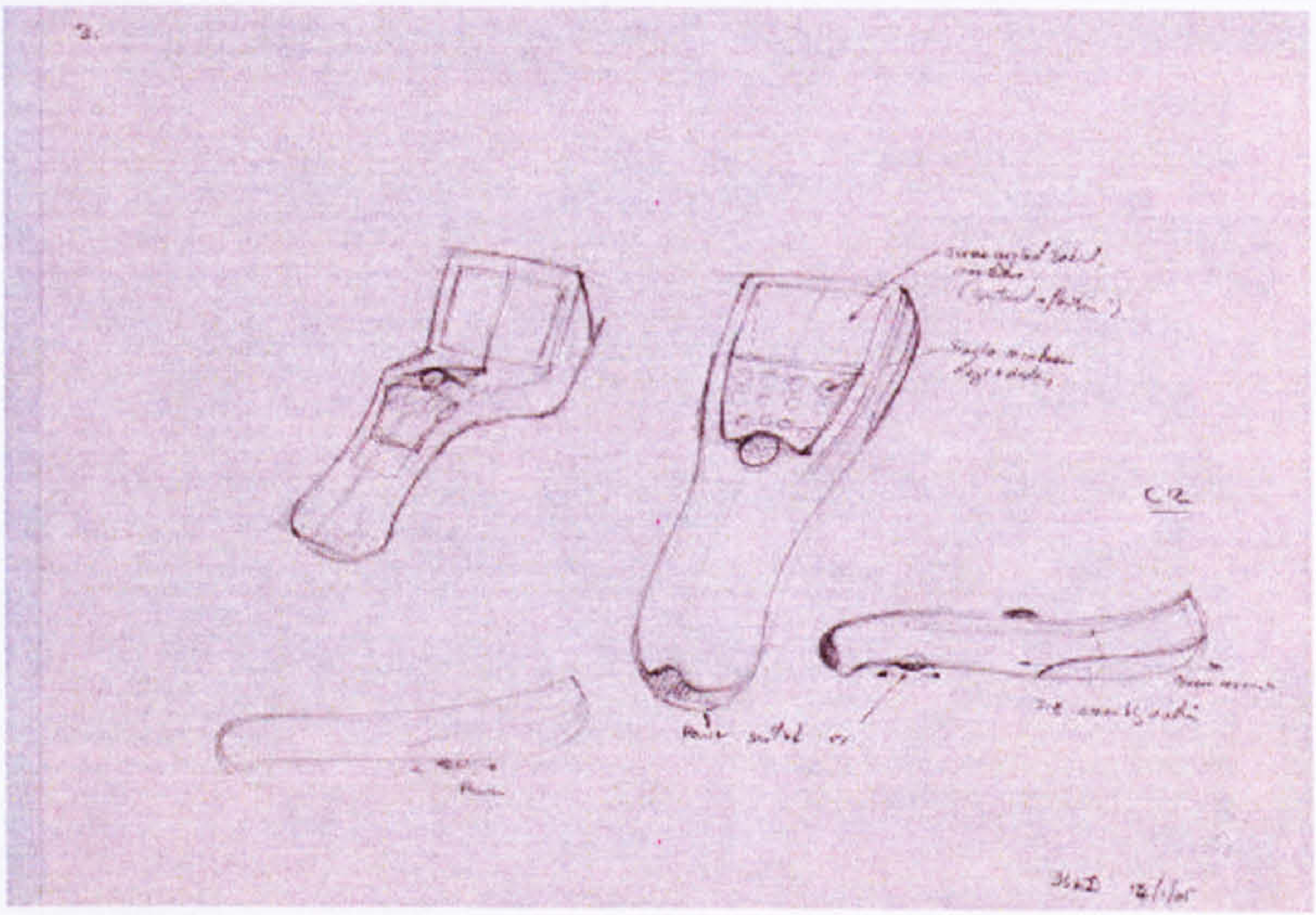
Participant Number 2



Sheet 1

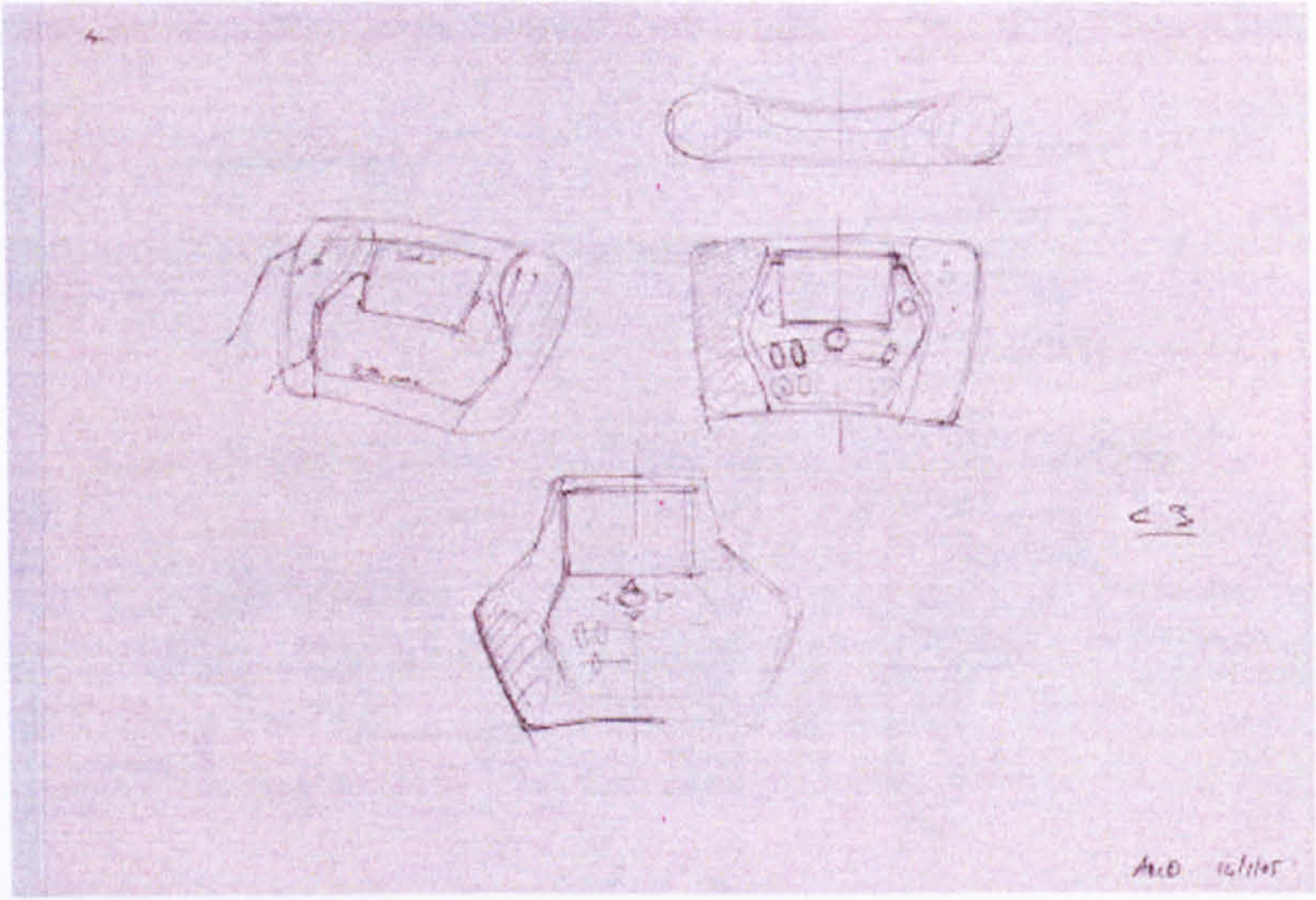


Sheet 2

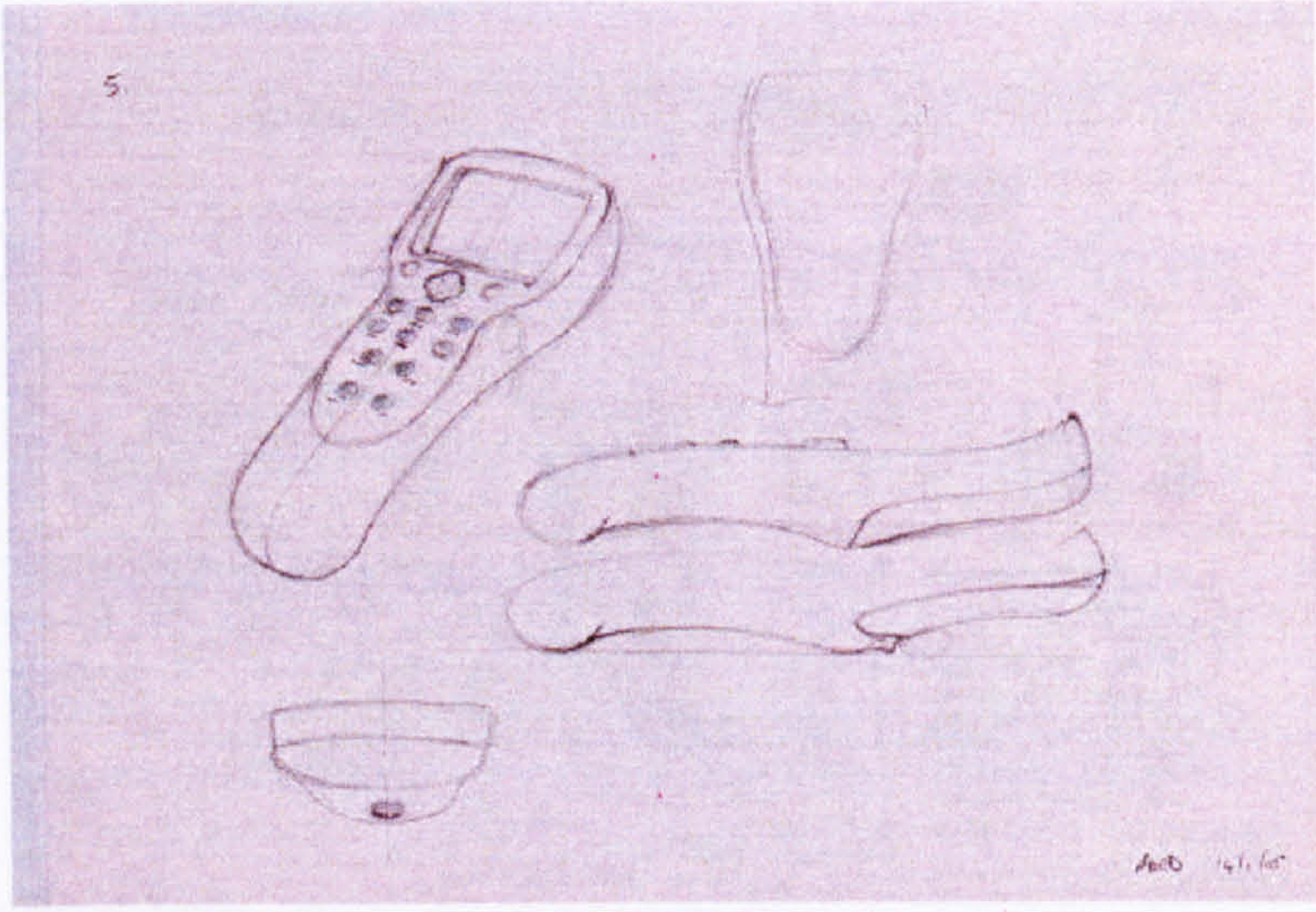


Sheet 3

Participant Number 2

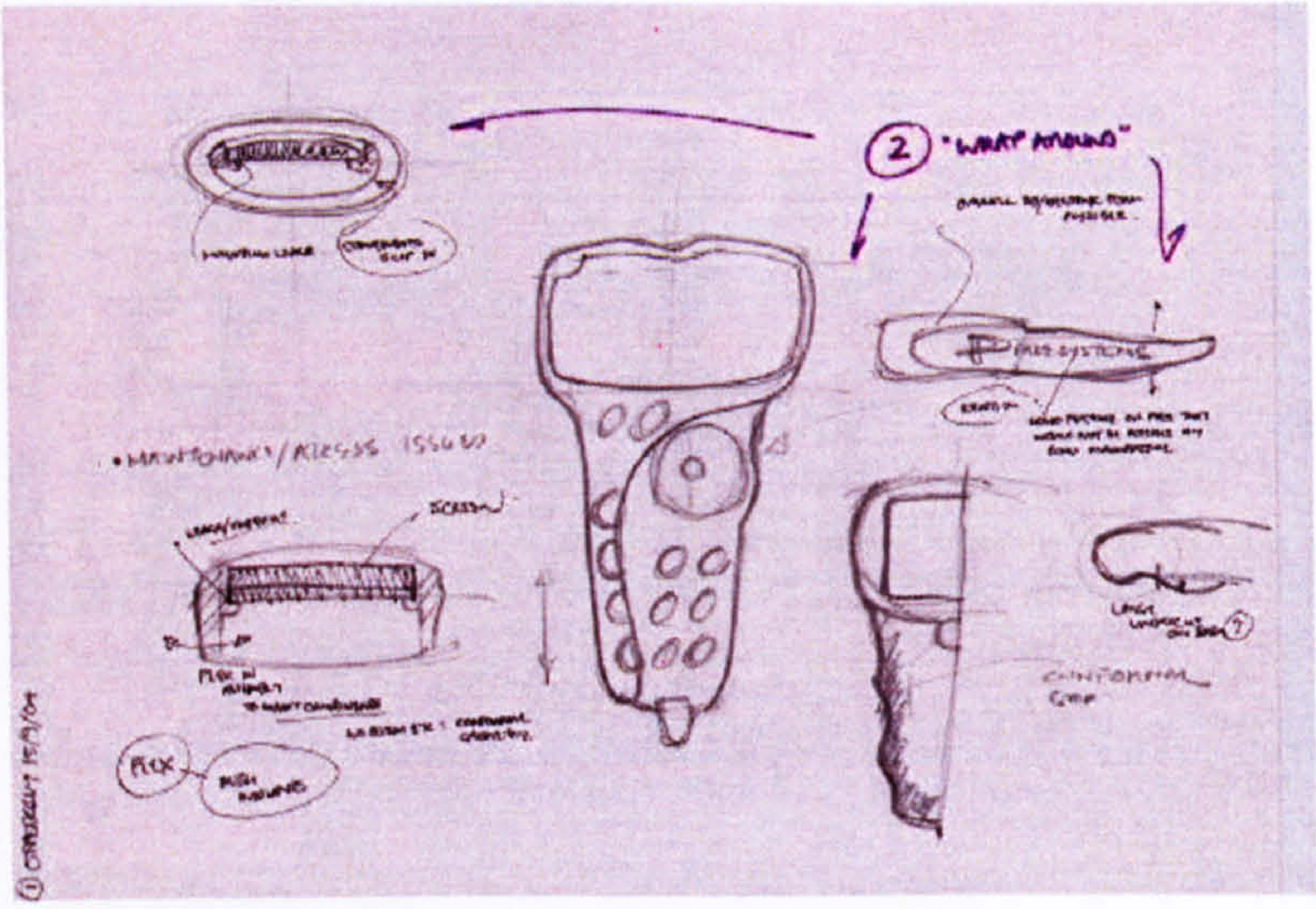


Sheet 4

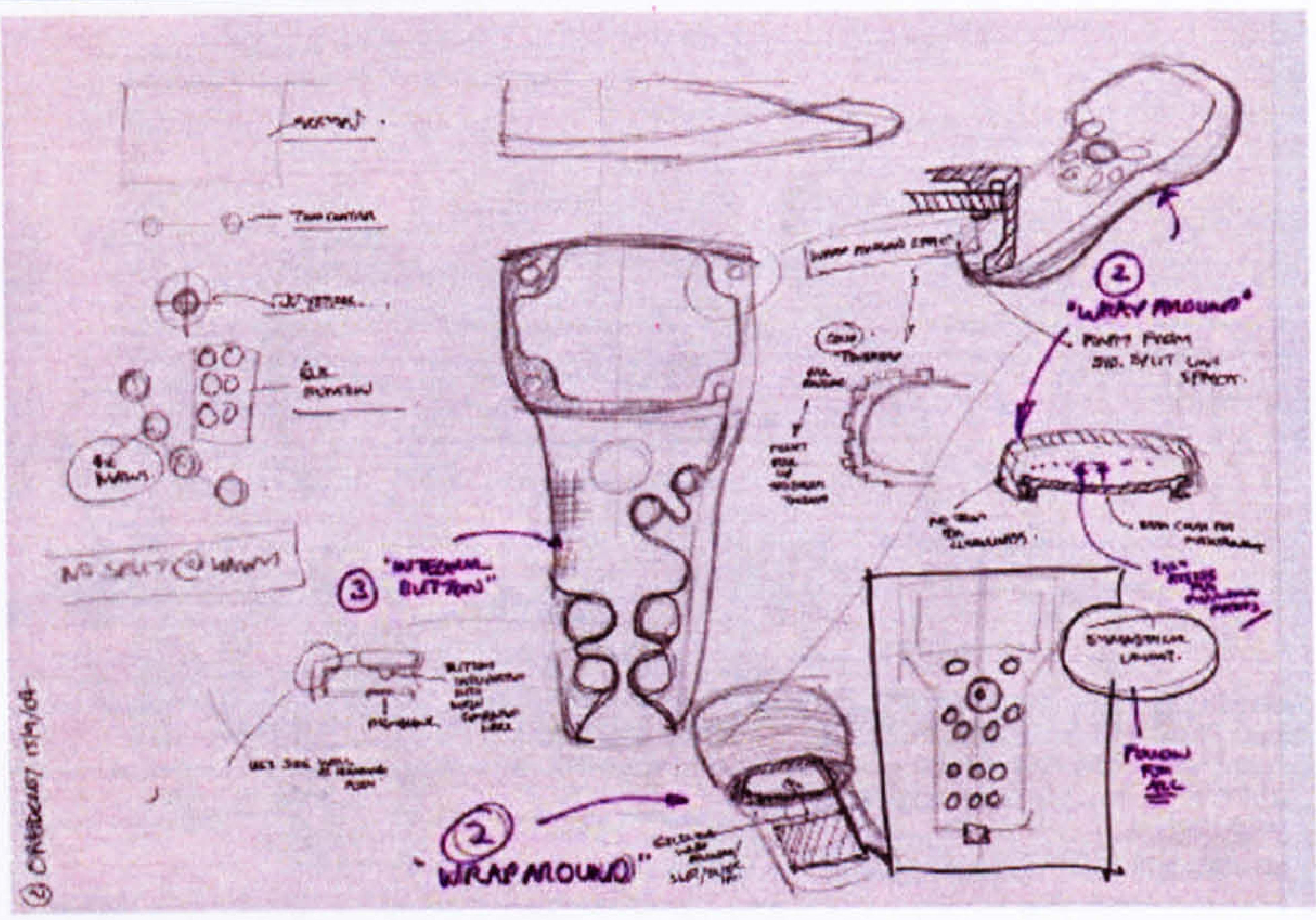


Sheet 5

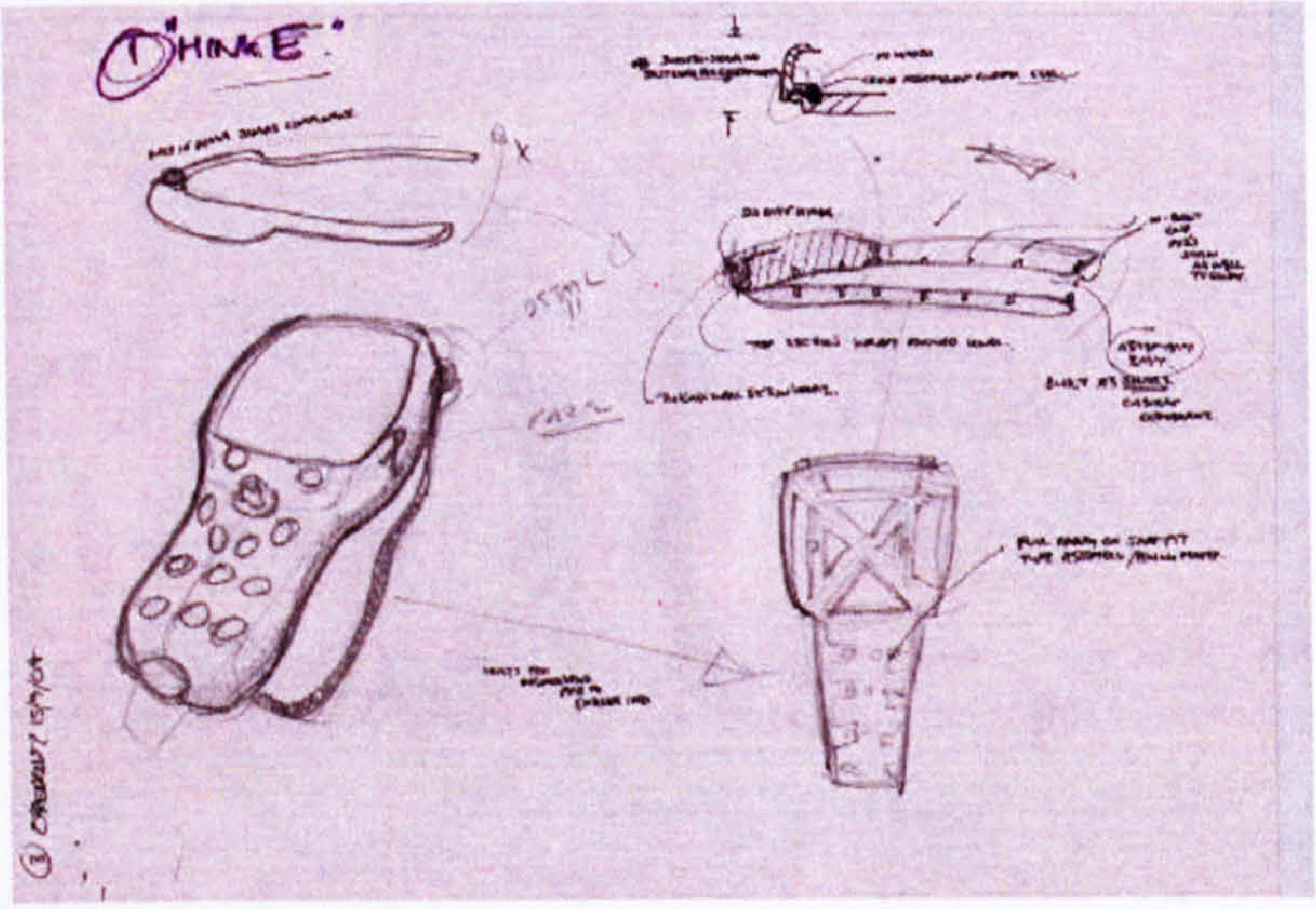
Participant Number 3



Sheet 1

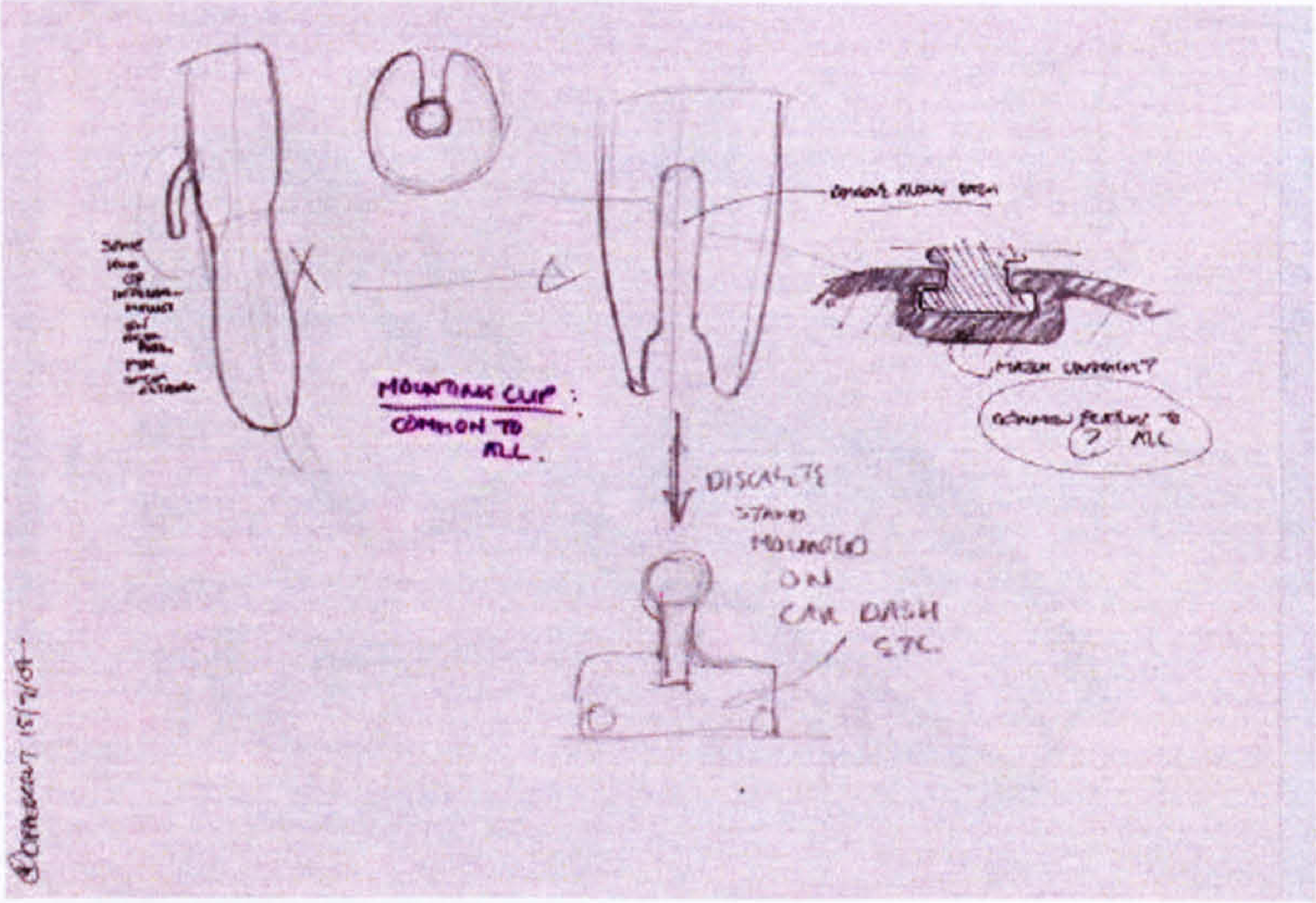


Sheet 2

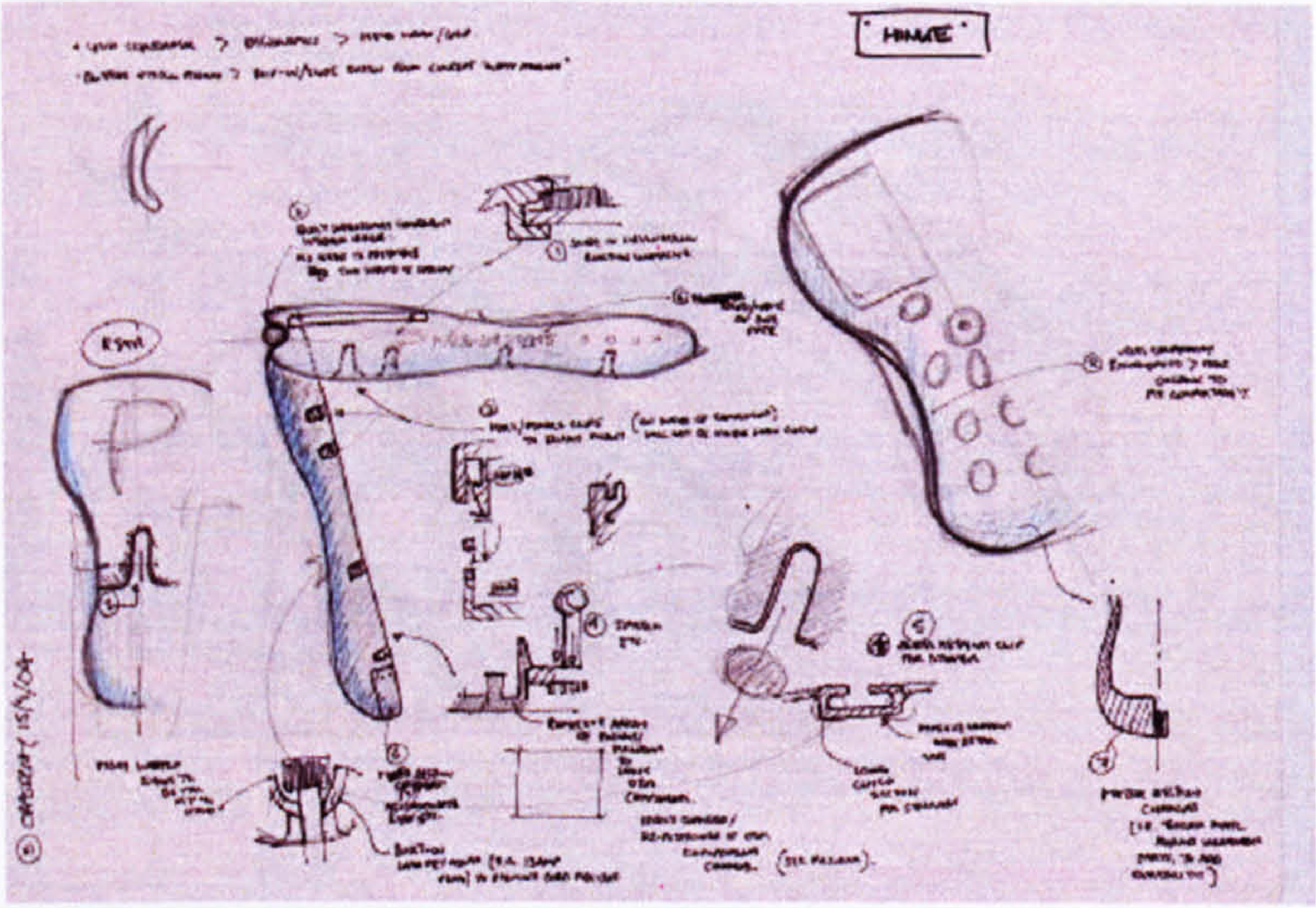


Sheet 3

Participant Number 3

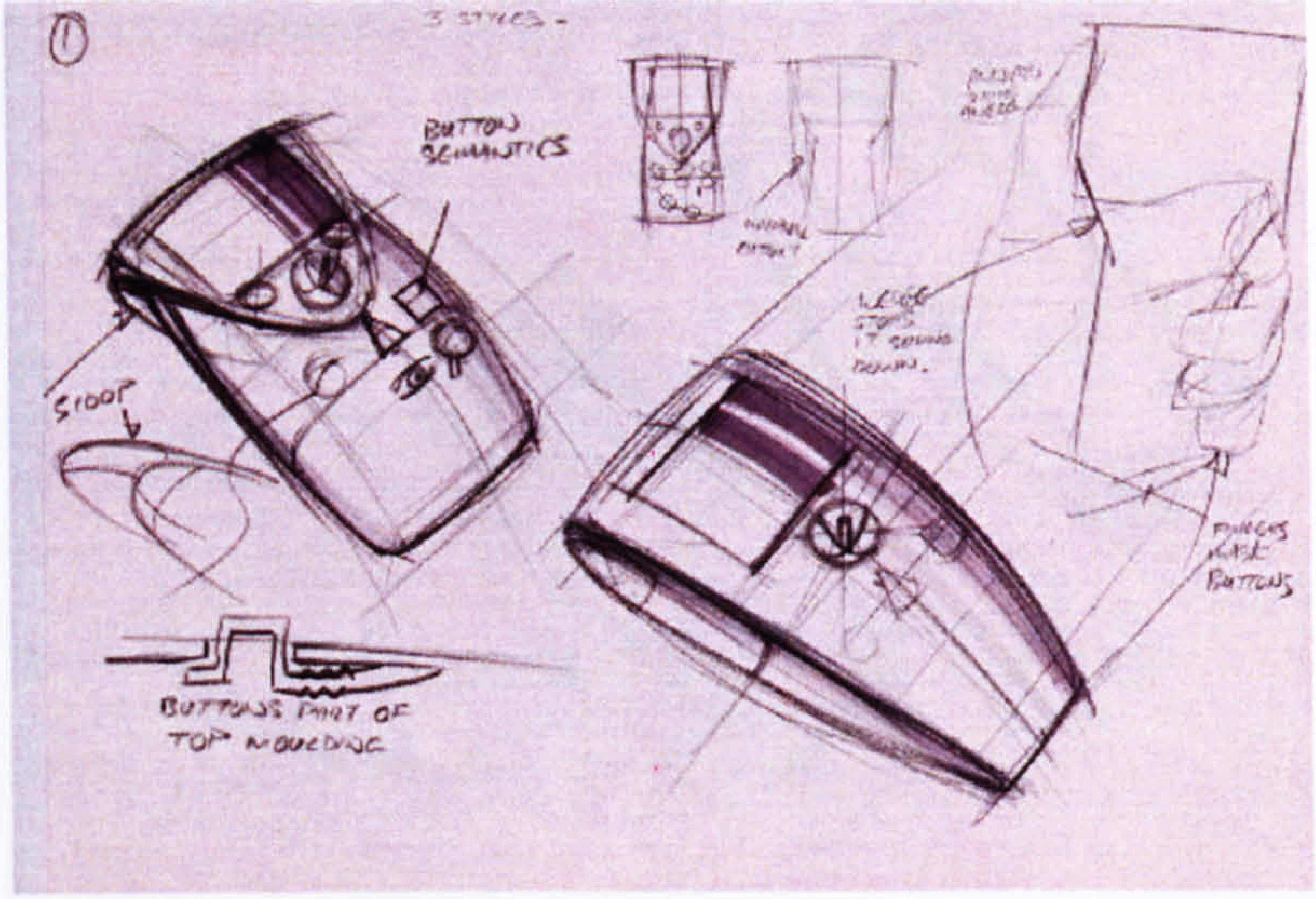


Sheet 4

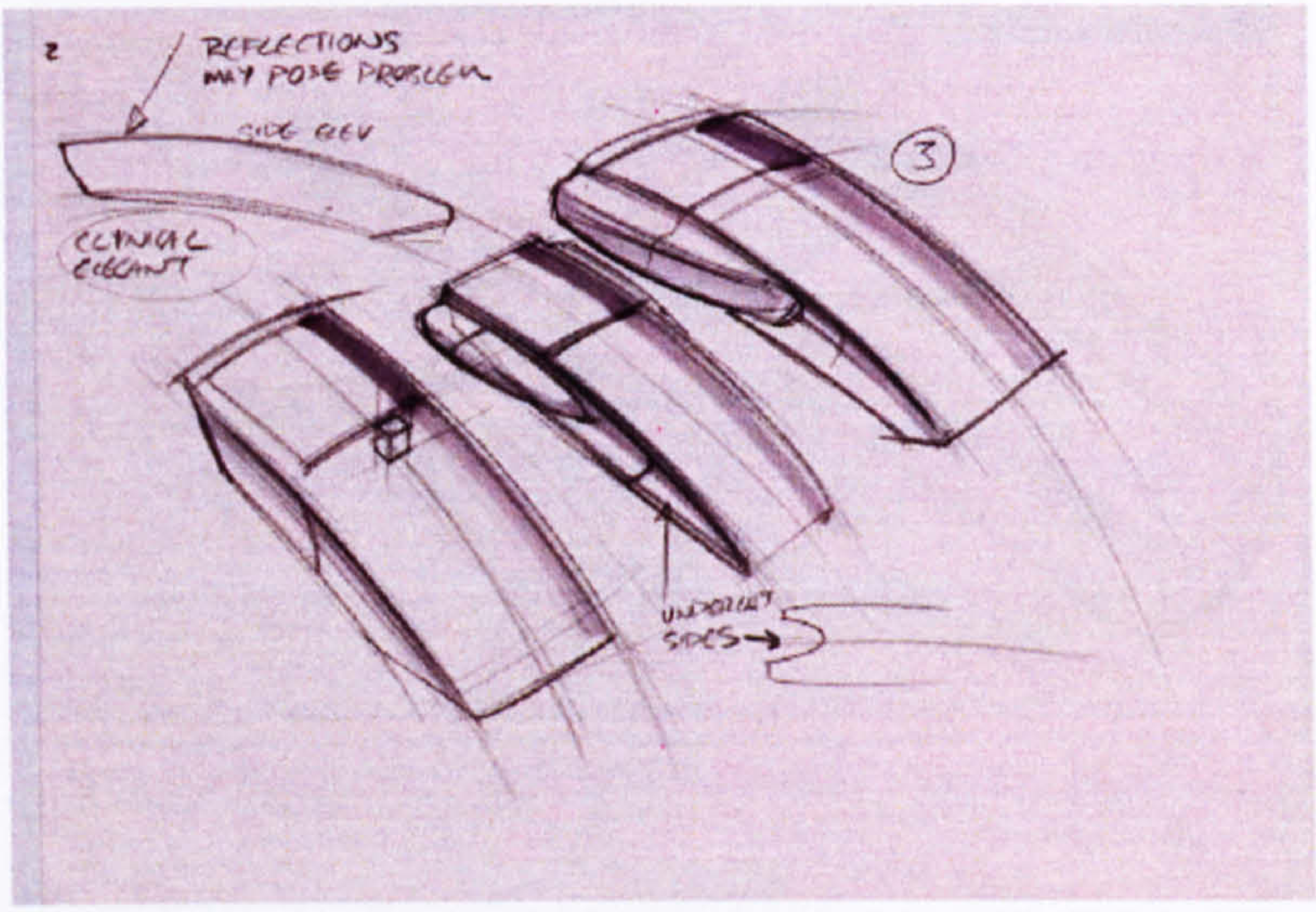


Sheet 5

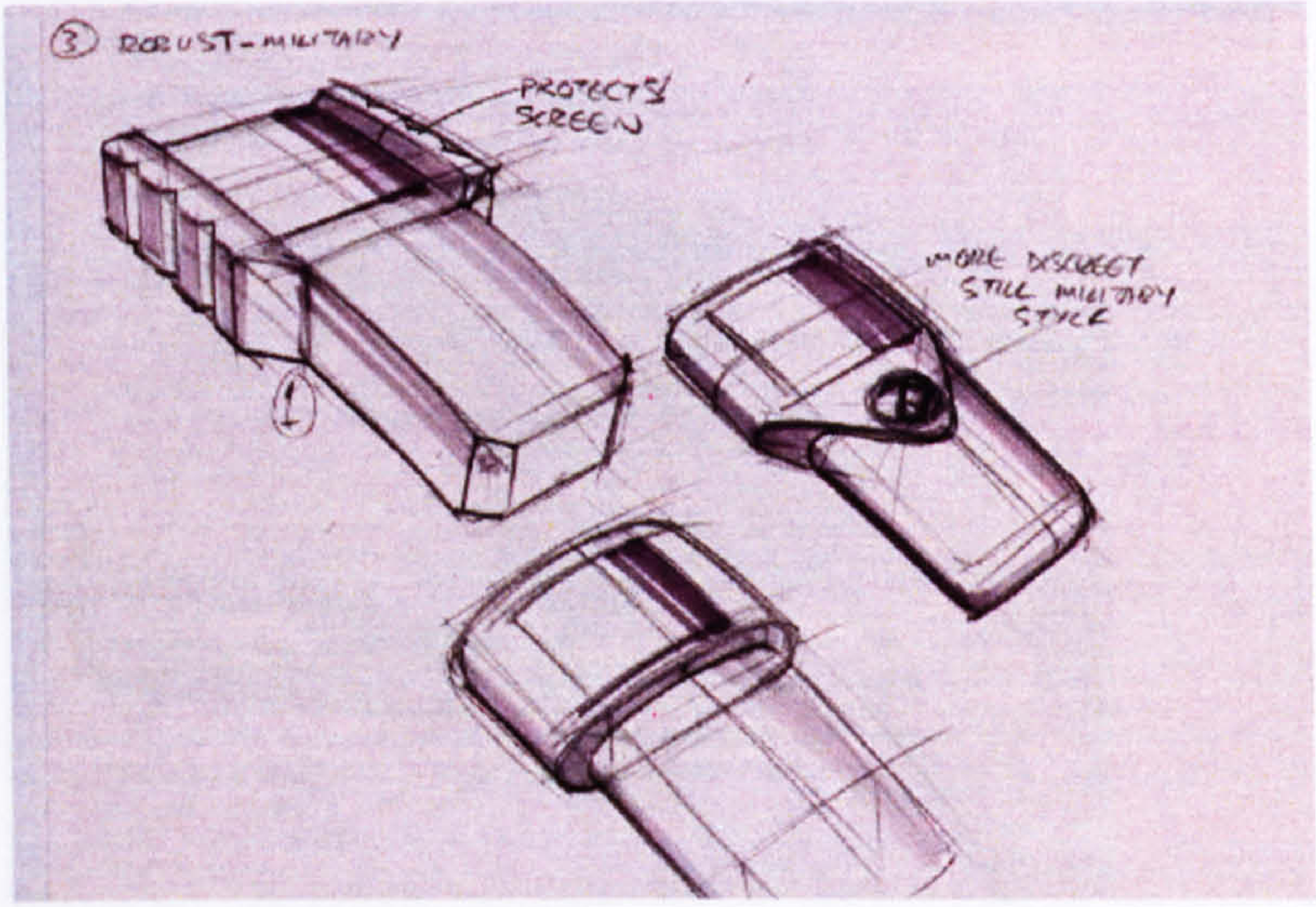
Participant Number 4



Sheet 1

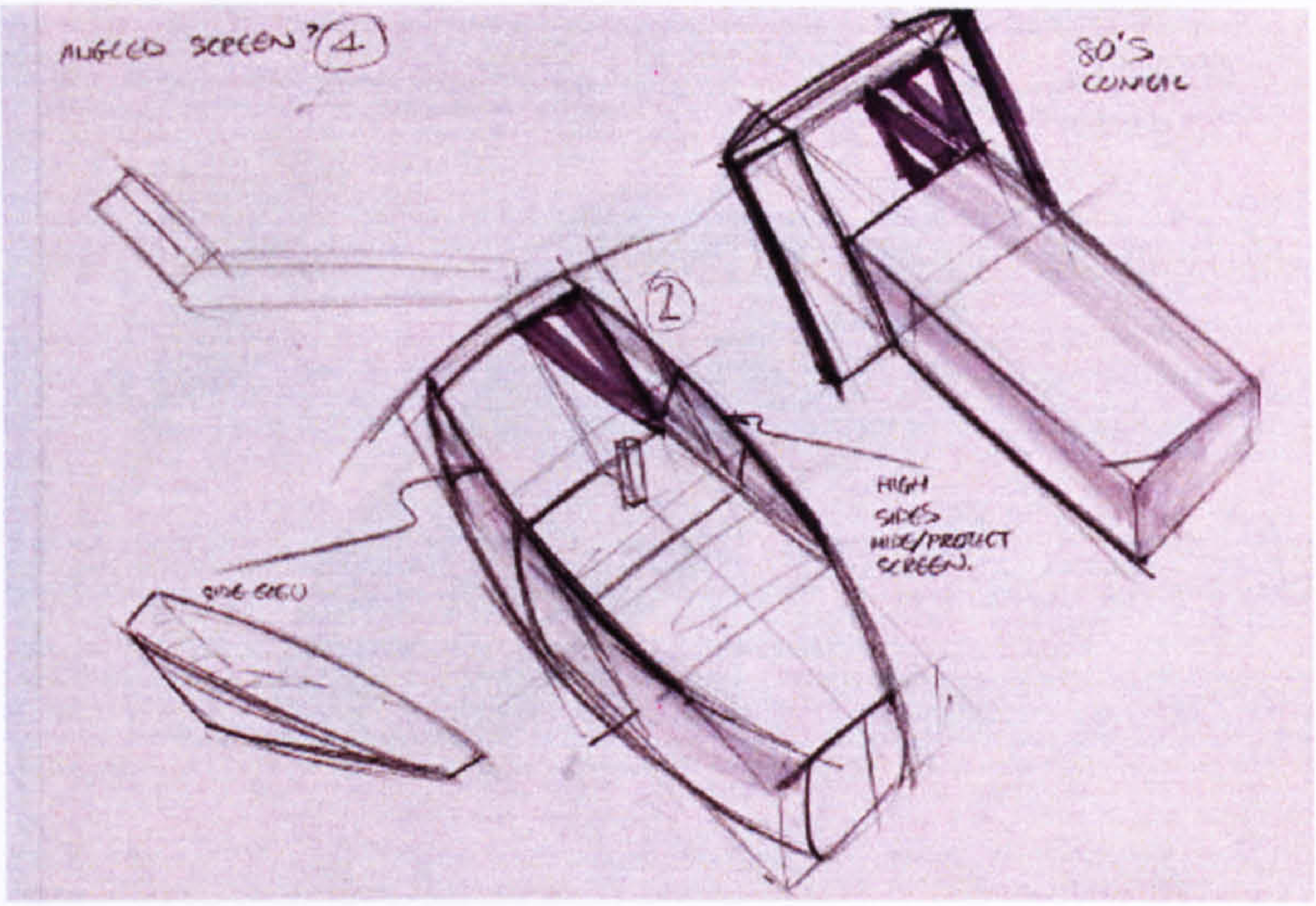


Sheet 2

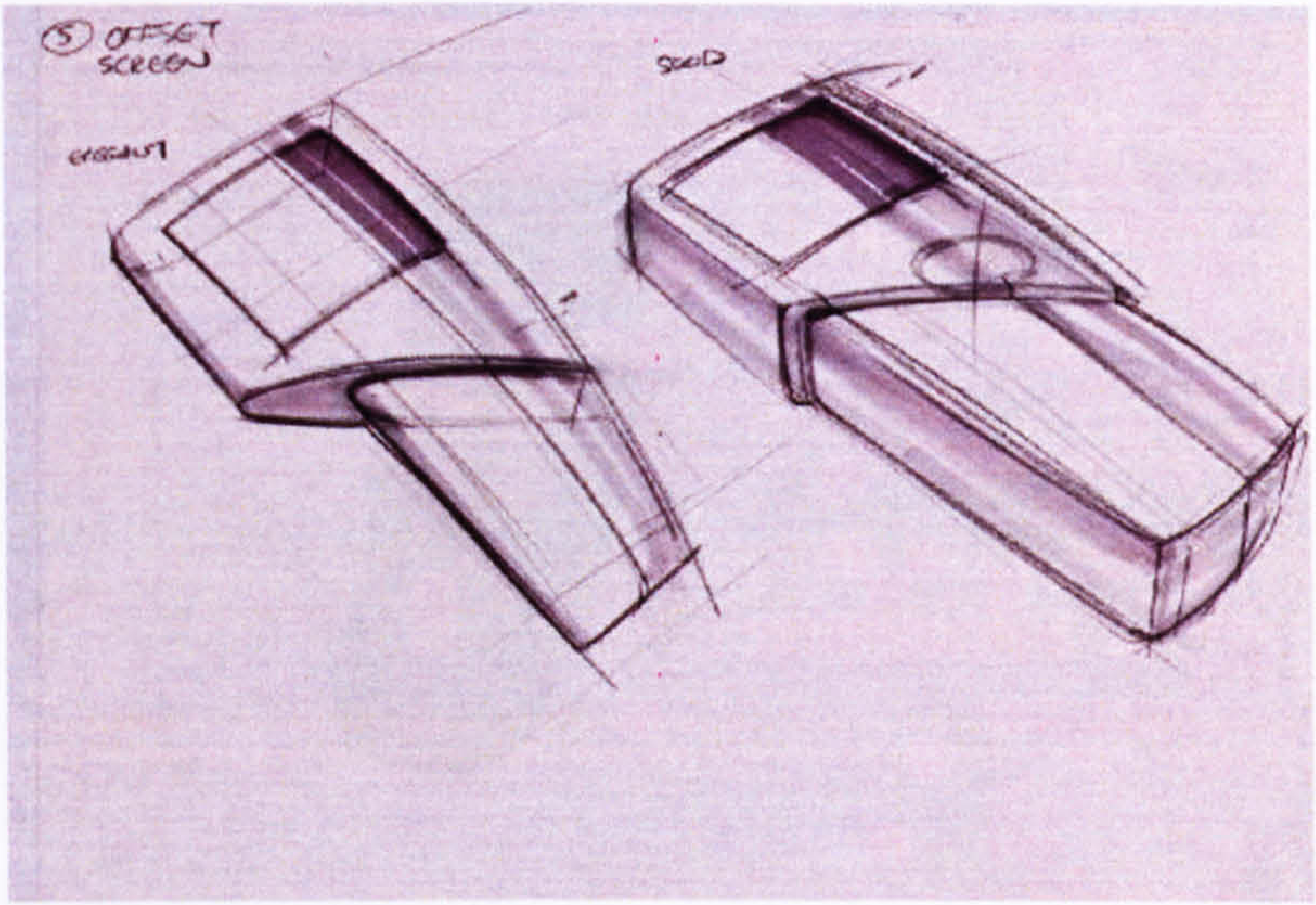


Sheet 3

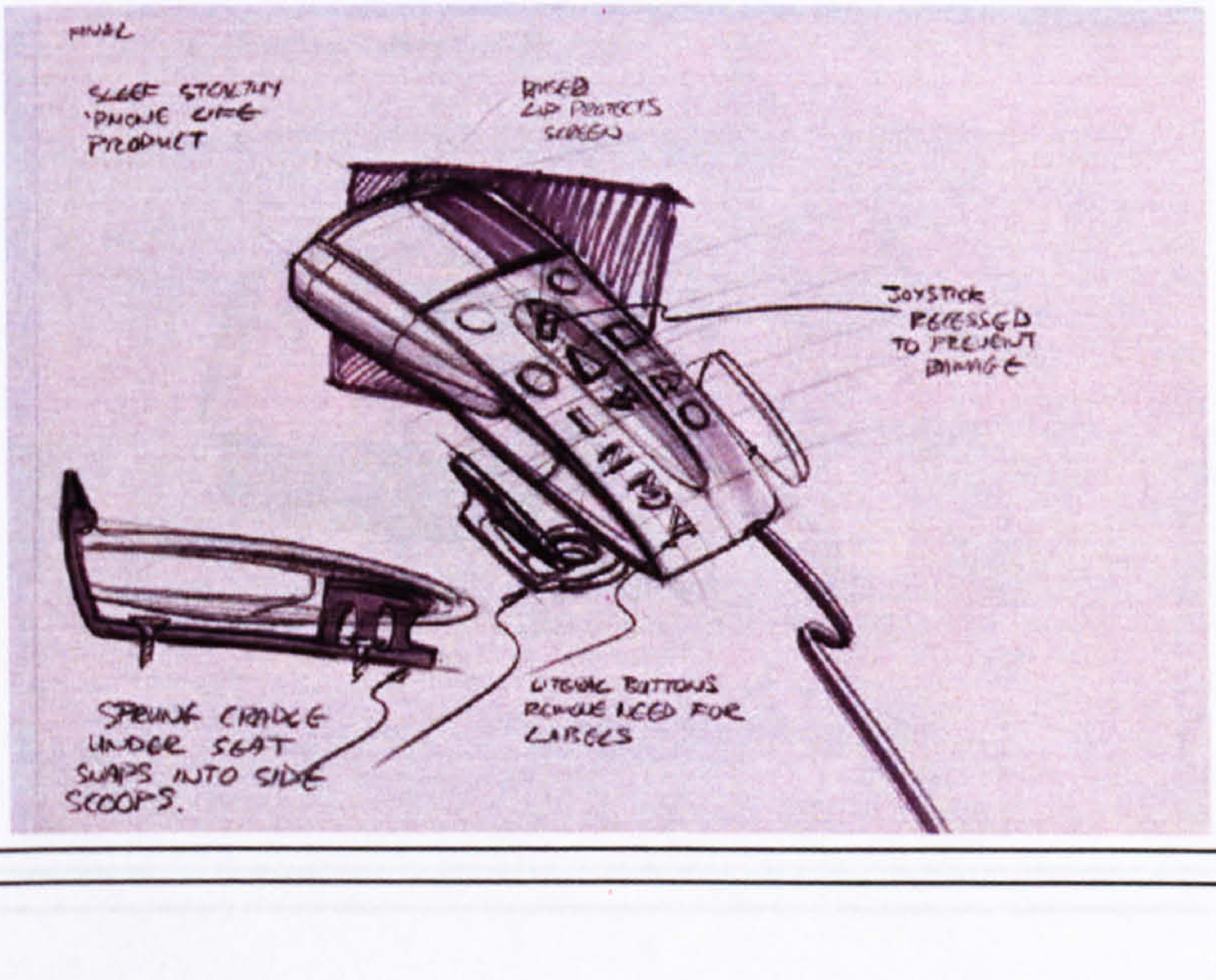
Participant Number 4



Sheet 4

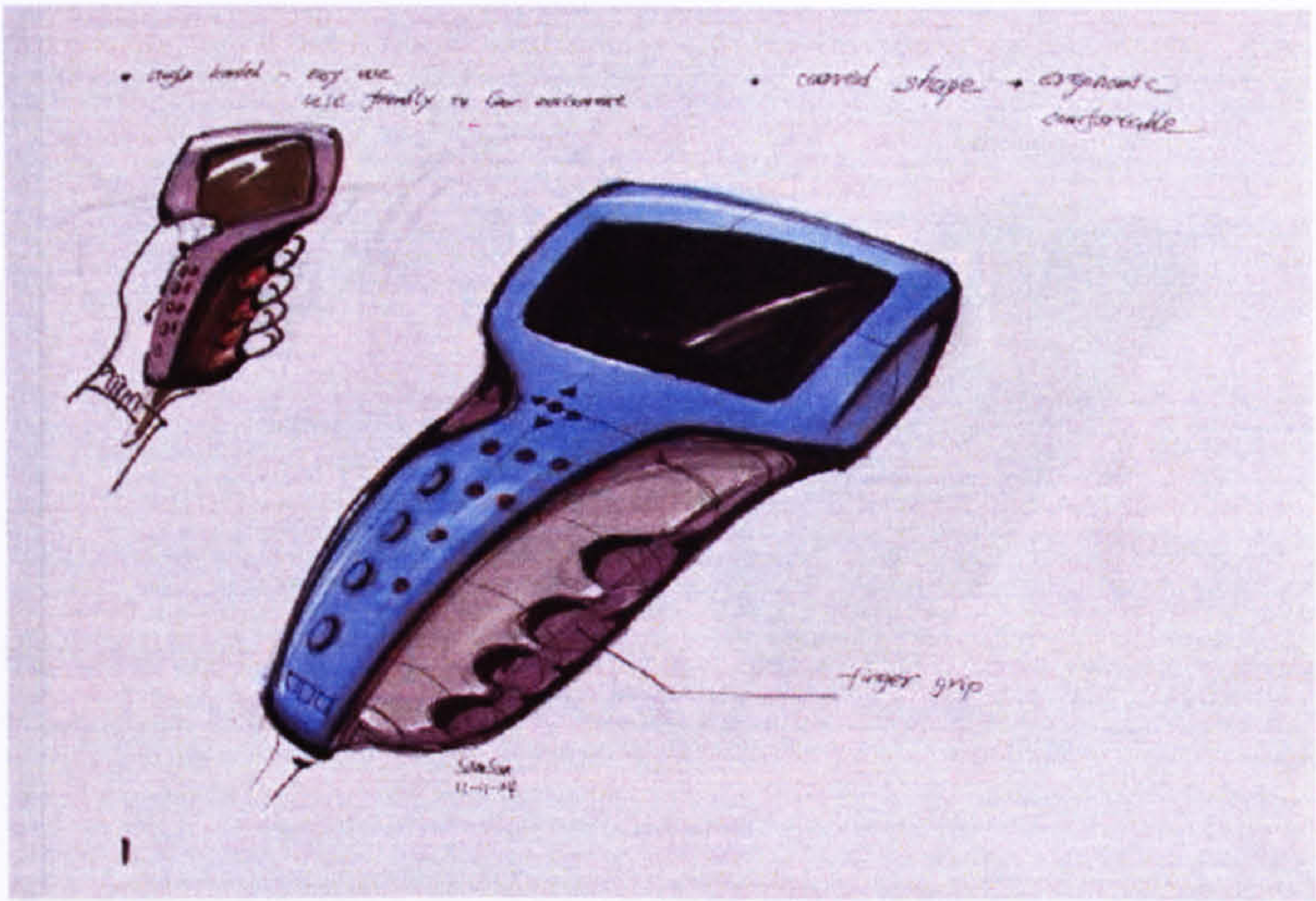


Sheet 5

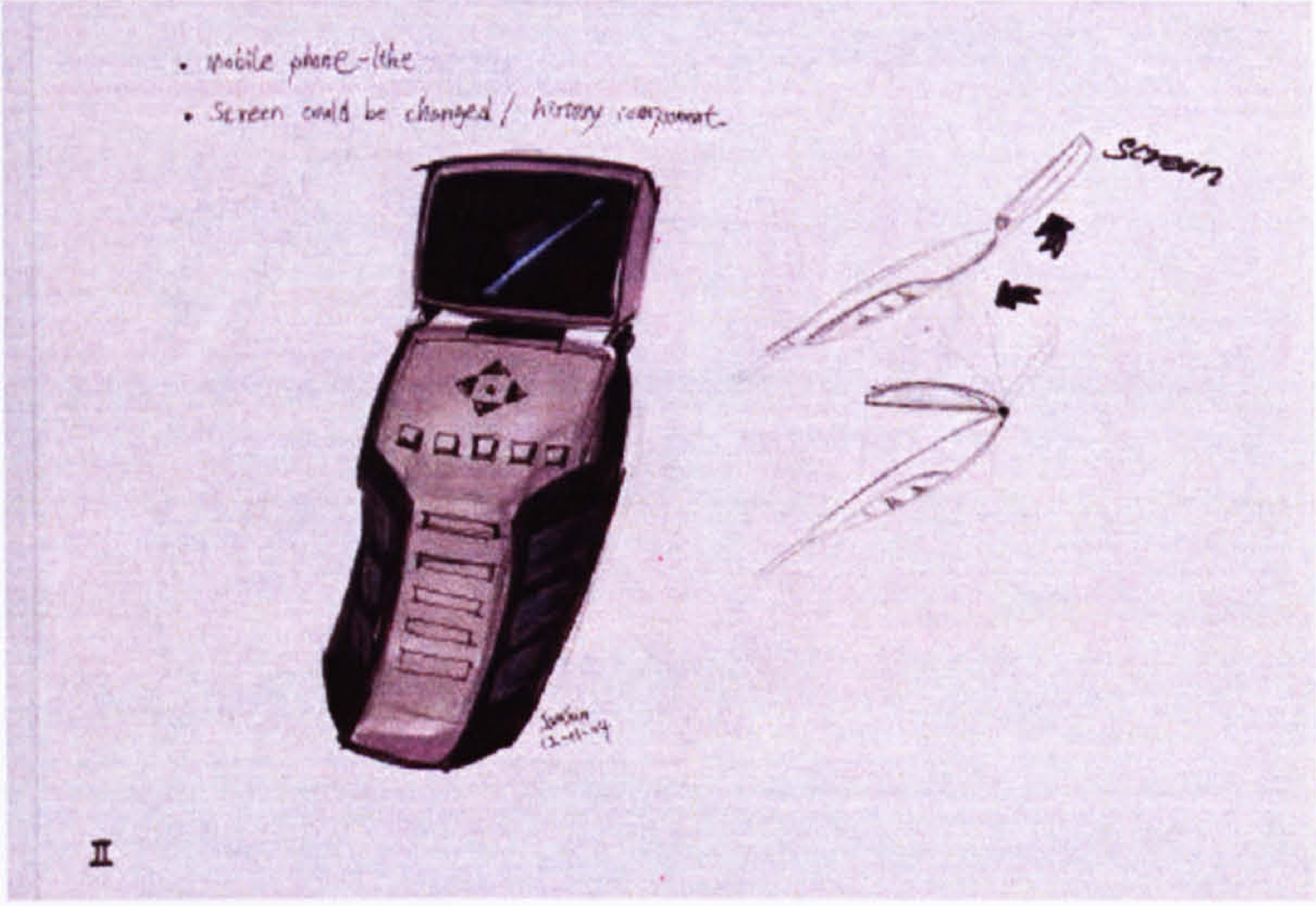


Sheet 6

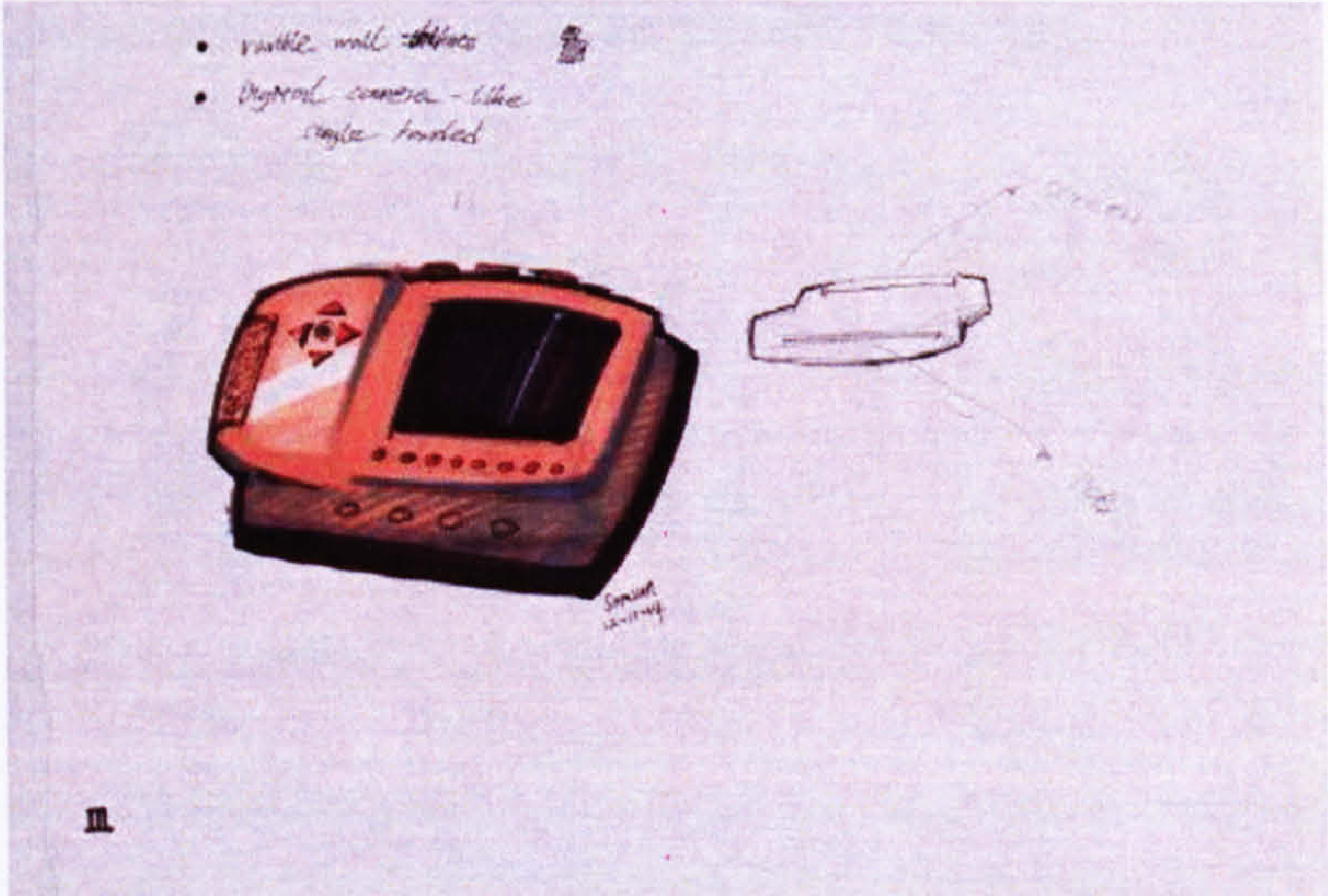
Participant Number 5



Sheet 1

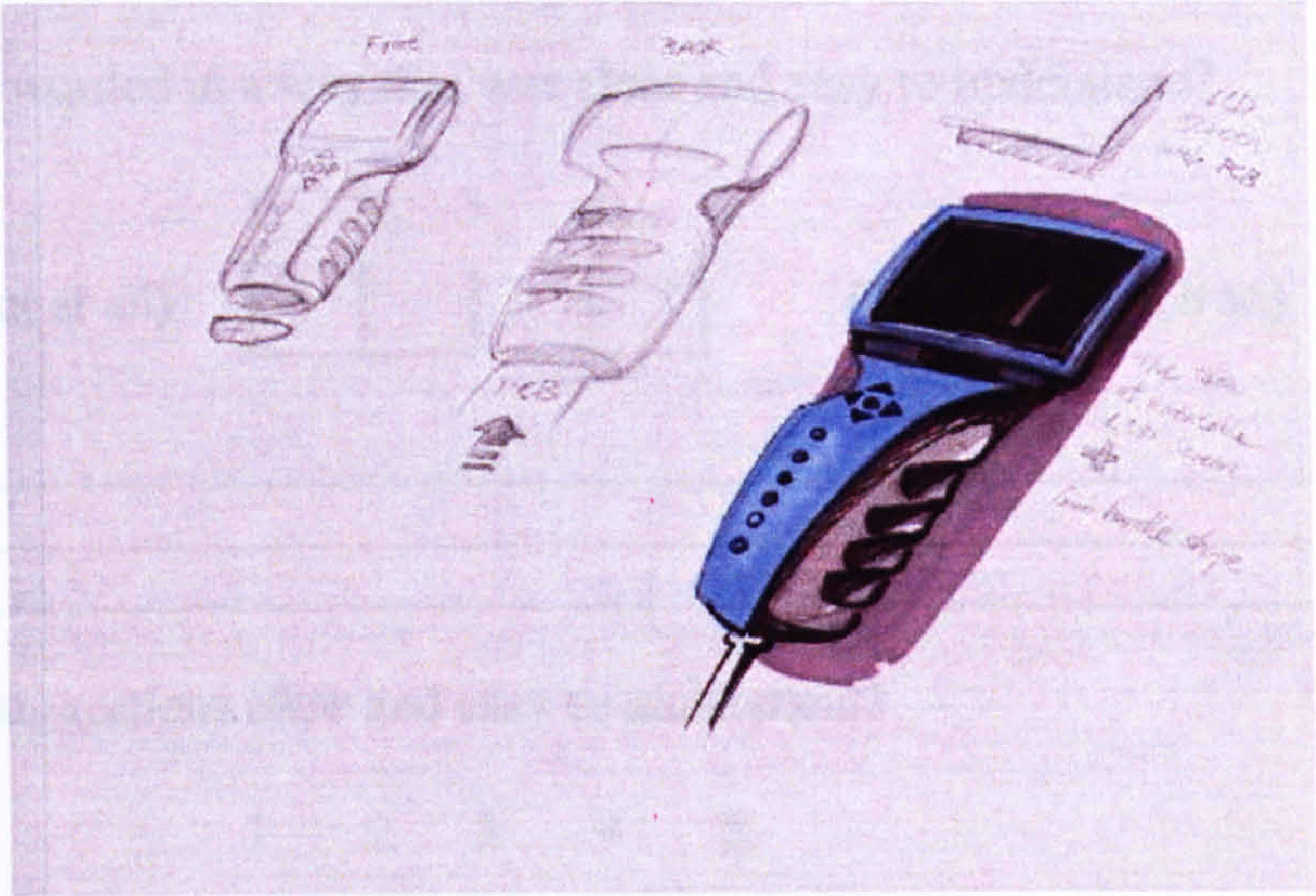


Sheet 2



Sheet 3

Participant Number 5



Sheet 4

Appendix F DFRM Feedback

1. Were the questions worded in a way that was clear and easy to understand?

	1	2	3	4	5	
(No, not at all)	☐	☐	☐	☐	☐	(Yes, very much so)

2. Were the concept suggestions clear and easy to understand?

	1	2	3	4	5	
(No, not at all)	☐	☐	☐	☐	☐	(Yes, very much so)

3. Were the concept suggestions useful when performing the design exercise?

	1	2	3	4	5	
(No, not at all)	☐	☐	☐	☐	☐	(Yes, very much so)

4. Do you feel your designs were influenced by the concept suggestions?

	1	2	3	4	5	
(No, not at all)	☐	☐	☐	☐	☐	(Yes, very much so)

5. What sort of method do you normally use when designing?

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

1 2 3 4 5

(No, not at all) ☐ ☐ ☐ ☐ ☐ (Yes, very much so)

____

____

____

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

1 2 3 4 5

(Less effective) ☐ ☐ ☐ ☐ ☐ (More Effective)

(Same)

____

____

____

8. How do you normally select a preferred design from a number of initial concepts?

____

____

____

9. Did you find the assessment matrix helpful in selecting a preferred design?

1 2 3 4 5

(No, not at all) ☐ ☐ ☐ ☐ ☐ (Yes, very much so)

____

____

____

10. Are there any other comments about the method that you would like to make?

____

____

____

Professional Designer – Number 1

Feedback Questionnaire

1. Were the questions worded in a way that was clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

Some needed clarification.

2. Were the concept suggestions clear and easy to understand?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

3. Were the concept suggestions useful when performing the design exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

4. Do you feel your designs were influenced by the concept suggestions?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

consolidation + geometric freedoms.

5. What sort of method do you normally use when designing?

Sketch.

Professional Designer – Number 1

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

(No, not at all) 1 [✓ 2] 3 4 5 (Yes, very much so)

Background info is always required
Product selection requires rating on
what is not important. in innocuous
design if important would affect everything else.

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)
(Same)

see above + FMEA used
again rates importance

8. How do you normally select a preferred design from a number of initial concepts?

Depends on brief - client choice
aesthetics
cost etc

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any other comments about the method that you would like to make?

See 6.

Professional Designer – Number 2

Feedback Questionnaire

1. Were the questions worded in a way that was clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

2. Were the concept suggestions clear and easy to understand?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

3. Were the concept suggestions useful when performing the design exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

4. Do you feel your designs were influenced by the concept suggestions?

(No, not at all) 1 [✓ 2] 3 4 5 (Yes, very much so)

5. What sort of method do you normally use when designing?

I try not to use pre defined methods/approaches
Try to be driven by each new problem – as a unique exercise.

Professional Designer – Number 2

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

In evaluation but not during idea creation.

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

(Less effective) 1 [✓ 2] 3 4 5 (More Effective)
(Same)

8. How do you normally select a preferred design from a number of initial concepts?

Very intuitively, initially.

verifying.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any other comments about the method that you would like to make?

I try not to use method/systems approach because they become comfortable. (Easy to use without so much thought.)

Professional Designer – Number 3

Feedback Questionnaire

1. Were the questions worded in a way that was clear and easy to understand?

(No, not at all) 1 2 3 4 ✓ 5 (Yes, very much so)

2. Were the concept suggestions clear and easy to understand?

(No, not at all) 1 2 3 4 ✓ 5 (Yes, very much so)

USE OF ILLUSTRATIONS HELPED A LOT. I.E. BEFORE/AFTER.

3. Were the concept suggestions useful when performing the design exercise?

(No, not at all) 1 2 3 4 ✓ 5 (Yes, very much so)

VISUAL CUE/REMINDER. CERTAINLY AS A NEWCOMER TO THE PRINCIPLES,

4. Do you feel your designs were influenced by the concept suggestions?

(No, not at all) 1 2 ✓ 3 4 5 (Yes, very much so)

~~INFLUENCED BY THE PRINCIPLES, BUT~~ YES. BUT LIKE A PDS:

5. What sort of method do you normally use when designing?

BRAINSTORM > IDEAS > CONCEPT GEN > CONCEPT SELECT > DETAIL!

NO SPECIFIC FORMAL METHOD,

Professional Designer – Number 3

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

CERTAINLY AS A NOVICE TO THIS AREA + AS A LEARNING TOOL. AFTER THAT, THE IDEAS SHOULD BE INTERNALISED. MATRICES ALWAYS A GOOD IDEA THOUGH – BUT SOMETIMES V. TIME CONSUMING. TEND TO AVOID ANY ONE 'SYSTEM' APPROACH TO DESIGNING: MORE ABOUT USING RIGHT TOOL @ RIGHT TIME.

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)
(Same)

NOT MUCH EXPERIENCE IN EXPLICIT METHODS SUCH AS THIS. CAN'T REALLY JUDGE, BUT IT WAS DEFINITELY USEFUL.

8. How do you normally select a preferred design from a number of initial concepts?

CLIENT FEEDBACK, EXPLICIT PROS/CONS BULLET POINTED. NORMALLY A DISCUSSION – NOT A MATRIX.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 [✓ 2] 3 4 5 (Yes, very much so)

HAD GUT FEELING TO GO WITH ONE CONCEPT RATHER THAN OTHERS, EVEN IF IT HAD DEFICIENCIES IN SOME AREAS. MOST USEFUL ASPECT WAS TO SEE HOW 'GUT FEELING' CONCEPT COULD BE IMPROVED BY SEEING HOW THE LESS PREFERRED CONCEPTS SCORED!

10. Are there any other comments about the method that you would like to make?

VERY SATISFACTORY APPROACH TO NEWCOMERS: I CAN NOW THINK ABOUT RAPID MANUFACTURING AS A POSSIBLE APPROACH IN MY OWN WORK + WHEN GOING THRU MANUFACTURING OPTIONS FOR PROJECTS.

THIS TASTER PROJECT HELPED INTERNALISE KEY ISSUES WITH R.M. THAT MAY NOT HAVE BEEN SO EASILY LEARNT IF JUST READING A BOOK!

Professional Designer – Number 4

Feedback Questionnaire

1. Were the questions worded in a way that was clear and easy to understand?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

2. Were the concept suggestions clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

3. Were the concept suggestions useful when performing the design exercise?

(No, not at all) 1 [✓ 2] 3 4 5 (Yes, very much so)

UP TO A POINT - MORE INFO ON STYLE / PROPORTION REQUIRED

4. Do you feel your designs were influenced by the concept suggestions?

(No, not at all) 1 [✓ 2] 3 4 5 (Yes, very much so)

STILL VERY OPEN BRIEF - MANY SHAPES WILL 'FIT' THE SUGGESTIONS

5. What sort of method do you normally use when designing?

VISUAL / STYLE RESEARCH — SEMANTICS
STATE OF THE ART INVESTIGATIONS
UTE STUDY
GUT FEELING SKETCHES
MORE CONSIDERED DEVELOPMENT
2D 3D MODELLING
EVALUATION
REFINE

Professional Designer – Number 4

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

(No, not at all) [✓ 1] 2 3 4 5 (Yes, very much so)

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

(Less effective) 1 [✓ 2] 3 4 5 (More Effective)

(Same)

8. How do you normally select a preferred design from a number of initial concepts?

PEER REVIEW / CLIENT REVIEW

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

MORE 'STYLE' MEASURES REQUIRED

10. Are there any other comments about the method that you would like to make?

PROJECT IS TOO VAGUE
GET MORE REALISTIC RESULTS
FROM A TIGHTER BREIF

Professional Designer – Number 5

Feedback Questionnaire

1. Were the questions worded in a way that was clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

992 very straight away. just few questions needed to me explaination.

2. Were the concept suggestions clear and easy to understand?

4-

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

I think the suggestion is quite clear and helpful. Since the concept is still in development, It will be more genuine after shaping up later.

3. Were the concept suggestions useful when performing the design exercise?

(No, not at all) 1 2 3 [✓ 4]+ 5 (Yes, very much so) 4+

Very.

4. Do you feel your designs were influenced by the concept suggestions?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

lots. The briefing is leading this redesign work.

5. What sort of method do you normally use when designing?

Well, hard to explain fully in only few words But generally.

Clint requirement → machanical / ergonommical → design specification → sketch → review → development → final design → review again → production / optimization

Professional Designer – Number 5

6. Do you think your design activities would benefit from using a systematic approach like the one you have just used?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

of course. especially for Design for RM.

7. How effective would you say this systematic approach is in comparison with any other design methods that you use?

3+

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)

(Same)

In current stage it is hard to compare because all design carried out for certain manufaction method. But this method will be potentially more advanced.

8. How do you normally select a preferred design from a number of initial concepts?

It depends on many elements. e.g. client review. Manufaction limitation etc. Normally designers have few freedom to realize what they really want. But with this method, It will change the situation.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

Yes. It represents the design method importantly.

10. Are there any other comments about the method that you would like to make?

Wish a really good luck. more communication with industry side.

Student Designer – Number 1

Name: [redacted]

Product: IRON

Design For Rapid Manufacture: Feedback Questionnaire

1. **Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?**

(No, not at all) 1 | 2 | 3 | 4 | [✓ 5] (Yes, very much so)

2. **How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?**

(Not at all) 1 | 2 | 3 | 4 ● | 5 (Very much so)

THEY WERE CLEAR & LEGIBLE

3. **Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?**

(No, not at all) 1 | 2 | 3 | ●4 | 5 (Yes, very much so)

YES, I HAD LITTLE EXPERIENCE OF THE SPECIFIC WAYS IN WHICH RM COULD HELP.

4. **Do you feel your concept designs were influenced by the suggestions that were made?**

(No, not at all) 1 | 2 | 3 | 4 ● | 5 (Yes, very much so)

5. **What sort of method or strategy do you normally use to generate and select concepts?**

MATRIX OF CRITERIA – BUT NO POINT SCORING SYSTEM – THIS CAN GLOSS OVER CRITICAL ISSUES. JUST USED TO CLARIFY & EXTERNALISE THINKING.

Student Designer – Number 1

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

IT IS USEFUL – BUT SHOULD ONLY BE USED AS A GUIDE – NOT TAKEN TOO LITERALLY. A CONCEPT CAN BE MORE THAN JUST THE SUM OF ITS PARTS.

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)

(Same)

IT IS SIMILAR BUT PERHAPS I USUALLY USE LESS FORMAL PRESENTATION OF DECISIONS.

8. How would you normally select a preferred design from several initial concepts?

SEE Q 5. IN ADDITION TO INTUITION, AESTHETICS, OVERALL FEEL, USER FEEDBACK.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

IN TERMS OF THE RM FEATURES IT WAS INVALUABLE. HOWEVER, A MATRIX FOR BROADER ASPECTS OF THE PRODUCT WOULD BEGIN TO GET TOO COMPLEX

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

IT IS NOT ALWAYS YOU HAVE SEVERAL DIFFERENT, FUNCTIONALLY SIMILAR APPROACHES FROM WHICH TO CHOOSE. THIS SYSTEM DOES NOT HELP IF YOU ARE MAKING ITERATIONS TO ONE DESIGN SOLUTION.

Student Designer – Number 2

Name: [redacted]

Product: WILKINSON SWORD FX DIAMOND RAZOR

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 4 [✓ 5] (Very much so)

It was good to get the ideas accross.

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

It helped a lot. Gave me ideas.

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

Come up with a few concepts and look at the good + bad points of each one + ~~[illegible]~~ weigh up the different aspects.

Student Designer – Number 2

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

Yes and no. This doesn't always allow for creative flair, for products with the x-factor.

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)
(Same)

As before it was good for a more manufacturing route but not for industrial design + styling

8. How would you normally select a preferred design from several initial concepts?

weigh up pros + cons, look at different aspects of the design.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

Yes I did but it was also important in this case to choose a concept that would look impressive in my portfolio.

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

No, ~~exp~~ except add a section for a concept that has the X-factor

Student Designer – Number 3

Name: [redacted]

Product: Shower Radio

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

   (No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

   (Not at all) 1 2 3 [✓ 4] 5 (Very much so)

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

   (No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

4. Do you feel your concept designs were influenced by the suggestions that were made?

   (No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

   Sketching initial ideas, investigating alternatives. Working out which ideas fit best together in the product

Student Designer – Number 3

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 4 [✓ 5] (More Effective)

(Same)

8. How would you normally select a preferred design from several initial concepts?

Basic selection on function + personal preference on aesthetics. Maybe ask some other people / designers. for feedback. At extreme using a decision matrix.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

Student Designer – Number 4

Name: [redacted]

Product: NG4-CONTROL

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 4 [✓ 5] (Very much so)

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

RAPID IDEA GENERATION + DEVELOPMENT BASED
ON FURTHER RESEARCH

Student Designer – Number 4

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 [✓ 3] 4 5 (More Effective)

(Same)

8. How would you normally select a preferred design from several initial concepts?

DECIDE WHICH WAS BEST BASED ON

① FUNCTION ② AESTHETICS ③ REALITY OF MAKING

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

IT IS MY EXPERIENCE THAT CONCEPTS WILL NOT BE DRAWN IF THEY DO NOT FIT THE BASIC CRITERIA IN THE FIRST PLACE

Student Designer – Number 5

Name: [redacted]

Product: CORDLESS DRILL

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

YES, QUICK TO FILL IN AND VERY STRAIGHT FORWARD & SOME QUESTION DIFFICULT TO UNDERSTAND WITHOUT GREATER TECHNICAL KNOWLEDGE OF RM.

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 [✓ 4] 5 (Very much so)

MAYBE A FEW MORE EXAMPLES OF RAPID MANUFACTURING IN THE 'REAL WORLD' WOULD HELP TO UNDERSTAND WHEN BEST TO USE CERTAIN FEATURES.

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

TO AN EXTENT BUT I DID NOT WANT TO COMPROMISE THE FORM OR FUNCTIONALITY IN ANY WAY.

5. What sort of method or strategy do you normally use to generate and select concepts?

FAST SKETCHES DEVELOPING DETAIL/FORM TO DEFINE CONCEPT IDEA. THEN SELECTION BASED UPON AESTHETIC AND FUNCTIONAL CRITERIA

Student Designer – Number 5

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 [✓ 4] 5 (More Effective)
(Same)

WEIGHTINGS OF IMPORTANCE HELPED TO FOCUS DESIGN EFFORT INTO AREAS THAT WOULD HAVE THE GREATEST IMPACT / BENEFIT.

8. How would you normally select a preferred design from several initial concepts?

THROUGH EVALUATION ON DESIGN CRITERIA AND RATING THE MERITS OF DIFFERENT ELEMENTS INFORMATIVELY – NO NUMERIC WEIGHTING

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

VERY DIFFICULT TO UNDERSTAND HOW EXACTLY YOU ARE MEANT TO DERIVE WEIGHTING AND APPLY A NUMERICAL VALUE. MAYBE SOME GENERAL GUIDELESS WOULD BE BENEFICIAL.

Student Designer – Number 6

Name: [redacted]

Product: Cordless Mouse

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

It was sometimes unclear what exactly was being required.

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 [✓ 4] 5 (Very much so)

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

Only because my product was not very conducive to redesign for manufacture.

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

For reasons given above

5. What sort of method or strategy do you normally use to generate and select concepts?

No formal matrix. Tends to be user and designer preference

Student Designer – Number 6

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

It made me think concisely about the importance of features and the process capabilities.

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 [✓ 4] 5 (More Effective)
(Same)

A lot more structured yet it does not hinder creativity.

8. How would you normally select a preferred design from several initial concepts?

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

Even when concepts appeared to be very similar.

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

Clarify what numbers in matrix are representing. Is it how important the feature is or how well the new concept meets the previously defined criteria.

Student Designer – Number 7

Name: [redacted]

Product: Sander

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 [✓ 4] 5 (Very much so)

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

Quick sketching, especially detail aspects, like fastenings

Student Designer – Number 7

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 [✓ 4 5] (More Effective)

(Same)

8. How would you normally select a preferred design from several initial concepts?

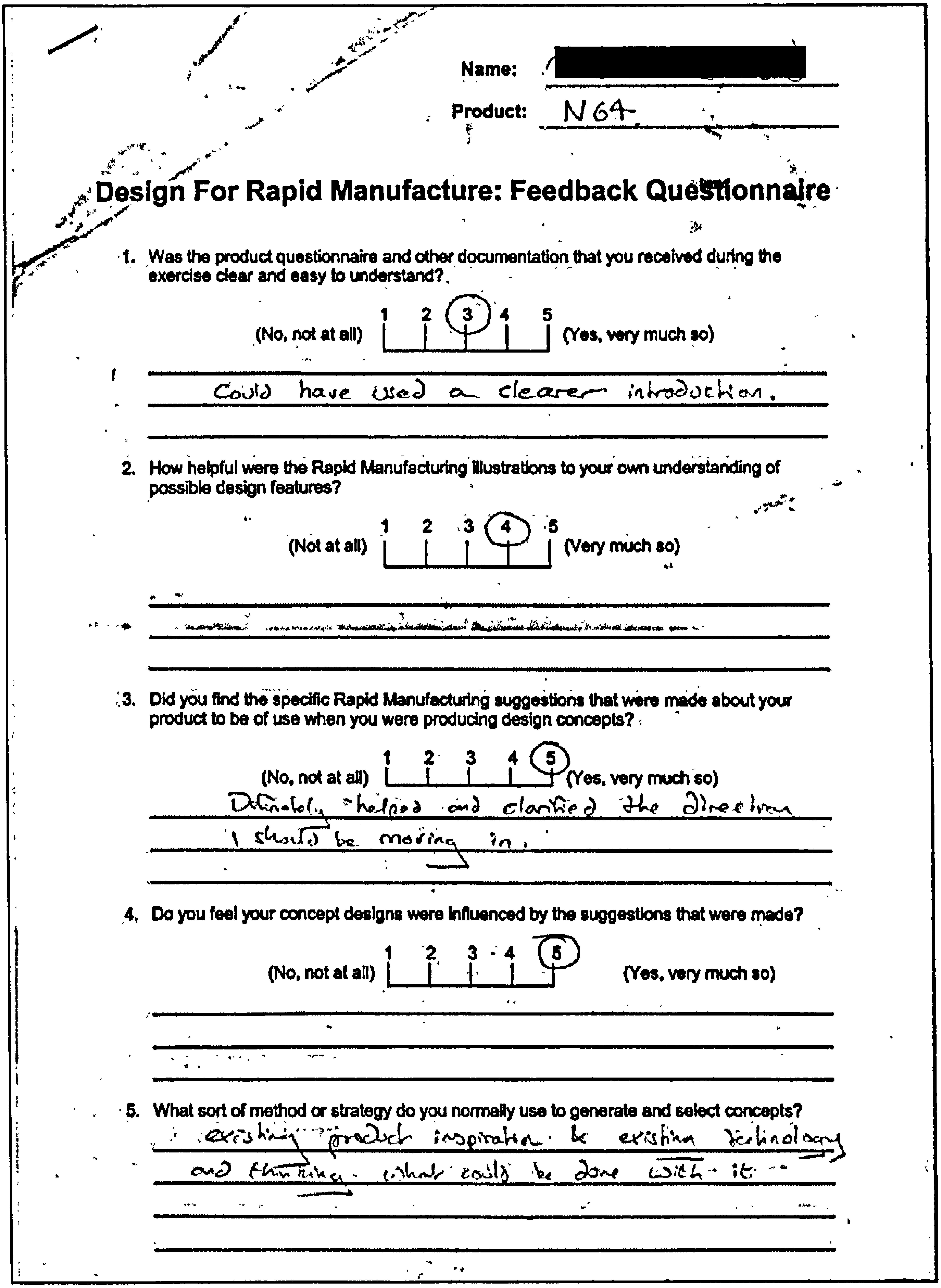
Evaluate products against a specification / with users

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

Student Designer – Number 8



Name: [redacted]

Product: N64

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 [✓ 3] 4 5 (Yes, very much so)

Could have used a clearer introduction.

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 [✓ 4] 5 (Very much so)

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

Definitely helped and clarified the direction I should be moving in.

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

existing product inspiration & existing technology and thinking what could be done with it

Student Designer – Number 8

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

To an extent yes (see prev answer)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 4 [✓ 5] (More Effective)

(Same)

Much faster and diverse ideas.

8. How would you normally select a preferred design from several initial concepts?

Pick the most likely to work

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

Student Designer – Number 9

Name: [redacted]

Product: X-BOX HANDSET

Design For Rapid Manufacture: Feedback Questionnaire

1. Was the product questionnaire and other documentation that you received during the exercise clear and easy to understand?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

2. How helpful were the Rapid Manufacturing illustrations to your own understanding of possible design features?

(Not at all) 1 2 3 [✓ 4] 5 (Very much so)

I THINK POSSIBLY THE MATERIALS AVAILABLE FOR RM SHOULD BE DESCRIBED AS IT WAS NOT TOO OBVIOUS WHAT MATERIAL PROPERTIES COULD BE PRODUCED THROUGH RM.

3. Did you find the specific Rapid Manufacturing suggestions that were made about your product to be of use when you were producing design concepts?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

4. Do you feel your concept designs were influenced by the suggestions that were made?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

5. What sort of method or strategy do you normally use to generate and select concepts?

RAPID, UNHINDERED AND WIDESCALE CONCEPT PROPOSALS, GRADUALLY PICKING UP ON VARIOUS DESIGN SUGGESTIONS, USING BACKGROUND KNOWLEDGE AND INTUITION AS A GENERAL GUIDE.

Student Designer – Number 9

6. Do you think your design activities would benefit from using a systematic approach like the one that you were asked to use in this exercise?

(No, not at all) 1 2 3 4 [✓ 5] (Yes, very much so)

7. How does the systematic approach that you were asked to use in this exercise compare with design methods that you would normally use?

(Less effective) 1 2 3 [✓ 4] 5 (More Effective)
(Same)

- IN ORDER TO BE OF SIGNIFICANT USE HOWEVER, WEIGHTINGS OF IMPORTANCE ETC ARE CRITICAL WHICH CAN LEAD TO MISLEADING FIGURES, HOW DOES SERVE AS A GOOD GUIDE.

8. How would you normally select a preferred design from several initial concepts?

EVALUATION ON VARIOUS MERITS/DRAWBACKS AS A 'DELIBERATIVE DESIGN' WITHOUT WEIGHTED MATRIX ETC.

9. Did you find the assessment matrix helpful in selecting a preferred design?

(No, not at all) 1 2 3 [✓ 4] 5 (Yes, very much so)

10. Are there any comments or changes that you would like to make about the systematic method that you were asked to use?

AS THE MODULE FOCUSES MAINLY ON OUR CAMM ABILITIES IT WAS HARD TO GIVE A TRULY CONSIDERED WEIGHTING TO CERTAIN CRITERIA WITHOUT PRODUCT RESEARCH AND SO ON.