Knowledge in the making: Prototyping and human-centred design practice.

WALTERS, Peter J.

Published version

WALTERS, Peter J. (2005). Knowledge in the making: Prototyping and human-centred design practice. Doctoral, Sheffield Hallam University (United Kingdom)..

Sheffield Hallam University

Author: PETER JAMES WALTERS

Title/Thesis Number: KNOWLEDGE IN THE MAKING....

Degree: Ph.D

Year: 2005

Knowledge in the making:

Prototyping and human-centred design practice

Peter James Walters

A thesis submitted in partial fulfilment of the requirements of
Sheffield Hallam University
for the degree of Doctor of Philosophy

December 2005

Contents

Part One: Contextual Review

Part Two: Practical Examples

Acknowledgements

I wish to express my gratitude to my supervisory team Professor Paul Chamberlain, Dr Tom Fisher, Professor Mike Press and Professor Anne Tomes who have supported, encouraged and inspired.

I am thankful to Professor Chamberlain for providing me with the opportunity to contribute to his program of research in medical device design, and also to the other members of the interdisciplinary project team: Dr Peter Gardner, Dr Rebecca Lawton and Dr Neil Carrigan (University of Leeds) and Dr Philip Bickford Smith (Bradford Royal Infirmary).

I would also like to thank Professor Sergio Pellegrino and Matthew Santer (University of Cambridge), Dr Alaster Yoxall (University of Sheffield), and Dr Muhammad Islam and Robert Glynn (Sheffield Hallam University) for taking an interest in my shape-changing structures and also for providing support and advice on computer modelling and simulation techniques in this area.

Thanks must also go to the skilled craftsmen and technicians in the design workshops of Sheffield Hallam University who have supported me in my making activities, especially Peter Downes, Howard Walker and John Walton, and also to Katie Davies for her assistance with photography.

Research funded by the Arts and Humanities Research Council

Knowledge in the making:
Prototyping and human-centred design practice

Abstract

This thesis presents an enquiry into the nature and role of prototyping within human-centred design practice, examining the capabilities and limitations of emerging prototyping technologies within this context.

A contextual review explores the significance of the human element in design. This leads to the proposal of a *paradigm statement* for human-centred design which informs the theoretical and practical research activity undertaken in the course of this investigation.

A critical review of literature aimed at the design and engineering professions identifies a rhetoric celebrating the *virtualisation* of design processes. Here, advocates of emerging virtual prototyping technologies argue computer-based simulation techniques may reduce or replace physical prototype iterations, thereby greatly increasing the speed and efficiency of new product development processes. This thesis questions the extent to which virtual prototyping can replace physical human input in design.

A counter argument to the designer's total immersion in the virtual design world is that valuable creative opportunities may be revealed through discoveiy-oriented physical prototyping. Furthermore, it may not be possible to adequately describe all aspects of a design proposal using virtual methods alone. This is demonstrated in practical investigations in which designers sought to exploit tactile qualities as essential features in design, and also in cases involving complex structural behaviour.

Despite significant advances in virtual prototyping technologies, there remain some types of design problem which may only be identified and addressed through the making and testing of physical models. Moreover, this thesis argues that the valuable practical knowledge which may be derived through *hands-on* engagement and manipulation of physical prototypes and materials must be retained as an essential human element in design.

1.0 Introduction, aims and objectives

> *'The feel for the physical world about us is being lost due to the intervention of computerised equipment and work is becoming an abstraction from the real world. In my view profound problems face us in the coming years due to this process.'*
>
> Cooley (1980 p 4)

Like many others, I have always enjoyed making. The research described within this thesis arises from this personal enthusiasm and also a deeply held belief in the value of physical making and testing as a means of exploring practical design ideas. For me, a childhood fascination with all things mechanical led to a period of employment as an engineering draughtsperson. I was trained to work on the drawing board and also in CAD (Computer Aided Design) for the production of engineering drawings for a variety of applications ranging from the fabrication of large industrial structures to precision-machined engineering components. Here I benefited from the practical knowledge and experience of those who had worked "on the shop floor". However, I soon grew tired of life in the drawing office, and so I embarked upon studies in industrial design, undertaken in the *hands-on* "ait school" tradition of studio and workshop-based leaning; a pragmatic approach which actively encouraged 'doing for the sake of knowing' (Dewey 1929 p 87, Gedenryd 1998 p 123).

Upon graduation, I entered employment in industrial design, where I gained professional experience in the use of industry-standard computer aided design and engineering techniques and rapid prototyping technologies within a range of product design applications. I later pursued postgraduate study, where I was inspired by the work of researchers and academics engaged in *practice-centred* design research, based upon an approach of 'experimental making' (eg Rust, Whiteley and Wilson 2000; Rust, Chamberlain and Roddis 2000; Rust 2004; Chamberlain, Roddis and Press 1999; Whiteley 2000).

The quotation from Mike Cooley cited above comes from a book which is sadly now out of print. In 'Architect or Bee? The human/technology relationship* Cooley anticipated problems which may result from the rapid intervention of 'computerised' technology aimed at increasing the productivity of the manufacturing industries.

Cooley, a senior development engineer at Lucas Aerospace in the 1970's, identified that the introduction of computer-aided design systems meant practical design tasks being taken out of the hands of makers; the highly skilled engineering technicians who possessed a working *tacit* knowledge of physical materials and processes acquired through years of making things and seeing them break and rupture' (Cooley p 81). He feared the likely consequences of the loss of physical human input into the design process when '...more and more, that knowledge has been abstracted away from the labour process and rarefied into mathematical functions' (Cooley p 5).

Cooley was an active trade unionist, but he was not only concerned for the de-skilling of the labour' force, since it may be argued that without valuable practical knowledge and experience, designers and engineers may lose touch with the physical reality of design problems. Press (1996) describes how Cooley led trade unionists at Lucas in a unique response to increasing numbers of redundancies at the company. The Lucas Aerospace Worker’s Plan contained innovative ideas for socially responsible design and *human-centred* technologies, including a portable life support machine, a vehicle for children with Spina Bifida, energy conserving products, and wind-powered generators for use in developing countries.

Design ideas were developed by Lucas engineers in collaboration with universities and healthcare institutions, and manufacture of the designs would capitalise on the skills of the workforce. The Lucas Plan was never taken up by the company although, as Press reports, its underlying principles provided inspiration for other initiatives in the UK and abroad.

Today, designers and engineers make extensive use of virtual and rapid prototyping technologies in the development of aeroplanes, bridges, buildings, cars and all manner of consumer items. Within virtual prototyping, designers and engineers use computer modelling techniques to simulate the appearance and/or functional attributes (for example structural behaviour or other physical properties) of a design proposal. Rapid prototyping technologies, such as the emerging 3D printing systems (Davey 2003), are providing new ways of obtaining physical output from three-dimensional computer models.

In literature aimed at the design and engineering professions, virtual and rapid prototyping techniques are often referred to as *time compression technologies,* since these processes promise shorter development times and a reduction in the number of physical prototype iterations required to get a product off the virtual drawing board and onto the production line. Here, advocates of virtual prototyping claim computer modelling and simulation technologies might reduce or replace physical prototype iterations in design.

A counter argument to the designer's total immersion in the virtual design world is that human knowledge and experiences may be elicited through *hands-on* interaction with physical prototype models. Chamberlain et al (1999, 2003), Rust et al (2000) and Rust (2004) identify how physical prototype artefacts may be instrumental in both eliciting and communicating knowledge within practice-centred design research. Here, physical prototypes provide a tangible 'bridge' between designers and other stakeholders within inter-disciplinary research (Rust et al 2000a). Valuable opportunities may therefore be lost through an over-reliance on *hands-off* virtual prototyping.

This thesis aims to explore and define approaches to human-centred design, and to investigate changes in the nature of prototyping within the context of human-centred design practice. Research investigates the essential role of physical making and testing in design, and points to a need to integrate both hands-on and hands-off approaches to prototyping within human-centred design practice.

The aims and objectives of the study were:

1 To review the literature within the discourses of design, human computer interaction and human factors engineering, to identify approaches to human-centred design adopted by practitioners within these fields.

2 To identify a *paradigm statement* for human-centred design - in this context, a statement of ideas, values or beliefs to guide the theoretical and practical research activity described within this thesis[1].

3 To review the literature from within product design and engineering discourse which describes the current state of the art in rapid and virtual prototyping.

4 To undertake practical design activities exploring approaches to prototyping within the context of human-centred design.

5 To communicate the findings and outcomes of the practical design activities and to identify the implications and conclusions of the theoretical and practical research undertaken as part of this study.

---

[1] In 'The Structure of Scientific Revolutions' Kuhn (1962 p 175) identifies that the term *paradigm* can refer to the '...beliefs, values and techniques...' shared by a community of practice.

Guba (1990) describes a paradigm as 'a set of beliefs that guides action' (p 17). Blackburn (1994) identifies a paradigm to be a conceptual framework or '... an open-ended resource ... A paradigm does not impose a rigid or mechanical approach, but can be taken more or less creatively and flexibly' (p 276)

In first half of this thesis, I present a *contextual review* which explores the significance of the human element in design. Here *Chapter 2* begins with Margolin's assertion that although '...the relationship between products and users has become a central theme of design discourse, users still remain little understood by designers' (Margolin 1997). Margolin's statement may seem somewhat controversial, since the benefits of *user-centred design* have been widely discussed within design, human computer interaction (HCI) and human factors engineering discourse.

Starting with Hemy Dreyfuss' 'Designing for People' (1955), an extensive review of literature from within the fields of product design, HCI and human-factors engineering introduces a range of definitions and methodological approaches to user-centred design. However the term user-centred design appeal s to have a *utilitarian* focus, in which people are defined merely as "users" and the emphasis is placed on product use, usability and the user experience (Buchanan 2001a, Bramwell-Davis 2002). Human-centred design implies a much broader concept, embracing the knowledge, experiences and relationships between the designer, the end-users and the other stakeholders within the system of production and consumption. For example Papanek (1972) calls for the designer to take on the role of advocate within a system of production and consumption which is socially, ethically and ecologically responsible.

In seeking to affirm human needs and human values through practical intervention, human-centred might be considered to be a form of pragmatic humanism. A discussion drawing on the writing of Buchanan, Manzini and Papanek further explores the *humane dimensions* of design. This leads me to propose the following as a *paradigm statement* which serves as a guide to the theoretical and practical research described within this thesis:

Human-centred design is a creative exploration of human needs, knowledge and experience which aims to extend human capabilities and improve quality of life.

Chapter 3 explores relationships between human knowledge, creativity and design, drawing on literature from the history and philosophy of science as well as writing from art, design and engineering discourse. Here, human-centred design is viewed within the context of other fields of creative human endeavour. Human creativity is introduced, in the form of the familiar romantic stereotype; individualistic, intuitive, unpredictable and irrational.

One may naturally assume that this creative approach conflicts with the 'scientistic' view of the world that is based on logic and rationality (Fisher 1997, Coyne and Snodgrass 1991). This conflict reflects a dualistic view of knowledge - Cartesian dualism - in which objectivity, logical deduction and theoretic reasoning are set apart from subjectivity, intuition and practical experience. Yet here the story of the scientists Newton and Hooke is presented; the intention is to illustrate how a coming together of theoretical and practical knowledge can lead to creative discoveries in science. Similarly it may be argued that creativity and invention in design come about through a combination of theoretical reasoning, intuition and practical experience.

At the Designing Design Research event held at London's Royal College of Art in March 2004, John Chris Jones called on the design research community to 'end the dualism and create integration'. Through the synthesis of theory and practice, reason and intuition, human creativity may provide the key to reconciling the conflict of dualism. Perhaps this is the creative challenge that design must continually seek to address.

The schism of dualism appears again in a discussion exploring the Heideggian concepts of *vorhanden* and *zuhanden* (present-at-hand and ready-to-hand) and Aicher's *Analogous and Digital* (1991). Parallels are identified between these concepts and changes in the nature of prototyping within human-centred design, specifically in the relationship between *hands-on* and *hands-off* approaches to prototyping.

Literature describing emerging virtual prototyping technologies aimed at the engineering and design professions celebrates a progressive *virtualisation* of product development processes, through which the requirement for physical prototype iterations might be reduced or even eliminated altogether (eg Connell 2004, Bocking 2003, Bussler 2003, Hollerbach et al 2000, Boswell 1998).

This thesis presents a counter argument to the designer's total immersion in the virtual design world since 1) it may be impossible to adequately simulate all aspects of a product design proposal using hands-off virtual prototyping technologies 2) human knowledge and experiences may be elicited through hands-on engagement with physical prototype models, and 3) hands-on making and testing can be a discovery-oriented activity, through which creative opportunities may be revealed.

Three examples are presented - Cooley's account of the development of a prototype aircraft engine (1980) and, more recently, the London Millennium Bridge and Thomas Heatherwick's sculpture 'The B of the Bang' in Manchester. These examples serve to illustrate the requirement for designers and engineers to confront the *physical reality* of design problems, and the importance of physical human input in design.

However the potential benefits of accelerated product development timescales promised by advocates of virtual and rapid prototyping technologies cannot be ignored, nor can the creative opportunities which may be afforded by new forms of making. Therefore these examples point towards a requirement for reconciliation and integration of hands-off and hands-on prototyping processes within human-centred design practice.

In the second half of this thesis, I present practical examples investigating approaches to prototyping within human-centred design. The aim is to demonstrate ways in which a combination of hands-on and hands-off processes can together make a mutual contribution to human-centred design practice.

Chapter 4 provides an overview of the methodological approach adopted within the practical investigations. Since human-centred design practice is the field of enquiry, a methodology based on practice clearly seems appropriate in this context. A practical approach to design research is introduced by Archer (1995). Here Archer describes an approach in which the researcher's own practice is the principal method of enquiry. This takes the form of *action research,* which Archer defines as:

> '... Systematic enquiry conducted through the medium of practical action, calculated to devise or test new, or newly imported, information, forms or procedures and to develop communicable knowledge ...
> Action Research findings are extremely valuable. They produce insights which might otherwise never be obtained ...'
>
> (Archer 1995)

Rust (1999, 2004) points to design as a tool for exploring the world, and suggests that insights gained through *design enquiry* might be different, and perhaps complementary, to those obtained with the tools of the natural or human sciences.

Through active engagement in creative practice, the researcher may gain unique insights which shed new light on the problem or process under investigation. An approach is therefore adopted in which the researcher's own creative practice forms an essential part of the research methodology.

Earlier it was identified that an aim of human-centred design is to extend human capabilities and improve quality of life. One area in which design can make a practical contribution directed towards this aim is within the field of medical technology. Research described in *chapter 5* relates to a pilot study forming part of an ongoing interdisciplinary investigation into the safety of medical devices led by the author's supervisor Professor Paul Chamberlain.

The project investigates the potential benefits of *tactile cues* within safety-critical product applications. Research focuses on the design and prototyping of a novel tactile identification system for connectors used in the administration of drugs to hospital patients; the aim is to help prevent potentially fatal misconnection errors since a number of fatalities have occurred because patients have been connected up to the wrong drug delivery line.

The chapter introduces the context for the human-centred design activity and describes the methods and outcomes of the research. In particular this study highlighted the significant challenges faced when using hands-off technologies (3D CAD and rapid prototyping) in the exploration of hands-on design problems, especially when the tactile qualities of the physical outcomes were of specific importance to the investigation. The limitations of current haptic feedback technologies made them unsuitable for use within this application (Hodges 1998, Evans 2002 and Evans et al 2005). Therefore, when designing the tactile components in the virtual design environment of 3D CAD it was necessary to rely on an intuitive sense of how the objects might feel to the touch. Here it is suggested intuitive sense or tacit knowledge may be developed over time through the designer's hands-on experience manipulating the physical form of objects in the real-world workshop.

Rapid prototyping was used to produce a series of physical prototype tactile components which were evaluated in identification tests conducted out by Psychologists at the University of Leeds, involving participants who were healthcare specialist from the intensive care and anaesthetics departments of Bradford Royal Infirmary.

In addition to practical insights into the design, prototyping and testing of the tactile identification system for medical connectors, findings from the research have been presented and published in international conference proceedings (Walters, Chamberlain and Press 2003; Walters, Chamberlain, Press and Tomes 2004). The tactile identification system has been the subject of UK and international patent applications (Identification System for Compatible Components, inventors: Paul Chamberlain and Peter Walters, 2003, 2004).

Following on from research investigating the concept of tactile cues, chapter 6 introduces a biological analogy - the pufferfish is a creature which appears to exhibit both visual and tactile cues, expanding and projecting spikes to ward off predators in a dramatic display of self defence. This chapter describes practical research investigating the design of bio-inspired indicators; devices which exhibit changes in shape and or surface texture in response to external stimuli. These devices demonstrate design principles which may in future by applied in the development visual and tactile safety indicators for use in safety-critical product applications.

A range of actuation technologies are explored, including shape memory alloys: "smart materials" which change their physical properties in response to an increase in temperature or with the application of electric current. Research also investigates the potential of a biological actuation system. The design and prototyping of the shape-changing indicators took place through a combination of hands-on making and testing and hands-off techniques, including the use of CAD-CAM and rapid prototyping technologies. The development of the indicators was informed by a knowledge of structural and mechanical possibilities derived from direct human engagement with physical materials, but the physical outcomes would have been difficult or impossible to achieve without the use of CAD-CAM and rapid prototyping technologies. The potential of virtual modelling in this context was explored through consultation with specialists at the Deployable Structures Laboratory at the University of Cambridge and the Department of Mechanical Engineering at the University of Sheffield.

Presentation of the physical prototypes to others revealed that the shape-changing indicators appeal' to exhibit gestural qualities that are surprisingly emotive. This unexpected practical outcome is discussed in the light of recent research into 'Design and Emotion' (eg McDonagh et al 2004, Norman 2004), highlighting a further dimension of human-centred design. Furthermore, through consultation with healthcare professionals and a leading packaging manufacturer, research identifies the potential for possible future developments in which shape-changing indicators may function as safety indicators within pharmaceutical packaging applications.

Finally chapter 7 draws together the findings and outcomes of the theoretical and practical research described within this thesis. A concluding discussion examines the implications of the study and identifies potential for future investigation within the areas of research, practice and education.

2.0 User-centred design literature, definitions and methods

2.1 Introduction

> 'The relation of products to users has become a central theme of design discourse, though users still remain little understood by designers.'
>
> Margolin (1997)

The benefits of user-centred design have been widely discussed, within product design discourse, and also in the areas of human computer interaction (HCI), human factors engineering and ergonomics. In light of this, Margolin's assertion that *users still remain little understood by designers* may now seem somewhat controversial.

If the aim is to improve the usability of products, it is essential for designers to acquire knowledge of product use that is derived from first hand experience. In some cases, such as when designing familiar consumer products, designers can draw on their own “real-life” experience of using these products. However, it becomes more difficult when designing products that are used in unfamiliar contexts, or for people whose age and/or capabilities lie outside of the designer’s own experience. It is therefore necessary for designers to build close collaborative relationships with product users and, where possible, to take part in user activities themselves.

When it came to researching the requirements of end-users, the pioneering American industrial designer Hemy Dreyfuss led by example:

> 'I have washed clothes, cooked, driven a tractor, run a diesel locomotive, spread manure, vacuumed rugs, and ridden in an armoured tank. I have operated a sewing machine, a telephone switchboard, a corn picker, a lift truck, a turret lathe, and a linotype machine... .We ride in submarines and jet planes. All this in the name of research.’
>
> Dreyfuss (1955 p 62)

Building upon the work of Dreyfuss and his contemporaries, practitioners from a range of disciplines have developed methods that aim to foster a greater understanding of the design task, end-user requirements and the context for the design activity.

The aim of this chapter is to review the literature from the discourses of design, human computer interaction, human factors engineering and ergonomics, in order to understand how practitioners within these fields apply user-centred design methods to support their work.

2.2 What is user-centred design?

Within product design discourse, McDonagh-Philp and Lebbon describe user-centred design as:

> '...a design methodology that utilises users as a designing resource, to increase understanding of the user.'
>
> (McDonagh-Philp and Lebbon 2000, McDonagh-Philp 1998)

And with Brusberg, in a more recent publication:

> 'User-centred design approaches aim to expand the designers' knowledge, understanding and empathy of users'
>
> (Brusberg and McDonagh 2003)

Here users and their experiences are considered a valuable source of inspiration and ideas. A relationship of empathy and understanding is emphasised that facilitates the communication of knowledge and experience between designers and users, in order to inform the design activity.

Tucker Viemeister, whose US-based consultancy Smart Design developed the award-winning Good Grips range of kitchen utensils, describes his approach to user-centred design:

> 'We as designers are the advocate for the end user - that's social responsibility right there... We're the only people in the development process who are really concerned with what people are going to do with our stuff. The whole idea of design is changing. In the future designers are going to be more like psychiatrists: people who help others do what they want rather than tell them what to do.'
> (Press 1995)

The Good Grips kitchen utensils feature chunky rubber handles to accommodate users with limited grip strength and dexterity. Both distinctive and affordable, these products exemplify the principles of'inclusive design' - designing with the needs of the widest possible range of users in mind.

Within Human Computer Interaction discourse, Kantrovich (2004) cites ISO 13407 (1999), the international HCI usability standard listing the benefits of design which:

> '....enhances effectiveness and efficiency, improves human working conditions, and counteracts possible adverse effects of use on human health, safety and performance'
> (Kantrovich 2004).

However, he acknowledges that the focus on efficiency, performance and safety - whilst being key elements of effective design - may give usability specialists the professional image of'... creativity police ...' (Kantrovich 2004) who prefer tried-and-tested solutions over more adventurous proposals.

Also within the HCI field, Preece Rogers and Sharp recommend that 'real users and their goals, not just technology, should be the driving force behind the development of a product' (Preece et al 2002 p 285)

This approach may be illustrated in the design of a wearable computer for children by Philips Design (figure 2.1). The computer features a location-tracking device, to enable parents to check on their whereabouts of their children. This is perhaps a more socially acceptable application for so-called 'Big Brother' technologies.

Figure 2.1 Wearable computer for children
Image www.design.philips.com (accessed 20 September 2005)

The ergonomists Stanton and Young (1999) define user-centred design as

> 'designing systems on the basis of a user-requirements specification, and an understanding of the capacities and limitations of the end-user population, sometimes involving user trials'
>
> (Stanton and Young 1999 p 122)

Ergonomics, in a literal translation, means 'the laws of work'. Ergonomics and Human Factors professionals appear to place an emphasis on the role of the 'design specification', formulated on the basis of knowledge of user requirements and human performance under task-specific conditions. The success or failure of a design proposal may be determined by comparing it with the specification, or by conducting user trails, where quantitative or qualitative data is recorded to assess the performance of the design.

Figure 2.2 In ergonomics and human factors engineering, anthropometric data often forms the basis of the design specification
Image: Dreyfus, 1955

In 'Human-Centric Design', Morrissey (1998) describes the role of user-centered research within mechanical and manufacturing engineering practice:

> 'The importance of investigating the human element, driven increasingly by contractual mandate, has pushed manufacturers to consider user issues much earlier in the design process'
>
> (Morissey 1998)

The final responsibility for the functional aspects of a new product or system, including all safety issues, usually rests with engineers. Within an increasingly litigious society, engineers are bound *'by contractual mandate'* to ensure the safety of end-users and other stakeholders, such as those who will manufacture, transport, sell or carry out maintenance on the product, system or service.

Engineers must therefore carry out a risk assessment to identify the various ways in which people are likely to use (or misuse) the new product or system. As part of this risk assessment, engineers will perform reliability calculations, and where appropriate, build in *'factors of safety',* in order to minimise the likelihood of design failure, or injury that may result from the use or misuse of the product.

Figure 2.3 The responsibility for user-safety in the design of products such as heavy machinery usually rests with engineers
Images: www.JCB.com accessed 20 September 2005

The above examples provide an introduction to user-centred design, from the perspectives of Product Design, HCI, Ergonomics and Human Factors Engineering. The theoretical and practical implications of different methodological approaches to user-centred design will now be discussed.

2.3 User-centred design methods

2.4 Design ethnography

Rothstein (2000) describes how have designers have adopted research techniques more commonly associated with ethnography and the social sciences. Ethnography, a sub-discipline of anthropology, refers to the study of human societies - by observing people's activities, and their interactions with one another. According to ethnographers Hammersley and Atkinson, ethnography literally means 'writing the culture' (Preece et al. 2002 p 288).

Practitioners of Human Computer Interaction first adopted ethnographic methods in the 1980s, to study how people interact within the workplace, observing people carrying out tasks, and their interactions with new technology (eg Suchman, 1987).

Rothstein describes how ethnographic observation - 'insights gained by watching and talking to people' - can provide an opportunity for greater interaction between designers and users, and encourage 'open-ended thinking', inspiring a greater level of innovation in product design (Rothstein 2000). He describes ethnography as a 'investigative, discovery-oriented process', and cites the creativity researchers Getzels and Cszikszentmihalyi (1976):

> 'The person who looks at problematic situations with an open mind, ready to let the issues reveal themselves instead of forcing themselves into a preconceived mould, increases his or her chances of discovering original responses.'
>
> (Rothstein 2000)

Ward (2002b) describes a study on the use of video ethnography in design, carried out at London's Royal College of Art. Video is used to record people in their home environments, doing everyday tasks such as loading the dishwasher or vacuuming the carpet. According to Ward, the knowledge that results from this observation can '"provide context" for creating or improving products and services' (Ward 2002b). Using video techniques, data on product use can easily be recorded, reviewed and analysed by designers. She reports 'one frame of video footage can show a multitude of detail about context and usage' (Ward 2002b)

Ward cites managers at two leading UK design groups, PDD and Seymour Powell. Here video has proved to be an ideal medium for communicating the results of research to both design teams and clients.

Shaw (2003) provides a powerful example of the application of ethnographic research methods, in a case study of the design of a new thermal imaging camera for use by firefighters, carried out by UK design consultants Alloy Design (figure 2.4). Alloy Designer James Lamb took part in comprehensive firefighter training in smoke filled buildings. This gave the design team a unique insight and understanding of the specific requirements associated with products intended for use in hostile, often life-threatening, situations.

Figure 2.4 Firefighting equipment by Alloy Design
Images www.theallov.com accessed Jan 2003

The designers at Alloy then worked closely with a team of firefighters, who played an active role in the evaluation of new product prototypes. The prototype cameras were subject to rigorous testing in environments that simulated real fire-fighting situations, and were demonstrated to fire crews around the world. As a result of the end-user validation of the design, the camera received approval for full-scale development.

Preece et al present a number of case studies where ethnographic research methods have been used to inform the development of new software applications within the HCI field. One such method, called 'Contextual Design', has been used in the development of office-based software applications. This method requires the software developer to work as an *apprentice* to the end user. It is based on a 'partnership principle ... the developer and the user should collaborate in understanding the work ... through discussion, observation and reconstruction of past events' (Preece et al 2002 pp 296 - 298)

Preece Rogers and Sharp also cite the ‘Presence Project’ (Gaver et al 1999) in which researchers adopted an innovative approach to data gathering. The project aimed to increase the presence of elderly people in their local community and research was carried out with groups in three European countries: one in Oslo, Norway, one near Amsterdam, the Netherlands, and one near Pisa, Italy.

The project highlighted the problem of designing for people living in unfamiliar communities and cultures. In order to help overcome this problem, participants from the different community groups were issued with *cultural probes* - packs which contained postcards, maps, a disposable camera, photo album and diary. Participants were asked to use the items contained within the packs to create a visual diary, and to use the postcards to respond to questions about their experiences living within their community. Participants used the maps to record the places they visited to meet and socialise with others, also places where they enjoyed being alone, and where they would like to visit but were unable to do so.

Preece et al. point out the aim of the cultural probes was not to identify specific needs or usability requirements. However the findings offered a rich source of contextual knowledge and experiences, from which the researchers could draw inspiration within their own field of practice.

The ergonomists Stanton and Young (1999) demonstrate a series of observational methods that have been applied in the analysis of the usability of existing products. As a case study, they describe techniques employed in a task analysis to evaluate the usability of car radios. They describe in detail how this data can be analysed, in order to compare the usability of different competitor products. In some cases adopting such a detailed approach in the analysis and interpretation of observational or ethnographic data may appear highly structured and formulaic. These highly "methodical" approaches may seem incompatible with the often "intuitive" processes evident within creative design practice.

Bruseberg and McDonagh-Philp concur

> 'design practice is extremely flexible and diverse - due to the nature of different kinds of projects and varying types of products, as well as the preferences of individual designers.... methods tend to be informal. User-centred design research methods should be adaptable to a range of design approaches, to take into account the intuitive nature of designing.'
>
> (Bruseberg and McDonagh-Philp 2001)

Significantly, some have argued that designers are perhaps not the best people to do user research, carried out in the spirit of "pure" ethnographic observation. Whilst ethnographic research can provide the designer with valuable insight into user activities, Preece, Rogers and Sharp point out that the goals of ethnography and the goals of design are in fact quite different. Ethnography is concerned with making observations from an objective standpoint, and 'making the implicit explicit'. Design, however, is concerned with making 'useful abstractions', turning observations into potential design opportunities. (Preece et al 2002 p 292).

Here Graham Moore, a researcher for Design Consultants Seymour Powell points out: 'Lots of people argue that the last person you should send towards this kind of enquiry is a product designer ... because they're always seeking solutions' (Ward 2002b).

When observing user activities, designers naturally seek to elicit possible solutions. Lebbon asserts that this 'colours what they see when they observe someone'. Lebbon, a design researcher at the Helen Hamlyn Research Centre at the Royal College of Art in London, considers that the 'best-case scenario ... is to have design researchers working alongside designers.' (Ward 2002b)

This may be one reason why design agencies such as IDEO or Sonic Rim in America, Philips Design in The Netherlands, or Seymour Powell Foresight (SPF) in the UK, employ user research specialists to carry out research on behalf of designers. These design researchers often come from disciplines outside of design, e.g. psychology or the social sciences. They are experts in fieldwork, gathering both quantitative and qualitative data, which can then be presented to designers, to feed into the creative process of product development (Kelley 2001).

2.5 Scenario-based design and performance ethnography

Saks-Cohen (1997) describes how *scenario-based design* was used as part of the DesignAge project at London’s Royal college of Art. The project included *user forums* where students worked alongside members of the University of the Third Age (U3A), a national educational organisation for active retired people. Student designers imagined a story or scenario into which a design concept or idea might fit, then observed what users do in the real life situation.

The user forums helped to encourage an exchange between a younger generation of designers to help them develop an understanding of the needs and aspirations of the increasing number of older consumers. Saks-cohen explains: 'We wanted to know who these consumers really are; their habits, lifestyles and aspirations and what adjustments they make to cope with daily living' (Saks Cohen 1997).

Saks-Cohen describes how the workshops helped to break down stereotypes the designers had formed about older users, and the preconceptions they had about how they might use or interact with new products. Through the use of storytelling and imaginative scenario building, designers and potential users were able to gain a clearer picture of what or may not be practical or possiblewhat are the dreams and what are the nightmares'.

Saks-Cohen observed a difference in the way the student designers and the U3A members responded to new ideas, for example, electronic shopping over the internet, a concept which was relatively new at the time the paper was published. Younger people may be more open to home shopping because it saves time. The U3A members were less enthusiastic because they viewed the idea of going out shopping as a valuable opportunity for social interaction when they might meet up with friends. They suggested it would be better to see more cafes incorporated into retail environments to enhance the shopping experience.

This example highlights the differences in the needs and aspirations of young and old that need to be accounted for in the development of new product ideas. The U3A members had enormous enthusiasm for the project: 'After years of having bad design thrust upon them, our older friends felt like they could influence change. The user forums inspired a revolution of design awareness' (Saks Cohen 1997).

Brenda Laurel (2003) introduces *performance ethnography;* a novel approach to user-centred research that draws inspiration from the techniques of "method acting" in the theatre. She reports:

> '...performance ethnography attempts to understand observed experience by memorising and performing it.'
>
> (Laurel 2003)

Following on from a phase of ethnographic observation, design researchers act-out scenarios as a way of experiencing for themselves the experiences and feelings of the user. Laurel has named the process of re-enactment *'informance'* since it is intended to directly inform the design activity.

Figure 2.6 The student used digital video to record the ice cream vendor operating a soft-serve machine. The student then re-enacted the physical actions of the ice cream vendor including the awkward posture required to operate the machine. Image: Laurel 2003

As a case study, she presents a student project investigating the design of a soft-serve ice cream dispenser. Using digital video, the student designer first observed and recorded ice cream vendors operating a soft-serve machine. Then, back in the design studio, the student re-enacted step-by-step the physical actions of the ice cream vendors.

This process uncovered ergonomic difficulties encountered by the ice-cream vendors in the design of existing dispensers, which required operators to hunch over for several seconds each time an ice cream was served. The re-enactment also alerted designer to the *'performative nature'* of ice-cream vending and the potential to incorporate this aspect into the design of a new dispenser: 'it was the performative nature of their work - glimpsed even when they were in tortuous positions - that took centre stage.' (Laurel 2003)

In the student's proposal, the dispenser machine is located overhead, and the ice cream is served at eye level so that the process is in the direct view of the customer, including the selection from a variety of flavours and styles of cones. Laurel describes the new design as 'Soft serve ice cream as virtuoso performance!' (Laurel 2003).

Figure 2.7 The student acts out her proposal, the soft serve machine is mounted overhead so that the whole process takes place in front of the customer, emphasising the performative nature of the task of serving ice cream. Image: Laurel 2003

2.6 Participatory approach

Preece, Rogers and Sharp (2002) describe the participatory approach to user-centred design:

> 'In contrast to Contextual Design (ethnomethodological approaches).... users are actively in involved in development. The intention is that they become an equal partner in the design team, and that they design the product in co-operation with the designers'
>
> (Preece et al 2002 p 306)

They go on to explain how participatory design methods were developed in Scandinavia in the 1960's, as a response to the increase in the complexity of information systems, and new labour laws that gave workers more control over the design of their own working environments.

One example often cited is the UTOPIA project (Bodker et al 1991, Ehn and Kyng 1991, both cited by Preece et al 2002). UTOPIA was a research project carried out between 1983 and 1994, involving collaboration between HCI specialists from the Royal Technical University in Stockholm, and the Nordic Graphic Workers' Union. A key aspect of the participatory methodology was the use of cardboard mock-ups to represent technology-based systems such as computer visual display units (VDUs), automated printing and soiling machines.

The mock-ups provided a quick and efficient way of communicating the functions of unfamiliar systems, in a way that everyone could understand. End-users were then able to interact and modify the configuration of the system. For example, if the end users wanted to change the position of a mock-up of sorting machine, they could simply pick it up and move it to a more move convenient position. If they wanted to change the way information was presented on a mock-up VDU, they could do so simply by drawing a new paper overlay with a marker pen (Rust, 2004).

En lokal fackktubb
forbereder slg for ny teknik:

— Rrtningama begriper vi inte
Vi gor attrapper och provar

Sort machine mock-up. The headline reads: "We did not understand the blueprints, so we made our own mock-ups."

Figure 2.8 UTOPIA project: *we did not understand the blueprints, so we made our own mock-ups*

User research specialists Sonic Rim have developed their own participatory methods. Sanders (1999, 2000) describes a set of *Make Tools* that include materials for creating 2D and 3D collages, drawings, images, photographs and maps, the aim of which is enable users to communicate their experiences, aspirations and hopes for the future:

> 'By accessing people's feelings, dreams and imaginations, we can establish resonance with them. Special Tools are needed to access deeper levels of user expression ... We have found that these tools are extremely effective in accessing people's unspoken feelings or emotional states'.
>
> (Sanders 1999)

Sonic Rim's methods appears to have a lot in common with art therapy - *Design Counselling* perhaps?

Figure 2.9 Design Counselling?

Sonic Rim: "Make Tools" for capturing user's experiences, aspirations and hopes for the future

One criticism of this participatory approach is that end-users are not designers. Whilst end-users can inform the design process in a uniquely valuable way ..they do not necessarily know the best solution to the problem' (Bothwick 2003); 'the Skill of the designer is first to abstract consumer needs and aspirations, and then to give them material form' (Rees 1997). Designers are not in the business of simply providing what end-users say they think they want; innovation requires designers to interpret user research in a creative and intelligent way.

In a recent study by Sener et al (2005), designers adopted a participatory or *co-design* approach by engaging consumers in the development of beauty care products for Proctor and Gamble (UK). This research highlights some of the limitations of participatory or co-designing as a methodology. The study found that whilst consumers could contribute much to the identification of problems with existing products, they appeared much less able to envisage possible features and functions of new products. According to Sener et al, this process requires 'design acumen' and involves innovative shifts in conceptual thinking. Sener et al. argue that as non-designers, consumers lack both training and confidence in envisioning new possibilities which can limit the range and depth of design ideas proposed.

Sener et al also suggests that the vocabulary of consumers for articulating design ideas can be limited, as can their awareness of new technologies and how these might be applied in products. As Henry Ford[1] once asserted: "If I'd have asked my customers what they wanted, they'd have said *faster horses!*" Furthermore, since it is said that a camel is a race-horse designed by committee, co-designing runs the risk of spawning a whole stable full of really fast camels[2].

---

[1] The author is grateful to his supervisor Professor Chamberlain for drawing attention to this anecdote from Henry Ford.

[2] Of course, if you're into camel racing then faster camels would probably be a really good thing.

2.7 Physical prototyping within user-centered design

Lebbon (in Ward 2002b) and Preece et al. (2002) questioned whether designers are the best people to carry out user-centred research in the ethnomethodological tradition. One reason given for this was that through their instinctive focus on problem-solving, the clarity of designers' observations may be distorted.

However, methods have been documented that demonstrate designers can work effectively with end-users, and that this can result in examples of highly innovative new products. The examples described below show how designers have capitalised on the early development and communication of design ideas to end-users, through the use of physical prototype models. Here, the involvement of users in the evaluation of new design concepts and ideas can take place within iterative cycles of action and reflection (Torrens, 1998).

Whiteley (2000) describes the development of an artificial arm that demonstrates new design principles for robotics and prosthetics applications. Whiteley adopted a practice-centred approach to research that made extensive use of exploratory drawing and prototype model-making to develop and communicate ideas. He identified that previous robotic arms, typically developed using the engineering methods of mathematical modelling and analysis, might present "optimised" mechanical solutions (eg figure 2.10). However such devices may be unsuitable for use within prosthetics applications because they fail to meet a broader range of user needs, including both functional and cosmetic requirements. Whiteley observed that, in the development of "engineered" solutions, user evaluation often takes place *after* rather than *during* the development process (Whitely 2000 pp 2.2 - 2.7).

Whiteley demonstrated that the production of physical prototype models allowed design concepts to be tested 'against reality' in a way that 2D drawings, mathematical models, or computer simulations would not permit. He used physical prototype models as a research tool, to stimulate criticism from "expert users", including surgeons and clinical anatomy specialists, as well as amputees themselves.

Figure 2.10 The DLR robotic hand, developed by engineers at the German Aerospace Centre. Whilst being of a mechanically "optimised" form, this artificial hand may fail to serve as an adequate replacement for a real human limb. Image: Butterfass et al 1998.

Whiteley's ongoing process of modelling and user testing formed an integral part of the development of a new artificial arm. Whiteley describes an iterative process, where the production and subsequent evaluation of physical models leads to an 'increasingly refined' level of development (Whiteley 2000 pp 2.2-2.7)

Creative Reasoning

Prototype / Model Development

Evaluation

Figure 2.11 An iterative model of practice-centred design research, used by Whiteley in the development of a prosthetic arm and hand

Figure 2.12 Illustration of Whiteley's skeletal model of the human arm, wrist and hand; an accurate mechanical analogy of the human upper limb

Pering (2002) discusses the role of prototyping and user testing in the development of a new hand-held personal communication device, carried out by in-house HCI specialists at Handspring Inc., USA.

Handspring's sequential design methodology was based on a series of iterative loops, beginning with the construction of *lowfidelity* prototypes of the product interface. These *paperprototypes* can quickly be mocked-up, tested by users, modified, and then re-tested. As the project progresses, and more knowledge is obtained on user requirements, the designers move on to create interactive, computer-based simulations of the interface, that include the layout of switches and controls, and the on-screen graphics. Users interact with the simulated interface via a touch screen. Feedback obtained from users at this stage enables designs to be further refined.

Further physical models are then constructed, in materials that simulate more closely the *form and feel* of a mass-produced item. These models, called *Buck* prototypes, contain working switches and controls that are linked to the computer-based simulation software that controls the on-screen graphics. Users can therefore *test-drive* both hardware and software elements of the product.

Following further feedback from users, the final phase of prototyping involves the production of an *"Alpha"* model, made from production-authentic materials, and containing all the working electronic elements, including the controls, software and graphical display. The Alpha prototypes are tested in user trials that last several weeks, to further validate the design, and to identify any "bugs" or "glitches" that can be ironed out prior to mass production.

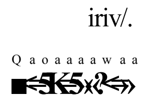

Figure 2.13a "Paper prototype" of the Handspring communicator (Pering 2002)

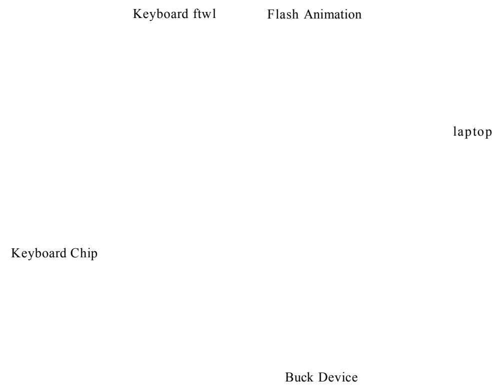

Figure 2.13b Working "buck" prototype connected to a software simulation of the communicator interface (Pering 2002)

Figure 2.13c Usability testing of the working "buck" prototype of the device (Pering 2002)

Figure 2.13d Handspring Treo communicator product (www.mobile-review.com accessed 20 April 2006)

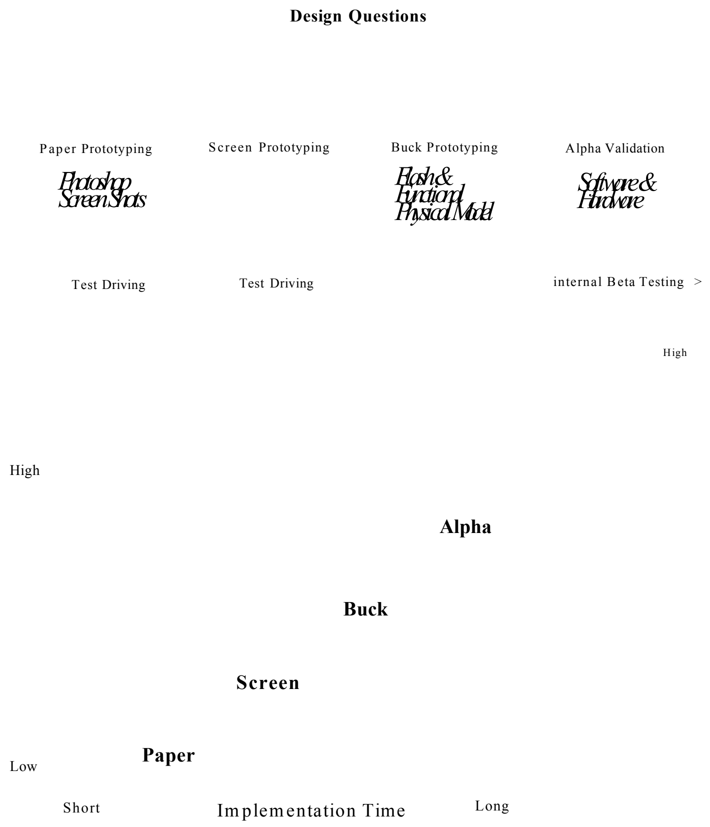

Figure 2.13e Iterative prototyping methodology employed by the Handspring design team. The graph shows how each prototyping step allows a greater level of functionality. The low fidelity prototypes are relatively quick to implement, but give a low level of functionality, whereas the high fidelity "buck" prototypes take comparatively longer to implement but give a much more "realistic" level of functionality. Images Pering 2002

Chamberlain (in Chamberlain and Roddis 2003, Chamberlain, Roddis and Press 1999, Rust, Hawkins, Whiteley and Roddis 2000) describes the development of vibro-acoustic furniture to be used therapeutically by children who are profoundly deaf, or both deaf and blind. The furniture allows people with sensory impairments to experience sounds and music, through the vibration of loudspeakers enclosed within furniture.

Early on in the project, the designers were able to discuss ideas with therapists who had expertise in working with children with sensory impairments, and also with loudspeaker technologists and potential manufacturers. However, because of their disabilities, the end users (i.e. the children) could not actively participate in the research until the designers produced working physical prototypes with which they could interact. The prototypes allowed the children to control their own sensory experiences.

Figure 2.14 **Tac-tile Sounds System** (Chamberlain, 2003)

Here the designers found that the working prototypes acted as a bridge between themselves, the therapists and the children, revealing new knowledge about the therapeutic needs of the end-user, and also as a catalyst for further research and investigation.

Nornian, Heath and Pedgley (accessed 2005) describe the development of a novel acoustic guitar with a plastic body. The development of the guitar formed a central part of Pedgley's PhD in Design at Loughborough University. An aim of the investigation was to explore the acoustic properties of polymer materials as an alternative to wood, which has inherent material inconsistencies, in addition to ecological concerns over diminishing stocks of trees harvested for prime tonewoods used in traditional guitar construction.

Design researchers Norman and Pedgley are themselves both active musicians. However, for the project they engaged the support of two "expert users" to assist them in the development and evaluation of the prototype polymer guitars in terms of construction, tone quality, playability and "feel". Here, they drew on the knowledge and experience of a world-renowned luthier (guitar maker) Rob Armstrong, and also a leading professional acoustic guitarist, Gordon Giltrap, who has endorsed the project and also composed, performed and recorded music on the prototype polymer guitars.

The relationship between musician and instrument is one of intimate, multi-sensory physical engagement, involving extreme sensitivity to subtle differences in sound. In his evaluation of the prototype polymer guitar, Giltrap commented that the instrument '...does not sound like plastic, whatever that's supposed to sound like, and anyone listening to it will hear a sound usually associated with a good quality wooden acoustic guitar' (Blincoe, 2002). Loughborough University has since filed a patent on the design of the innovative polymer guitar, and has established a company, Cool Acoustics, to commercialise the technology.

Figure 2.15 Owain Pedgley with the prototype polymer-bodied guitar

Image: www.coolacoustics.com

In this section, user-centred design methods involving physical prototyping have been discussed. Here prototypes take on the role of *probe* or *provocative agent,* eliciting further knowledge of the design task, and enabling both designers and end-users to experience the physical reality of design ideas. The prototyping activity is discovery-oriented, and the knowledge and experiences that result from each stage form the basis for the next phase of development.

A model for iterative physical prototyping based on a "snowballing principle" is proposed in figure 2.16. In the physical action of rolling a snowball along in the ground, the snowball grows bigger, accumulating snow as it drives forward with each cycle of rotation. This model serves to illustrate the cumulative development of knowledge and experience which may take place through iterative prototyping and testing - a processes that is both cyclical and progressive in nature.

Figure 2.16 **Snowballing principle:** Creative development is both iterative (cyclic) and progressive (moving forwards)

1.8 User-centred or human-centred design?

By adopting user-centred methods and techniques, the designer places end-user needs and aspirations at the centre of the design and innovation strategy.

However, some notable criticisms have been voiced against the use of the term user-centred design, and its apparent emphasis on utilitarian aspects of product use, usability and the user-experience. User-centred design, it is argued, reduces *human beings* to the status of *users* (Buchanan 2001a, Bramwell-Davis 2002). Therefore the term *human-centred* design has emerged from design discourse. Human-centred design implies a much broader concept - a creative exchange of knowledge, experiences and ideas between the designer and the other stakeholders within the system of production and consumption. Papanek, for example, calls on the designer to take the role of advocate in a system of production and consumption that is socially and ethically responsible (Papanek 1984 p 110).

According to Buchanan, human-centred design emphasises the central place of human beings ' within the design activity. He warns '...we often forget the full force and meaning of the phrase ... when we reduce our considerations of human-centred design to matters of sheer usability and speak merely of "user-centred design"' (Buchanan 2001a).

Buchanan goes on to describe human-centred as:

> '.... one of the practical disciplines of responsible action... fundamentally an affirmation of human dignity. It is an ongoing search for what can be done to support and strengthen the dignity of human beings as they act out their lives in varied social, economic, political and cultural circumstances.'
>
> (Buchanan 2001a)

Through their creative actions, human beings may extend their capabilities and improve quality of life. In 'The Prometheus of the Everyday' Manzini emphasises the role of human creativity and invention. Prometheus, who in ancient Greek Myth furnished humankind with fire which he stole from the gods, stands to represent that which is creative, inventive and daring. Manzini goes on to identify how the purposeful actions of the designer may '...contribute to the production of a habitable world, a world in which human-beings not merely survive but also expand their cultural and spiritual possibilities' (Manzini 1995 p 220).

Human-centred design seeks to affirm and support human needs and human values through practical intervention. Here, human-centred design may be considered to be a form of pragmatic humanism. In light of this, the author offers the following description as a *paradigm statement* for human-centred design, to serve as a guide to the theoretical and practical research activity undertaken within this study:

Human centred design is a creative exploration of human needs, knowledge and experience which aims to extend human capabilities and improve quality of life.

The following chapter introduces some key arguments surrounding this statement, in a discussion which explores interrelationships between human knowledge, experience, creativity, and design. The discussion, which engages with writing from the histoiy and philosophy of science as well as the discourses of art, design and engineering, aims to provide a link between theoretical and practical research described within this thesis.

3.0 Human-centred design: Knowledge in the making

3.1 Introduction and overview

In the previous chapter, human-centred design was introduced as a creative exploration of human needs, knowledge and experience. This chapter seeks to identify and explore some key theoretical arguments surrounding this statement. The discussion draws upon ideas from the history and philosophy of science, as well as writing from within art, design and engineering discourse, the aim being to link the theoretical and methodological frameworks of human-centred design with the practical realities of the design activity, in order to inform and support practice-centred research undertaken as part of this study.

The chapter begins by exploring some ideas about creativity and its role in the development of human knowledge. In the familiar romantic stereotype, creativity is considered to be a mystical quality only possessed by truly gifted people. According to this view, the activities of creative practitioners are unpredictable and involve individualistic, highly subjective and non-rational mental process. These processes appear to conflict with an approach to human knowledge that is based on logic and rationality (Fisher 1997, Coyne and Snograss, 1991). The conflict reflects a dualistic view of human knowledge - *Cartesian dualism* - in which objectivity, logical deduction and theoretical reasoning are set apart from subjectivity, intuitive judgement and practical experience.

In his 'Critique of Pure Reason' Immanuel Kant (1724-1804) sought to reconcile this dualism, asserting that human knowledge is only possible through the synthesis of reason and experience (Kant trans. Kemp-Smith ed. Caygill 2003; Scruton 2001). Similarly, it may be argued that creative discoveries come about through a combination of theoretical reasoning, intuition and practical experience, and that these approaches appear to be complementary. A historic example is used to illustrate how a combination of theoretical and practical approaches may lead to advances in scientific knowledge.

The chapter goes on to consider the relationship between science and design, an area of enquiry explored by Rust (2004), Broadbent (2003), Cross (2001) and others. In his 'Conjectures and Refutations', Kail Popper argues that scientific knowledge advances through an iterative 'chain of linked problems and their tentative solutions'

(Magee, 1973 p 67). According to Popper, the evolution of scientific knowledge involves intuition, creative imagination and trial and error learning. The same is true for processes of creative discovery in design.

Broadbent (2003) provides a chronological review of attempts to integrate scientific methodology into design. This was first evident in modernist architecture and design of the 1920s, and later in the Design Methods movement, introduced by academics in the 1960s. Design Methods aimed to provide logical, rational, methodological frameworks to enable design to better respond to increasing social and technological complexity. However, Design Methods became a source of conflict; the movement was rejected by the design community as a whole, since its highly analytical approach failed to accommodate the intuitive nature of creative practice and lacked the '..vital human element' of design (Heskett 1980 p 208).

The 'hard systems' of Design Methods were followed by a 'soft systems' approach, drawing on methodological frameworks from the post-positivistic social sciences (Broadbent 2003). However soft systems too have met with notable criticisms. Buchanan points to the 'impossibility of design relying on any one of the sciences (natural, social, or humanistic)' to provide adequate solutions to the highly complex problems encountered by humans within social and technological systems (Buchanan 1995). Whilst design may draw on scientific methods and ideas, science alone may prove insufficient as a basis for design.

Buchanan sees design as an integrative discipline; a 'new liberal ait of technological culture'. Here, Buchanan uses Dewey's understanding of technology as *an art of experimental thinking* to provides a common link between art, science and design. Through their creative actions, artists, scientists and designers may engage in an exchange of knowledge and ideas; human creativity may provide the key to reconciling the conflict of dualism.

Turning to technology, the chapter goes on to introduce arguments from Heidegger's essay 'The Question Concerning Technology' (1954). Here the philosopher points to the *danger* within technology that poses a threat to the future of humanity and the planet, yet he also suggests that a *saving power* may be found. For Heidegger, the *essence* of technology is found in *poiesis*: the poetic processes of making, revealing and knowing, through which the human being can enter into a *free relationship* with technology.

However, the schism of dualism is further exposed in literature exploring the relationship between technology and human knowledge. Aicher (1991) uses the terms *analogue* and *digital* to describe a dualistic conflict which parallels that which is described above. For Aicher, *digital* represents abstraction, objective analysis, logical precision and quantitative results; *analogue* represents human sensuality, subjective judgement, qualitative responses and practical experience. He expresses concerns that 'digital technology is making man into an increasingly digital being'. (Aicher 1991 p 47)

The chapter goes on to discuss the relationship between analogue and digital processes within design, focusing in particular on changes in the nature of prototyping within human-centred design practice. In this context analogue prototyping refers to *hands-on* making and testing of physical prototype models; digital prototyping technologies include CAD-CAM, virtual and rapid prototyping. Examples are presented in which designers and engineers made extensive use of computer modelling and simulation techniques at the design stage. However in these cases - London's Millennium Bridge and 'The B of the Bang' sculpture in Manchester - the full extent of complex, real-world problems only came to light through the physical realisation of design proposals.

These examples point to a requirement for the reconciliation of digital and analogue processes within design practice. Benefits may be identified in digital prototyping in a number of areas. For example, in some large-scale engineering projects the time and cost involved in producing a full-size mock up may be prohibitive. In architecture, the first full-size physical prototype is likely to be the building itself. Here, virtual prototyping techniques have been shown to be beneficial (eg Connell, 2004). Also, in collaborative projects, digital prototyping enables design data to be shared between different members of the development team. Within product design applications, rapid prototyping processes can enable the production of physical objects that would be difficult or impossible to create by another means; for example, when prototypes of small or intricately detailed parts are required.

The chapter concludes that advantages may be found in both analogue and digital prototyping processes. Therefore, following this chapter, two practical projects are presented which identify and explore some areas of compatibility between analogue and digital processes in design. The aim is to explore a combination of analogue and digital approaches to prototyping within the context of human-centred design practice.

3.2 Do not look at my songs!

Do not look at my songs!
I lower my eyes
as if I were caught in a crime.
Even I do not dare
to watch them as they grow -
your curiosity is a betrayal
Bees, too, when they build their cells,
let no-one watch,
nor do they watch themselves.
When they have carried the rich honeycombs
to the light, of day,
then you shall taste them first!

This poem by Friedrich Ruckert (1788-1866) was set to music by Gustav Mahler; a composer who, perhaps more than any other, might stand to represent the culmination of the late-romantic era in western classical music. The poem describes the familiar romantic stereotype of the artist-genius whose creative processes are kept a closely guarded secret. The methods and processes of creativity are perhaps intangible, unknown even to the creative individuals themselves.

According to Epstein (1996), there are some common myths that surround human creativity. Traditionally, creativity has been viewed as a mystical quality only possessed by artists and other truly gifted people. A creative action was seen as an ‘individual act of genius, the radical breakthrough, the moment of inspiration’ (Jackson, 1995 p 37). Fisher (1997) identifies the stereotypical figure of the romantic genius as a recurrent theme within design practice and design education. He highlights common assumptions that the creative activities of designers may be biased towards subjective, individualistic and non-rational mental processes. It may be naturally assumed that this creative approach conflicts with a *scientistic* view of the world based on logic and rationality. Coyne and Snodgrass (1991) refer to this conflict as the *dual knowledge thesis*; human knowledge and experiences are divided in two, reflecting a *Cartesian dualism,* separating logical objectivity and rational analysis from subjective judgment and intuitive experience.

Cartesian dualism refers to the rationalist philosophy of Rene Descartes (1596-1650). Descartes was a mathematician who invented a branch of theoretical mathematics based on algebra and analytical geometry. Descartes believed that in the pursuit of certainty and absolute truth, mathematical logic and rationality could be applied to problems relating to non-mathematical knowledge. His well known statement "I think therefore I am" emphasises the primacy of rational thought over action and experience. According to Descartes the human senses were to be mistrusted, and therefore knowledge must be the result of cognitive reasoning and not practical experience (Magee, 1998).

In contrast to this view, the empiricist philosopher Locke (1632-1704) believed that human knowledge is derived from experience, through a process of sensation and reflection. Locke's position is clearly captured in his statement 'no man's knowledge here can go beyond experience' (Magee, 1998 p 105). Empiricism provided a basis for scientific enquiry that sought to extend human knowledge and understanding through practical experimentation. Immanuel Kant (1724-1804) set out to reconcile the conflict between the rationalist and empiricist philosophies. In his 'Critique of Pure Reason', Kant argued that neither reason nor experience alone could provide knowledge. It is only in the synthesis of reason and experience that human knowledge is possible (Kant trans. Kemp-Smith ed. Caygill 2003 pp 92-95 Scruton, 2001 pp 27, 35). In a similar way, it may be argued that the task of designing requires a creative synthesis of theoretical reasoning and practical experience.

Writers within the field of design have recognised problems posed by the dualistic view of knowledge which come about through the separation of reason and experience (eg Cooley 1980 and 1988, Jones 1991). Examples from the field of engineering design will be discussed later in this chapter. In *'Architect or Bee?* The Human-Technology Relationship' Cooley (1980) emphasises the importance of both theoretical and practical approaches and he also identifies the role creativity plays in extending human knowledge across diverse areas of practice:

> It may be regarded as romantic or succumbing to mysticism to emphasise the importance of imagination and of working in a non-linear way. It is usually accepted that this type of creative approach is required in music, literature and art. It is less well recognised that this is equally important in the field of science, even in the so called harder sciences like mathematics and physics.' (Cooley, 1980 p 27)

Returning to Ruckert's image of the beehive, we can see that whilst the honeycomb takes on a logical, clearly defined structure, the creative fuel contained within its cells remains fluid, non-linear and is, in itself, unconstrained by physical form.

Rust (2004) discusses how discoveries and invention in both science and design can come about through the creative application of practical knowledge. Drawing on the work of Michael Polanyi, Rust considers the theoretical and practical processes that can lead to *illumination*; a discovery, invention, or the formulation of a new theory or hypothesis.

One such *illumination* is present in the story of the tempestuous relationship between Sir Isaac Newton and the lesser-known scientist and inventor Robert Hooke. The story illustrates how a combination of theoretical and practical approaches led to advances in scientific knowledge. The different approaches of Newton and Hooke appear complementary, however their relationship eventually broke down completely. This conflict may reflect the dualistic view of human knowledge, which remains a subject for debate.

3.3 By Hooke or by Crooke?

A dualistic conflict appears to be played out in the lives of the scientists Sir Isaac Newton and Robert Hooke. Both were pursuing an inquiry into gravity and planetary orbits. Newton's approach was to apply the Cartesian methods of analytical geometry and algebra in the formulation of theoretical solutions to scientific problems, whilst Hooke was a designer, practical experimenter and inventor. The two corresponded, exchanging ideas in a series of letters in 1679-1680. The combination of different approaches appeared to bear fruit in Newton's application of the inverse square law describing the relationship between gravitational force and distance, and defining elliptical planetary orbits. However, when Newton failed to acknowledge Hooke's contribution, their relationship ended in conflict.

William Blake’s famous portrait of Newton is shown in Figure 3.1. For Blake, a "true romantic", Newton's classical physics represented the Age of Reason, 'a soul shuddering vacuum... of abstractions and formulae, not of experience ' (Raine, 1970 pp 76, 114). In the painting, Newton is depicted abandoning the creative imagination in favour of reason. Disconnected from human experience, he concentrates his vision solely on the geometric figure inscribed by his compasses. For Blake, the compasses symbolise Newton's god-like status as architect of the universe, or the ‘divine geometer' (Hamlyn and Phillips 2000, p 212 also Blunt 1959).

Figure 3.1 Newton. Painting by William Blake (1757 - 1827).

In his critically acclaimed biography of Newton, Gleick (2003) paints the scientist in a slightly more favourable light. Gleick describes the technological advances taking place in England at the tune of Newton's birth. People had learnt to harness the power of wind and water, and to work skillfully in copper, iron and glass. 'These crafts and materials were prerequisites ... to a great leap in knowledge' enabling the production of 'lenses, paper and ink, mechanical clocks, numeric systems capable of denoting indefinitely small fractions, and postal services spanning hundreds of miles.' (Gleick, p 11)

As a boy, Newton appeared small for his age, lonely, and somehow disconnected from community life. He was, however, preoccupied with changes in the physical world around him, observing the position of the sun in the sky, and the projection of shadows. Gleick describes how the boy charted seasonal changes in the sun's position against fixed stars, tracing 'a slowly twisting figure eight, a figure invisible except to the minds eye' (Gleick, p 12). He found this movement, in his later study of the motion of planets, to be due to the earth's elliptical orbit and tilting axis.

The young Isaac was also an accomplished model maker 'building ingenious watermills and windmills'. Gleick recounts how, when the town of Grantham was building a new mill, Newton built a replica, 'internalising the whining and pounding of the machine and the principles that govern gears, levers, rollers and pulley wheels.' (Gleick, p 18)

On completion of his schooling in Grantham, Newton went on to study at Trinity College, Cambridge. He became a Fellow of the college and was elected Lucasian Professor of Mathematics in 1669. Here Newton developed and refined the Cartesian methods of geometry and algebra, applying these in the formulation of his theories and laws of gravitation, mechanics and optics, which he published in the Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), or *Principia* as it is known.

Biographers have made much of the conflict between Newton and his contemporary Robert Hooke. Gleicke describes Hooke as 'Newton's goad, nemesis, tormentor and victim' (p 64). Hooke was Curator of Experiments for the Royal Society of London, formed in 1662 to communicate and promote a new experimental philosophy in science. The society's motto 'Nullius in Verba' may be translated as 'Don't take anyone’s word for if (Glieck, p 64). Actions speak louder than words, and knowledge advances not only by wordplay but also by action and experiment (Chapman, 1996).

Chapman describes Hooke's experimental approach:

> '...he was no methodological purist. As every modem scientist knows, no original investigator can be the rigid adherent of a pre-detennined method, for creativity in science is more than recipe-following.'
>
> (Chapman 1996)

Hooke was a prolific inventor of scientific and optical instruments including telescopes, microscopes and quadrants; devices for measuring altitude in astronomy and navigation. His aim in developing these instruments was to extend human perception. 'Hooke understood very well that although technology can progress without science, science needs technology' (Beavan, 2001). He invented the iris diaphragm found in modem cameras and the universal joint used in vehicle transmission systems. Hooke successfully constructed an air pump which enabled Robert Boyle to carry out his research into the relationship between pressure, temperature and volume in gases.

Working with Sir Christopher Wren, Hooke designed the Monument to the fire of London, which to this day remains Europe's tallest free standing stone column. Hooke and Wren used the high platform at the top of the Monument to conduct experiments on gravity, weight and atmospheric pressure, and Hooke had hoped to use the hollow column as a long telescope tube, in but this was found to be impossible due to structural vibration (Inwood 2002).

Both Newton and Hooke were seeking to explain the relationship between gravity and planetary orbits. Much of Hooke's work in this area paralleled Newton's, although Gleick reports 'Hooke's system lacked the mathematical foundation' (p 120). In 1679-1680 they exchanged a series of letters with drawings in which they considered a hypothetical experiment to demonstrate the path taken by a object falling towards the earth. Hooke put it to Newton that the object would behave like an orbiting planet, moving in an ellipse, and that the force of attraction acting between the object and earth might be 'always in duplicate proportion to the Distance from the Centre of the Reciprocall [sic]' (Gleick p 123). Here Hooke suggests that the elliptical planetary orbits established by Kepler may be explained in terms of a single force of gravitational attraction acting between bodies that is inversely proportional to the square of the distance between them.

Hunter (2003) asserts that Hooke's synthesis was entirely innovative at the time, citing Koyre's conclusion that 'this episode played "an important, perhaps a decisive, role in the development of Newton's thought"' (Hunter, 2003, pp 155, 156). Hookes ideas, 'sketched on the back of an envelope, so to speak', were taken up by Newton, who went on to publish the inverse square law of universal gravitation as part of his *Principia* (Hunter 2003 pp 155, 156).

It seems Newton's mathematical genius was complemented by Hooke's experience as inventor and practical experimenter. Earlier in a letter to Hooke, Newton famously wrote 'if I have seen further it is by standing on the shoulders of giants’. However it is not clear whether this was intended to be a genuine acknowledgement of Hooke's contribution or, as Gleicke puts it, 'a finely calibrated piece of faint praise and lofty sentiment' (p 100). In any case Hooke was clearly affronted[1] that he had not been given sufficient credit in Newton's publication of the *Principia.* Newton became angry about this and, according to Beavan, delayed the publication of a future work until after Hooke's death. It is even suggested that Newton destroyed Hooke’s portrait, for none remains.

3.4 Art, science and design

The story of Newton and Hooke ended in conflict. However, the account suggests that a complementary combination of approaches was evident in their relationship. In the formation of his theories and laws, Newton sought mathematical proof of scientific phenomena, whilst Hooke's approach was to test out ideas through practical experimentation, drawing on his experience as designer of mechanical and scientific instruments (Hunter 2003).

Hooke's creative synthesis and his contribution to Newton's *Principia* “sketched on the back of an envelope” reflects a spontaneous, designerly approach to discovery and invention. However Newton'... distinguishes the mathematical sciences of mechanics from the practical mechanics and the manual arts...' an approach which reflects the view that the practical knowledge and intuitive ability of designers is somehow subordinate to the logical analysis and theoretical explanations 'from first principles' offered by the sciences (Buchanan 2001b p 5).

---

[1] In his book 'On the Shoulders of Giants', Professor Stephen Hawking comes out in support of the unsung hero when he states that Hooke's complaints were '... not without merit...' (Hawking 2002 ' p 731)

Hawking is Lucasian Professor of Mathematics at Cambridge University, the position once held by Newton.

So what is the significance of the story of Newton and Hooke to this thesis? The story demonstrates that a combination of theoretical knowledge and *hands-on* practical experience can lead to creative discovery and invention. Newton's childhood, in which he built ingenious mechanical models and plotted the paths of celestial bodies as they moved across the heavens, served as a prelude to his later scientific theories and laws governing the mechanics of the universe; laws which remained in place without improvement for over two hundred years.

In the formulation of Newton's Principia, Hooke played his part. Through the invention of mechanical clocks and scientific and optical instruments, Hooke demonstrates his understanding of practical mathematics. Whilst he may not have mastered calculus, he certainly had sufficient grasp of theoretical mathematics to be able to communicate to Newton, through words and pictures, the physical principles which formed the basis of the Inverse Square Law of Universal Gravitation. Despite their fierce professional rivalry, no doubt fuelled by jealousy and pride, Newton and Hooke shared much common ground. Here, theoretical and mathematical modelling combined with hands-on practical experience yielded creative insights that led to scientific breakthrough.

Writers have explored the relationship between design and science. Broadbent (2003) points to what has been, in the history and evolution of design, a source of conflict and contradiction; if science is largely concerned with theory, objectivity and the pursuit of absolute truth, then design focuses on practical, real-world problems that defy objective analysis. However, Rust (2004) highlights the potential for co-oporation; design can make a practical contribution to the creative processes of scientific discovery that lead to advances in human knowledge.

Advances in science that took place during the early years of twentieth century turned Newton's classical physics on its head. Einstein's relativity theory indicated that Newtonian mechanics, when applied to very large objects or to objects moving at high speed, gives incorrect results, whilst quantum mechanics showed that Newtonian theory does not work at the very small scale of atomic particles. (Okasha 2002 p8) Similarly, the twentieth century philosopher of science Karl Popper rejected classical scientific method, on the grounds that it is difficult or impossible to verify or prove absolutely any scientific theory or "law". Popper held that refutation of a hypothesis, not verification, should be the aim of scientific enquiry.

Bruce Archer, formerly Director of Research at the Royal College of Art in London, presents a well-known example from Popper:

> 'No number of observations of white swans allows us to logically derive the universal statement: "All swans are white". Searching for, and finding, more and more white swans does not prove the universality of the white swan theory. However, one single observation of a black swan allows us to logically derive the statement: "NOT all swans are white".'
> (Archer 1995 p 7)

Popper describes the development of human knowledge as 'a chain of linked problems and their tentative solutions'. Popper advocates 'Boldly proposing theories ... trying our best to show that these are erroneous... and of accepting them tentatively if our critical efforts are unsuccessful' (Popper 1963 p 68).

Popper uses the following equation to describe the development and testing of new theories or solutions to problems:

Pi ▶TS — +*EE* —*P2

The various components of this equation may be defined as follows:

Pi = problem situation
TS = tentative solution *(prototype)*
EE = error elimination *(testing)*
P2 = resulting situation, a new problem emerges when errors are exposed

The process continues in an iterative chain as follows:

Pi — ▶TS —>EE — ▶P2
p2 — ▶TS — ▶EE — ▶P3
P 3 — ▶TS — »EE — *-P4
P 4 _ ▶TS — ^EE — ▶Ps etc

(Magee 1973 p 65)

Popper's 'chain of linked problems and their tentative solutions' may be considered analogous to the iterative development and testing of ideas in design. Archer (1995), discusses methods employed within design research. He emphasises Popper's acceptance of the role of "inspired guesswork", in the formulation of new theories and ideas.

In his autobiography 'Unended Quest' Popper himself acknowledge that his *Conjectures and Refutations* apply in fields of creative endeavour other than science, including art and music.

'So we are led to include art and, in fact, all human products into which we have injected some of our ideas, and which incorporate the result of criticism... Indeed a great work of music (like a great scientific theory) is a cosmos imposed upon chaos - in its tensions and harmonies inexhaustible even for its creator.' (Popper 1976 pp 63, 228)

Mahler uses a similar metaphor to illustrate the creative force which he believed to be present in his music, when he describes '...this chaos which is constantly giving birth to new worlds and promptly destroying them again...' (La Grange and Weiss ed. 2004 p 179). Perhaps this is the creative force which carries us forward in progressive stages of conjecture and refutation, through the creation and critical, even destructive testing of ideas, in the ongoing search for truth and understanding. Here Magee reflects on Popper's philosophy:

'...it puts the greatest premium of all on boldness of imagination ... The scientist and the artist, far from being engaged in opposed or incompatible, are both trying to extend our understanding of experience by the use of creative imagination ... both are using irrational as well as rational faculties ... both are seekers of truth who make indispensable use of intuition.'

(Magee 1973 pp 68 - 69)

Popper acknowledged that intuition, creative imagination and learning through trial and error play key roles in the formulation of new ideas and the development of human knowledge. The same is true for processes of innovation in design.

Cross (2001) and Broadbent (2003) identify a desire amongst some theorists and practitioners to 'scientise' design. According to Cross, this first emerged strongly as part of the modern movement within twentieth century art and design; for example, in the works of the *De Slijl* group and Le Corbusier, who described the house in terms of an objectively designed "machine for living'" (Cross 2001 p 49). This approach was based on the theory that men and women had evolved through natural selection into perfect human mechanisms, functioning according to the immutable laws of 'economy'. The aim of the designer was therefore to create functional objects which most closely satisfied these laws (Heskett 1980 pp 94, 95). This highly reductive approach appears to revert back to the rationalism of Descartes, the outcomes of which may lack qualities appropriate to human experience.

The Design Methods movement, introduced by academics in the 1960s, was an attempt to make design respond better to the increasing complexity of social and technological structures. Heskett (1980) describes Design Methods as 'a rational, analytical sequence intended to identify the fundamental nature of any given design problem, enabling a solution to be devised to meet defined needs' (p 207)

In 'Design Methods: seeds of human futures' Jones (1970) presents a system of methods that aim to make process of designing entirely explicit. Mystical assumptions about design are removed and replaced by rational, systematic methods and processes. Jones views the 'systematic designer' as a 'human computer', into which information about a particular design problem can be fed. This information is then processed by the designer/human computer through a logical and predetermined sequence of analysis, synthesis and evaluation. The sequence may be repeated several times until the designer/human computer is able to output an optimum solution.

Figure 3.2 The designer as computer. Jones (1970) p 50

Gedenryd (1998) identifies the absurd contradiction evident in Jones' human-computer analogy, and points to the failure of Design Methods as a whole. The positivistic 'hard systems' approach proved unacceptable to the design community since it did not fit with the often intuitive activities of practicing designers, and failed to provide what Heskett refers to as the '...vital human element' of designing (p 208). Cross (2001) describes how even two of the movement's pioneers later rejected Design Methods.

In 'Notes on the Synthesis of Form' (1964), Christopher Alexander had applied Design Methods thinking within the context of architectural design. In a newsletter of the Design Methods Group (1971) he later writes:

> 'I've disassociated myself from the field.... there is so little in what is called "design methods" that has anything useful to say about the design of buildings that I never read the literature anymore... I would say forget it, forget the whole thing.'
>
> (Alexander cited by Cross, 2001 p 50)

In 'Designing Designing' Jones (1991) writes:

> 'We looked in enormous detail at the process of eating. We discovered all the kinds of food and all the actions of eating. The result was nothing like the knives and forks we now use. Our designs looked like dental instruments ... I found that a great split had developed between intuition and rationality ... I realise now that rational and scientific knowledge is essential for discovering the bodily limits we all share, but that mental process, the mind, is destroyed if it is encased in a fixed frame of reference.'
>
> (Jones 1991 pp16-22)

Buchanan (1995) reports that a similar split developed between theoretical and studio courses at the Hochschule fur Gestaltung in Ulm. This school of design, established in 1953, was perceived by some to be Germany's 'New Bauhaus'. In an interview with the school's former head Tomas Maldonado, Friemart and Bruttel (2003) present an account of the crises which occurred prior to the school's closure in 1968.

Maldonado recounts:

> In Ulm there was a clash over methods. I have always taken a keen interest in scientific theory ... I was also extremely interested in methodological questions, especially decision theory ... I introduced methodology into the School, but after a while I realised that this methodology was not connected with certain cultural values ... It had degenerated into a self-referential methodology. The situation became unbearable - the methodologists had arrived. Nobody designed anything any more.
>
> (Friemart and Bruttel 2003 p 20)

So the 'hard systems' of the Design Methods movement gave way to a 'soft systems' approach, drawing on methodological frameworks from the social sciences, in an effort to bring design closer to end users and the other stakeholders in the system of production and consumption (Broadbent 2003). Developing areas such as design ethnography and user-participatory design were discussed earlier in this thesis. Proponents of these areas may be specialists from fields outside of design practice. For example, Kelley (2001) reports how the design team at IDEO includes psychologists who carry out observational research and human factors studies. IDEO researcher Jane Fulton Suri is described as '... part anthropologist, part seer ... Jane tries to get under people's skin to figure out what they think and do, as well as why.' (Kelley 2001 pp 37-39).

However, the aims of anthropology are different to the aims of design. Buchanan identifies that propositions offered by 'behavioural and social sciences do not lead directly to the specific, particular features of successful products. There is a profound, irreducible gap between scientific understanding in this area and the task of the designer.' (Buchanan 2001b p 16)

Furthermore, criticisms have been voiced against design researchers and usability specialists, some of whom may find it difficult to understand the informal, intuitive methods at work within creative design practice. For example, Olson (2002) asserts You can't research or test your way to good design; you can only design your way there' (pi6).

Olsen argues that, through practical experience, designers and engineers internalise the knowledge that is necessary for them to carry out their work. In doing so, they develop an intuitive sensitivity to end-user requirements, a factor which some researchers and usability specialists may fail to grasp:

> 'For some reason, too many usability specialists seem unable or unwilling to step into the role of design - which is where the real action is and why usability specialists may become an endangered species unless they're willing to take off their white labcoats and dirty themselves in design.'
>
> (Olsen 2002 p 13)

Yet Friedman and Ainamo seem determined to keep their labcoats firmly buttoned up. In 'Establishing design as a science based profession', they maintain:

> '...design ought to move from traditional skills-based rules of thumb based on trial-and- error methods to the use of theory and scientific method.'

and without rigorous methodological frameworks:

> 'The work of the ... intuitive ... unconscious designer is no more and no less the product of evolution than the tools evolved by homo habilis in 2,500, 000 BC ... the individual who has produced them has not yet learnt to walk upright as a designer.'
>
> (Friedman and Ainamo 1999 pp 294, 309)

Friedman and Ainamo argue that the design profession should adopt scientific methods, in order to take its rightful place alongside other science-based professions such as medicine, engineering and management. Design should aim to become a theory-rich profession, applying logical, analytical methods to solve clearly defined problems. They go on to claim that an approach based on scientific method is likely to be more successful than any other approach, at least in terms of competitive effectiveness.

However Coyle asserts the view:

> 'Design researchers should resist any call to adopt any call to legitimate their activities through the adoption of pseudo-scientific mechanistic descriptions.' (Coyle 1997)

According to Coyle, pseudo-scientific methods run the risk of being sterile, inflexible, machine-oriented and devoid of life, often failing to take into account the complex reality of human activities. He emphasises the difference between 'methods as stated' and 'methods as used'; 'what people say they do' may appear straightforward; 'what people really do' is far more complex. Coyle identifies a conflict between theory and practice; whilst some design theorists are absorbed in detailed methodological descriptions '... Practitioners think it's all madness.' (Coyle 1997)

Both Coyle and Olson identify the irony that whilst researchers in the hard sciences increasingly recognise the existence of complexity, *uncertainty* and chaos, some researchers in design attempt to adopt pseudo-scientific methods in the hope that they will achieve *certainty* in their results.

The above examples support the view that dualism, evident throughout human history, has permeated design discourse, manifesting itself in the conflicting agendas of design theory and design practice. The conflict between theoretical and practical courses at Ulm School of Design reflects the rejection of the Design Methods movement of the same period. Friedman and Ainamo's call for design to be established as science-based profession is strongly reminiscent of earlier attempts to 'scientise' design. This approach is rejected by Olson and Coyle, who argue that soft systems and pseudo-scientific methods fail to accommodate the intuitive nature of design and the complex reality of human experience.

According to Broadbent (2003) successive waves of interest in the application of scientific methodology in design may be attributed, at least in part, to the accelerated pace of social and technological change. Pointing to the 'double exponential' growth in technology that appears to follow an evolutionary pattern, He observes a similar' pattern emerging in the successive adoption and later, the inevitable rejection of design methodologies:

> 'Methodological advances will always be found wanting for, in farther exposing the complexity of the real world, they provide the rationale for the next methodological generation.'
>
> (Broadbent 2003 p 9)

Put differently, rapid advances in technology lead to an increase in real-world complexity. Attempts are made to find a methodological framework that accommodates the latest changes in complexity, by which time even more changes have come along, at an even faster rate.

Broadbent anticipates the emergence of the next generation in design methodology; an 'evolutionary systems methodology' which draws on methodological frameworks from both 'reductionalist' and 'holistic' sciences:

> 'the reductionalist and holistic sciences will together largely, perhaps completely, account for the design activity of humans.'
>
> (Broadbent, 2003 p 9)

In the philosophy of science, *holism* considers complex systems as unified *wholes* rather than assemblies of isolated parts; the whole is considered to be greater than the sum of its parts. Broadbent implies a complementary relationship may exist between reductionism and holism. However, according to Quinton, holism is hostile to reductionalist analysis 'which it conceives to be a falsifying mutilation of what it is applied to' (Quinton 2000 p 400).

The combination of seemingly contradictory sciences may therefore prove to be a further source of conflict. Furthermore, whilst design may seek to engage with one or more of the sciences, and to draw upon scientific methods and ideas, science, on its own, may prove to be an insufficient basis for the design activity. Here Buchanan points towards 'the impossibility of design relying on any one of the sciences (natural, social or humanistic) for adequate solutions to what are the inherently *wicked problems* of design thinking' (Buchanan 1995 p 19).

Wicked problems refer to the complex, indeterminable problems encountered by humans within social and technological systems. Rittel and Webber (1972) argue that rigid, linear methods of analysis and synthesis are unable to address problems characterised by uncertainty and competing variables. Coyle calls for a new class of method - *wicked methods* - a set of adaptable methods capable of accommodating the complexity of the design activity and the flexibility of design in practice. Design defies delineation, adapting in the face of chaos and complexity; adaptivity, according to Brand (1994 p 188) is said to thrive 'on the edge of chaos'. Here, flexibility is a key strength; design eludes reduction and is unconstrained by established methodological boundaries. (Buchanan 1995).

Design is an 'integrative discipline' which draws upon - *but is not bound by* - methods and ideas from other disciplines. Buchanan (1995) develops this view when he identifies design as a 'new liberal art of technological culture'. He uses Dewey's understanding of technology - *an art of experimental thinking* - to link creative activities within art, science and design. Dewey's philosophy connects theoretical and practical knowledge in an approach which emphasises the value of 'doing for the sake of knowing' (Dewey 1929 p 87).

Popper also recognised that human creativity provides the key to the integration of seemingly contradictory elements (Magee 1973 pp 68 - 69). It is through the application of creativity that artists, scientists and designers seek to extend human capabilities and improve quality of life. If design is to become a truly integrative discipline, then creativity is also required in the reconciliation of internal conflicts that can lead to dualistic schism. In his resolution of Cartesian dualism, Kant identified that human knowledge is only possible through the synthesis of reason and experience. Similarly, in design, integration is only possible the through the reconciliation of previously conflicting elements; theory and practice; intellect and intuition; method and madness.

At the 'Designing Design Research' event held at London's Royal College of Art in March 2004, John Chris Jones called on the design research community to 'end the dualism and create integration.' Resolving this truly wicked problem is a creative challenge that design must continually seek to address.

* * *

It is to technology - Dewey's art of experimental thinking - that the discussion now turns. Dewey viewed technology as a human process through which knowledge is created.

It is well known that the term *technology* is derived from two Greek words: *Techne* meaning skill or art '...the knowledge of how to do things and make things...' and *Logos* meaning principles, theories and laws through which '...human reason guides human action...' (Blackburn 1994 pp 224, 373). Therefore technology brings together theoretical reasoning and practical action in a creative synthesis of theoretical and practical knowledge.

Yet Buchanan identifies that since the rise of the industrial revolution, technology is almost exclusively thought of in terms of its products, systems and machines. The human process of technology may seem all but forgotten. He is optimistic, however, observing that 'in the work of individual designers and in reflection on the nature of their work, design is slowly restoring the richer meaning of the term "technology"' (Buchanan, 1995 p 18). Central to this process of restoration is the reconciliation of technology's dual identity; redressing the balance between technology as product and technology as human process.

Here Buchanan's views on technology appear to echo arguments in Heidegger's essay 'The Question Concerning Technology' (1954) in which the philosopher enquires into the nature of the *essence* of technology. For Heidegger, the essence of technology is nothing technological; it is not to be found in mere machines. Nor is it sufficient to say that the essence of technology lies in human activity, if those activities subjugate the human being to the constrictive existence of a cog in a machine. Here Heidegger anticipates fears that the human being may *lose itself* to technology in ways which present an imminent threat to the future of humankind and the planet.

Heidegger says of man '...he comes to the very brink of a precipitous fall...' if he allows himself to be subsumed into the seemingly unstoppable mechanisms of technological progress which he himself has set in motion (Heidegger 1954 trans. Lovitt in Farrell Krell ed. 2002 p 332). Trapped on the treadmill of technological progress, human beings become "human resources" to be exploited. Human activity is governed by the rules of efficiency, and nature is manipulated through the application of a regulating, calculating logic 'driving on to the maximum yield at minimum expense' (Heidegger 1954 pp 320-324; Collins and Selena 1999 p 160) Here humanity faces a *supreme danger* (Heidegger 1954 p 332).

Yet as well as great danger, Heidegger argues a *saving power* may be found in technology, but only if the human being is able to grasp the *essence* of technology. Here he cites the German poet Holderlin (1770-1843):

> But where danger is, grows
> The saving power also ...
>
> ... poetically man dwells on this earth

Heidegger looks back to the origin of the word technology; within *techne* he rediscovers a lost meaning:

> '... *techne* is the name not only for the activities and skills of the craftsman but also for the arts of the mind and the fine arts. *Techne* belongs to bringing forth, to poiesis; it is something poetic.' (Heidegger p 318)

For Heidegger, the essence of technology is to be found in *poiesis* - the processes of creation - an *essential unfolding* or poetic revealing. Further to this, he identifies a relationship between *techne* and *episteme* '...Both words are terms for knowing in the widest sense. They mean to be entirely at home in something, to understand and be expert in it. Such knowing provides an opening up. As an opening up it is a revealing' (Heidegger pp 318 - 319). By grasping the lost meaning of techne - in poetic revealing and knowing - the human being opens up the possibility of a 'free relationship' with technology (Heidegger 1954). The essential unfolding of technology presents the possibility of new relationships between making, revealing and knowing.

However, in an exploration of relationships between technology and human knowledge, Aicher (2001) identifies a further dualism, paralleling those described earlier. Aicher adopts the language of technology: for him *digital* represents abstraction, objective analysis, logical precision and quantitative results; *analogue* represents human sensuality, subjective judgement, qualitative responses and practical experience. Aicher expresses concerns that 'digital technology is making man into an increasingly digital being' (Aicher 1991 p 47).

Virilio voices concerns relating to rapidly emerging digital technologies, including virtual reality and real-time global information and communication technologies, which compress time and distance and blur the boundaries between the physical and virtual worlds. According to Virilio, the *digitisation* of human sensory information will lead to '...the decline of immediate sensations, the *analogue resemblance* between what is close at hand and comparable would yield primacy to the *numerical probability* alone of things distant - of all things distant. And would in this way pollute our sensory ecology once and for all.' (Virilio 2000 p 114)

However artists, scientists and designers are exploring the potential of digital technologies as a medium for human creativity. This is evident, for example, in the work of the MIT Media Lab, and Bill Gaver's Interaction Design Research Group at London's Royal College of Art. The artist and designer Michael Hohl expresses a desire to transform 'remote, abstract, "dry" digital data' into a sensuous, graspable human experience. Hohl designs interactive environments to enable participants to access data from remote sources via an interactive map of the earth; his aim is to create a feeling of 'presence, global awareness, holistic overview and interconnectedness.' (Hohl 2004)

Views expressed by Aicher, Virilio and Hohl point towards a requirement to establish an interconnected equilibrium between analogue and digital design worlds. In light of this, relationships between analogue and digital design processes are now discussed, focussing in particular on the emergence of digital prototyping technologies within the context of human-centred design practice.

3.5 Human digits and digital design

Emerging digital design technologies include virtual and rapid prototyping. Within virtual prototyping, designers and engineers use computer modelling techniques to simulate the appearance and/or some of the functional attributes of a design proposal, for example, the structural behaviour of a component, or other aspects of product performance. Rapid prototyping technologies are providing new ways to obtain three-dimensional physical output from virtual modelling systems.

Current rapid prototyping technologies include stereolithography (SLA) in which data from three-dimensional modelling software is translated into physical form by solidifying photo-sensitive resin using a laser. Another rapid prototyping technology is fused deposition modelling (FDM) in which physical prototypes are "printed" layer by layer in molten plastic which fuse together to create the finished form (Davey 2003, Sherman 2004).

In literature aimed at the design and engineering professions, virtual and rapid prototyping are often referred to as time compression technologies. Here it is argued that such technologies can lead to shorter development times and a reduction in the number of physical prototype iterations required to get a new product off the virtual drawing board and onto the production line. Advocates of virtual prototyping claim computer-based simulation may reduce or in some cases entirely eliminate the requirement for physical prototype iterations, (eg Connell 2004, Bocking 2003, Bussler 2003, Hollerbach et al 2000, Adams and Askenazi 1999, Boswell 1998).

A counter-argument to the designer's total immersion in the virtual world is that valuable human knowledge and experiences may be both elicited and communicated through active *hands-on* engagement with physical prototype models. For example Chamberlain, Roddis and Press (1999), Chamberlain and Roddis (2003), Rust et al (2000a, 2000b) and Rust (2004) describe how physical models can provide a tangible bridge between designers and other stakeholders within interdisciplinary design research.

Here the present author and colleagues assert:

> 'Designing for physical action requires both the designer and the end-user to develop an intimate understanding of the *task in hand*, experienced through all five of the human senses. This highlights the multi-dimensional nature of design, where opportunities for innovation may be revealed through discovery-oriented physical prototyping.'
>
> (Walters et al 2004)

Designers literally construct their own realities which later become the realities of other people. If an aim of design is to create physical products which will exist in the real world to be experienced by people, then there may be no substitute for the experiences which may be derived through active engagement with real physical prototypes in the real physical world. Furthermore, since it may be impossible to simulate all aspects of a design proposal using computer-based modelling techniques, valuable creative insights may be lost through an over-reliance on virtual prototyping technologies.

Virilio holds the view that advances in technology carry with them the danger that something essentially human may be lost. (Virilio 2000, Armitage 2000, 1999). Moreover, the rapid and uncritical acceptance of virtual prototyping technologies may result in loss of an essential human element of design via the amputation of valuable hands-on knowledge and experience. The following discussion of virtual reality draws on post-modernist theory and Heideggerian philosophy; the aim is to provide a platform from which the *virtualisation* of design processes may be critically appraised.

3.6 More real than reality?

The concept of virtual reality - in which humans can interact with computer-generated worlds - is most commonly attributed to American computer scientists of the 1980s and 90s, and to the simulation systems which NASA and the American Air Force developed to train astronauts and pilots (eg Ottosson 2002). However, Gray (2004) identifies that the idea of virtual reality was anticipated some decades earlier by the Polish science fiction writer Stanislaw Lem.

In his 1964 book 'Summa Technologiae', Lem described a machine called the 'Phantomat' through which people could enter a simulated world of their own choosing, liberating themselves from the material world.

Users of the Phantomat experienced life in a perfect dream-world free from conflict and human suffering: '...in the Phantomat we can live over and over again and be whatever we want to be ... nothing can be hurt or destroyed because nothing really exists' (Gray 2004 p 52). Lem feared that people would naturally come to prefer the perfect world of the Phantomat to the harsh reality of their own existence. Gray, who is School Professor of European Thought at the London School of Economics, translates Lem's science-fiction world of the Phantomat into our own epoch:

> 'New media technologies enable us to blank out the environments in which we live ... Each day, we may encounter a filthy environment and dysfunctional public services, but in the virtual world conjured up by interactive television we are all only a moment away from wealth and freedom. For many people this fantasy world is more real than their own disjointed everyday actions and perceptions.'
>
> (Gray 2004 p 51)

Gray's prognosis echoes the concept of hyper-reality put forward by post-modern thinkers including Jean Baudrillard and Umberto Eco. Here the reality of the material world is increasingly obliterated by the images and symbols provided through electronic media. In the world of hyper-reality it is impossible to distinguish between what is real and what is simulation (Bullock and Trombley ed 2000 p 409). These ideas are captured in Baudrillard's controversial 1995 book 'The Gulf War Did Not Take Place' in which he argues that, whilst the Gulf War did actually take place, the reality of the combat was only experienced by a comparatively small number of people; the war as it was broadcast by the global media was an illusion - a video game - a simulation in which America and the rest of the world were active participants.

Ironically, recent reports indicate that US Army soldiers are increasingly being trained using video-game style simulation software. According to Soller (2004) the US Army spends $1.4 billion a year on training simulations and has recently founded The Institute of Creative Technology, a Hollywood-based enterprise through which it plans to develop and market its expertise in virtual combat. Full Spectrum Warrior, a video game based on US Army combat simulation software was released on sale to the public in June 2004. It has been widely suggested that this game - and an earlier release called America's Army - are intended to function as a recruitment tool for the US military.

According to one leading Army simulation expert, virtual combat has taken the shine off live training in which soldiers 'go out in the woods and mess around' (Soller, 2004) This view reflects one of the problematic characteristic of hyper-reality; virtual simulations can appear more real than reality itself. The distinction between reality and simulation becomes blurred, and 'holding on to material reality becomes a near impossible task'. Reality disappears before our very eyes. This tendency is referred to as 'the theft of reality ... the perfect crime'. (DeGrandpre, R 2001 p 22) As Baudrillard asserts:

> 'Virtuality only gives possibilities virtually, while taking back the reference and the density of things, their meaning. It gives you everything, and subtly, surreptitiously it takes everything away at the same time.'
>
> (Baudrillard 1996)

Some argue that this theft of reality is clearly evident in the area of childhood play where, instead of engaging in the active and imaginative world of outdoor games, children choose the prescribed, pre-packaged hyper-reality of the Playstation. Formative practical and social experiences are sacrificed in favour of the passive isolation of'plugged-in play' (DeGrandpre, 2001 p 23). Others indicate computer games can have a positive effect on children's social and educational development. Here it suggested that "group gaming" may encourage social interaction, and that playing computer games can improve children's "visual intelligence". Computer games have been used in the classroom since the 1980s as tools for developing skills and motivation in a range of subject areas (Negroponte 1996, Subrahmanyam et al 2000).

In his recent book ‘Everything Bad is Good For You: How Popular Culture is Making Us Smarter’, Johnson (2005) cites research carried out by Rochester University that investigated the effect playing video games has on visual intelligence and memory, (see Green and Bavelier 2003).

Subjects were required to undertake visual recognition tests, for example, to count the number of objects appearing simultaneously on a screen, or to identify a target object from amongst a group of distractors. The study compared the performance of regular “habitual” video game players with that of non video game players. Results of the study indicated that subjects who were regular “gamers” outperformed “non-gamers” in all aspects of the tests. From this outcome Johnson concludes ‘... Games were literally making them perceive the world more clearly’ (pp 152-153). Poole disagrees, arguing that all the study demonstrates is that ‘...video-gamers were better at performing video game-style tasks. This is not a very surprising result’. (Poole 2005)

Significantly recent research published by the Department for Education and Skills found that computers are widening the gender gap in schools. Research carried out by Leeds and Sheffield universities found that boys spend more of their spare time playing computer games whilst girls use home computers for schoolwork. Research demonstrated that pupils who used computers for schoolwork achieved higher GCSE grades, whereas those (mainly boys) who regularly played computer games scored significantly lower grades (Richards 2005).

The overuse of computers amongst children may inevitably leave less time for outdoor sports and games and real-world social activities, and concerns clearly exist over excessive game playing, especially the effects violent computer games may have on children and teenagers (Anderson 2003, Anderson 2004, Subrahmanyam et al 2000, Subrahmanyam et al 2001). Furthermore, Subrahmanyam et al cite research indicating that playing virtual reality games (eg role-playing games within so-called "multi-user domains") may lead to some young people having difficulty distinguishing between fantasy and reality.

DeGranpere argues that our understanding of the everyday world is being distorted by our exposure to the abstract hyper-realities of the electronic media. Whilst we may be seduced by the slick surface appeal of the virtual experience, the substance and meaning of things becomes increasingly difficult to grasp. The corporeal is displaced by the hyper-real and the world is dematerialised - disembodied through the removal of physical references, substance and meaning.

For Heidegger, our understanding of the everyday world is primarily grounded in the concrete, embodied reality of *being there*[3] or *being-in-the-world*[4] (Heidegger 1927 trans. Macquarrie and Robinson 1962). Within his major work 'Being and Time' (1927), Heidegger undertakes an enquiry into human understanding in a world of everyday *practical concerns.* These *concerns* refer to 'all the ways in which we relate ourselves to the enviromnent - producing, constructing, enjoying and so forth' (Macquarrie, 1968 p 15).

Heidegger calls these practical concerns our 'dealings in the world'. He gives primacy to '[t]he kind of dealing which is closest to us ... not a bare perceptual cognition, but rather that kind of concern which manipulates things and puts them to use; and this has its own kind of "knowledge".' (Heidegger 1927 p 95)

In the course of his enquiry, Heidegger describes a workshop in which entities - tools and materials - are encountered. These entities may be considered in a mode of detached observation, viewed from a distance, without practical engagement. In this case, Heidegger would describe the entities as being *present-at-hand* (vorhanden).

But physically taking hold of one of the entities - a *hammer* - its manipulability and usability is discovered - *it is a thing for hammering.* Through close practical engagement, the hammer is understood. Heidegger would then describe the hammer as being *ready-to-hand* (zuhanden). For Heidegger, the practical *ready-to-hand* understanding has primacy over the detached, abstract, theoretical *present-at-hand* mode traditionally favoured by the intellectual disciplines of science and philosophy (Heidegger 1927 pp 95 - 103; Collins and Selena 1999 p 56).

---

3. Heidegger uses the word *Dasein.* The verb *dasein* may be translated as 'to exist' or 'to be there'. The noun *Dasein* has as its root meaning 'being there' or 'being here'. According to Inwood '*Dasein* is Heidegger's way of referring both to the human being and to the type of being humans have.' (Inwood 1997 p 22)

4. *in-der-Welt-sein* (Heidegger 1927)

Through practical engagement, the craftsman in Heidegger's workshop develops an understanding of all of the tools and materials available at his disposal; he 'discovers them in their usability and servicability ... these things are incorporated into the significant world and understood' (Macquarrie, 1968 p 22). In this way the craftsman 'sees his workshop as a field of possibilities for him, and is perhaps wondering what to do next' (Inwood, 1997 p45).

It is in dealing with this field of possibilities for action - the *open future* into which the human being projects itself forward - that determines the *authenticity* of its existence - its *being-in-the-world.* For Heidegger, the human being that takes hold of its own possibilities and thus determines the direction of its own life exists *authentically,*; the human being that allows this direction to be determined by external factors (circumstances, social pressures, mass-media communication) exists *inauthentically.* The individual human being can therefore 'choose itself or 'lose itself. (Heidegger 1927, Macquarrie 1968 p14).

When considering human interaction with virtual-reality technologies, it is possible to identify parallels with the Heideggerian concepts identified above. For example, within the hyper-reality of the Playstation, children enter a fantasy world in which they are equipped with super human-powers beyond their wildest dreams. Yet within this fantasy, possibilities for action are restricted to the content provided by the game designers and the limitations of the software and hardware technologies. In this sense, the children's possibilities for action are largely determined by external factors; the interaction may therefore be analogous to Heidegger's concept of *inauthenticity.* Furthermore, the action takes place behind a *glass screen* - inside the abstract, disembodied world of the video game - analogous to the distant, detached mode of *present-at-hand* (vorhanden).

In the real world of outdoor play, children may be - to a far greater extent - free to take hold of their own possibilities for action and to apply their own creative imagination. Through close engagement with the physical world, children discover new possibilities for themselves and create their own toys and games; a broomstick becomes a horse; a branch becomes a tree-house. This kind of discovery-oriented play may move children towards a mode of engagement with the world that is analogous to Heidegger's *authenticity* and *readiness-to-hand* (e.g. Heidegger 1927 pp 140-141).

Through similar close engagement, a designer working in Heidegger's workshop is able to develop a hands-on understanding of a broad range of materials and processes. The designer discovers opportunities afforded by these materials and processes, and also learns of their limitations. Manipulation of these *ready-to-hand* materials can lead to the discovery of the possible mechanical, structural, and kinetic relationships afforded when materials are placed in combination with each other. Exploration and manipulation of materials in this way can lead the designer to discover new practical uses for various material configurations and also new opportunities for manufacture.

Furthermore, the knowledge of structural, mechanical and kinetic possibilities gained through close physical engagement may be retained and put to good use next time the designer is called upon to address a new design task. Developed over time, this practical *ready-to-hand* understanding is taken-to-heart and so becomes second nature to the designer. Cooley refers to the taken-to-heart understanding possessed by experienced practical designers and engineers as '...tacit knowledge ... It comes about through years of practical experience at the point of production itself... All their knowledge of the physical world about them acquired through years of making things and seeing them break and rupture.' (Cooley 1980 pp 80 - 81).

Cooley reports how an aircraft company engaged a team of four mathematicians to write a computer programme to model the complex three-dimensional form of the afterburner of a large jet engine. The mathematicians attempted to create the shape using “Coon's patch surface definitions”, an advanced form of geometry. However, after two years, they were unable to find a satisfactory solution.

The aircraft factory had an experimental workshop, where a skilled sheet metal worker, working alongside an engineering draughtsman, had actually succeeded in drawing and making the complex afterburner shape. However, one of the mathematicians commented '"they may have succeeded in making it but they didn't understand how they did it"' (Cooley 1980 p 81) Cooley asserts:

'In the past, skilled workers have had in the main, a tacit understanding of mathematics through their ability to analyse the size and shape of components by actually working on them. More and more, that knowledge has been abstracted away from the labour process and has been rarefied into mathematical functions.' (Cooley 1980, p 5)

Through their tacit knowledge of mathematics and materials, skilled workers succeeded in producing what highly trained mathematicians had failed to achieve. Cooley refers to tacit knowledge as the 'things we know but cannot tell' (Cooley 1988 p 201 after Polanyi 1962). Tacit knowledge is a deeply internalised form of human knowledge, developed over time until it becomes second nature to the practitioner.

This example points to the value of tacit knowledge within a practical engineering context, but it also suggests that such knowledge might sadly be undervalued by some. However, there now appeals to be a growing research interest in tacit knowledge across a range of disciplines. Rust (2004) explores the tacit dimensions of design within the context of interdisciplinary research. He identifies how tacit knowledge might be invoked and put to use through direct human engagement with physical objects.

Recent developments in computer-aided design and manufacturing technologies have set in motion a process of dramatic change within design and engineering professions, academic research, and design education. According to Evans (2004), developments in virtual and rapid prototyping technologies mean the emergence of a *virtual design workshop* appears increasing viable. The advantages to the manufacturing industries of the virtualisation of design processes might appear obvious; by eliminating the requirement for costly, time-consuming physical prototyping, advocates of virtual technologies promise to significantly increase the efficiency of product development processes. For example, at the American National Science Foundation Design and Manufacturing Research Conference (2000) Hollerbach et al assert:

> 'The goal of virtual prototyping is to replace physical mockups with computational mockups, thereby greatly decreasing costs and speeding up iterations in the design.' (Hollerbach et al 2000)

Here Bussler (2003) anticipates some of the potential benefits of virtual prototyping:

> 'In the future, current simulation technologies will lead to tine virtual prototyping, in which CAD assemblies of entire products or mechanism are used in simulations including all the environmental factors a product may experience. By seeing the behaviour of a design on the computer, engineers will develop useful real-world insights into their designs.' (Bussler 2003)

In literature aimed at the design and engineering professions, a number of writers seem to make the assumption that it is both inevitable and desirable for hands-on physical prototyping to be eliminated altogether. For example, Connell (2004) asserts that virtual modelling ' breaks vicious circle of design, physical prototype, review and test... there are in fact already some companies, such as BAE systems, that have successfully integrated the necessary technology and techniques to take them from 3D CAD through to full digital mock-up [virtual prototype] to manufacture' (Connell 2004). Boswell (1998) and Booking (2003) cite Boeing as being one of the first companies to make extensive use of virtual prototyping technologies. The Boeing 777 aircraft was '... the first airplane to be 100-percent digitally designed and preassembled on computer.' (Boeing 1995)

According to Davey (2003), the emergence of low cost 3D printing technologies provides product designers with a virtual "Valhalla". Desktop rapid prototyping systems, some of which look surprisingly like high-tech vending machines, enable physical prototypes to be printed directly from a virtual model. All this takes place in the safety and comfort of the design studio, so designers may never again have to dirty their hands in the real-world workshop, or be required to draw upon the 'artisan-derived skills' of an 'old-school' modelmaker or technician (Davey 2003, pp 16 - 17). Yet Sherman (2004) identifies that the physical output from current 3D printing systems is typically limited to just one or two materials[5], clearly indicating that as yet such systems are unable to simulate the physical properties or surface qualities of the richer range of materials that may be encountered by the designer in the real-world workshop.

---

[5] Despite recent advances, rapid prototyping polymer materials are still unable to fully reproduce the range of physical characteristics available from production typical plastics.

For example, the mechanical properties and surface finish of a rapid prototype part made in nylon via selective laser sintering will typically fall some way below that of the same part made by injection moulding nylon. Satisfactory replication of the flexible ‘live hinge’ properties of polypropylene has also proved to be problematic for rapid prototyping techniques.

Moreover, in the virtual design workshop, the action takes place behind a glass screen, very much like the abstract, disembodied video-game world identified earlier; the level of engagement appears analogous to Heidegger's distant, detached mode of *present-at-hand.* In the real-world workshop, the designer develops an intimate *ready-to-hand* understanding of the product being designed, including the complex combination of functional, ergonomic, material and aesthetic factors to be resolved in an object that will ultimately inhabit the physical world.

Currently the virtual workshop deprives the designer of the practical hands-on understanding that comes through direct physical engagement and manipulation of material objects in the real world. As McCullough asserts 'What good are computers, except for mundane documentation, if you cannot even touch your work?' (McCullough 1998 p 25).

Hardware and software manufacturers are now responding to this obvious shortcoming in current virtual design technologies. Evans (2002, 2004) Shillito (2004), Sener et al (2002) and Evans et al (2005) report on recent developments in tactile and force feedback devices and their potential applications in virtual modelling systems for use by designers, artists and engineers. Their investigations focus on the latest interface archetype - the SensAble Phantom Haptic feedback device - which comprises a stylus attached to the end of an articulated arm (figure 3.3).

Figure 3.3 “Virtual clay” or “poking at the world with a stick?”
SensAble Technologies Phantom stylus-and-arm haptic interface
(www.sensable.com accessed August 2005)

Through the stylus and arm, users of the device can 'feel' the external boundaries of a virtual model and, using the dedicated 'Freeform' software provided, they can carve and sculp 'virtual clay' (Evans 2004, Sener et al 2002).

Proponents of haptic feedback technologies promise palpable tactile experiences. However, others highlight the shortcomings of current devices. For example, Harvard Professor Robert Howe, a specialist in tactile feedback devices, describes the experience of using current stylus-based haptic interfaces as 'like poking the world with a stick' (in Hodges 1998). The author and colleagues have identified that as yet such systems have been unable to provide an adequate substitute for the experience of manipulating physical materials in the real-world workshop. Evans (2002) and Evans et al (2005) report that current technologies lack the necessary accuracy and control of surface continuity required within industrial design applications. Having significant shortcomings in the SensAble Phantom interface, Evans et al (2005) point designers in the direction of glove-based haptic technologies.

Figure 3.4 Cybergrasp cable-actuated exoskeleton haptic interface
www.immersion.com (accessed 31 August 2005)

A leading glove-based haptic device, the Immersion Cybergrasp interface is shown in figure 3.4 and 3.5. This system is based on a cable-controlled "exoskeleton". Borst and Voltz (2003) report that the Cybergrasp interface is both cumbersome and restrictive, and system is unable to provide satisfactory haptic rendering of surface details and edges. Maceil et al (2004) encountered problems with the cable-operated Cybergrasp mechanism in the delivery of sudden changes in output force that are required, for example, when rendering abrupt surface discontinuities.

Figure 3.5 The day of the virtual workshop is at hand! Immersion Technologies Corporation Haptic Workstation with force feedback exoskeleton arms and Cybergrasp gloves. In the picture the system is configured to function as a driving simulator.

Image www.immersion.com (accessed 31 August 2005)

Salisbury of MIT Artificial Intelligence Laboratory identifies the significant challenges faced by developers of future haptic interface systems 'To sense the shape of the cup we do not take a simple tactile snapshot and go away and think about what we felt. Rather we grasp and manipulate the object, running our fingers across its shape and surfaces in order to build a mental image of the cup' (Hodges 1998).

It appears touch technologies are still some way off recreating the experience of manipulating physical objects and materials in the real-world workshop - a view expressed by Malcolm McCullough, in his opening address to Pixel Raiders 2004, an international conference exploring creative applications of digital technologies. Here, McCullough reported that developments in haptic technologies are some twenty years behind state-of-the-art visual display technologies such as Silicon Graphics. He asserted (halfjokingly, perhaps) 'Silicon Haptics - perhaps I'll get some in my lifetime!'

Writing in Time Compression Technologies', a journal aimed at the virtual and rapid prototyping industries, Bussler (2003) discusses recent developments in Finite Element Analysis (FEA) software; virtual modelling software that enables engineering designers to simulate the mechanical and structural behaviour of products and systems.

According to Bussler, over the last 10 years software companies have focussed on developing FEA systems which make it easy for engineers to create increasingly realistic simulations of mechanical events, including those which require both motion and stress analysis. Mechanical systems can be designed and tested within a virtual environment and their behaviour observed and, if necessary, modifications can easily be made to the design. Reid (2004) reports that software developments are bringing simulation techniques typically regarded as the domain of highly-trained specialists within reach of product designers and engineers. Using the latest simulation software '... Product designers can now evaluate their intuition and play with their models giving them a far greater realm of discovery and innovation' (Reid 2004).

Whilst the time compression technologists extol the virtues of virtual prototyping, significant issues are raised by the assumption that these technologies can replace physical human input in design. Key amongst these issues is that within virtual prototyping, it is impossible to model an object with physical properties that lie outside the parameters incorporated into the software, or which exceed the technical capabilities of current software and hardware technologies. Moreover, if the scope of the design activity is limited to what can currently be simulated using virtual prototyping technologies, the range of potential physical outcomes may be significantly restricted.

Yet Evans 2002 maintains:

> '...with the exponential increases in computing power over the past decade, the emerging capabilities of this technology should not be underestimated. It is therefore possible to predict a scenario towards the end of the next decade where the form and interface of an industrial design proposal could be effectively evaluated through the use of virtual reality and haptic feedback, without the need for a physical artefact' (Evans 2002 p 275)

However, at this point it may be concluded that despite the confidence in virtual prototyping techniques expressed by advocates of these emerging technologies, it is impossible for designers and engineers to escape the physical reality of the task in hand. By allowing themselves to be totally immersed in virtual design worlds, designers and engineers run the risk of failing to grasp full complexity of real-world problems.

London's Millennium Footbridge provides a powerful example since it appears to demonstrate the consequences of an over-reliance on virtual modelling. Despite the engineers' use of advanced mathematical and computational modelling techniques, the problem of “synchronous lateral excitation” - the notorious wobble - did not come to light until the bridge existed in reality and could be experienced by people.

3.7 A bridge too far?

London's Millennium Bridge opened to the general public on June 10, 2000. The bridge was designed by sculptor Sir Anthony Caro, the architect Sir Norman Foster and the engineers Ove Arup and Partners. The designers intended the bridge should appear like a 'blade of light' crossing the Thames (Sudjic, 2001) For the opening ceremony, Newland (2003) describes how over 1000 people assembled on the south side of the bridge with a band playing out in front. As they began to walk across, the pedestrians experienced a pronounced swaying motion in the deck of the bridge. This movement was sufficiently dramatic that people had to stop walking to retain their balance and hold onto handrails for support.

On the first day of opening, an estimated 80 to 100,000 people crossed the bridge. However, because of the unexpected sideways motion and out of concern for public safety, the bridge was closed two days later and did not re-open until February 2002. The swaying motion of the footbridge is known as Synchronous Lateral Excitation, a phenomenon which can occur in bridge structures due to the sideways forces people generate as they walk. These sideways forces result in lateral motion in the bridge deck. People then find it more comfortable to change their pace in order to walk "in-step" with the movement of the bridge. This instinctive behaviour further reinforces the motion, and the cumulative effect when large numbers of people walk at the same pace can be dramatic. The design of the Millennium Bridge was vulnerable to the problem because the bridge's natural resonant frequency - the frequency at which a structure is naturally most inclined to vibrate - was close to the walking pace of pedestrians.

Figure 3.6 London's Millennium Bridge.
Images: Sudjic (2001), Foster and Partners (2004)

Clarke (2002) points out that 'rhythmic walking has been a well-known bridge problem since the first armies marched over the first bridges'. He observes many bridges close to barracks have notices instructing soldiers to "break step". For example, a notice is displayed on the entrance to London's Albert Bridge, built in 1873. Also, some will remember from school history lessons that even Roman soldiers knew to break step as they crossed bridges, in case the combined effect of marching in-time caused the structure to collapse (Clarke, 2002, Sudjic, 2001).

However engineers Ove Arup report that the phenomenon of synchronous lateral excitation had not previously been widely published, and therefore was not known to practicing bridge designers (www.arup.com/millenniumbridge). Whilst Newland describes a number of cases recorded in the literature, it seems that the problem was not so widely known as to be incorporated into relevant bridge building codes, the official standards and guidelines to which all bridge structures must comply.

As part of the bridge's design, Clarke reports that the engineers carried out a structural analysis using GSA Fablon software. The software was used to predict the structural behaviour and aerodynamic stability of the bridge. Yet despite the sophistication of these virtual prototypes, the structural analysis and mathematical modelling, it appears that the engineers may have overlooked an essential human element - the effect of people actually walking on the bridge. Problems with the design only came to light when the footbridge existed in the physical world and could be experienced by people.

Figure 3.7 Millennium Bridge Engineering CAD model - plan and elevation
Image: Sudjic 2001

Petrovski (1992) emphasises the importance of human judgement and human experience in the design of structures, and warns of the dangers of over-reliance on computer aided design systems in this context:

> 'The electronic brain is sometimes promoted from computer or clerk at least to assistant engineer in the design office. What is commonly overlooked in using the computer is the fact that the central goal of design is still to obviate failure, and thus it is critical to identify how a structure may fail. The computer cannot do this by itself... thus far the computer has been as much an agent of unsafe design as it has been a super-brain that can tackle problems heretofore too complicated for the pencil and paper calculations of a human engineer.'
>
> (Petrovski 1992, p 195)

Dr Allan McRobie, a Structural Engineer based at Cambridge University, heard about the swaying motion from members of his family who had visited London on the day of the opening. Determined to find out more about the problem, McRobie constructed a model of a section of the bridge in his Cambridge Laboratory. This was the same width as the real bridge but just 4m long. When people walked across the model bridge, the structure duly swayed. McRobie and colleagues went on to use motion capture video techniques to analyse the physical relationships between the swaying motion and changes in people's gait (McRobie 2000, Purves 2000)

Figure 3.8 Human cantilever model illustrating the physical principle of the Forth Rail Bridge. Image: Boyd-Whyte et al (1997)

Petrovski (1996) describes the design of another famous bridge, this time over the Firth of Forth in Scotland. The Forth Rail Bridge, opened in 1890, was by far the largest of its kind anywhere in the world, spanning about twice the distance of any previous cantilever bridge. Because it was such an ambitious design, and also because of the collapse of the Tay Bridge in 1879, the engineers John Fowler and Benjamin Baker went to great lengths to communicate the principle of cantilever construction, in order to win the confidence of investors and the public at large.

Baker employed a 'human cantilever' model which consisted of two people seated on chairs supporting a third person on a swing seat, representing the suspended portion of the bridge (figure 3.8). The anus of the people on chairs are held in tension, whilst broom handles act as struts in compression. The bricks act as counterweights to provide balance. The 'human cantilever' provided a powerful means of communicating the structural principles which, importantly to the public, looked nothing like an earlier suspension bridge design proposed by Bouch, the engineer of the ill-fated Tay Bridge.

The Millennium Footbridge re-opened once the problems with the design had been diagnosed and appropriate modifications made to the structure, including the addition of a system of mechanical dampeners to limit the motion of the deck. The original cost of the bridge was £18.2 Million, with the modifications costing a further £5 Million.

It is impossible to know whether the knowledge derived from McRobie's physical models could have saved considerable expense and public embarrassment had it been available to engineers prior to the construction of the bridge. What is clear is that the reality of the problem was only confronted once the Millennium Bridge existed in the physical world.

Whilst for centuries marching soldiers have been instructed to break step when crossing bridges, it appeal s that the phenomenon of synchronous lateral excitation exhibited by the Millennium Bridge was not sufficiently accounted for in bridge building codes of practice (Newland 2003). The engineers Ove Arup report that problems with the Millennium Bridge have prompted modifications to be made to the British Standard codes for bridge construction, the aim being to prevent pedestrian-induced movement of this sort occurring in future.

3.8 Bang up to date!

A further recent example highlights challenges faced by practitioners working at the interface between engineering and art, and demonstrates that despite advances in computer-based modelling techniques, there remains an essential requirement for designers to confront the physical reality of design problems. This case involves the design and construction of Britain's biggest sculpture - Thomas Heatherwick's *The B of the Bang* -commissioned to commemorate the 2002 Commonwealth Games in Manchester. The B of the Bang is an impressive structure standing 56 m tall, almost three times the height of Anthony Gormley's Angel of the North. Inspired by British sprinter Linford Christie's statement "I'll be gone by the 'B' of the Bang!", the work was conceived by Heatherwick to represent the explosion coming from the barrel of a starting pistol. The sculpture resembles a giant starburst having 180 steel spikes projecting from a central core. Helping Heatherwick to realise the work, London-base structural engineers Packman-Lucas were engaged to undertake the engineering design of the sculpture, including computational stress analysis, wind loading and vibration analysis, and wind tunnel testing of a small-scale model of the structure.

SPOwicm

Figure 3.9 The B of the Bang. A most impressive sight when lit up at night. Image www.360spin.co.uk/bofthebang/ (accessed 31 August 2005)

Figure 3.10 The B of the Bang - Height comparison
B of the Bang (56 m)
Leaning Tower of Pisa (55.9 m)
Nelson's Column (57 m)
Statue of Liberty (46.5 m)
Angel of the North (20 m, wingspan 54 m)
Image www.bofthebang.com (accessed 31 August 2005)

Fabrication of the central core of the sculpture was earned out by AK Heavy Engineering in Sheffield, a company specialising in the production of large scale engineering structures. Projects undertaken by the company include the Channel Tunnel boring machine, components for the Thames Barrier, the opening mechanism for the new Gateshead bridge, as well as mining machinery and capital equipment for heavy manufacturing industries around the world. On 23 March 2005 the author visited Paul Madin, Fabrication Technical Manager at AK Heavy Engineering. Madin, a metallurgist with over 20 years experience with the company, was intimately involved in the realisation of the sculpture.

Madin explained that significant challenges were faced in the fabrication of the sculpture's central core. AK Heavy Engineering had been supplied with full-sized computer plots showing the cutting profile and three-dimensional coordinates of the base section of each of the 180 spikes. This data was essential to ensure that the spikes intersected correctly at the central point of convergence. The plots were generated from a 3D computer model of the core of the sculpture, which was also used to help determine the order in which the separate parts would be welded together.

Figure 3.11 The B of the Bang. Steel fabrication of the central core of the sculpture was undertaken by skilled engineering craftsmen at AK Heavy Engineering in Sheffield. Photograph kindly provided by Paul Madin, AK Heavy Engineering.

However, once fabrication work began, it soon became apparent that distortion in the structure due to thermal expansion and contraction from welding steel sections up to 40mm thick resulted in unacceptable inaccuracies in the shape of the core. It was therefore necessary to modify and re-align each part in turn in order to accommodate this distortion. According to Madin, knowing what allowances to make for this kind of distortion in large, irregular structures is something of a "black art", and as yet no CAD techniques exist which take account of this. Madin's view reflects Cooley's description of the valuable tacit knowledge of structures and materials possessed by skilled engineering craftsmen: 'There are things we know but cannot tell' (Cooley 1988 p 201 after Polanyi 1962).

Once these difficulties were overcome and fabrication work in Sheffield was complete, the core was transported to Manchester where the legs and spikes were welded into place. Site assembly, undertaken by Alfa Construction, was hampered by poor weather conditions. A string of delays in completion resulted in the sculpture acquiring the nickname "The G of the Bang". The sculpture caused considerable controversy, as the cost of the project increased from a predicted £750,000 up to £1.42m (Ottewell 2005).

Figure 3.12 The B of the Bang. The finishing touches being put to the sculpture on site in Manchester. Image: Sheil and Packman (2005)

In December 2004, when the site work was complete, Madin and his team travelled to Manchester to see the finished sculpture. Their visit was recorded by the BBC and later broadcast as part of a documentary programme Thomas Heatherwick and Britains Biggest Sculpture' shown on January 12 2005. The Sheffield team were clearly delighted to see the finished work, yet some anxieties remained.

In order to be as light as possible, the tapered steel spikes are of a hollow, thin-walled construction, and as such are relatively flexible. Heatherwick and the structural engineers Packman-Lucas intended that this flexibility would provide a dynamic design feature as the spikes would sway in the wind. However, on visiting the sculpture, Madin and his team expressed some concern over the extent of the movement exhibited by some of the shorter spikes.

Then, on January 7 2005, a week before the sculpture was due to be open to the public, a seven-foot section of one of the spikes broke off and crashed to the ground. Fortunately nobody was hurt as the sculpture was still fenced off to the public. In a report on the spike failure, BBC Newsnight broadcast concerns that'... the welders were convinced the spikes were going to fall off…', whilst the engineers Packman-Lucas remained confident the structure was sound (BBC Newsnight 7 January 2005). Although the opening ceremony went ahead as planned, the sculpture remained fenced off out of concern for public safety.

The spike failure was initially blamed on an isolated welding fault. In March 2005 Ottewell reported that all similar welds had been removed, replaced and certified as safe. New East Manchester, the regeneration company that commissioned the sculpture, claimed that no evidence could be found linking the spike failure to wind-induced movement, and that measurements taken on site had indicated that the motion of the spikes was no greater than that anticipated at the design phase. However, as a safety precaution, the company announced that mechanical dampeners were to be fitted to a number of the spikes in order to prevent excessive movement in future (Ottewell, 2005).

The task of attempting to predict wind-induced movement in a structure as complex as The B of the Bang should not be underestimated. Packman-Lucas employed a combination of computer-modelling and wind-tunnel testing of a small-scale model of the sculpture. However both approaches are fraught with opportunities for inaccuracy, especially regarding the apparently random, turbulent flows around structures which can cause wind-induced vibration known as *galloping* - wind-induced resonance that can lead to catastrophic structural failure (as in the infamous Tacoma Narrows Bridge which collapsed in 1940).

Figure 3.13 The B of the Bang. Computational analysis of the core in its first mode of vibration, www.bofthebang.com (accessed 31 August 2005)

Figure 3.14 The B of the Bang. 1-100 scale model in wind tunnel testing carried out by wind loading specialists BMT Fluid Mechanics Limited
Image http://www.bmtfm.com (accessed 31 August 2005)

Within the field of computational fluid dynamics, Castro and Graham (1999) argue that it will be decades before sufficient computing power is available to enable turbulent flows to be realistically modelled without making simplifying assumptions which inevitably lead to inaccuracies. They assert '..there are serious dangers inherent in relying on computer-based tools for design purposes in the wind engineering context.' (Castro and Graham 1999).

Augustini et al (2001) concur, recognising that turbulent flows and complex fluid-structure interactions continue to present significant challenges within the computational environment, hence the continued reliance on the testing of small-scale physical models in the laboratory setting of the wind tunnel. Yet wind-tunnel testing is itself not without inaccuracies, which principally come about through problems associated with scaling. Here Scanlan (2002) argues that in wind-tunnel tests conducted on small-scale models, proper realisation of equivalent full-scale turbulence and other aeroelastic factors is a practical impossibility.

Writing in the July/August 2005 edition of the architecture journal AD, Packman indicates that at the design stage engineers were aware of potential problems of galloping in some of the spikes, and that these problems were unresolved at the time of construction (however the article, Sheil and Packman 2005, refrains from mentioning the spike failure). It appears that the extent of the movement of the spikes and the subsequent requirement for mechanical dampeners only became fully evident when the full-sized structure existed in three dimensions within the real environment.

On Thursday 12 May 2005, the author attended a lecture on the design and construction of the B of the Bang, given to the Manchester Association of Engineers by Ron Packman of structural engineers Packman-Lucas and Paul Madin of AK Heavy Engineering. The lecture was chaired by Professor Michael Burdekin, Professor of structural engineering at University of Manchester Institute of Science and Technology, and Fellow of the Royal Society. In correspondence following the lecture, the author put it to Professor Burdekin that the B of the Bang appeared to demonstrate that despite the ever-increasing sophistication of computer modelling systems, some types of design problem may only be identified and addressed by confronting the physical reality of the task in hand. He responded:

> 'I agree with you that whilst computer based modelling is becoming ever more powerful, it is important to recognise that the results depend completely on the validity of the model and comparisons with experimental results are vital in critical cases ... The sculpture is an extreme example of the fact that computer modelling cannot cover all possible occurrences and that physical behaviour has to be checked.'[6]

Ramm and Wall (2004) describe the physical characteristics of hollow, thin walled 'shell structures' which may in some cases be prone to an almost unpredictable structural response when subject to complex, dynamic loading conditions. This 'capricious character' has led Ramm and Wall to refer to these as 'Prima Donna' structures. Ramm and Wall identify that Prima Donna structures can be in a 'good mood' or a 'bad mood' depending on slight changes in loading conditions and other design parameters (Ramm and Wall 2004).

---

[6] E-mail correspondence from Professor Michael Burdekin to the author 24 May 2005

On 20 May 2005 disaster struck again, when firefighters had to be called to remove a second spike which broke away from the B of the Bang sculpture. This prompted yet further anxiety over the safety of the structure (BBC News 20 May 2005; Dowling 2005). A section of road adjacent to the sculpture has now been closed off. For safety reasons the sculpture will clearly have to remain fenced off until all parties are confident that the structural problems have been fully resolved, and so it seems that the future of this Prima Donna sculpture is as yet unknown.

3.8 Discovery-oriented prototyping

It is not only problems that come to light through physical modelling. By engaging in physical making and testing, designers create new opportunities for discovery and invention. Myerson (2001), reports on the prototyping methods employed at US design consultants IDEO:

> 'Building crude, approximate but usable models that can be evaluated in use was shown to be central to the IDEO design process, encapsulated by the motto ‘fail often in order to succeed sooner’ - Enlightened trial and error succeeds over the planning of the lone genius.'
> (Myerson 2001 pp 10, 89)

Kelley (2001) describes prototyping as 'the shorthand to innovation'. He presents a number of case studies demonstrating iterative physical prototyping methods adopted by designers at IDEO and Apple Computers. Kelley describes how the process of building prototype models can often lead to the discovery of unexpected solutions:

> 'Call it serendipity or even luck, but once you start drawing or making things, you open up new possibilities of discovery. It's the same method that's helped scientists unlock some of the greatest secrets of nature.'
> (Kelley 2001 pp 108- 109)

Rust (2004) and Kelley (2001) explain how the Nobel Prize-winning scientists Crick and Watson built physical models of molecular structures to help them visualise and test their hypotheses. Kelley reports 'Watson and Crick's freethinking style and openness to two-dimensional and three-dimensional prototyping helped guide them towards the momentous discovery of the structure of DNA' (Kelley 2001 p 109).

Figure 3.15 Watson and Crick: Hands-on physical modelling informed the discovery of the double helix structure of DNA
Image: www.nature.com/nature/dna50/index.html
accessed 21 February 2006

In a further example, scientists using 21st century medical imaging techniques have presented strong and compelling evidence in support of the possibility that Leonardo da Vinci constructed a physical model of the human aortic track: a glass model which allowed him to observe and record the formation of vortices in the flow of blood through the heart. Leonardo's notebooks contain schematic drawings and descriptions of how to make such a model by blowing glass into plaster moulds (Figure 7.1a). He includes instructions for an experiment in which water containing grass seeds is poured through the glass model. The motion of the grass seeds in the water reveals the formation of vortices in the Sinus of Valsalva, and here Leonardo provides drawings and descriptions of the vortices and their influence on the closure dynamics of the aortic valve (Figure 7.1b).

Gharib et al (2002) used medical imaging technologies to demonstrate the accuracy of Leonardo's studies. A magnetic resonance image of a living human heart shows the vortices similar to those illustrated by Leonardo (Figure 7.1 d), whilst laser imaging technology was used to visualise the flow of fluid through a reconstruction of the glass model, the results of which clearly correlate with Leonardo's drawings (Figure 7.1 c) In his notebooks, Leonardo also illustrates his own design for an artificial heart valve; itself an innovation some 500 years ahead of its time (Gharib et al 2002 pp 219-223).

^ 7 ;
>,

’V i
V rtr
tuffs
/ • 1 ^ * 1 *
W fT ,

Figure 7.1 **Studies of vortices in the human aortic track**

a. Leonardo's schematic drawing of a glass model of the aortic track and

b. his drawings illustrating the formation of vortices in the Sinus of Valsalva (in Mallay and Saunders, 1952)

c. Laser imaging results indicating fluid flow through a glass model constructed according to Leonardo's schematic (Gharib et al 2002)

MRI scan of blood flow through a human aortic valve showing formation of vortices in the Sinus of Valsalva (in Yacoub et al 2004)

According to Kemp, a renowned authority on the remarkable renaissance artist-scientist-engineer:

> 'Essentially Leonardo had learnt all that is needed to work out the mechanics of the kind of artificial heart valve that extended my mother's life for a goodly span of years.1(Kemp 2004 p 112)

One of the reported benefits of emerging digital design technologies is the ability to share data between members of the design team. This facilitates collaborative working, enabling teams of designers and engineers to work simultaneously on different aspects of the same design project. Here the time compression technologies identified earlier are central to the approach known as *concurrent* or *simultaneous engineering* (Ranky 1994, Kalpakjian 1992, Mumby 2003). Design and engineering activities which would have previously been carried out sequentially can now take place simultaneously, thus reducing time-to-market, providing manufacturers which a quicker return on their investment.

Concurrent engineering and virtual prototyping are directed towards optimising the speed and efficiency of design and engineering processes, and the elimination of the 'vicious circle' of physical prototyping and testing (Connell 2004 pp 44 - 49). However, through the compression of product development timescales, the danger exists that valuable iterative cycles of action and reflection could get squeezed out of the design process.

Driven by the pursuit of optimisation and efficiency, concurrent engineering appears to represent a *technical rationalisation* of design and engineering processes. However, technical rationalisation may fail to adequately reflect the demands of real-world practice *1.* Here, Schon emphasises the value of iterative reflection-in-action, when he describes the 'art of engineering design' as 'a reflective conversation with the materials of a situation' (Schon 1983, p 172).

7 Schon asserts:

> 'If the model of technical rationality is incomplete ... so much the worst for the model. Let us search instead for an epistemology of practice implicit in the artistic, intuitive processes which some practitioners do bring to situations of uncertainty, instability and value conflict.' (Schon, 1983 pp 45, 49).

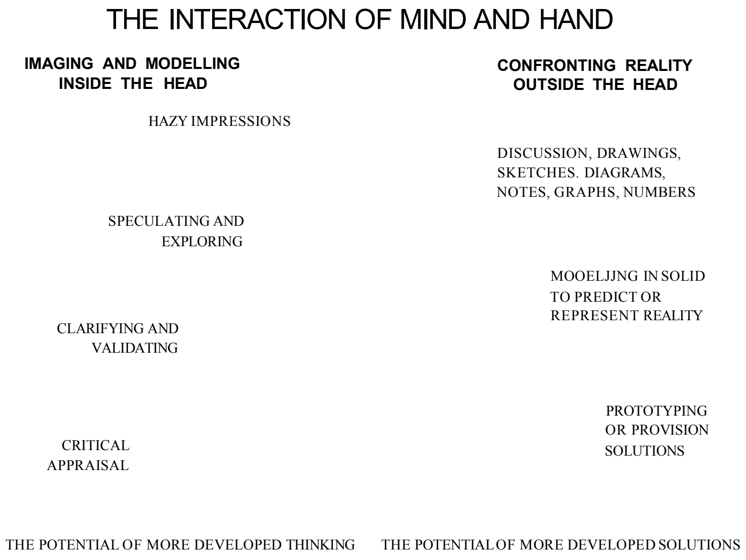

Figure 3.16 The Interaction of Mind and Hand (Kimbell, 1990)

An example of this 'reflective conversation' is illustrated in Kimbell's model 'The Interaction of Mind and Hand' which comes from within design education discourse. Kimbell's model demonstrates an iterative, interconnected relationship between *mental modelling* 'internal images in the minds eye' and *physical modelling* 'concrete expressions that allow us to examine the reality of an idea'. Here design ideas develop from first hazy impressions and early speculative concepts, through iterative phases of exploration, clarification, validation and critical appraisal. The reality of ideas is confronted at each stage through the making and testing of prototype models. Through successive stages of action and reflection design ideas are developed and refined. (Kimbell et al 1990 pp 18-25).

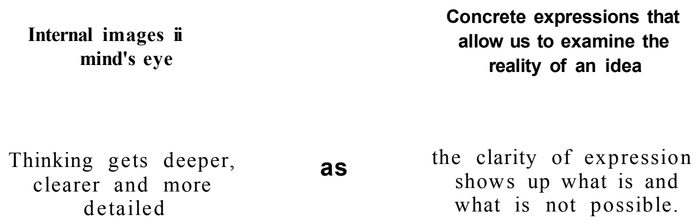

Figure 3.17 The Interaction of Mind and Hand (Kimbell, 1990)

3.9 The best of both worlds?

An aim of virtual prototyping is to increase the speed and efficiency of new product development processes. However, through the uncritical application of these so-called *time compression* technologies, opportunities for reflection-in-action could be reduced or restricted, and tacit, physical, human elements of design could be lost. Furthermore, through the virtualisation of design processes, opportunities to capture and capitalise on creative insights through discovery-oriented physical prototyping could be closed off. Here we may be reminded of Baudrillard's *theft of reality* echoed here in Virilio's assertion:

> 'Every time there is a gain, there is a loss too'
>
> (Virilio in Armitage 1999, p 42).

Yet both virtual and rapid prototyping have been shown to be beneficial in a number of areas of design, architecture, and engineering practice. For example, within architecture, small-scale physical models can form an integral part of the development and communication of design ideas, but the first full-sized physical prototype is likely to be the building itself. It is now common for leading architects to present design proposals as fully-rendered virtual models, sometimes involving animated 'fly-throughs' (Whyte, 2002). Virtual modelling and visualisation techniques are evident in the work of architects including Sir Norman Foster, Daniel Libeskind and Zaha Hadid (eg Hadid 2004, Fireman, 2004).

Within large-scale engineering projects it may not be possible or feasible to construct full-sized mock-ups which adequately represent the physical properties of a design proposal without going to the time and expense of building the real thing. In such cases virtual prototyping may be used extensively for the development, visualisation and optimisation of design proposals prior to physical construction. Yet Cooley's example from within aeronautical engineering serves to emphasise that the valuable practical knowledge which may be derived through physical making and testing must not be overlooked. Furthermore London's Millennium Bridge and The B of the Bang sculpture demonstrate the requirement for designers and engineers to face up to the physical reality of design problems when developing proposals and solutions which will ultimately exist in the real world.

Within industrial design practice, rapid prototyping technologies enable physical prototypes to be obtained from virtual modelling systems. Rapid prototyping allows designers to realise design ideas that would be difficult or impossible to create using traditional hands-on techniques, for example when prototyping hollow parts with complex internal details. However, it has been identified that currently the material properties available through rapid prototyping is limited when compared to the range of physical materials that may typically be available in the real-world workshop. Furthermore, direct hands-on manipulation physical materials can contribute the development of a designer's ready-to-hand knowledge of material possibilities. Also rapid prototyping may lack the immediacy of hands-on workshop-based modelling, for the creation and modification of sketch models and functional test rigs or "lash-ups", for example.

It is clear from examples discussed within this chapter that significant benefits can be found in the digital design technologies of virtual and rapid prototyping and also in the analogue approaches of hands-on making and testing. This points towards a requirement to identify how analogue and digital approaches can together make a mutual contribution to human-centred design practice.

A key argument identified in the first half of this chapter was John Chris Jones' call to *end the dualism and create integration.* By integrating the world of ideas with the world of actions, design can proceed through both *thought experiments and practical experiments.* Here theory goes hand in hand with practice and two worlds are intimately connected. The need for integration identified by Jones may be extended to include both analogue and digital processes in design.

Therefore, in the chapters which follow, two practical projects are presented through which areas of potential compatibility between analogue and digital approaches are explored. These projects examine the capabilities and limitations of emerging digital prototyping technologies - including virtual and rapid prototyping techniques - within the context of human-centred design practice, through investigations in which designers seek to exploit tactile qualities as essential features in design, and also in cases involving complex, dynamic structural behaviour.

Together the two projects demonstrate a requirement to combine digital technologies with hands-on human input in design.

4.0 Practical investigations - methodological overview

This chapter provides an introduction and overview of the methodological approach adopted for the two practical projects that together form the central part of this research enquiry. Then, in the chapters which follow, the research methods and outcomes of the practical investigations will be described in detail.

Since human-centred design practice is the field of enquiry, a research methodology based on *practice* clearly seems appropriate in this context. Therefore a *practice-centred* approach is adopted, in which the researcher's own creative practice forms an essential part of the research methodology (Rust, Chamberlain and Roddis 2000).

An alternative research strategy might have been to use questionnaires or to conduct interviews with other design practitioners to gather qualitative and/or quantitative data on the nature and role of prototyping activities within their creative practice. However concerns existed over whether such an approach would provide sufficient depth of insight; doubts were raised over the effectiveness of questionnaires or interviews as research tools to elicit knowledge of the real-world complexities inherent in creative practice. Here Coyle (1997) acknowledges that in practice there may be a difference between what people say they do, which is apparently straightforward, and what people really do, which is complex.

Archer (1995) introduces a practical approach to design research. He describes an approach in which the researcher's own practice is the principal method of enquiry. This takes the form of *action research,* which Archer defines as:

> '... Systematic enquiry conducted through the medium of practical action, calculated to devise or test new, or newly imported, information, forms or procedures and to develop communicable knowledge ... Action Research findings are extremely valuable. They produce insights which might otherwise never be obtained ...'
> (Archer 1995)

According to Evans (2004)'... action research has been described as an on the spot procedure designed to deal with a concrete problem in an immediate area'. These approaches recognise the validity and potential benefits of insights gained through the researcher's practical involvement within the area of enquiry.

Furthermore, practice-centred research in design may seek to capitalise on the researcher's own creative skills, knowledge, experience and personal enthusiasms. Here Norman, Heath and Pedgley of Loughborough University's Design Research Group describe practice-centred design research as:

> '...a mode of enquiry that resembles action research ... in which research questions become apparent through designing (i.e. through the investigative techniques that are characteristic of design activity) and can be addressed through designing (i.e. through the engagement of intentional reactive responses that are characteristic of the design activity. Hence, as with action research, the researcher is participant (or intervenes) in the situation under study, to make some desired or anticipated events happen or circumstances avail.'

Rust (1999, 2000, 2004) identifies design as a tool for exploring the world, and suggests that insights gained through practice-centred design research might be different, and perhaps complementary, to those obtained with the tools of the natural or human sciences. Through active engagement in creative practice, the designer-researcher may gain unique insights, shedding new light on the problem or process under investigation.

Recent examples of doctoral research in design where creative practice has been central to the research methodology include: Bunnell's investigation of the integration of new technologies within the context of ceramic designer-maker practice (1998); Whiteley's development of design principles for upper-arm prostheses based on close mechanical analogies of human anatomy (2000); Harris' exploration of processes for the digital representation of textiles within computer graphics and animation applications (2000); Warburton's enquiry into the impact digital modelling media for communication within industrial design practice (2001); and Evans' investigation of the use of rapid prototyping technologies within industrial design practice (2002).

The above examples share similarities in overall methodological approach to the research described within this thesis in that the author's creative practice forms a central part of the enquiry. There are however some clear differences in context, focus and outcomes of the research. For example the recent practice-centred PhDs of Evans (2002) and Warburton (2001) are both tightly focussed on the requirements and activities of "mainstream" industrial design practice. Warburton uses case studies to investigate how digital modelling may be applied as a tool for communication within commercial product design practice. Warburton's PhD was awarded in 2001, however the practical investigations forming the core of her research took place between 1992 and 1996. Therefore, this research does not include recent advances in digital modelling technologies such as haptic feedback modelling and the integration of simulation capabilities into 3D CAD software used within product design and engineering applications.

Evans' study investigates the use of rapid prototyping techniques for the production of appearance models within industrial design. His research incorporates practical case studies typical to mainstream industrial design practice, in which rapid prototyping is used for the production of appearance prototypes of an electric garden strimmer, handles for children's cutlery, and enclosures for consumer electrical and electronic products.

In contrast to research by Evans and Warburton, the author is less concerned with the activities and requirements of mainstream/commercial industrial design practice. Theoretical and practical research described within this thesis takes place within the broader, holistic paradigm of human-centred design practice.

Here, the author was particularly inspired by Graham Whiteley's practice-centred PhD (Whiteley 2000; Rust, Whiteley and Wilson 2000). Whiteley employed a pragmatic, designerly approach to multi-disciplinary research in a field more commonly investigated using the analytical methods of science and engineering, and which might traditionally have been viewed as lying outside the scope of "art-school" based design research. Yet the success of Whiteley's approach and the quality of the outcomes - his mechanically-analogous model arm and hand was adopted by scientists at NASA investigating future robotics technologies - provides clear and tangible evidence of the benefits of interdisciplinary design-led research within this context (Rust, Whiteley and Wilson 2000).

Rust (2004) points to significant contributions made by designers working in an interdisciplinary context, for example, through engagement with specialists within the sciences and in medicine. A notable champion of interdisciplinary design-led research, Rust argues '... investigative designing ... can be complementary to other research practices'. He goes on to state '... one of the most interesting features of designing - it takes place in almost every context and can contribute to understanding in almost every context'. A central feature of Rust's research paradigm is his identification that a designer may '... embody ideas and knowledge in artefacts'. These artefacts can then be used instrumentally as a means to elicit knowledge from others and to stimulate the development of further ideas (Rust 2004).

Citing research by Chamberlain and Roddis as an exemplary case, Cooper (2003) emphasises the effectiveness of a methodology in which the making and testing of prototype artefacts plays a key role in eliciting knowledge and facilitating communication between designers and other stakeholders in interdisciplinary research. Similarly Bunnell identifies an emerging interest in 'designing through making' as research methodology, and demonstrates that the value and validity of this approach extends beyond traditional disciplinary boundaries (Bunnell 2000).

In the practical examples which follow, the approach adopted is that of interdisciplinary 'design enquiry' (Rust 2004). Through consultation and collaboration, research engages with academic and professional specialists in other fields. Here, experimental designing through making is employed as a research methodology (Bunnell, 2000; Rust, 2000 and 2004) to investigate the capabilities and limitations of emerging prototyping technologies within the context of human-centred design practice. The investigative approach is speculative, exploratory, eclectic and at times playful in nature.

The first practical example refers to a pilot study forming part of an ongoing interdisciplinary investigation into the safety and usability of medical devices led by Professor Paul Chamberlain. This project focuses on the design, prototyping and testing of an identification system for medical connectors used in the administration of anaesthetics and other drugs to hospital patients. The aim is to prevent potentially fatal misconnection errors. The interdisciplinary project team included a clinical specialist - a consultant anaesthetist - and specialists in cognitive ergonomics from Leeds University Institute of Psychological Sciences.

The methodology for this investigation comprised a survey of literature significant to the study, followed by 'rapid ethnography' (eg Norman 1999 pp 194-195). This included a short but intense phase of observation and discussion taking place with hospital staff on the intensive care ward at Bradford Royal Infirmary, giving the project team essential insights into the research problems under investigation. Leading on from this was the iterative designing, making and testing of the new identification system, which incorporates tactile cues in the form of contrasting shapes and textures applied to the outside surface of the connectors. A series of physical prototype connectors were evaluated in tests conducted by specialists in cognitive ergonomics; participating in the tests were healthcare professionals from Bradford Royal Infirmary. The project provided the opportunity to examine the appropriateness of virtual and rapid prototyping in this context, whilst the methods and outcomes of this research form part of a ongoing interdisciplinary investigation directed by Chamberlain, supported by the UK Department of Health and a leading medical device manufacturer.

In the second practical investigation, the author begins by further exploring potential applications for tactile cues in safety-critical medical contexts. In consultation with hospital pharmacists, the opportunity is identified for a safe-storage indicator for pharmaceutical items with temperature and/or time-critical storage requirements. The author suggests that in future "smart packaging" might incorporate a visual and tactile indicator to wain if items have not been stored correctly and therefore are unsafe to use.

Because of the time constraints of the PhD, the author did not set out to design a smart packaging system. Instead, the investigation focuses on the development of prototype devices demonstrating transferable design principles to bring about a change in size, shape or surface texture which in future may be applied in smart packaging or other products. The methodology includes a review of literature pertinent to the project, including "smart materials" which might be employed to initiate visual or tactile changes in the prototype devices. Following this, an approach of experimental designing through making is adopted in the development of physical prototype devices, including the use of CAD CAM and rapid prototyping as well as hands-on making and testing.

Then, having successfully prototyped a series of shape-changing devices, the author consulted leading specialists in computer-modelling and shape-changing structures base at Cambridge University Deployable Structures Laboratory and Sheffield University Faculty of Engineering. Here the aim was to gain insight into virtual modelling and simulation techniques adopted within engineering design to describe the behaviour of shape-changing structures and devices, and to compare the appropriateness of such techniques with the physical modelling approach adopted by the author within the context of this investigation.

In the chapters which follow, the methods, findings and outcomes of these two practical examples are reported in full. Then, following on from this, a summary discussion draws together the theoretical and practical implications of research described within this thesis, leading to the statement of conclusions and identification of opportunities for future investigation.

5.0 **Well Connected:** An interdisciplinary investigation into the benefits of tactile cues within safety-critical product applications

5.1 Introduction

This chapter describes a human-centred design process by detailing the methods and outcomes of an interdisciplinary, collaborative study investigating the safety and usability of medical devices. This ongoing research, directed by Professor Paul Chamberlain, investigates the design of medical connectors used in the administration of drugs to patients in intensive care and emergency medicine. The aim is to help prevent potentially fatal misconnection errors; a number of patients have died because they have been connected to the wrong drug delivery line. The research described within this chapter focussed on the design, prototyping and testing of an identification system for medical connectors based on tactile cues: contrasting shapes and textures are applied to the outside surface of prototype connectors to aid discrimination between different drug delivery lines. The chapter details the methods employed in the development and testing of the new identification system.

The author was engaged to work as a designer-researcher on the project. This active involvement afforded valuable insights into the application of virtual and rapid prototyping technologies in the design of the tactile identification system. These practical insights are of particular significance within the context of this thesis.

The chapter begins by introducing the concept of tactile cues. It then proceeds to the problem of misconnection errors, and establishes the scope of the study. A literature review identifies research from within perceptual psychology that explores the various dimensions of human tactile perception. Literature from the fields of ergonomics and human factors engineering identifies potential benefits of the application of tactile cues within product interface design.

The interdisciplinary project team comprised:

Professor Paul Chamberlain and Peter Walters of the Art and Design Research Centre, Sheffield Hallam University

Dr Peter Gardner, Dr Rebecca Lawton and Dr Neil Carrigan of the Faculty of Psychological Sciences, University of Leeds

Dr Philip Bickford Smith, Consultant Anaesthetist, Bradford Royal Infirmary and Chair the European Committee for Standardisation (CEN) Medical Connectors Working Group

The chapter goes on to describe observational research carried out in the intensive care unit at Bradford Royal Infirmary. This gave an invaluable first hand insight into the challenges faced by healthcare staff using current drug delivery systems and associated devices.

Iterative design development followed, involving 3D CAD modelling and rapid prototyping of a series of physical prototype tactile connectors. Here the chapter highlights critical issues encountered in the use of "hands-off' virtual modelling technologies when seeking to explore tactile qualities as essential features of design, and also points to the benefits of rapid prototyping for the production of physical test components within this context.

Physical prototype connectors were evaluated in a series of object identification tests conducted by specialists in cognitive ergonomics at the University of Leeds, with healthcare professionals from Bradford Royal Infirmary as participants. The chapter closes by detailing the theoretical and practical implications of the study, highlighting the limitations of virtual design processes within this context and the importance of physical models as a vehicle through which design ideas could be tested and evaluated by people.

The new identification system for medical connectors has been the subject of UK and international patent applications (PCT/GB2004/001745 Inventors: Paul Chamberlain and Peter Walters). Additionally, the methods and outcomes of this research have been disseminated at two international conferences (Walters, Chamberlain and Press 2003; Walters, Chamberlain, Press and Tomes 2004).

Insights gained through the author's participation in the project, as a designer and researcher directed by Chamberlain, provided valuable material for the present thesis. Research described within this chapter relates to a pilot study that forms part of an ongoing programme of research led by Chamberlain and funded by the Department of Health that is independent but related to this thesis, and to which the author continues to contribute.

5.2 Tactile Cues

The North American Raccoon has extremely sensitive paws. In order to process all the sensory information received from its paws, the racoon uses for touch about the same proportion of the brain as humans use for sight. When hunting for food in rivers and streams, racoons rely on the sense of touch. The ability to interpret tactile cues enables racoons, in a split second, to detect the difference between an edible clam and a pebble. Scientists believe that through touch, racoons are capable of constructing a picture of the world that is as complex as humans perceive through sight[1].

This human reliance on sight has strongly influenced design. A traditional view of the industrial design profession is that it tends to be preoccupied with visual appearance at the expense of other factors. In America the first industrial designers were known as stylists since their chief concern was the appearance of products (Margolin 1997, Chamberlain et al 1999, Rothstein 2000).

However, the sense of touch has in the past been used in products to help prevent human error. Early medicine bottles often had a distinctive surface texture so that they could be identified in the dark and to act as an indication that the contents could be harmful if accidentally consumed (figure 5.1). The use of tactile cues in cases such as this has been the exception rather than the rule, until recently that is. A change of direction appears to be taking place, as Myerson (2001) and Ward (2002a) report a demand for products to satisfy all the human senses, not just the visual.

Research described within this chapter set out to investigate how both the visual and tactile qualities of products might be exploited. The study explores how tactile cues such as contrasting shapes and surface textures might be applied in product interface design to improve usability and help prevent error.

[1] Encyclopaedia Britannica (1977) Macropaedia Volume 3 pp 930-931
BBC Television The Life of Mammals' broadcast 8 January 2003

Figure 5.1 Antique poison bottles. The bottles and glass stoppers have a distinctive surface texture to enable identification in the dark and to warn of harmful contents.

(images: www.antiquebottles.com accessed 6 September 2005)

5.3 Misconnection errors

In February 2001 an 18 year old leukaemia patient died after receiving a spinal injection of a drug that was meant only for intravenous use. A number of similar cases have been reported occurring in the last 15 years, and the number of "near misses" is unknown (Toft 2001, DOH 2000). Woods (2001) highlights concerns that a syringe containing an intravenous drug could be wrongly connected to a spinal needle.

Current drug delivery systems employ the same connector fitting irrespective of the drug type or route into the body (figure 5.2). Proposals for physically incompatible connectors for spinal and intravenous routes have been considered by the European Committee for Standardisation (CEN), however concerns exist that the use of a non-interchangeable system could create further hazards. For example it could lead to problems identifying the correct connector, especially in time pressured situations (Bickford-Smith 2001).

Figure 5.2 The standard 'Luer' type connector

This study focuses on the development of an identification system to make it easier to select and use the correct connector. This could be employed either as a "stand alone" system, or in conjunction with a system of mechanically non-interchangeable connectors, to eliminate the physical possibility of misconnection altogether.

Colour coding could be used to identify the five most common delivery routes (intravenous, intrathecal, respiratory, cardio-vascular and enteral). However, the low levels of ambient light maintained in some hospital ward could make colour based identification problematic. Also there already exists in hospitals a whole gamut of colour coding systems; to introduce a further set of colours may add a further layer of complexity to the problem.

This study set out to investigate the potential benefits of an identification system employing both visual and tactile cues, such as shape and surface texture, in order that connectors might be identified by touch as well as sight. This could be particularly beneficial in situations when clinicians are required to identify connectors which are not in their immediate field of vision, such as when concentrating their primary visual attention on a VDU monitor.

Clothing, blankets, bandages or other medical devices may obscure immediate sight of the connectors. In an emergency, clinicians face a barrage of visual and auditory information. The use of an alternative sensory channel - the sense of touch - may therefore be appropriate in this context.

5.4 Literature

A literature review identified studies in perceptual psychology describing various dimensions of human tactile sensitivity and the ability to recognise and discriminate between objects using the sense of touch (Ledennan and Klatzky, 1998; Gibson, 1962; Hughes and Jansson, 1994). Whilst useful and relevant, these studies are not directly or specifically applicable to the design of products. However, texts from the fields of ergonomics and human factors engineering provide evidence of the potential benefits of the application of tactile cues within product interface design (Burnett and Porter, 2001; Sanders and McCormick, 1993).

Norman (1988) stresses the importance of design product controls so that they 'look and feel different' especially in safety critical applications. The example is given of a control panel from a nuclear power plant. Control room operators have modified similar-looking switches by fitting them with different beer pump handles to help avoid misidentification (figure 5.3).

Figure 5.3 Control switches from a nuclear power station, where the handles have been modified by fitting them with different beer pump handles to prevent misidentification (Image: Norman, 1988)

The US Air Force have investigated the benefits of "shape-coded" aircraft controls (Jenkins 1947; Air Force System Command, 1980). In one study Jenkins (1947) found that blindfolded pilots could identify specially shaped control knobs using only the sense of touch (figure 5.4)

Two sets of knobs for levers that are distinguishable by touch alone. The shapes in each set are rarely confused with each other. (Source: *Jenkins. 1947.*)

Figure 5.4 Shape-coded Aircraft control knobs (Image: Jenkins 1947)

Whilst the control knobs shown here are much larger in size than medical connectors (the knobs in Jenkins' study were approximately 36 mm diameter - standard Luer connectors have an outside diameter of approximately 15 mm) they do indicate the potential benefits of an identification system based on shape. The present study focuses on the development of an identification system incorporating tactile cues based on contrasting shapes and surface textures at a size appropriate to medical connectors.

5.5 Observational research - challenges and constraints

In order to gain insight into the use of existing drug delivery systems and associated devices, a period of observational research was to be carried out in the intensive care unit at Bradford Royal Infirmary. The aim was to observe and record the activities of hospital staff in real-life situations.

Video ethnography was first considered as a potentially valuable research method in this context since it would allow activities to be recorded, reviewed and analysed in detail. Here Ward identifies '...one frame of video footage can show a multitude of detail about context and usage.' (Ward 2002b).

However it quickly became apparent that conducting observational research in the setting of the intensive care unit was going to be an ethical and practical minefield. Here research draws attention to the difficulties of undertaking human-centred design research within ethically challenging contexts.

Ethical guidelines warn against conducting research without the consent of research subjects. Clearly intensive care patients are in no condition to be asked to give consent to being recorded on video since they are seriously ill and in most cases unconscious. Also the Health Service advises against the activities of hospital staff being recorded in this way, either in photographs or on video. If staff were to make an error, the recording could be used as evidence against the clinicians involved. This is entirely understandable bearing in mind the highly demanding nature of the work and current trend towards litigation relating to medical errors.

Concerns were also raised over the difficulty of discussing actual or potential errors with staff who may understandably find it difficult to acknowledge their own potential to make mistakes since they might view this as reflecting badly on their own professional competency. Again this is perhaps symptomatic of a blame culture that was reported to exist in the NHS up to and around the time the research was being carried out (Ahmed 2002; Department of Health 2000).

It was, however, permissible to undertake a short period of unrecorded observational research in the intensive care unit at Bradford Royal Infirmary. This observation took the form of'Rapid Ethnography' which Norman defines as:

'...an observational technique for going to the prospective users of a product and observing the activities they perform, their interactions and the subculture in which they live, work, learn and play. Rapid ethnography is critical to the invention of new product classes. New product concepts come from the observation of the needs of prospective users, devising tools that will simplify and enhance their lives.'
(Norman 1999 p 195)

Within the time constraints of the study, a brief but intense period of observation provided a valuable insight into the nature of the problem and context for design. Additionally, a proposal will be submitted to the Hospital Ethics Committee to obtain full ethics approval in order to enable more extensive observational research to be carried out in future.

5.6 Rapid Ethnography

First-hand research began with a visit to the intensive care unit at Bradford Royal Infirmary on Monday 4 February 2002. Consultant Anaesthetist Dr Philip Bickford-Smith introduced clinical staff working on the intensive care ward. The aim of the visit was to observe staff at work and to discuss their experiences using existing connector system.

Observation and discussion revealed an urgent need for a standardised identification system for medical connectors. Intensive care staff demonstrated a "makeshift" identification system currently in use. The system requires nurses to attach a self adhesive paper strip to individual drug delivery lines. A drug code or name can be written onto the paper label. This labelling system causes problems, largely because it is not standardised across the health service, or even across departments within the same hospital. Therefore when patients are transferred between departments (eg between the accident and emergency department and the intensive care unit) the labelling systems may conflict. It is easy to see how inexperienced, newly qualified or temporary staff might become confused.

Figure 5.5 These tubes connect a patient to an automated drug delivery system. All of the tubes shown here have the same interchangeable connector. Healthcare staff have to rely on a makeshift labeling system to distinguish between different drugs and delivery lines into the body.

(Photographed by the author in the intensive care unit of Bradford Royal Infirmary. Patient not shown for reasons of privacy)

A patient was observed being brought into the intensive care unit on a trolley. It was necessary for the patient to be disconnected from a number of portable dosing pumps and electronic monitoring devices, in order to be connected to equivalent non-portable devices based on the ward. The aim here is to make the transfer swiftly in order to limit patient trauma. As the patient is being transferred from trolley to hospital bed, tubes and wires become tangled around one another and caught up in the patient's clothes and blankets. A profusion of beeping noises and flashing lights emanate from monitoring devices and other equipment. The whole process appears fraught and very stressful, and so it was easy to imagine how misconnection might occur in this context.

Discussion revealed that staff may sometimes be required to connect up a patient when sight of the tubes or connectors is obscured by clothing, blankets or bandages. Also it may be necessary to for staff to make connections whilst performing other tasks, or when their immediate visual attention is directed elsewhere such as when reading a trace on a monitoring screen.

Figure 5.6 An emergency patient is brought into intensive care on a trolley. (Image www.imagebank.com accessed 8 September 2005)

To summarise, observation and discussion with healthcare professionals revealed the need for a standardised identification system for medical connectors. Healthcare staff are sometimes required to make connections whilst multitasking, or when connectors and tubes lie outside their immediate field of vision. Therefore an identification system that employs tactile cues may be advantages, in order for connectors to be identifiable by touch as well as sight.

5.7 Designing, making and testing the tactile identification system

The underlying design principal behind the tactile identification system is that one connector with a particular external shape, recognisable through the sense of touch, should be matched with another connector of the same external shape. Put simply, connector shapes should be matched like-for-like. The design of the prototype identification system is based on combinations of simple, contrasting geometric shapes. Some contrasting features may be interpreted as "opposites", for example concave versus convex sides, or longitudinal versus transverse ribs. The cross sections of the components are based on geometric "primitives" i.e. a square, circle or triangle. Other distinguishing features include the presence or absence of small surface details such as bumps or dimples (Figure 5.7).

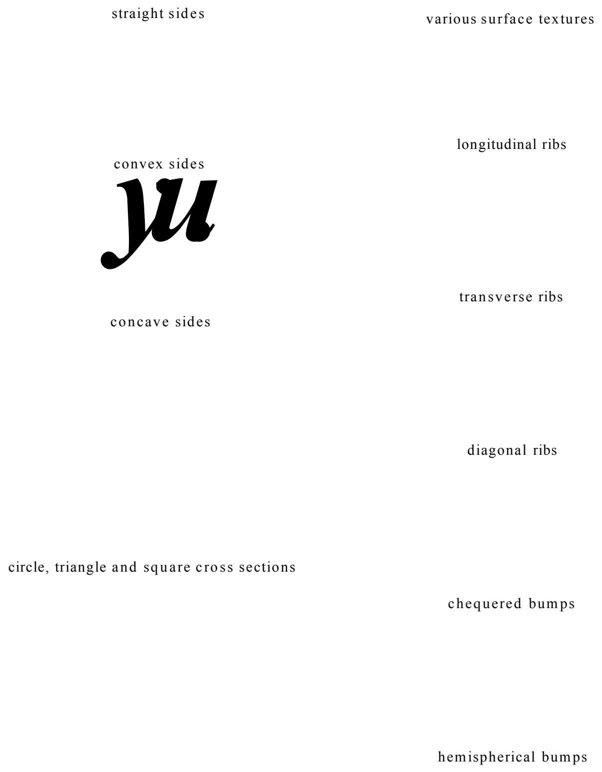

Figure 5.7 Contrasting shapes and textures (Design: Chamberlain and Walters 2003).

Figure 5.8 The elements of the drug delivery system are linked by mating components that have a distinctive shape and surface texture. These can therefore be matched like-for-like with the other elements in the system (Design: Chamberlain and Walters 2003).

Early design ideas were developed through freehand sketches and drawings leading to 2D CAD drawings and 3D CAD models (figure 5.9). Because of the small size of the prototype components and the intricate nature of the surface details, it was extremely difficult to produce accurate physical sketch models of the tactile shapes. Therefore, when developing the tactile components in the virtual design world of 3D CAD, it was necessary to rely entirely on an intuitive sense of how the objects might feel to the touch.

Here it may be argued that designers develop this intuitive sense through practical engagement in hands-on making activities in the real-world workshop, just as musicians, through singing and playing music, develop aural awareness and "inner hearing".

A significant disadvantage of conventional CAD systems available to industrial designers is that no physical feedback is available in terms of the shape and size of the object being modelled, or of other material properties such as weight, hardness or surface texture. Here designing literally takes place behind a glass screen. The reported shortcomings of the emerging haptic interface technologies were discussed in chapter 3 of this thesis.

Figure 5.9 3D CAD models of the tactile connectors created in Rhinoceros (Design: Chamberlain and Walters, 2003)

During the early stages of this study, the opportunity arose to 'test drive' the SensAble Technologies Phantom haptic interface, the only commercially available haptic feedback modelling system. The Phantom interface was demonstrated by the UK distributors of the device, at an exhibition at Barnsley Design Centre in Spring 2002. The two designers (Chamberlain and the author) both took the opportunity to try out the Phantom device. In the demonstration it was possible to "carve" a block of virtual material using the Phantom interface and the Freeform "Virtual Clay" software.

However, after a just a few minutes working with the device it was apparent to both designers that the physical feedback provided by the Phantom interface was extremely limited. Interacting with the modelling software via the Phantom stylus and aim does provide some sense of the three-dimensional boundaries of the model and the resistance of the virtual material as it is carved, but interface does not enable the virtual object to be *grasped* with the hands. Here Howe has described the stylus-based haptic interface as 'like poking at the world with a stick' (Hodges 1998).

The "non-graspable" nature of the feedback afforded by the Phantom device made it unsuitable for use within the present study[2]. Clearly the interface would be unable to provide an adequate simulation of the experience of *handling* the tactile connectors i.e. manipulating them between the fingers, as would be the case when handling physical objects in the real world.

Therefore it was only through the production of the first set of physical prototypes that the tactile qualities of the objects could be evaluated (figure 5.10) Physical models were produced directly from 3D CAD data through the rapid prototyping process of stereolithography. This proved to be a most effective method of accurately and consistently realising multiple sets of test components which have intricate surface details at a jewellery-like scale. These physical models became a vehicle through which the design ideas could be tested and evaluated.

Figure 5.10 Stereolithography models of the tactile connector shapes (Design: Chamberlain and Walters 2003)

[2] A deeper evaluation of the Phantom interface was not undertaken since the limitations of the device were clearly apparent after a just a short period of use. Furthermore, Evans et al (2005) have since identified that the lack of accuracy and control afforded by the interface make it unsuitable for use within industrial design applications.

Psychologists on the project team had originally planned to conduct an extensive phase of object identification tests using this first set of prototypes. However Bickford-Smith recommended that as this first set appeared to be easily identifiable, a second set of prototypes should be produced at a smaller scale to see if the tactile cues were still perceptible. If found to be successful, the tactile cues could then be applied to components smaller in size than the standard Luer connector.

A second set of prototypes was therefore produced, this time measuring typically 8.5mm x 8.5mm x 15mm. These were assessed in a rigorous phase of user tests conducted by specialists in cognitive ergonomics based at Leeds University School of Psychology (figure 5.11).

The testing procedure involved 21 participants who in pilot tests were psychology students and staff from Leeds University Department of Psychology. Participants were required to carry out matching tasks using the prototype connector shapes, with their hands and the prototype components hidden from sight by a screen. A "target" connector was first placed in the participant's open hand. The participant was allowed to freely manipulate the target connector using both hands. The target was then handed back, and the participant was then presented with a set of all 6 -prototype connectors, and asked to identify the target from amongst the set. The test was repeated using each of the six connectors as the target

The time taken to carry out the matching task was recorded, using a millisecond stopwatch. Tests were carried out with both gloved and ungloved hands, using standard latex-free surgical gloves, and any identification errors were recorded.

Psychologists carried out a statistical analysis of the mean identification times and this revealed an average rate of error of 2.72%. The mean identification times for 4 of the 6 prototype connectors was between 5 and 6 seconds. Two of the connectors took significantly longer to identify. This was because, at such a small scale, certain tactile features appeared to "overlap"; for example, the spacing of ribs on one type of connector correlated almost exactly with the spacing of the pattern of bumps on another.

Figure 5.11 Testing of the tactile components was coordinated by Dr Neil Carrigan of the Human Factors Research Group at Leeds University School of Psychology

Modifications were made to the design so that the tactile features no longer overlapped, and a third set of prototypes produced. The test procedure was repeated, this time involving 23 participants who were healthcare professionals working in intensive care and anaesthetics departments of Bradford Royal Infirmary.
This included eight nurses, eight senior house officers, three registrars and four consultants. The matching tasks were carried out as before and, in this second round of tests the mean rate of error chopped from 2.72% to 1.73%.

The matching tasks showed that healthcare professionals could identify the prototype connectors using only the sense of touch. The mean rate of error for identification was 1.73%. This appears to demonstrate the potential benefits of tactile cues in this context. However, whilst the figure of 1.73% may seem low, it would be unwise to rely on tactile cues to provide adequate protection against misconnection errors.

For this reason, future research will seek to investigate the application of tactile cues in combination with a failsafe mechanical system. Tactile cues would enable clinicians to quickly and easily identify the correct connector, whilst a failsafe mechanical system would prevent misconnection altogether.

5.8 Discussion

This study clearly shows the potential benefits of an identification system based on tactile cues. This was demonstrated in tests where participants were required to perform matching tasks with two sets of prototype components using only the sense of touch. Some of the prototype components were identified more quickly and easily than others. The components that could be identified most easily were those based on simple, contrasting three-dimensional elements. However in the first round of tests it took participants significantly longer to identify components that had tactile features that appeared to "overlap". For example, the spacing of ribs on one component correlated closely with the spacing of bumps on another. Therefore, these features were modified so that they no longer overlapped.

Results of the second phase of tests showed an average rate of error of 1.73%. Although low this figure is likely to be considered unacceptable for safety-critical applications since the consequences of any error would be very serious. Therefore it is recommended that future research should seek to combine visual and tactile identification with a mechanically non-interchangeable connection system in order to make misconnection errors a physical impossibility.

There is clearly a need for further investigation. In order for any design solution to be fully validated, tests must be carried out in an environment that simulates the working conditions of the intensive care unit, including high stress levels, high workload, distractions, multitasking, low light levels, inexperienced staff etc. A suitable setting might be an intensive care simulator - a training environment in which healthcare professionals and students are able to develop skills by practicing medical procedures on a patient "manikin" so as not to put real patients at risk. Medical simulators are used in training scenarios designed to help prepare trainees to deal with clinical emergencies and to teach the principles of crisis management.

In September 2003 the author travelled to Boston, Massachusetts to visit Professor Daniel Raemer, Director of the Center for Medical Simulation at the MIT/Harvard Center for the Integration of Medicine and Innovative Technologies, to present findings from this study and to discuss the feasibility of using such a simulator for future product testing. Raemer was supportive of the research undertaken so far, and has provided contacts at a high-fidelity medical simulator in the UK (See Appendix).

Through a design-led approach to interdisciplinary research, this study demonstrates a unique contribution to developing knowledge in the field of human centred design and medical product development. The research describes an approach to interdisciplinary 'Design Enquiry' (Rust, 2004) in which experimental 'Designing Through Making' played a central role in the development and subsequent evaluation of possible design solutions (Bunnell, 2000; Rust, Whiteley and Wilson, 2000).

The study highlighted the often-intuitive nature of the design process. Because the tactile test components were developed in the virtual design environment of 3D CAD, physical feedback was unavailable. At this stage in the development process design decisions were therefore based on an intuitive sense of how the components might feel to the touch. Here it is suggested that this intuitive sense is an example of tacit knowledge - in this case knowledge that is based on previous experience handling and manipulating the physical form of material objects. The comparison is made between a designer, who may develop this intuitive sense through physical making activities in the real-world workshop, and a musician who, through singing and playing music, can develop aural awareness, inner hearing[2] and empathy for musical material.

Despite claims that the SensAble Phantom haptic modelling system can provide the tangible tactile experience of manipulating "virtual clay" (www.sensable.com accessed 9 Sept 2005) this study has highlighted that current haptic modelling technologies are unable to offer the truly graspable experience that is required to explore tactile properties as essential features in product design.

[2] It is said of the composer Beethoven 'As a gifted and thoroughly trained musician with a perfect "inner ear", he could hear music, even complicated music, by looking at it, and could write down the ideas that came into his head.' p 267 This extraordinary, almost superhuman ability enabled Beethoven to compose some of his finest music after he had gone deaf (Sadie and Latham 1999 p 267).

The development of inner hearing through singing and other practical musical activities forms a central part of an approach to music education pioneered by the Hungarian composer-educator Zoltan Kodaly 1882-1967 (Ittzes, 2004; Christmass, 2004; Finney, **2000**)

Moreover, as design processes become increasingly virtual, greater reliance may be placed upon the intuitive "inner feel" and tacit knowledge to inform the creative development of design ideas. Whilst designers may rely on intuition and "inner feel", the virtualisation of design processes may mean that in future fewer opportunities exist to develop this vital tacit dimension through real-world manipulation of form and materials in the workshop.

Within this study, physical realisation of test components confirmed designerly intuitions that the objects would by identifiable by touch alone with few errors. Tacit knowledge also played a role in the Consultant Anaesthetist's informal evaluation of the first set of prototype components.

Prototype components were produced by stereolithography, a process which enabled the accurate, consistent and efficient realisation of multiple sets of test components. The intricate surface details and jewellery-like scale of the test components meant consistent production of prototypes through a more traditional "hands-on" process would have been unfeasible in this context.

So far research has investigated tactile differentiation through the use of shape and surface texture. There is clearly scope to explore tactile properties of different materials alone or in combination with shape and texture. For example, a set of five components having contrasting shapes and/surface textures could be available in 3 different materials such as hard plastic, soft rubber and metal. Practical limitations on material selection exist in some medical applications for example metal components would not be suitable for use in MRI scanners.

Future research could investigate potential applications for tactile cues within the wider context of the hospital, for example, to assist in the identification of pharmaceutical packaging items. Other possible areas for future exploration include the design of equipment used in poor visibility situations such as in smoke filled buildings, or switches and controls in vehicles or other machinery that is used when the operator's visual attention is directed elsewhere.

The medical connectors research is ongoing, as Chamberlain has since successfully obtained funding from the UK Department of Health and B Braun, one of the world's largest medical device manufactures, for a two-year study investigating the feasibility of combining visual and tactile identification with a mechanically non-interchangeable connection system. An aim of this research is to inform the development of a new international standard in this field.

6.0 Bio-inspired indicators

6.1 Introduction

In nature the peacock fans its tail in a flamboyant courtship display, whilst the pufferfish expands and projects spikes in a dramatic gesture of self defence. For animals, gestural movements and changes in shape provide an effective means of communication. This chapter describes the creative development of a series of biologically-inspired indicators: mechanical devices that change shape in response to external stimuli such as a change in temperature, pressure or with the application of electric current. It is anticipated that such devices may in future be incorporated into physical product interfaces enabling information to be communicated through touch as well as vision.

The previous chapter described the development of a tactile identification system for medical connectors. The identification system employs tactile cues; contrasting shapes and surface textures to distinguish between different drug delivery lines into the body. Tactile cues were considered particularly beneficial in a busy hospital environment where substantial demands are made upon the visual and auditory senses of hospital staff. This research identified that tactile cues could also be applied to pharmaceutical packaging, syringes and other medical devices, to improve usability and help prevent error.

Research described within this chapter begins by further exploring potential applications for tactile cues within medical product and packaging design. In consultation with hospital pharmacists, research identified a requirement for temperature-responsive packaging for insulin, cancer treatments, some vaccines, anaesthetics and other drugs which loose their effectiveness if not stored at the correct temperature. Here a *smart packaging system* could employ a change in shape or surface texture, providing both a visual and tactile indication to alert healthcare staff if drugs have been incorrectly stored. Pharmacy staff were supportive of the smart packaging idea, and the incorporation visual and tactile cues could be particularly beneficial in providing a clear and rapidly recognisable indication when handling a large number of drugs, when multi-tasking and working under stress.

However, because of the time constraints of the author's PhD research, concerns were raised that in may not be possible to develop and test a complete smart packaging system. Therefore research described within this chapter has focussed on the design and prototyping of a series of shape-changing indicators, the aim of which is to demonstrate transferable principles which may later be developed and applied in product or packaging design.

This chapter includes a literature review identifying developments in smart materials technologies which may provide a means of initiating changes in shape in the bio-inspired indicators. The literature review also investigates the field of biomimetics - the process of using design principles abstracted from nature to advance technology. A biomechanical investigation of the pufferfish is then presented, focussing on the means by which the fish expands and projects spikes. This provided the inspiration for the development physical design principles for shape-changing indicators as described below.

The design development described within this chapter includes an array of deployable spines which emerge from a surface in response to an increase in temperature or with the application of electric current. These are arranged in linear and rotary configurations, and in both cases movement in initiated by temperature-responsive shape memory alloy springs. In a further development, an elastomeric indicator comprises an array of spikes projecting from the surface of a *bistable* diaphragm. The indicator expands and contracts in response to changes in air pressure which may be provided for demonstration purposes by a small syringe. In alternative embodiments, movement of the indicator is provided electromechanically, using a miniature servo, and also biologically, by exploiting the expansion produced by a biological agent such as yeast.

Having successfully designed and prototyped the series of shape-changing indicators, the chapter goes on describe the author's consultation with specialists in the field of shape-changing structures and computer modelling and simulation techniques, based at the Deployable Stinctures Laboratory, Cambridge University, and the Department of Mechanical Engineering at the University of Sheffield. This interdisciplinary engagement enabled the author to explore the feasibility of using finite element analysis, a virtual prototyping technique, to provide a predictive simulation of the behaviour of the bistable indicator.

The aim here was to use computer modelling techniques to further refine the design of the bistable indicator such that it might respond at a predetermined pressure. This enabled the author to compare predictive modelling and simulation techniques applied within engineering with the "hands-on" approach of physical making and testing adopted within this study.

In the design and prototyping of the indicators, the author had been largely pre-occupied with the devices' mechanical function. Therefore it came as some surprise to discover that these small shape-changing devices appealed to exhibit some seemingly emotive characteristics. This became evident when the author demonstrated the objects to others, and is further explored through consultation with an academic specialist researching the affective qualities of materials, and an artist, designer and maker of jewellery. The chapter closes by pointing towards this affective aspect as being a further significant dimension of human-centred design.

6.2 Pharmaceutical packaging

Building on the previous chapter's research into the development of a tactile identification system for medical connectors, research described within this chapter began by exploring other potential applications for tactile cues within the medical context. Here, an internet search identified that the American National Federation for the Blind has been campaigning for some years to get drug companies to consider incorporating tactile cues on insulin packaging. This is to assist diabetics in the identification of different types of insulin, and to warn of potentially harmful drug interactions.

Writing in the on-line journal *'Voice of the Diabetic'* Bryant (2001) asserts:

> *'Blind people, and those losing vision, have always had difficulty identifying their medications and telling them apart. Serious consequences can follow, when prescriptions, oral or injectable, are mistaken, and the wrong dose given. One of those medications is insulin.*
>
> *For years I have worked to make insulin manufacturers aware of this problem, of the need to make insulin vials distinguishable from each other by type/duration, without sight. The drug companies have not been particularly interested. We have been left with our home-made Braille labels, rubber bands, tape, and other temporary "recognition systems". '*

Figure 6.1 Insulin vials and syringes used in the treatment of diabetes (www.imagebank.com)

Pharmaceutical packaging appeared to be promising area for further exploration. Therefore, in order to investigate this area in more depth the author met with specialist diabetes nurses and senior pharmacists working within the Sheffield Teaching Hospitals NHS Foundation Trust. Here, pharmacists reported that problems may be experienced not only with drug identification, but also with storage requirements for insulin and numerous other drugs including some anaesthetics, vaccines, immunoglobulin treatments, and growth factor drugs used by cancer patients.

Such drugs need to be stored within a specific temperature range. For example, it is necessary for insulin to be stored in a refrigerator as the drug can deteriorate over time if it is exposed to temperatures outside the recommended range, and becomes useless if frozen. In some cases this can clearly have a detrimental effect on treatment. The problem also extends to pharmaceuticals such as vaccines which may be shipped abroad, for example, to developing countries where they may be exposed to extreme climatic conditions.

The pharmacists identified that currently there is no means of checking whether such drugs have been stored correctly on the hospital wards, or when patients are prescribed drugs for treatment at home. In some cases hospital staff may throw drugs away if they are worried they have not been stored within the correct temperature range, for example, if they may have been left out of the refrigerator for too long. Some of the drugs are very expensive, and so in order to prevent waste it is important for pharmacists to know whether the drug has been stored at the correct temperature. When pharmaceutical items are delivered to the hospital, some are accompanied by a "tell tale" data sheet recording the storage temperature on the delivery van. However, monitoring does not continue once the drugs arrive at the hospital pharmacy.

The problem of safe storage of such items presents the possibility of a "smart" pharmaceutical packaging system that indicates whether or not drugs have been stored at the correct temperature. By changing shape, a safe storage indicator incorporated into the package could provide both visual and tactile cues that clearly inform the patient or healthcare worker of the status of the drug.

Pharmacists were generally supportive of the smart packaging idea. They said such a system would be very useful, providing it was reliable and the indication was clearly marked to prevent confusion. A combination of visual and tactile cues might be particularly helpful in providing a rapid and readily recognisable indication to healthcare staff when handling a large number of drugs, when multi-tasking or when under stress.

Figure 6.2 Pharmacy at Weston Park specialist cancer hospital, Sheffield

Figure 6.3 Large walk-in refrigerator for storing temperature-sensitive drugs at the Royal Hallamshire Hospital, Sheffield

250m'

c) **d)**

Figure 6.4 A small sample of pharmaceutical items requiring refrigerated storage:

a) eye drops in bottle with pipette dispenser and cardboard outer carton b) syringe and vial in plastic case, used for various drug types c) epidural analgaesic in plastic pouch d) anti-HIV drug Kaletra in container with cardboard outer carton.

Photographed by the author in the walk-in refrigerator at the Royal Hallamshire Hospital, Sheffield

Regarding packaging specifically for insulin, phamiacists noted that blindness is a common side effect of diabetes. They agreed that in this context tactile indication may be helpful, but stated that tactile cues may not be appropriate for all diabetics since some develop numbness or loss of sensation in the hands and feet known as diabetic neuropathy. A smart packaging system for insulin would therefore need to incorporate marked changes in both visual and tactile modalities.

Visits to the hospital pharmacies highlighted the enormous range and scope of drug packaging. This is an exciting area for investigation, and clearly there is potential for the development of a "smart" packaging system for drugs with specific storage requirements, for example, those requiring storage within a specific temperature range or those with a limited shelf life.

However, under the time constraints of the remainder of the PhD, concerns were raised that it may not be possible to develop and test a complete smart packaging system, especially because of technical issues around the miniaturisation of such a system to a size and scale appropriate to pharmaceutical packaging. Also, as the previous project had focussed on very specific usability requirements, in this case it was considered potentially beneficial to explore design ideas that might demonstrate transferable principles, rather than focussing too early on a specific target market or user group.

Therefore, it was proposed that one or more model indicators should be developed. These should have the ability to change shape in response to external stimuli. The model indicators should aim to demonstrate transferable principles which may in future be developed and applied within a smart pharmaceutical packaging system, or in other product areas where such systems would be beneficial, for example, a safety indicator on a control panel that is recognisable even when the operator's visual attention is directed elsewhere.

The following section identifies "smart materials" technologies - materials which change their physical properties in response to external stimuli. It is anticipated that such materials may be used in the bio-inspired indicators to initiate changes in size, shape or texture.

6.3 Smart materials

Smart materials have the ability to change their physical properties in response to external stimuli. It is anticipated that smart materials technologies may be used to provide a means of initiating changes in the visual and tactile characteristics of smart bio-inspired indicators. This section presents an introduction to smart materials technologies developed in recent year for use in engineering and medical technology applications.

Of particular interest to engineers are materials which exhibit changes in size, shape or stiffness in response to external stimuli, as these may be used as sensors and/or actuators: devices that provide motion in robotics and other "intelligent" machines. A range of materials have been developed, each responding to different stimuli. For example, materials which respond to changes in temperature or when an electric current is applied to the material, materials which respond when placed within electromagnet field, and materials which respond when exposed to a particular wavelength of light.

Shape memory alloys (SMAs) are some of the most commonly available and widely used smart materials. NiTinol, an alloy of nickel and titanium, exhibits a property known as the shape memory effect. The alloy has a uniform crystalline structure that changes to a radically different structure at a distinct transition temperature. Through a heat treatment process, mechanical components made from NiTinol can be "programmed" to take on a particular shape. After heat treatment, when the component is below the transition temperature, it can be deformed out of shape without damage. When the component is reheated to the transition temperature it will return to the pre-programmed shape. This deform/reform cycle can be repeated many thousands of times, making the material suitable for use in a wide range of applications (Gilbertson 2000).

Easily stretched at lower temperature

Reforms at higher temperature

Heating

Cooled to lower temperature

Figure 6.5 Illustrating the deform/reform cycle for shape memory alloys (Gilbertson 2000 p 1.3)

The temperature-sensitive switch found in modem kettles often contains a spring made from NiTinol with a transition temperature at or around that of boiling water. When the kettle is turned on, the switch mechanism deforms the NiTinol spring. Then when the water boils, the NiTinol reaches its transition temperature and the spring returns to its original shape, pushing the switch into the off position.

Figure 6.6 Mondotronics Inc. shape memory alloy spring for robotics applications shown above in its "pre-programmed" shape and below in a deformed condition (Santer and Pellegrino 2004)

Gilbertson describes a number of robotic devices developed using SMA actuators, and also prosthetic devices intended to function as artificial human limbs. These are electronically controlled, and the heating effect is achieved by passing an electric current through the SMA actuator. However Whiteley (2000) identifies that a drawback of SMA actuation in this particular application is that once activated, the time needed for the SMA to cool clearly slows down the cycle time and therefore can limit the overall responsiveness the prosthetic device.

Figure 6.7 Robotic finger and robotic hand both employing shape memory alloy actuation (in Gilbertson 2000 pp 1.10, 1.11)

Further medical applications for shape memory alloy actuators include micro-valves and micro-pumps for drug release systems to be surgically implanted into the body, and also surgical stents. Stents are tubular structures used to open up narrowed or blocked blood vessels of the heart. Expanding stents can be made from shape memory alloy with a transition temperature at or around human body temperature. The stent is chilled prior to insertion into the blood vessel then, once inserted, it warms up to body temperature, expanding and opening up the blood vessel (Duerig et al 1997, Sim et al 2003).

Nishi et al (2004) describe the development and testing of another prosthetic device using SMA actuation; an artificial anal sphincter to be implanted into patients suffering from fecal incontinence. In this device a rubber tube is attached to the end of the patient's intestinal tract. A pair of SMA strips act together to constrict the tube in a sphincter-like action when heated electrically (figure 6.8 A and B). An arrangement of inductive coils means that electric power is transmitted to the device without the need to pass wires through the skin. So far the device has been tested successfully on a piglet. It is hoped that the artificial sphincter will soon be implanted into human patients, providing relief from this severe and debilitating clinical condition.

Figure 6.8 Prototype prosthetic anal sphincter which uses a pair of shape memory alloy actuators to constrict a rubber tube attached to the end of the intestinal tract (Nishi et al 2004)

One of the next generations of smart materials to attracted significant attention recently are electroactive polymers (EAPs). These are plastics having the ability to change shape in response to an electric field or current. According to Ashley (2003), lightweight plastic materials which grow or shrink in length or volume in response to electrical stimulation promise to become the artificial muscle of the future, replacing electric motors, which are often too bulky for use, for example, in small-scale medical devices.

Two groups of EAPs are described, each with different advantages and disadvantages. The first group, called ionic EAPs, achieve changes in shape through the movement of charged ions within the material. This electrochemical effect is activated by relatively low voltages so devices using ionic EAPs can be battery operated. However one disadvantage is that the materials normally need to be kept wet in order to operate, so devices must be sealed within a flexible housing. Another disadvantage of many ionic EAPs is that when a voltage is applied to the material, the material is unable to hold a fixed shape or position. Also the material can be irreversibly damaged by higher voltages (Ashley, 2003).

Otake et al (2001) describe experimental research investigating the design of robotic devices using ionic EAP actuation. This research focuses on the development and testing of a series of "robots" made from electro active polymer gel. The gel robots are two-dimensional flat shapes resembling starfish, butterflies and worms. In an experiment the robots were placed in the bottom of a tank of water, necessary as the ionic actuators have to be kept wet. An array of electrodes was placed above the tank. When the electrodes were energised with an applied voltage of 10V, the gel robots responded, producing significant movement, as shown in figure 6.9.

Figure 6.9 Movements of ionic EAP gel robots when activated underwater

(Otake et al, 2001)

The second group of electroactive polymers, known as electronic EAPs, are activated by an electric field. These require high voltages to operate - in the order of one to five kilovolts - making them generally unsuitable for battery operated mobile devices. However electronic EAPs respond quickly, delivering strong mechanical forces, and they do not require sealing within a protective coating. Also, when activated, electronic EAP actuators are able to hold a fixed shape or position (Ashley, 2003).

Ashley illustrates the physical principles behind electronic EAP actuation, shown in figure 6.10. The electronic EAP is an elastomeric material which is sandwiched between two parallel conductive electrodes. When a voltage is applied to the electrodes this creates an electromagnetic field. The EAP contracts in the direction of the field lines and expands perpendicular to them. When the voltage is removed, the EAP returns to its original shape.

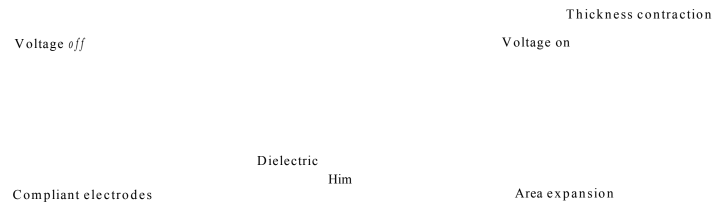

Figure 6.10 Electronic EAP material sandwiched between compliant electrodes. The drawing on the right illustrates the expansion in area exhibited by the material when a voltage is applied across the electrodes.

Cylindrical actuators are formed by placing a rolled up sheet of electronic EAP and flexible electrodes inside a tubular container. When activated, the EAP roll expands lengthways causing the cylindrical actuator to extend. Ashley presents a number of design concepts for robotic and prosthetic devices using cylindrical roll actuators to provide linear motion. A bending effect can be achieved by placing two independently energised EAP rolls side by side within a flexible tube. Applications for bending actuators include snake-like robotic devices, steerable endoscopes and catheters and pointing mechanisms for antennas (figure 6.11).

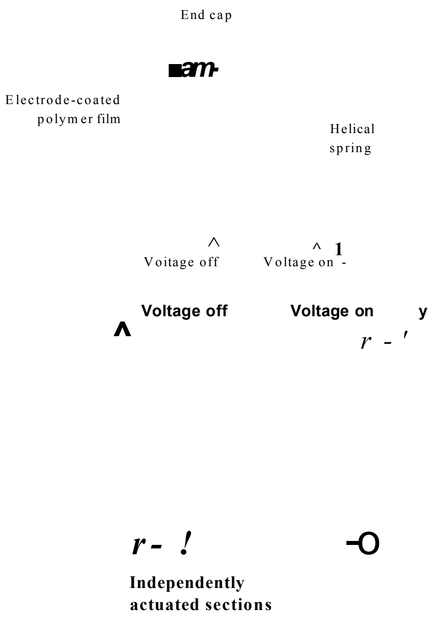

Figure 6.11 Cylindrical actuators formed by rolling the electronic EAP material into a tube.

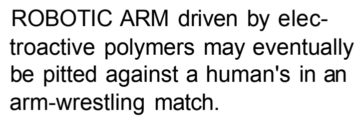

Figure 6.12 Concept illustration of a prosthetic arm incorporating a cylindrical electronic EAP actuator

Ashley also describes how loudspeakers and diaphragm pumps can be constructed by stretching a flat sheet of electronic EAP membrane across a rigid frame or aperture (figure 6.13). The EAP membrane can be configured so that when energised it moves in or out, displacing a volume of air or fluid. In future the same principle could be used to create changes surface texture. Ashley identifies possible applications for this including "active" camouflage for military vehicles, systems for controlling the flow of air or water flow over surfaces and haptic displays.

Voltage off

Voltage on

Electrode-coated
polymer film

Figure 6.13 Medical pumps created using electronic EAP diaphragm actuators.

Whilst the deflection in the diaphragm shown on the right appears impressive, it should be noted that the operating voltage for this actuation is 5 kilovolts.

Two companies working with electroactive polymer technologies are the Eamex Corporation in Osaka, Japan and California-based SRI International. These new materials are still in the relatively early stages of development. Santer and Pellegrino (2004) report that electroactive polymers have yet to be used in mainstream applications, and the availability of samples for experimentation and testing is unclear.

In order to demonstrate the future potential of electroactive polymers, Yoseph Bar-Cohen, a leading specialist in artificial muscle technologies at NASA Jet Propulsion Laboratories recently held an international competition: an arm wrestling contest in which robotic anus powered by EAP actuators competed against a human opponent - in this case, not a champion aim wrestler but a 17 year old female high school student.

Three robot arms were entered into the competition, each employing different approaches representing the current state of the art in EAP technologies. However, in every case the human competitor won "hands down". This result seems to confirm an earlier view held by Bar-Cohen that it may take decades for the technology to approach the performance of human muscle power (Graham-Rowe 2005).

a)

b)

Figure 6.14 a) NASA human-versus-machine arm wrestling challenge

b) Girl-versus-robot arm wrestling competition held in March 2005
Three robot arms actuated by electroactive polymers competed against a human opponent. The mechanical arm pictured was developed by researchers at Virginia Polytechnic Institute and State University. Other entries were submitted by research teams from New Mexico and Switzerland.

Images: NASA Jet Propulsion Laboratory

Moreover, both ionic and electronic EAPs have signification disadvantages; whilst ionic EAPs generally have to be kept wet to operate and do not hold their shape, electronic EAPs require high voltages, making them unsuitable for use in many compact, portable or wearable devices. In order to overcome the disadvantages of EAP actuation, scientists at the University of Dallas Texas are in the process of developing a new generation of artificial muscles based on carbon nanotube technologies. Carbon nanotubes are cylinders of graphite measuring just a few nanometres in diameter, a fraction of the diameter of the human hair, that contract in length when an electric charge is applied. Those developing these new technologies claim that in future artificial muscles woven from carbon nanotubes will be able to generate forces may times greater than human muscles. However the technologies are still some years from being available for practical applications (Knight 2002, Richardson 2003, Catchpole 2004, Zhang et al 2004).

Taking into account the disadvantages of current electroactive polymer technologies and the concerns over limited availability, it may be concluded that for the purposes of practical work undertaken as part of this study, shape memory alloys may provide the most flexible and readily available means of actuation. Shape memory alloys respond to both temperature and electric current, combining sensing and actuation "all-in-one".

Having identified shape memory alloys as a potential means of actuation, the section which follows returns to the source of inspiration for this investigation into shape-changing indicators. A starting point for the development of bio-inspired indicators was the identification of examples from nature of animal communication through changes in shape and gestural movements. The following section investigates biomimetics; how scientists, engineers and designers use nature as a source of inspiration for the development and application of new technologies. It is anticipated that knowledge of the processes and outcomes of biomimetics may inform the design of the bio-inspired indicators.

6.4 Bio-inspiration

In the development of new technologies, humans have often drawn inspiration from nature. Vincent (2002) traces this pattern back over 3000 years, to historical records describing how ancient Chinese sages attempted to produce an artificial form of silk. Other historic examples include the structural design of the Eiffel Tower, which is said to be inspired by studies into the way the hip bone transfers loads, and Velcro, whose inventor observed how burred seeds attached themselves to the coat of his dog. Today, the terms "Biomimetics", "Biomimesis" and "Bionics" are used to describe the processes of using ideas from nature to advance technology. This section seeks to present an introduction to the literature describing how the biological world may inspire the development of human-made technologies and design.

In the natural world, living organisms have evolved over millions of years into optimised forms. Natural organisms have to compete in order to survive. Plants aim to grow higher and out of the shade of their rivals in order to obtain a greater share of the sun’s energy. Animals have to compete for food and also to attract a mate, and to defend themselves and their territory from predators. Developing through natural selection - the survival of the fittest - animals and plants display a naturally-evolved fitness for purpose which enables them to function and survive within their natural living environments.

The performance and efficiency of biological systems, together with a beauty and elegance which often appears to be inherent in nature's optimised forms, has been a source of inspiration for designers, artists and engineers throughout history. As Papanek asserts:

> 'One source that never seems to go out of style is the handbook of nature. Here, through biological and biochemical systems, many of the same problems mankind faces have been met and solved. Through analogues to nature, man's problems can be solved optimally.' Papanek (1984) p 186

Papanek also identifies the aesthetic satisfaction that humans appear derive from natural forms '... The reason we enjoy things in nature is that we see an economy of means, simplicity, elegance, and an essential rightness there ...' (ibid p 4). One may aesthetically admire the dolphin's streamlined hydrodynamic shape, which has of course evolved for the purpose of efficient swimming.

The spiral shell of the chambered nautilus derives its shape from the growth pattern of the mollusc contained within. As it grows, the mollusc constructs larger and larger chambers for itself, the proportions of which remain unchanged, so the mollusc need not adjust its balance as it grows. Similar spiral patterns are present in the arrangement of florets on the head of the sunflower. The arrangement facilitates the exposure of the maximum surface area of the flower to the sun in order to improve photosynthesis. It is often said that the spiral growth patterns of both the nautilus shell* and the sunflower conform to *phi* - the so called "golden ratio" or "divine proportion", a property which has fascinated and inspired both artists and mathematicians for centuries and which Livio (2002) discusses at length in his book ' The Golden Ratio ... the Extraordinary Number of Nature, Art and Beauty.'

The golden ratio may be illustrated by a line that is divided into two segments as shown in figure 6.15. Here the ratio of the smaller segment to the larger segment is equal to the ratio of the larger segment to the line overall.

a b c

Figure 6.15 The golden ratio bc/ab = ab/ac = 0.618 approx (Lidwell et al 2003)

Figure 6.16 Spiral with proportions approximating the golden ratio

Figure 6.16 shows a spiral contained within a rectangle having the ratio of height to width approximately equal to the golden ratio. The rectangle is subdivided into a square and a smaller rectangle as shown, the proportions of the smaller rectangle also conform approximately to the golden ratio, and this subdivision continues. The curved line forming the spiral intersects with the corners of adjacent squares as shown.

In should be noted that the spiral of the nautilis shell does not conform exactly to the golden ratio, but it does follow another celebrated curve - the *spira* ***mirabilis*** or 'wondrous spiral'. This is a logarithmic spiral, the proportions of which remain the same as the spiral grows, so that an increase in the length of the spiral is always accompanied by a proportional increase in the radius of the spiral curve (Livio 2002).

Figure 6.17 Spira mirabilis

Robert Hooke’s study of the fossilised shell of the chambered nautilus. Illustration taken from “London’s Leonardo - The life and Work of Robert Hooke” (Bennett, Cooper, Hunter and Jardine 2003)

The golden ratio appears in the works of Albrecht Durer and Leonardo da Vinci, most famously in Leonardo’s "Vitruvian Man", illustrating the proportions of an "idealised" human body. The proportions of the body of the Stradivarius violin conform approximately to the golden ratio, as does the Parthenon in Athens, a structure which for some came to symbolise ancient Greece as the "cradle of civilisation", and which provided a model for Roman, renaissance and neo-classical architecture. Twentieth century advocates of the golden ratio include the painter Mondrian and the architect Le Corbusier. More recently, the proportions of the Apple iPod conform to the golden ratio, and *phi* features prominently in Dan Bown's popular novel *The Da Vinci Code*, and so it seems that (in some circles at least) this recurrent phenomenon in nature and the human-made world continues to inspire (Livio 2002, Lidwell et al 2003).

The natural world may offer human designers a rich source of functional and aesthetic inspiration. Moreover, in nature, form and function appear to be inextricably linked.

Here Vincent identifies that when seeking functional solutions to practical problems, care should be taken in the way ideas are abstracted from nature, citing a well-known example from Greek mythology. Daedalus attempted to equip his son Icarus with wings made from feathers attached with wax. When Icarus flew too near the sun the wax melted and the feathers came off, leaving Icarus to fall to earth. It seems Daedalus made the mistake of attempting to imitate the appearance of birds without understanding the underlying principles of flight (See Vincent and Pan-, accessed April 2005).

Kemp (2004) describes how Leonardo made detailed observational studies of the flight of birds of prey gliding in thermals above the hills of Tuscany. Leonardo paid particular attention to the way birds glide, circle and descend without flapping their wings, and he described how these manoeuvres might be achieved through the bird making subtle shifts its centre of gravity or with small motions of the tail. Based on the principles he observed, Leonardo went on to produce detailed sketches of his own prototype hang-glider having a skeletal wooden frame with wings covered over with cloth.

Nichol (2004) recalls a famous pronouncement by Leonardo which is often taken to mean his planning of a test flight of this flying machine: 'The big bird will take its first flight above the back of the Great Cicero [Monte Cicero, just north of Florence] filling the universe with amazement, filling all the chronicles with its fame, and bringing eternal glory to the nest where it was born' (Nichol p 32). Kemp notes that there is no evidence Leonardo actually built and tested the glider, however some 500 years later a replica was made to his design and was flown successfully by world hang-gliding champion Judy Leden, on the Sussex Downs in 2003.

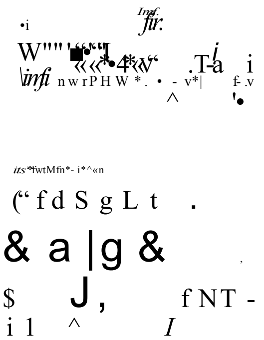

Figure 6.18 Leonardo's sketches of birds in flight from the Turin Codex c 1505 (Nicholl 2004 p 32) and his 'Design for the Wings of a Flying Machine' in the Codice atlantico 858 (Kemp 2004 p 128)

There is now a growing interest in biomimetics as a means to advance technology. For example, scientists at the University of Bonn have been investigating the "self-cleaning" properties of the leaves of the lotus plant, which are covered in microscopic waxy bumps that minimise the surface contact area to which dirt may stick. It is anticipated that this research may lead to the development of new exterior coatings for buildings and perhaps even sterile self-cleaning surfaces for hospitals (Stephen 2005, Barthlott accessed April 2005).

Shelley (2004) reports how studies of the complex tail movements of dolphins have lead to improvements in the efficiency of marine propulsion and water power generation devices. In another study (Ayres et al 2000) robotics engineers used motion capture video techniques to analyse the rhythmic, undulatory body motion of the swimming lamprey. This analysis formed the basis of the development of control systems for an autonomous underwater vehicle (figure 6.19).

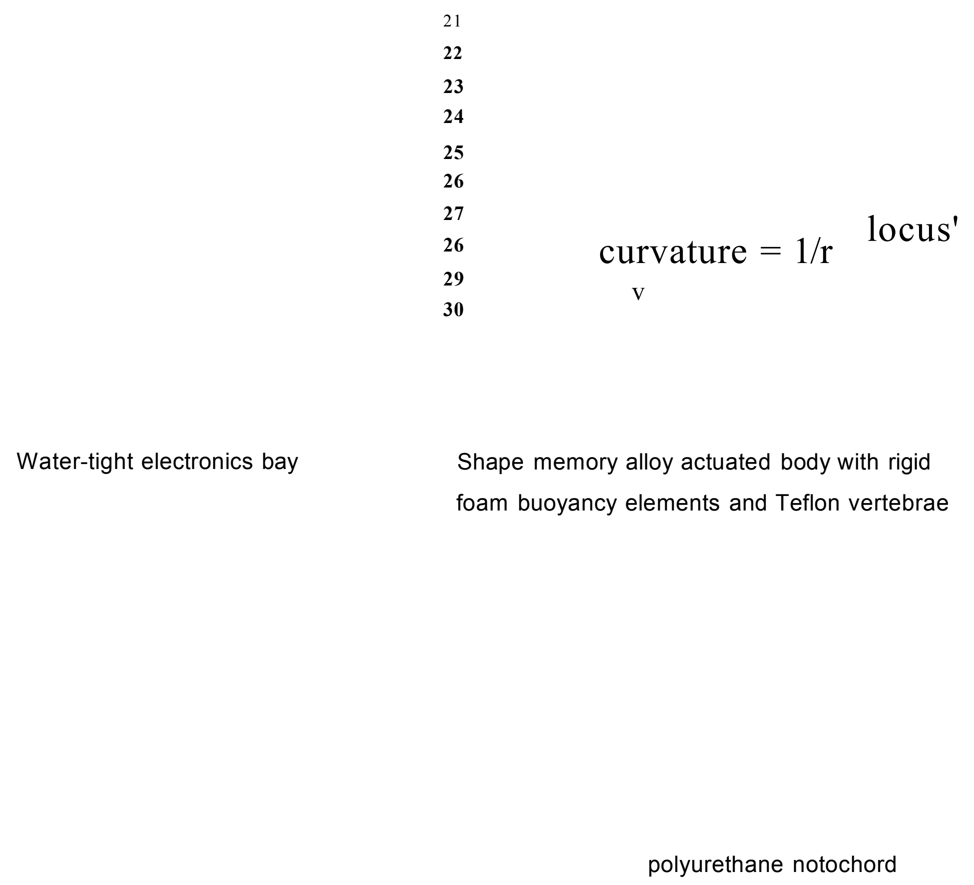

Figure 6.19 Studies of the undulating body movements of the swimming lamprey led to the development of this novel underwater robot

(Ayres et al, 2000)

Meanwhile, scientists and engineers at NASA's Jet Propulsion laboratory and Stanford University are developing a climbing robot to be used in future surface expeditions on Mars. They aim to develop a robot which can access the side of cliffs on the planet's surface to carry out geological investigations, but the robot could also be used on earth in disaster scenarios such as earthquakes. The prototype four-legged robot moves like a human rock climber as it scales an indoor climbing wall (figure 6.20). On the end of each limb the robot has a claw which it uses to gain a secure foothold. Engineer Tim Bretl of Stanford University comments *'It's like a human climber using a single finger'* (Knight, 2004).

Control and
communication unit

Motor in
each joint

Cameras

Figure 6.20 Climbing robot developed for use in future explorations of the planet mars, moving like a human rock climber (Knight 2004)

Researchers at Sheffield Hallam University describe the development of a mechanically analogous model of the human arm and hand (Whiteley 2000; Rust et al 1999, 2000; Rust 2004). In order to understand the mechanics of the human arm, Whiteley engaged extensively in observational drawing, working from skeletons, anatomical models and photographs. This lead on to exploratory and technical design drawings and a series of physical prototype models representing a close mechanical analogy to the human arm and hand. Physical prototypes were evaluated by clinical specialists who found that in a number of ways the Sheffield model arm and hand represented human movement more closely than previous prosthetic archetypes. Furthermore, specialists for the fields of surgery, medical physics and prosthetics technology helped to identify ways in which this research might inform the development of a new generation of prosthetic limbs and surgical implants, also medical simulation and robotics applications.

The above examples of designs inspired by human or animal movement point towards the potential for a kind of technological "body language" analogous to animal gestures. Earlier it was identified that the peacock creates a flamboyant display by fanning its tail feathers in order to attract a mate, and the pufferfish expands and projects spines in a dramatic gesture of defence. An exploration of how such changes may be brought about through technological means may add a new multi-sensory dimension to the way in which humans interact with products.

Of particular interest here is how changes in visual and/or tactile qualities might provide an effective means of communication. The section which follows introduces the natural mechanisms through which the pufferfish achieves a dramatic transformation in size, shape and surface texture. Knowledge of these mechanisms may inspire the development of design principles for shape-changing indicators.

6.5 Pufferfish biomechanics

As identified earlier, the pufferfish appears to present a powerful biological analogy as it exhibits visual and tactile changes, expanding and projecting spikes to ward off predators. This section describes the biological mechanisms by which such a dramatic transformation is achieved.

Summers and Bensusen (2001) present a biomechanical study of the pufferfish *diodon holocanthus.* They identify how, in the natural world, animals exhibit changes in their physical appearance in response to dangerous or threatening situations. For example, in order to deter predators, some toads and snakes have the ability to inflate themselves, whilst hedgehogs and porcupines raise their protective spines. However they note that the pufferfish is unique in its ability to combine inflation with the projection of spikes in a dramatic display of defence. When relaxed the pufferfish has a stocky, box-like appearance, with spines laid flat against the skin. However when threatened the fish transforms itself, inflating up to three times its original size and taking on the appearance of a ball covered in spikes: '... not a good design for swimming but decidedly discouraging to attackers.' (Summers and Bensusen, 2001)

Figure 6.21 A puffer fish shown inflated and at rest

Citing a study by Brainerd (1994), Summers and Bensusen describe the biological systems that enable the pufferfish to undergo such a dramatic transformation. The fish inflates by pumping water into its stomach which is pleated to enable it to expand to almost a hundred times its original volume. The fish's backbone bends in order to accommodate the expanding stomach, and when inflated the fish's skin is stretched to one and a half times its original length.

It is therefore necessary for the skin to be stretchy, but when inflated the fish becomes strong and rigid. This is achieved because the fish has a double layer of skin; an outer elastic layer and an inner fibrous layer which is pleated and becomes stiff when extended.

Stomach

Water
fJow

Stomach

Figure 6.22 The pufferfish inflates itself by pumping water into its stomach, its spine arches to accommodate the expansion, until the fish becomes almost spherical (Summers and Bensusen 2001)

The fish's spines have evolved from scales into spikes, each with a three-legged base embedded in the skin. When relaxed the spines lay flat, but as the fish inflates the skin stretches and the three legs move apart. Two of the legs move backwards causing the spine to snap upright[1]. The three legs provide a stable base supporting the rigid spike in its upright position.

When threatened, the pufferfish undergoes dramatic changes. As a defence mechanism these changes act firstly deter potential predators and secondly, should a predator be foolish enough to attack, make the fish very difficult to eat. When spiky and inflated, the pufferfish may not make for easy eating.

[1] The author is grateful to Professor Elizabeth Brainerd, a leading authority on pufferfish inflation at the University of Massachusetts Amherst, who kindly provided a video clip showing the pufferfish undergoing its remarkable transformation.

Figure 6.23 Engraving of a puffer fish by J. H. Richard c 1840. The illustration shows details of the spikes each with a three-legged base. http://www.150.si.edu/chap3/3fish.htm accessed 15 November 2005

Within the present study, the pufferfish provides a powerful design analogy for the development of shape-changing indicators. Changes in shape, size and texture may be used to communicate information about the status of a product or system, for example, to indicate that a product has changed from a safe to a dangerous state. The fish also provides a number of biomechanical systems which may be useful and effective in the development of bio-inspired indicator mechanisms. These include the method of expansion through inflation, the combination of rigid and elastic materials, the use of pleating and folding, and the means by which spikes are projected.

The following section describes practical design activity exploring the development of shape-changing indicators inspired by some of the principles identified above.

6.6 Deployable spines

This section details the design development of a series of bio-inspired indicators. These are mechanical devices that change shape in response to external stimuli. It is intended that these devices should demonstrate physical design principles which may in future be applied within product interface design, for example, in the design of visual and tactile safety indicators. Through the design of novel shape-changing mechanisms, the author explored the creative potential of emerging prototyping technologies, including CAD-CAM and rapid prototyping techniques.

The pufferfish has been identified as a biological analogy which may inspire the development of design principles for such devices. A dramatic aspect of the pufferfish's transformation is its ability to project spikes. This biological mechanism informed the author's development of an indicator system that deploys a series of spines in response to changes in temperature or the application of electric current.

The natural mechanism employed by the pufferfish in the projection of spikes is explored in sketches shown in figure 6.24 overleaf. Each spike has legs at its base embedded into the skin. As the fish expands its skin stretches. This stretching action causes the legs to move apart, which in turn causes the spikes to rotate into an upright position.

Figure 6.24 Pufferfish spike erection

a. Plan view showing a group of spikes layed flat. The base of each spike is embedded into the fish’s skin.

b. Side view sequence showing spike erection. As this fish expands its skin stretches causing the spike to snap into the upright position.

Sketches by the author after an engraving by J H Richards
(c. 1840, Smithsonian Collection, Washington DC).
Photographs: www.aquaticreations.com

When the pufferfish is in its un-inflated state, the spikes are clearly visible laid flat against the surface of the skin. However, in the development of an indicator system with deployable spines, it was considered advantageous for the spines to retract completely beneath a surface - "out of harms way" so to speak - in order to achieve a greater level of visual and tactile contrast when the spines are deployed.

Design ideas were developed for an indicator system as illustrated in figure 6.25. The system comprises a series of spines (2) attached to a sliding member (1), and a series of slots (3) through which the spikes can emerge. The point at which the base of each spine attaches to the sliding member acts as a hinge. As the sliding member moves underneath the apertures (4) the spines begin to emerge (5). The slots are angled so that they urge the spines into an erect position. Then, if the sliding member moves in the opposite direction, the spines are drawn back through the slots into the retracted position.

a. Spines retracted

b. Spines deployed

Figure 6.25 Drawings illustrating the deployable spines indicator concept

a. As the sliding member moves in the direction of arrow (4), the spines emerge through slots as indicated by arrow (5). The slots are angled to urge the spines into the upright position.

b. The Spines (2) attached to the sliding member (1) are shown in the upright position protruding through angled slots (3).

This design was first realised as a sketch model made by hand from sheet polystyrene material (figure 6.26). Although this first physical model was very crude, it successfully demonstrated the mechanical principle, thus providing a basis for further development.

b.

Figure 6.26 Sketch model - crude but functional

Sketch model fabricated from polystyrene sheet material. Surgical tape is employed as a hinge attaching the spines to the sliding member. The model successfully demonstrates the deployable spines concept, shown here in (a) the retracted position and (b) when the spines are deployed.

Later prototype iterations were first developed in 2D CAD (AutoCAD) This enabled the geometry of what is effectively a 2D mechanism to be refined "on screen". Here, multiple parts could quickly and easily be copied, moved and rotated relative to one another in order to check the position and clearances between the various components of the mechanism as it moves between retracted and deployed states (Figure 6.27)

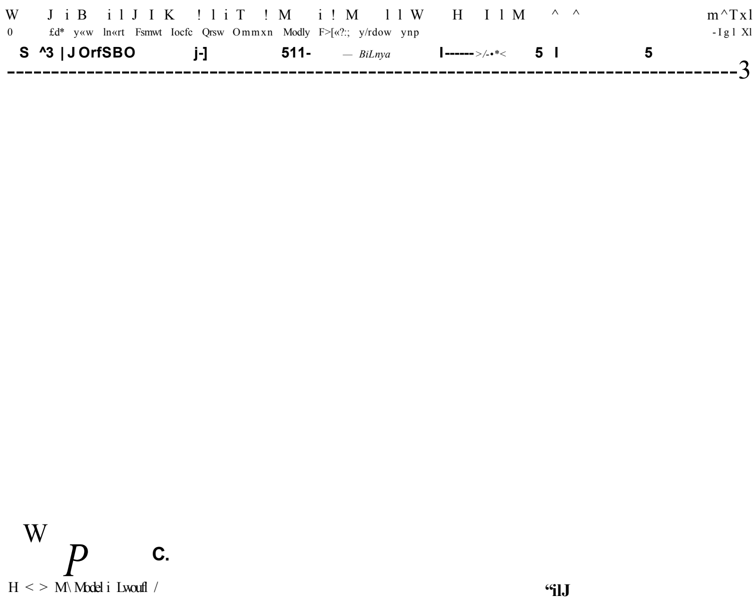

Figure 6.27 Mechanism layout in AutoCAD

Showing the spines moving from retracted to deployed positions.

Test components for the mechanism were produced directly from the 2D CAD data in 3mm acrylic sheet using a laser cutter. This enabled small and intricately detailed mechanical components to be physically realised extremely rapidly and with great precision. This process was ideal for quickly and easily translating 2D CAD component data for the mechanism into 21/2D physical working mock-ups. The laser cutter was utilised as a CAD-CAM sketch modeller, through which physical output could be obtained directly from the CAD system located in close proximity to the design workshops where the laser cutter was installed.

This rapid method of physical realisation meant that any problems with the design could be confronted and opportunities for improvement identified and implemented "on the fly", in much the same way as when working with traditional hands-on sketch modelling materials and processes.

Prototyping the hinge feature at the base of each spine initially presented some practical problems. It was envisaged that in a mass-produced item such as packaging these features could be realised as "live hinges" integral to the spines and sliding member, together forming a single injection-moulded component in polypropylene or nylon.

In order to produce a working prototype hinge, pin jointing was first considered but this was immediately rejected on the grounds that the pivot assembly may become too bulky. A second option was to insert individual live hinges cut and scored from sheet polypropylene into the laser-cut acrylic components. However, securely attaching polypropylene hinges to acrylic proved problematic. Rapid prototyping the spines, hinges and lower "all-in-one" was also considered a potential option at this stage. The Belgian prototyping bureau Materialise (www.materialise.com accessed 12 August 2005) are able to produce rapid prototypes in nylon through the process of selective laser sintering (SLS). The company claims that through this process, components with thin sections may be produced that are strong and flexible enough to function as live hinges. A sample hinge was obtained, but this appeared brittle in comparison to production-typical materials and broke with repeated flexing.

A final option that was considered for the creation of prototype hinge features was to mould compliant/elastic inserts in silicon rubber. This option appeared particularly attractive at this stage since moulds for the hinge inserts could easily be made on the laser cutter. Inserts were designed to fit securely into pockets in the laser-cut mechanism components, as shown in figure 6.28. This combination of rigid and compliant/elastic materials proved to be successful.

220

b.

a.

Figure 6.28 Linear array of deployable spines

Shown (a) retracted and (b) deployed. Compliant hinge inserts connecting the spines to the sliding member are moulded in silicon rubber (c). Dimensions in the drawing are in mm.

Figure 6.29 **Laser cut prototype linear array of deployable spines**

Prototype photographed on a light-box for clarity.

Figure 6.30 **Laser-cut prototype of the linear array of deployable spines**

Shown in (a) retracted and (b) deployed states

Having designed and prototyped a linear array of deployable spines, it became apparent that the same mechanical principle could be applied in a rotary configuration as shown in figure 6.31. In this arrangement, spines are attached to the perimeter of a central hub which rotates relative to an outer ring with apertures through which the spines are configured to emerge. This design was prototyped in exactly the same way as the linear arrangement.

Figure 6.31 Rotary arrangement of deployable spines

y t i

Figure 6.32 Laser cut prototype of rotary arrangement of deployable spines

Prototype photographed on a light-box for clarity.

a.

b.

Figure 6.33 Laser cut prototype of rotary arrangement of deployable spines

Shown in (a) retracted and (b) deployed states.

Prototypes of both linear and rotary mechanisms were actuated using shape memory alloy extension springs, as illustrated in figure 6.34. The springs shorten in length in response to an increase in temperature, or by the application of an electric current. In the linear mechanism, the spring is configured to pull the sliding member, drawing the spines through the apertures and into the raised position. In the rotary configuration actuation is achieved by mounting the spring in an arc in order to provide the necessary rotational movement.

Figure 6.34 **Temperature-responsive indicators**

Linear and rotary deployable spine mechanisms fitted with temperature-responsive shape memory alloy springs.

The spring changes from the extended position (1) to the contracted position (2) when heat is applied, pulling the sliding member thus raising the spines.

Figure 6.35 Temperature-responsive indicators

Using a hot air gun to demonstrate the performance of the temperature-responsive indicators

The springs used in the prototypes were made from nitinol wire with an activation temperature of 45-55 deg C, available as a stock item from Monotronics in the USA (www.robotstore.com). However, since nitinol alloy can be manufactured with transition temperatures ranging from -100 deg C to 100 deg C, the indicators could be configured to respond at other temperatures also. When heated using a hot-air gun, the indicators react very quickly, deploying their spines. Once the spring has cooled down, the indicators are reset by pulling the spring back into the extended position. In the current prototypes, the indicators are reset by hand. However in a future development, by fitting an elastic band or spring in opposition to the nitinol spring, the indicators could be configured to reset automatically.

A discovery which came about as a result of prototyping the rotary indicator mechanism was that the silicon rubber hinge inserts were springy enough to cause the spines to pop out on their own accord. In a future development, this feature - discovered serendipitously through physical modelling - could be exploited as a potential benefit as follows. The spines could be held in the retracted position by a small nitinol barb or catch. When activated by heat or electric current, the catch would release the mechanism, allowing the spines pop out[1]. Replacing the extension spring actuator with a small nitinol "trigger" in this way would certainly enable the mechanism to be reduced in size, which would most likely be necessary if a device of this sort were, for example, to be incorporated into packaging or other compact, portable or wearable devices.

6.7 Expanding bistable spikes

The linear and rotary indicator mechanisms described in the previous section deploy spines in response to an increase in temperature or with the application of electric current. Whilst these mechanisms work successfully, in their current state of development they contain several mechanical elements and therefore represent relatively complex assemblies. Additionally, in the biological analogy, the puffer fish exhibits expansion as well as the projection of spikes. Therefore at this stage it was considered desirable to investigate the feasibility of producing a single-component indicator mechanism incorporating both expansion and spine projection.

In the search for appropriate mechanical principles for producing such an indicator, the author investigated the structural behaviour of rubber teats from infant feeding bottles, and also the elastomer membrane springs found underneath the keys in most computer keyboards (figure 6.36). These are both examples of rubber or rubber-like components which, when compressed, pop back up again. They behave as *monostable* structures: structures which have one stable state of rest. Hands-on exploration of the physical characteristics of these monostable structures helped to inform the development of prototype pop-up spikes.

---

[1] This arrangement would rely on the hinges retaining their springiness i.e. not relaxing if held in the retracted position for an extended period of time. Should this not work, due to "creep" in the hinge material, then an alternative strategy would be to make the hinge inserts themselves out of a shape memory material.

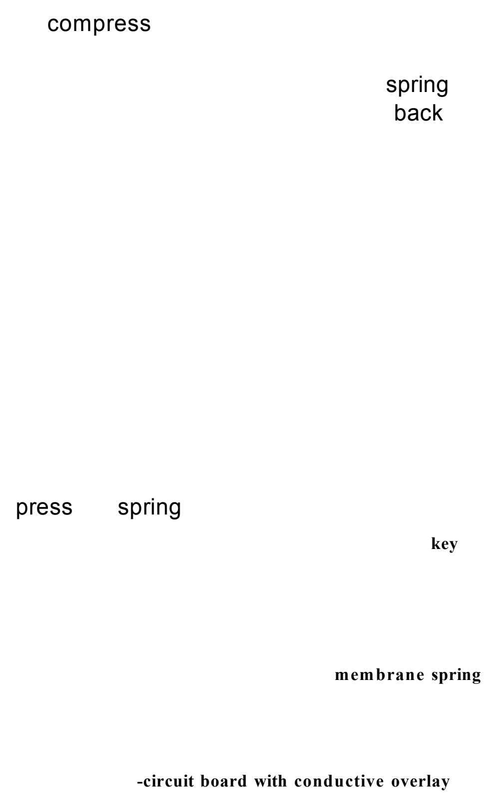

Figure 6.36 **Rubber teats and elastomer membrane keyboard springs**

These are monostable structures, having one stable state of rest - when compressed they pop back into shape.

A series of prototype pop-up spikes were moulded in various shapes and sizes, made in silicon rubber using the vacuum casting facilities in the design workshops at Sheffield Hallam University.

For the first set of prototypes, moulds were taken from wooden patterns which the author turned by hand on a lathe. These early prototypes were unsuccessful, firstly because the cross-sectional shape of the spikes did not allow flexing up and down, and secondly because making the patterns by hand meant it was difficult to control the wall thickness of the moulded parts, even when using templates to aid accuracy. However, this process did allow the author to develop valuable hands-on knowledge of the physical properties of silicon rubber, and also of vacuum casting techniques for producing thin walled components, both of which helped to inform later developments.

Spike deployed

Spike retracted

Wooden tooling

Figure 6.37 Silicon rubber spikes

First prototype mouldings made using turned wooden patterns

The investigation returned to the elastomeric keyboard springs, in order to identify how the cross-sectional shape of these components allow free flexing up and down. Further exploration revealed that if the keyboard spring is constricted around its perimeter (achieved using a draughtsman's circle template) then rather than springing freely up and down according to its intended function, the component latches in one of two states. When sufficient force is applied to the component, it "snaps through" to the opposite state. These are characteristics associated with *bistable* structures: structures having two stable states of rest, but which pass through a zone of instability when moving from one stable state to the other.

Press

spring up

press and latch

a. b. c. d.

Figure 6.38 **Elastomer membrane keyboard spring**

It its intended function, the membrane spring (a) is free to flex outwards when pressed down (b) and it immediately returns to its original shape when released.

However this monostable spring function may be subverted by constraining the component around its perimeter. This was achieved using a draughtsman's circle template. The membrane then behaves as a bistable structure, latching in the depressed position (d).

Subsequent prototype spikes were made with cross-sectional shapes that allow free flexing between retracted and deployed positions. Moulds for these were taken from patterns produced in aluminium using a computer-controlled lathe. This enabled the shape and wall thickness of the moulded components to be controlled extremely accurately. A series of prototype spikes were moulded in silicon rubber. Prototypes were made in progressively smaller sizes, with wall thicknesses ranging from 1 mm down to just 0.5 mm thick. This process enabled the author to develop a hands-on feel for the structural characteristics of the material in this context.

h-

Figure 6.39 Silicon rubber spikes moulded in a range of sizes

The smallest measuring 5 mm diameter and having a wall thickness of just 0.5 mm

Figure 6.40 **Dimensions of prototype spikes moulded in silicon rubber**

The spikes are shown in cross section in retracted and deployed positions. Additionally in (e) and (f) plan views show the addition of ribs in radial and concentric configurations.

When mounted within a rigid frame, the prototype spikes exhibit bistable behaviour, latching in the retracted position. When sufficient pressure is applied at the base of a spike it pops back up again. The bistable spike shown in figure 6.41, which has a diaphragm angle of 45 degrees, is able to expand to approximately three times its retracted height.

w

a

Figure 6.41 Bistable spike

The spike with a diaphragm angle of 45 degrees expands to approximately three times its retracted height

At this stage it was anticipated that actuation of the bistable spike mechanism could be achieved either by a small shape memory alloy lever acting on the rear of the component, or alternatively the mechanism could operate in response to a change in pressure. For example, a bistable spike could be mounted within the wall of a vessel subjected to increasing internal pressures as shown in figure 6.42. When the pressure inside the vessel reaches a critical level, the spike would pop out. Since the "pop out pressure" may be determined by the wall thickness of the component and the physical properties of the rubber material from which the component is made, the ability to control these parameters at the design stage presents the possibility that the mechanism could be employed as a visual and tactile pressure indicator capable of responding at a pre-determined pressure.

Pressure Pressure

Figure 6.42 **Visual and tactile pressure indicator**

A bistable spike may be configured to provide a strong visual and tactile indication showing that pressure within a vessel has reached a critical level.

6.8 Multiple spikes on a bistable diaphragm

Following on from the previous section in which prototypes were produced of individual spikes exhibiting bistable properties, design ideas were then developed for a single-component bistable indicator which projects multiple spikes. The mechanical principle for this indicator was derived in part from the observation that a hemispherical rubber shell can demonstrate bistable structural behaviour. For example, a hollow rubber ball may be sliced into two equal halves. If one of the halves is turned inside out, it may hold its position in this inverted state, thus demonstrating that the structure has two stable states of rest.

The design for the indicator shown in figure 6.43 consists of a hollow hemispherical shell with an array of spikes on the outside. If sufficient pressure is exerted on the outside surface of the indicator, the structure turns inside out, drawing the spikes inwards so that they nest neatly within the inverted shell. The indicator may then be returned to its everted state by applying pressure on the rear surface of the inverted shell, thus causing the spikes to pop back out again. There is a wide flange around the perimeter edge of the hemispherical shell to enable the indicator to be mounted within a rigid frame.

^7^ ^777. V77//

C.

Figure 6.43 Concept design for the bistable indicator with multiple spikes

(a) is a plan view of the indicator, (b) and (c) show the indicator in cross section in its everted and inverted states.

This idea seemed simple in theory. However, the physical shape of the indicator component meant that a method for producing prototypes to test out the mechanical principle was not immediately obvious. The design was to be moulded in silicon rubber, however the array of spikes on the outside of the component results in complex re-entrant or undercut features on the inside of the mould. Because of these complexities it could be difficult or impossible to produce prototype moulds using traditional workshop techniques.

In order to help identify a possible method for the producing physical prototypes of the indicator, the author consulted rapid prototyping specialists at the Regional Engineering and Technology (REACT) Centre in Rotherham. Through discussion it was identified that stereolithography could be used to create a "master" part directly from a 3D CAD model of the indicator component. Silicon rubber moulds could then be taken from this master in order to provide the tooling for the prototype indicators, also to be made in silicon rubber via the vacuum casting process. This process, known as soft tooling, is quite common in the rapid prototyping industry.

Concerns existed, however, that because of the complex shape of the indicator component it could be extremely difficult to get the brittle stereolithography master to withdraw from the soft tooling without causing damage and/or leaving broken remains of the master behind in the mould cavity.

Therefore the author suggested that rather than creating soft tooling from a stereolithography master, it might be less problematic to use stereolithography to create the tooling itself. This process is known in the industry as direct tooling, since rapid prototyping is used to create the moulds directly rather than the master part, thus removing the soft tooling stage from the prototyping process. In the case of the indicator prototypes, silicon rubber would be then injected into the stereolithography moulds in order to create the prototype parts.

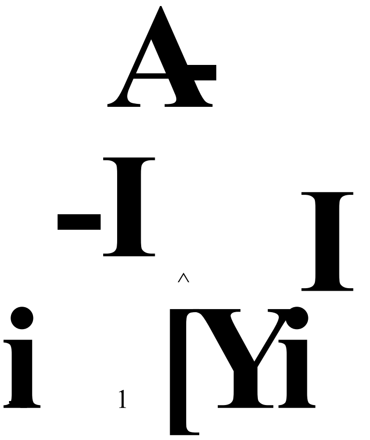

Figure 6.44 Direct tooling for the indicator prototypes

Stereolithography was used to create moulds into which silicon rubber may be injected to create prototype parts

Yet uncertainty still remained over how successful the prototyping strategy would be; the complex shape of the component could still make it difficult to remove the silicon rubber prototypes from the tooling, since the spikes might stick in the mould cavity or even tear off completely. Also bubbles of air could get trapped at the tips of the spikes resulting in parts of the mould being left unfilled. However, despite these uncertainties, 3D CAD data was created and rapid prototype moulds ordered for the indicator components.

0.75

Figure 6.45 **CAD geometry of the prototype indicator component**

The CAD geometry of the of the indicator used by the author to generate 3D CAD models for the production of rapid prototype tooling

Figure 6.46 **Stereolithography tooling and prototype moulding**

Upon receipt of the rapid prototype moulds, test components for the indicator were produced in silicon rubber via vacuum casting. There were some teething problems at this stage. Initially the silicon rubber failed to set in the moulds, possibly because of a chemical reaction with the rapid prototype resin. This was unexpected, since the type of silicon rubber used was specified by the manufacturers as being compatible with stereolithography resin. The problem was overcome by changing to an alternative type of silicon rubber and also by applying a mixture of petroleum jelly and white spirit to the inside of the moulds to create a barrier. Also a small number of prototype components were rejected because they contained small pockets of trapped air.
It was anticipated that this problem would not occur if a more powerful vacuum chamber was used than the one available at SHU. Significantly, however, a number of mouldings were successfully produced, and this enabled the mechanical principle of the indicator to be demonstrated.

The prototypes work very successfully indeed. The central moulding sprue or stem on the rear of the component is left attached as this provides a convenient way to demonstrate the mechanical action. The indicator component is mounted in a rigid frame, held by clamping the outer edge of the flange. By pulling on the stem, the spikes are drawn inwards until the indicator reaches the point at which it flips inside out. It rapidly snaps through into the inverted state. The spikes nest together and the flange dishes to create a stable concave form. The extent of the dishing of the flange, which was unexpected, appears to increase the visual and tactile contrast between the indicator's two states. In its inverted state, if a small force is applied to rear of the indicator, the structure quickly pops back out to its everted position.

The indicator has a surprisingly organic quality, perhaps reminiscent of the mouth of a sea urchin or a sea anemone which turns parts of its body inside out to feed. For this reason, the indicator comprising multiple spikes on a bistable diaphragm will henceforth be known as the *anemone indicator.*

Figure 6.47 **Anemone indicator**

CAD visuals showing the indicator in everted and inverted states. The cross sectional views show the stem on the rear of the indicator

NB whilst 3D CAD modelling may have provided a rapid and effective means of visualising design ideas for shape-changing indicators, these virtual models are of course untouchable! (The shortcomings of current haptic feedback modelling technologies are described in earlier sections of this thesis).

Figure 6.48 **Anemone indicator**

Physical prototypes in silicon rubber

*

Figure 6.49a Anemone indicator

Physical prototypes illuminated from the rear

Figure 6.49b Anemone indicator

Physical prototypes illuminated from the rear

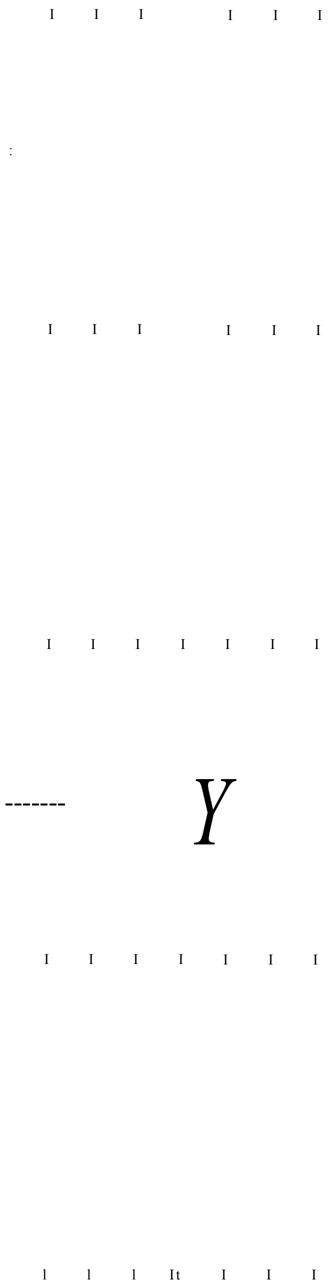

Figure 6.50 **Anemone indicator**

Sequence of cross-sectional drawings illustrating the deflection of the indicator when a load is applied to the stem on the rear of the component.

The anemone indicator has been demonstrated using three different systems of operation:

1. Pneumatic or hydraulic operation is demonstrated using a small syringe connected via a tube to the back of the indicator which is mounted in a sealed enclosure. Plunging the syringe creates a change in pressure behind the indicator, causing it to pop in or out. Automated operation may be achieved using an electronically controlled pump, although this was not attempted in the prototypes.

a. b. f.

c.

a	indicator in inverted state
b	front mounting bezel
c	sealed enclosure
d	flexible pvc tubing
e	small syringe
f	indicator in everted state

1

Figure 6.51 Pneumatic actuation test rig

Figure 6.52 Pneumatic actuation demonstrated using a syringe

Figure 6.53 Electro-mechanical actuation using a miniature servo

2. Electro-mechanical operation is demonstrated with a miniature electrical servo commonly found in robotics applications. A crank mechanism is fitted to the servo, which transmits linear motion via a cable to the stem on the back of the indicator component, moving it in or out. The servo is controlled using a digital "puppet board" which can be programmed so that the device can operate automatically. However, in the view of the author, this method of operation is clumsy when compared to pressure responsive actuation described above.

a. b. j-

indicator in everted state
front mounting bezel
crimp
inner cable
rear mounting cable
flexible PTFE sleeve
cable restraint
crank
micro servo
micro servo
indicator in inverted state

9

Figure 6.54 Electro-mechanical test rig

3. Finally, biological operation is demonstrated. A biological substance such as yeast can be placed inside a small sealed container mounted behind the indicator in its inverted state. As the yeast begins to ferment it generates carbon-dioxide which gradually builds up pressure behind the indicator, causing it to pop out when the pressure reaches a critical point.

For demonstration purposes, a mixture of ordinary dried bakers yeast, sugar and water was found to be effective. The response of the indicator was found to be accelerated at elevated temperatures, for example, if the prototype is suspended above a cup of boiling water.

f.

Figure 6.55 Bio-actuation test rig

a.	indicator in inverted state
b.	front mounting bezel
c.	sealed capsule
d.	mixture of yeast, sugar and water
e.	active yeast produces carbon dioxide
f.	indicator in everted state

In the literature, certain modified varieties of yeast are described which remain alive at refrigeration temperatures, and become active at elevated temperatures. For example, US Patent No 6261613B1 (2001) describes a yeast-based leavening agent available in capsule form. The capsules are covered in a lipid coating which melts at a predictable narrow temperature range, in order for the yeast to become active for the proving of dough.

A temperature-responsive biological substance which becomes active within a predictable temperature range could provide an effective means to activate a temperature-sensitive indicator.

With the rapid emergence of the biotechnology industries (Schmidt, 2004), biological agents might even be developed which have the ability to respond in different ways to a range of external stimuli such as temperature, pressure, light, or which become active after a pre-determined period of time. This presents the possibility of a multi-sensitive biological indicator, which may be explored in future research.

Figure 6.56 Anemone indicator

3D CAD visuals

6.9 It's not rocket science...?

Visit to the Deployable Structures Laboratory, Department of Engineering, University of Cambridge

Following the design and prototyping of a series of shape-changing indicators, the author visited a group of leading specialists in shape-changing structures, based at the Deployable Structures Laboratory, part of Cambridge University's Department of Engineering. The visit provided a valuable opportunity to present the prototype indicators to researchers working within the laboratory, enabling the author to gain specialist insight into how computational modelling and simulation techniques adopted within engineering science for the design of shape-changing structures might be applicable within the present study.

The Deployable Structures Laboratoiy was established in 1990 by Professor Sergio Pellegrino. The laboratory specialises in the development of folding, collapsible and other shape-changing structures used for booms, solar arrays and antennas in spacecraft. Other applications for deployable structures include retractable roofs and portable shelters, and actuation systems used in robotics. A focus of the research carried out by the laboratory has been the development of advanced computational tools for use in the modelling of complex structures. These tools enable accurate simulation of folding and unfolding processes, and shape optimisation of structural elements. The centre has strong links with the aerospace industry and the European Space Agency.

Figure 6.57 Professor Sergio Pellegrino of Cambridge University's Deployable Structures Laboratory with a deployable space structure, and a computer model of a folding reflector antenna. (Images: http://www.eng.cam.ac.uk/~sp28/ accessed 28 June 2005)

On Wednesday 17 March 2004 the author met Professor Pellegrino and Matthew Santer at the Deployable Structures Laboratory in Cambridge. Santer is a researcher in the laboratory and a tutor in the Department of Engineering. His recent research has focussed on the development of bistable structures. Santer demonstrated a working prototype of his "Jumping Bunny" mechanism; a novel bistable actuator which is capable of leaping a predetermined distance into the air.

This project has been developed in collaboration with the Field Space and Robotics Laboratory at Massachusetts Institute of Technology. The purpose of the project is to demonstrate the potential of bistable actuators, and to inspire the development of all-polymer bistable mechanisms. In future robotics applications actuators powered by electro or thermo-active polymers may eventually replace standard electro-mechanical elements such as motors, servos and solenoids.

In their paper 'An Asymmetrically-Bistable Monolithic Energy-Storing Structure', Santer and Pellegrino (2004, 2005) present a detailed mathematical analysis of the structural behaviour of the Jumping Bunny, and describe the working prototype - a large-scale all-metal version powered shape memory alloy springs. The next stage is to develop small-scale all-polymer version of the actuator.

Figure 6.58 Jumping Bunny all-metal prototype using shape memory alloy springs (Images: Santer and Pellegrino 2004)

The author had the opportunity to present working prototypes of his bio-inspired indicators to Pellegrino and Santer, and to explain the development process. Pellegrino and Santer responded positively to the approach taken and the quality of physical outcomes. They showed a particular interest in the author's combination of rigid and elastic/compliant polymer materials. In discussion it was identified how a similar combination of materials might be applied within an adaptive structure the laboratory were developing at the time. In a follow-up to this discussion, Santer reported:

> 'Sergio and I were both veiy impressed by the quality of your models - he has (on the basis of the meeting) decided to make some compliant hinges using the techniques you described!' [2]

At the meeting in Cambridge, Santer went on to demonstrate the laboratory's use of computer-based modelling and simulation tools including finite element analysis (FEA). FEA is a predictive simulation technique that can be employed to model the physical behaviour of structures and mechanisms that do not yet exist in the real world[3].

The author was keen to explore how these virtual prototyping techniques could be applied within the bio-inspired indicators project, in particular to identify whether FEA could be used to predict the load required to make the anemone indicator snap between its two states. If so, design of the indicator could be "fine-tuned" virtually. For example, the effect of making modifications to the material properties and/or of the wall thickness component could be evaluated within an FEA simulation, in order that the indicator might be designed to pop-out at a predetermined pressure. This could be a necessary design feature, should the device in future be applied as a visual and tactile pressure indicator.

[2] E-mail correspondence from Matthew Santer to the author 22 March 2004

[3] The aim of FEA in this context is to predictively model the physical performance of structures in order to provide quantitative results for the purposes of engineering analysis and specification. It should not be confused with the sort of 3D computer graphics/animation techniques that are used in cinematic special effects, cartoons and design visualisation.

Within FEA simulation, a 3D computer model of the structural component under consideration is divided up into discrete parts or elements in a process called meshing. The finite element mesh provides an approximate representation of the component as a whole. The discrete elements are assigned the material properties of the component. Then, when simulated loads and constraints are applied to the model, the FEA software calculates the stresses and displacements in the individual elements and the effects on neighbouring elements, combining these to approximately predict the behaviour of the component as a whole. Finite element analysis is an *approximate* method. The accuracy of the FEA simulation may be increased by refining the density of the finite element mesh, thus increasing the number of elements (Kurowski, 2004; Kaliakin, 2001; Adams and Askenazi, 1999; Robinson 1981).

In Cambridge, Santer's colleagues had recently developed a bistable strut mechanism as shown in figure 6.59 (Schioler and Pellegrino 2004). Thirty of these struts form the vertical members of an adaptive space frame structure illustrated in figure 6.60. The structure can be configured to assume 230 different shapes, each shape associated with different states of the individual struts.

7K 5 mm

46.5 mm

Figure 6.59 Schioler and Pellegrino's bistable strut.

Drawings illustrate the strut in each of its two states, the photograph shows the physical prototype moulded in nylon.

(Images: Schioler and Pellegrino 2004)

Figure 6.60 Schioler and Pellegrino's adaptive space frame structure.

The vertical members of the structure comprise 30 individual bistable struts. The image on the left is a computer simulation of the structure, the photograph on the right shows the physical prototype in a state of articulation.

(Images: Schioler and Pellegrino 2004).

Schioler and Pellegrino used the commercial FEA software ABAQUS to model the behaviour of their bistable strut, in order to determine the critical buckling load that is required for the mechanism to snap through. The mechanical principle is shown in figure 6.61a. The strut comprises a pair of trusses which snap through when a load is applied at the apex as shown in figure 6.61b. FEA was used to simulate the behaviour of one truss. Finite element models of the snap-through truss are shown in figure 6.62. Here the finite element mesh is visible on the surfaces of the plates.

Two buckling modes were modelled - symmetrical and asymmetrical buckling. The two bucking modes were arrived at by imposing small additional loads acting on the plates in order to influence the way the structure collapses. The analysis was used to predict the maximum load which could be supported by the truss prior to snapping through. When Schioler and Pellegrino built and tested physical models of the bistable strut, they found that the results of the physical tests were in good agreement with predicted values.

Load

'O"

b

Figure 6.61 The mechanical principle of the bistable strut (a) is based on a pair of trusses which exhibit snap through buckling when a load is applied at the apex (b).

1

Mode t: Ei*«fcValua • 6.0437IE-03

«

Mo© 1: EigefVsim 6.03952E-03

Figure 6.62 Schioler and Pellegrino's FEA simulation showing symmetrical and asymmetrical buckling of the truss under load. The simulation was used to predict the critical buckling load i.e. the load at which the bistable structure would snap through.

(Images: Schioler and Pellegrino 2004).

Schioler and Pellegrino's study demonstrates that finite element analysis may be employed to predict the critical buckling load for a bistable structure. However, the 3-dimensional shape and structural behaviour of the author's anemone indicator appears to be significantly more complex than that of the truss structure under consideration in Schioler and Pellegrino's analysis. The behaviour of the anemone indicator involves a large deflection, snap-through buckling and inversion of the hemispherical shell, together with the deflection of the wide perimeter flange, and the spikes which make contact with each other and nest together as the structure inverts.

Furthemiore, the silicon rubber from which the indicator is made is a *hyperelastic* material; it has non-linear properties, becoming stiffer the further it is stretched. This adds a further layer of complexity to the problem of modelling the structural behaviour of the indicator.

Following the meeting in Cambridge, the author contacted Santer by e-mail in order to seek his opinion on the feasibility of using FEA to model the behaviour of the anemone indicator. Santer responded by advising that it should be possible to use FEA to estimate the critical buckling load of the indicator. However he went on to describe the feasibility of producing a dynamic simulation of the snap-through as '... pie-in-the-sky!'[4]

Since using FEA to estimate the critical buckling load of the indicator appeared to be a possibility, the author endeavoured to achieve this using the FEA software CosmosWorks, part of the industry-standard engineering CAD package SolidWorks. Additionally, with the support of computer modelling specialists at Sheffield Hallam University and the University of Sheffield, predictive modelling of the indicator was also attempted using the FEA packages ABAQUS and ANSYS LSDYNA. This process is described in the section which follows.

6.10 Finite element analysis of the anemone indicator

The strategy proposed for the of the anemone indicator was first to constrain the indicator model around the outside edge of the perimeter flange, then to apply a simulated load to stem on the rear of the component, pulling it through to arrive at the inverted shape. Then, once the inverted shape is found, to apply pressure load to the rear surface of the indicator in order to pop it back out again (figure 6.63).

---

[4] E-mail correspondence from Matthew Santer to the author 22 March 2004.

a.

d.

Figure 6.63 Proposed strategy for finite element analysis.

In (a) the indicator model is constrained around the outside edge of the perimeter flange and a load is applied to the stem on the rear of the component in order to pull it through to the inverted state as shown in (b). Having arrived at the inverted state, a pressure load is then to be applied to the rear surface of the indicator as shown in (c) so as to pop the component back out again (d).

The author found setting up the indicator model for analysis in CosmosWorks to be on the whole fairly straightforward. The software has a "Windows-style" interface and basically operates as an extension of the engineering CAD package SolidWorks, a program with which the author was already familiar. The first stage in setting up the model was to import the 3D CAD geometry for the indicator component into CosmosWorks. The CAD data was exported as an ACIS file from the AutoCAD model used previously to generate the mould cavities for the rapid prototype tooling. The indicator model was successfully imported into CosmosWorks. Material properties could then be assigned to the model. The software has a library of standard material models, including a rubber model. This standard rubber model was assigned to the indicator. To begin with no modifications were made to the properties of the standard material model.

Having assigned the rubber material properties to the indicator, the next stage was to apply necessary constraint to the model in order to fix the outer edge of the perimeter flange as shown in figure 6.64 and then to apply a simulated load to the stem. A load of IN was applied normal to the bottom face of the stem as shown in figure 6.65.

Figure 6.64 Edge constraint applied to the perimeter flange on the CosmosWorks indicator model

Figure 6.65 Load applied to the stem on the rear of the indicator model

The final stage prior to running the analysis was to mesh the model. In CosmosWorks the meshing process is automated, meaning the software automatically divides the component into discrete elements. The user can modify the density of the mesh in order to increase or decrease the number of elements should this be necessary, however at this stage the software's default mesh density settings were used. The finite element mesh is shown in figure 6.66. Once meshed the model was ready for analysis.

Figure 6.66 Finite element mesh of the indicator model in CosmosWorks.

The analysis took several minutes to run. Once completed, the results of the analysis are presented as static images which show the displacement and stress concentration across the model due to the load applied to the stem. The results can also be viewed as an animation showing the displacement of the model under load.

Results from the first analysis were unsatisfactory, principally because the standard rubber model in the CosmosWorks material library has a significantly higher modulus of elasticity than that of the silicon rubber used in the physical prototype indicator. However, the simulation showed the component exhibiting some deflection in the perimeter flange and also a very small deflection at the apex of the hemispherical shell (figure 6.67). It was therefore necessary to modify the default modulus of elasticity to a more suitable value.

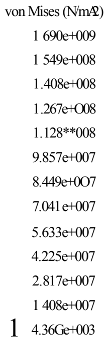

Figure 6.67 Results from the first CosmosWorks study show some deflection in the perimeter flange and a very small deflection at the apex of the hemispherical shell.

Physical prototype indicators were moulded in 30 Shore A silicon rubber. The elastic properties of rubber and rubber-like materials tend to be described using the Shore A hardness scale, rather than by specifying the Young's modulus of elasticity for the material. Young's modulus is widely used for general engineering materials such as metals and also in finite element analysis. The Shore A hardness scale is a percentage scale which refers to the depth of penetration of an indentation probe pressed under a known load into the surface of the material. Hardness values are inversely related to the depth of penetration of the probe; the higher the Shore A hardness value, the greater the modulus of elasticity of the material (National Physical Testing Laboratories www.npl.co.uk accessed 8 July 2005).

The manufacturer Dow Coming provides data sheets which describe the physical properties of silicon rubber, and also provides equivalent values for the Young's modulus of elasticity for materials covering a range of Shore A hardness values. Here the modulus of elasticity for 30 Shore A silicon rubber is given to be 0.89 N/mm2. The CosmosWorks rubber material model was therefore modified by entering this value (www.dowcoming.com/mbber accessed 8 July 2005).

A further teething problem the author initially experienced with CosmosWorks was due to the software automatically applying a scale factor to the deflection of the component under load. This default function may be very useful in some cases, for example, when modelling engineering structures that are designed to exhibit very small deflections under load. The function enables such small deflections to be automatically magnified in order to make the results clearly visible on screen. However, in the case of the anemone indicator which exhibits large deflections, it was necessary to override this default scaling function in order to ensure the results were displayed at the correct scale.

With modifications made to the rubber material model and the displacement scale factor set to 1:1 the analysis was repeated. The results were surprising. As can be seen in figure 6.68, the deflection of the perimeter flange is grossly exaggerated, as is the stretching of the stem. Instead of snapping through, the hemispherical shell suffers extreme distortion - the spike at the apex is pulled too far down, whilst the five surrounding spikes are stretched out of shape.

Figure 6.68 Results from the second CosmosWorks study showing gross distortion of the model (deformation scale 1)

Disappointed with these results, the author consulted specialists at FusionWorks, authorised dealers for the CosmosWorks software, sending them a short video clip of the real indicator in action as well as the data for the FEA analysis. FusionWorks responded by advising that the demands of modelling the complex behaviour of the indicator lay outside the capabilities of Cosmosworks and most other FEA packages on the market (e-mail correspondence 25 February 2005). However, they went on to suggest that the author could try the "high-end" FEA package ABAQUS. This software was used by Schioler and Pellegrino to model the behaviour of their snap-through strut. The author noted that Santer had also advised ABAQUS was a possibility. However, regarding the complexity of the anemone indicator, he had earlier warned that the model was possibly too detailed, particularly with the spikes (e-mail correspondence 03 May 04). Later Santer went on to suggest modelling the indicator in ABAQUS with the spikes removed.

Sheffield Hallam University runs the ABAQUS software on its network of Sun Workstations used by researchers in engineering and also for taught courses in Computer Aided Engineering and Design. Here, the author was able to call upon the help of engineering student Robert Glyn, working under the supervision of Dr Muhammad Islam, a lecturer in engineering who is experienced in the use of ABAQUS within research and professional practice.

In ABAQUS the indicator was modelled in simplified form using shell elements as shown in figure 6.69. A uniform shell thickness of 0.75 mm was chosen - this corresponds to the wall thickness of the physical prototype component at its thinnest point. Whilst in reality the wall thickness of the component varies, the aim was to make the model as simple as possible to begin with. Variation in thickness and other detail could be added later on if the simplified analysis proved to be successful.

Figure 6.69 Model of the indicator in simplified form without spikes created in ABAQUS 6.3-1

Materials properties were assigned to the ABAQUS model. The same modulus of elasticity was chosen as that used in the CosmosWorks analysis i.e. 0.89 N/mm2. Additionally, the analysis required a value the Poisson's ratio[5] for the material. For rubber and rubber-like materials the Poisson's ratio is approximately equal to 0.5 (Seymour, 1990). The value 0.49 was chosen, since this was also the Poisson's ratio value in the CosmosWorks standard rubber material model. The indicator model was constrained at the edge of the perimeter flange as before and a load was applied at the apex of the hemispherical shell.

---

[5] Poisson's ratio refers to the elastic properties of a material expressed in terms of the ratio of the fractional contraction in breadth to the fractional increase in length for a sample of material being stretched. Poisson's ratio = transverse strain/longitudinal strain (Collins Lexicon 2002, Seymour 1990).

The results of the ABAQUS analysis are shown in figure 6.70. Unfortunately the analysis aborted before the model reached the snap through point. Attempts were made to resolve the problem by increasing the density of the finite element mesh, however the analysis continued to abort. The author therefore contacted Santer for his advice.

Figure 6.70 ABAQUS model showing the point at which the analysis aborts

Santer responded by suggesting that the difficulties with the ABAQUS analysis were likely to be due to the model's individual finite elements being critically distorted as a result of the large deflection. He stated that this problem would certainly not be easy to overcome, (e-mail correspondence 06 June 05)

The anemone indicator appeared to present a serious challenge to finite element analysis techniques, even with the spikes removed. Moreover, the author was concerned that without the spikes, the validity of the finite element model would be compromised; the spikes certainly seem to contribute significantly to the structural behaviour of the indicator. In addition to colliding with each other and nesting together as the structure inverts, the spikes provide localised stiffening in the hemispherical shell, in the form of two concentric rings of "thick spots". Therefore any numerical results which may be derived from a simplified model without spikes would be of limited value.

In addition to engaging with researchers in Cambridge, the author also contacted Dr Alaster Yoxall, a computer modelling specialist working within the Mechanical Engineering Department at the University of Sheffield. Yoxall has significant experience in modelling the behaviour of "soft structures". His recent research includes the finite element analysis and simulation of the opening mechanism of the human aortic valve, in a study which aims to inform the development of future artificial heart valves (Howard, Patterson and Yoxall 2003)

Yoxall kindly offered to undertake an analysis of the indicator using ANSYS-LSDYNA, a finite element program he has used previously in modelling the complex structural behaviour of human heart valves and other soft structures. The author provided the 3D CAD data for the indicator model which Yoxall imported into ANSYS and applied the finite element mesh as shown in figure 6.71. As can be seen, the resolution of the mesh is considerably finer than that of earlier models created in CosmosWorks and ABAQUS. Yoxall reported that this mesh contains nearly 57,000 elements.

• ;

w

6

Figure 6.71 Finite element mesh of the indicator model in ANSYS 8.0 created by Dr Alaster Yoxall, University of Sheffield

Self-contact was defined across the model, in order that the analysis software would automatically detect elements coming into contact with each other and model their behaviour accordingly. The indicator model was constrained around the outside edge of the flange and a load applied to the stem.

Yoxall made several attempts at modelling the behaviour of the indicator. He created models with linear elastic material properties and also models with non-linear rubber material properties. However significant problems were encountered. Instead of snapping-through, the models exhibited exaggerated stretching around the loading region. Figure 6.72 shows excessive distortion concentrated around the spike at the apex of the hemispherical shell.

Figure 6.72 Results for the indicator modelled in ANSYS LS DYNA

The model exhibited excessive stretching around the apex region of the hemispherical shell

Yoxall concluded by stating that modelling large, non-linear deflections with snap-through buckling is extremely complex. However, he went on to suggest that with substantially more time and resources it may be possible to generate solutions to analysis problems such as this.

For the purposes of comparison, the author identified a recent PhD in engineering mechanics (Ionita, 2001) involving the finite element analysis of a rubber diaphragm used in industrial hydraulic systems. A number of these diaphragms had failed prematurely due to cracking. The aim of the study was to use finite element analysis to simulate the behaviour of the diaphragm in use in order to help identify why the existing components were failing. The diaphragm in Ionita's investigation is shown in figure 6.73.

Figure 6.73 Ionita's finite element model of a rubber diaphragm used within an industrial hydraulic system. The diaphragm is shown in cross section in the drawing on the right. (Ionita, 2001)

Although Ionita's diaphragm model involves a large, non-linear deflection and snap-through buckling, it appeared to the author that the shape of the component is considerably less complex than the anemone indicator. Ionita's diaphragm does not have the added complication of spikes. Also, the diaphragm is shallower in comparison to the author's indicator, and the large radius at its edges means that the finite element model would not be subject to such large localised strains. Ionita's model is constrained right at the edge of the diaphragm, whereas in the anemone indicator, the hemispherical shell is coupled to the wide perimeter flange which also deflects as the structure inverts.

Given Yoxall's expertise in finite element analysis and soft structures, he was asked to comment on the complexity of modelling the author's anemone indicator in comparison to Ionita's diaphragm. Yoxall described the problem of modelling the indicator as '...incredibly more complex' 6. In the case of Ionita's recent study, an extended investigation in engineering mechanics was required to model the behaviour of an existing component considerably less complex than the anemone indicator. On this basis, the feasibility of producing a valid predictive model of the indicator appears to lie beyond the scope of the present study.

---

6 E-mail correspondence from Dr Alaster Yoxall to the author 4 February 2005

Moreover, finite element analysis is an *approximate* method (Kaliakin 2001 pp 18-19, 279; Robinson 1981 p vii). In general, factors influencing the accuracy of a finite element model include the density of the finite element mesh, together with any simplifying assumptions made regarding material properties, loading and boundary conditions. Further to this, in the case of moulded components, physical inaccuracies may come about through deviation from the specified wall thickness of the part. Therefore, even if the indicator's structural behaviour were to be modelled using finite element techniques, it would still be necessary to evaluate the accuracy and validity of the virtual model through the making and testing of physical prototypes.

The author contacted Santer once more to seek his views on the limitations of finite element analysis for modelling complex structural behaviours. He responded ...

> '...in theory, provided the user chooses a sensible analysis technique and makes the correct assumptions, there is no fundamental limitations to the software. The problem is that neither of these are necessarily obvious and it is usually a highly iterative process to get problems to converge ...'[7]

The author asked Santer whether he meant that because the correct techniques and assumptions are not always obvious, it can be necessary to try different approaches to see which works best in order to predict or represent what happens in reality. He answered:

> '... Your summary is absolutely correct. The use of finite element analysis is not an exact science and often it is necessary to try several approaches before the more complex problems can be solved. Even if an analysis appeals to have produced a solution, it is by no means certain that the answer is in any way representative of reality.'[8]

He went on to express concerns about the recent emergence of finite element software which is integrated into 3D CAD software. An example of this is CosmosWorks, part of the SolidWorks engineering CAD package. Here Santer argues '... it is extremely dangerous to have integrated solvers with 3D CAD software which mesh and define analysis steps on the analysts behalf. By taking several decisions out of the analyst's hands there are a whole host of potential problems that could be disguised.'[9]

7, 8, 9 E-mail correspondence from Matthew Santer to the author, 5th and 9th May 2005

Santer's responses suggest that in some cases it may be dangerous to over-rely on virtual modelling techniques such as finite element analysis, especially when designs involve complex structural behaviour. Furthermore, in such cases it may be difficult to anticipate and predict as-yet-unknown structural behaviour without reference to a physical model. This supports the view that despite the ever-increasing virtualisation of product development processes, there remains an essential requirement for physical modelling in design.

Having been unable to model the behaviour of anemone indicator using finite element methods, the author sought to identify whether any other analytical techniques were available which may shed light on the complex structural characteristics of the indicator. The section which follows introduces shell theory, a numerical method for predicting the performance of curved, thin-walled structures.

6.11 Shell theory: Numerical analysis

The branch of engineering mechanics which sets out to describe the complex characteristics of curved thin-walled structures is shell theory. Here Ramm and Wall (2004 pp 381-427) identify ‘Shell structures are the most often used structural elements in nature and technology. ’ Examples from nature include cells, blood vessels bones, petals and egg shells, and in the human-made world aircraft fuselages, vehicle body panels, cooling towers and pressure vessels. The shell’s continuous curvature enables the structure to carry loads in an optimal way primarily by membrane actions in the plane of the surface of the shell (Ramm and Wall 2004). On the structural performance of shells, Galileo once pondered ‘Why is it that an egg held in your hands by its top and bottom and pressed with great force cannot be crushed?’ (King 2001 p 43).

Yet Ramm and Wall warn that a consequence of this outstanding structural efficiency is that shell structures can be extremely sensitive to certain parameter changes such as loading and boundary conditions and wall thickness. Furthermore they identify that the task of attempting to numerically describe the behaviour of shell structures is in some cases extremely complex, asserting '... shells are the most complicated and sophisticated structural models.' (Ramm and Wall 2004 p 392).

Brodland and Cohen (1987) use shell theory to formulate equations which may be used to predict the critical buckling load of a hemispherical shell. Brodland and Cohen used these equations to predict the theoretical value for the critical buckling load for a rubber shell, in this case a hemispherical specimen sliced from a rubber ball. They conducted an experiment to test the validity of their theoretical model by measuring the load required to cause the rubber shell to snap through. Brodland and Cohen found that in practice the experimental buckling load for the shell was lower than the value predicted by their theoretical model. They explained that this inaccuracy is an inevitable result of minor imperfections that are always present in physical objects causing the shell to collapse at a lower load. This clearly demonstrates a further aspect of unpredictability in the relationship between virtual - in this case mathematical - modelling and real physical behaviour.

Brodland and Cohen considered the case of a spherical shell freely supported at the edges and loaded at the apex, as shown in figure 6.74. Their theoretical model covers a range of shell geometries from shallow spherical shells up to fully hemispherical caps.

p

Figure 6.74 The geometry of a freely supported spherical shell loaded at the apex (Brodland and Cohen, 1987)

As has already been explained, the anemone indicator comprises a hemispherical shell, spikes and a wide perimeter flange. Temporarily ignoring the spikes and flange, the author endeavoured to investigate whether Brodland and Cohen's theorical model might reveal something of significance relating to the buckling behaviour of the indicator.

Brodland and Cohen explain that the deformation of a freely supported spherical shell loaded at the apex as shown in figure 6.74 is characterised by two geometric parameters. These are the shell half angle *%0* and a non-dimensional parameter *A* which for a fully hemispherical cap is defined by:

$$X2= [12\ (1 - v2)]\ 1/2\ (a/h) \qquad (1)$$

When v is the Poisson's ratio of the material from which the shell is made, *a* is the mid-surface radius of the shell (i.e. the radius of curvature of the spherical shell measured mid-way through the shell's thickness) and *h* is the shell thickness. Seymour (1990) takes the Poisson's ratio v for elastomeric materials to be 0.5.

Load

Geometry of the hemispherical shell of the anemone indicator

The dimensions of the hemispherical shell of the anemone indicator are shown in figure 6.75. The shell’s geometry may be summarised as follows:

a	mid surface radius	5.5 mm
h	shell thickness	1 mm
£*o*	half angle	90°

From equation (1) the geometric parameter *A* was found to be 4.06.

Brodland and Cohen provide the graph in figure 6.76 which may be used to obtain the buckling load *P* for a shell with mid-surface radius *a* and thickness */?*, made from material with modulus of elasticity *E* . The graph shows results from their numerical model alongside results from previous studies carried out by others.

Pa

3 i ------

X

Figure 6.76 Graph of critical buckling load as a function of X (Brodland and Cohen 1987)

For a hemispherical shell of equivalent dimensions to the indicator in an elastomeric material (Poisson's ratio = 0.5) it is apparent from the graph that the value of $X = 4.06$ is very close to the lower limit of the curve predicted by Brodland and Cohen and those of other investigators. All the curves cut off at or around $X - 4$. This may reflect earlier observations reported by Baker, Kovalesky and Rish that spherical caps with unrestrained i.e. freely supported edges will not buckle if X is less than around 3.8. Baker et al. go on to identify that theoretically, shells with clamped edges will not snap through if X is less than about 8 (Baker, Kovalesky and Rish 1972 pp 254 - 255). The reason for the higher limit of X for the clamped condition is that by clamping the shell around its perimeter, the edges are restricted from moving outwards when load is applied, so the structure is stiffened at its base (figure 6.77).

a b c.

Figure 6.77 Deflection of a hemispherical shell under load

For a hemispherical shell (a) subjected to a concentrated load at its apex, in the simply-supported case (b) the base of the shell is free to spread outwards as indicated, whereas in the fully clamped case (c) outward movement is restricted, stiffening the shell at its base.

An historic example of similar edge restraint is found in the dome of Saint Paul's Cathedral in London. As with many of his architectural works, in the design and construction of this magnificent dome Wren called upon the assistance of'... his most ingenious friend Dr Robert Hooke' (Wren family records cited by Jardine 2002 p 294). Jardine explains that in order to counteract the structure's huge outwards thrust, an iron chain is fixed in a channel around the base of the dome (Jardine 2002 pp 420 - 424). According to Singmaster (2003) others have claimed that the chain was an unnecessary precaution. However, when work was carried out on the dome in c. 1926, the chain was uncovered and found to be taut, doing its job, just as the designers intended.

Figure 6.78 Built to the glory of God

Wren's "hemisphere from heaven" (Lamson, 2004). The Dome of Saint Paul's stands as a testament to the theoretical and practical knowledge of structures and materials possessed by its designers Christopher Wren and Robert Hooke.

The remarkable achievements of Robert Hooke, and the story of London's Millennium footbridge (in the foreground) are discussed in chapter three of this thesis (Image: Foster and Partners 2005).

Now, whilst the edges of the hemispherical shell of the anemone indicator are not fully clamped, the perimeter flange undoubtedly has a significant stiffening effect since it acts to restrict outward movement and rotation at the base of the shell. Furthermore, as identified earlier, the spikes will provide additional localised stiffening in the shell. The value of A for the hemispherical shell is close to the limit of 3.8 identified by Baker, and almost off the graph in Brodland and Cohen's theoretical model for rubber shells. Viewed in isolation, these studies might seem to suggest that the indicator's hemispherical shell will only just snap through, even with unrestrained edges.

On the basis of the additional stiffening factors identified above, one might be tempted to mistakenly assume that according to shell theory the indicator will not snap-through[10]. Such an assumption, however compelling, would be unwise, especially since the physical prototype provides irrefutable evidence that the indicator does, in reality, snap through.

Therefore, in order to further explore the structural characteristics of the indicator the author turned to physical testing. In the section which follows, the author describes preliminary testing to investigate the relationship between the critical buckling load of the indicator and the elastic properties of the material from which the indicator is made. It is anticipated that knowledge of this relationship may help to inform the future development of a visual and tactile pressure indicator.

---

[10] To further investigate this aspect would require the development of a numerical model that takes into account the additional stiffening effects of the flange and the spikes and the non-linear material properties. Such an undertaking - if at all feasible - would entail significant investigation at a most advanced level, requiring expertise in the application of numerical methods in engineering, and as such lies beyond the scope of the present thesis. Here it is accepted that '...shells are the most complicated and sophisticated structural models.' (Ramm and Wall 2004 p 392)

6.12 Mechanical testing of the anemone indicator

This section describes physical testing undertaken to explore the relationship between the critical buckling load of the indicator and the elastic properties of the material from which the indicator is made. These investigations aimed to measure the critical buckling load and pop out pressure for indicators made in rubber materials of a range of hardnesses, in order to observe how the elastic properties of the materials influence structural response.

Mechanical testing of prototype indicators involved two test procedures. In the first, a tensile testing machine was used to measure the force applied to the stem on the rear of the indicator that is required to cause the device to snap through into its inverted state. In the second test, a manometer was used to measure the pressure that is required to cause the indicator to pop back out again. Results were obtained for prototypes made in silicon rubber (20 and 30 Shore A) and polyurethane (45 Shore A). The elastic properties of the prototype materials are listed in Figure 6.79.

Material	Shore A Hardness	Modulus of Elasticity (N/mm^)
Silicon Rubber	20	0.54
Silicon Rubber	30	0.89
Polyurethane	45	1.94

Figure 6.79 Elastic properties of prototype indicator materials
(Data: Dow Corning and PSP Inc)

The first test was carried out in the engineering laboratories of Sheffield Hallam University. The prototype indicator under investigation was held in a specially constructed jig mounted in the lower jaws of a J J Lloyd tensile testing machine (figure 6.81 and 6.82). The arrangement of the machine required the indicator to be mounted upside down as shown in figures 6.80 and 6.82. Stiff wire was attached to the stem on the rear of the indicator. The wire was gripped in the upper set of jaws of the machine.

The upper jaws of the tensile testing machine are attached to a load cell. In the experiment, the upper jaws were displaced upwards, pulling the stem on the rear of the indicator. This movement causes the indicator to snap through. The load cell measures the force pulling the stem of the indicator as the jaws are displaced. The tensile testing machine is attached to a pen plotter which provides a graph showing the load-deflection characteristic for the indicator being tested. This enables the load at snap through to be recorded.

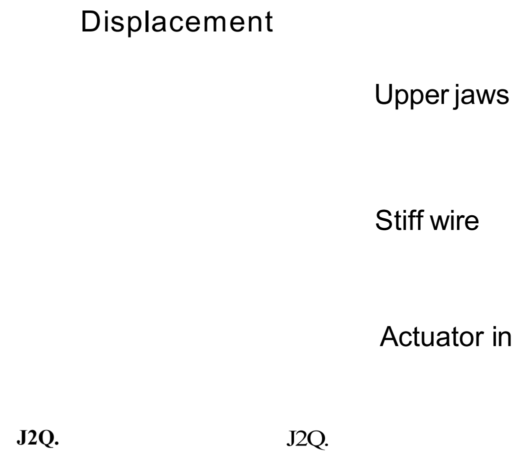

Figure 6.80 General arrangement drawing of the indicator jig in the jaws of the tensile testing machine

Figure 6.81 **J J Lloyd tensile testing machine**

Engineering student Robert Glynn assists with the tensile testing procedure

Figure 6.82 Close-up showing the indicator jig in the jaws of the tensile testing machine

Figure 6.83 overleaf shows the load-displacement characteristics for the indicators tested on the tensile testing machine. The graph shows results obtained for prototypes made in silicon rubber (20 and 30 Shore A) and polyurethane (45 Shore A). By following the curve on the graph for the indicator made in 45 Shore A material, it can be seen that from the initial state at A, the load increases with displacement up to a maximum corresponding to the critical buckling load for the indicator, at which point the load suddenly drops as the indicator snaps through at B. The load reaches zero at C when the indicator arrives its stable, fully-inverted state. The slight dips in the curves suggest points at which the load overcomes "stiff spots" in the hemispherical shell that result from the presence of spikes.

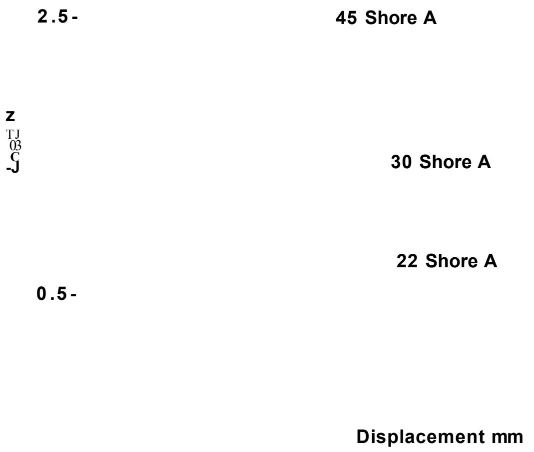

Figure 6.83 Load-displacement characteristics for indicator prototypes made in 20, 30 and 45 Shore A material.

Figure 6.84 Indicator deflection.

Diagrams A, B and C correspond to points A, B, and C on the curve for the prototype in 45 Shore A material. The indicator exhibits *asymmetric* buckling at snap-through as illustrated in B.

In figure 6.84, diagrams A, B and C show the indicator's deflection, corresponding to points A, B and C on the curve of the graph above. A noticeable aspect of the indicator's behaviour is that it exhibits asymmetric buckling, performing a slight shimmy as it snaps through to the inverted state. The results for critical buckling loads for the prototype indicators are shown in figure 6.85. The results clearly demonstrate that modifying the stiffness of the material has a strong effect on the critical buckling load of the indicator.

Shore A Hardness	Modulus of Elasticity (N/mrr^)	Critical Buckling Load (N)
20	0.54	0.65
30	0.89	1.4
45	1.94	2.55

Figure 6.85 Critical buckling loads

A second test was carried out to measure the pop-out pressures for the prototype indicators in 20, 30 and 45 Shore A material. Here the prototype indicator under investigation was attached via tubes to a reservoir manometer as shown in figure 86. The reservoir manometer is a portable device that is used for measuring pressure. Pressure readings are taken by measuring the displacement of a column of water inside a vertical a tube. The manometer that was used to measure the pop-out pressure of the indicators in 20 and 30 Shore A material was borrowed from a central heating engineer (the instrument is used by its owner for measuring gas pressure in central heating systems). However, the pop-out pressure of the indicator in 45 Shore A material exceeded the range of this existing device. It was therefore necessary for the author to construct a purpose-built measuring instrument. This comprised clear flexible PVC tubing and a tape measure attached to a softwood baton, all of which were available at low cost from the local DIY store. The investigation took place within the design workshops at Sheffield Hallam University (figure 6.86).

The testing began with the indicator in the inverted position. The pressure acting behind the indicator is steadily increased by blowing into the tube. The pressure is increased very gradually until the indicator pops out. Pressure readings were taken immediately prior to the indicator popping out, and the procedure was repeated several times to ensure consistency. This test required considerable breath control and strong lungs, especially for the indicator in 45 Shore A material - fortunately here the author is a former trumpet player[11]. The results for pop-out pressures of indicators in 20, 30 and 45 Shore A material are shown in figure 6.87.

---

[11] It is worth remarking here that carrying out the experiment certainly provided the author with a truly visceral, embodied sense of the indicators' structural response.

Figure 6.86 Pressure test rig

Shore A Hardness	Pop-out pressure (millibar)
20	8.5
30	19
45	51

Figure 6.87 Pop-out pressures

Results from these preliminary investigations clearly indicate that modifying the elastic properties of the material has a significant effect on the critical buckling load and pop-out pressure for the anemone indicator. A more comprehensive experimental investigation should seek to obtain results across a broader range of material hardness, for example, in the range 15 to 60 Shore A hardness, and research should also investigate the effect of increasing or decreasing the wall thickness of the component. Additionally, future investigations into pop-out pressure should consider the performance of the indicator within a dynamic system, taking into account the rate at which pressure is increased and also the damping effect of the rubber material from which the indicator is made.

For applications requiring higher pop-out pressures than that which may be achieved by increasing the wall thickness and/or the stiffness of the material, the indicator could be held in its inverted position using a suitably-calibrated extension spring. Biasing the indicator in this way using a spring could also be explored as a means of increasing the accuracy of the indicator's response, should this be a requirement in some applications.

In the previous section it was identified that the geometry of the indicator's hemispherical shell lies just within the range covered by Brodland and Cohen's theoretical model for the buckling of freely supported spherical caps. By comparing theoretical values derived from Brodland and Cohen's model with the test results for the indicator, it should now be possible to gain some indication of the combined stiffening effect of the spikes and perimeter flange.

The geometric parameter X for the indicator's hemispherical shell was found to be 4.06. From Broadland and Cohen's model (figure 6.88 below) $Pa/Eh3$ is approximately equal to 1.25 when P is the critical buckling load of the shell, a the mid-surface radius of the shell, E the elastic modulus of the material and h is the shell thickness.

1.25

X

Figure 6.88 Graph of critical buckling load as a function of X (Brodland and Cohen 1987)

Shore A hardness	Modulus of elasticity (N/mm2)	A Theoretical buckling load 'P' of hemispherical shell (N)	B Test results for buckling load of indicator (N)	Factor (B/A)
20	0.54	0.12	0.65	5.4
30	0.89	0.2	1.4	7
45	1.94	0.44	2.55	5.79

Figure 6.89 Comparing theoretical buckling loads of a hemispherical shell X - 4.06 with test results obtained for the anemone indicator.

The table in Figure 6.89 shows theoretical buckling loads for the hemispherical shell calculated using Brodland and Cohen's model alongside the test results for the indicator. Here it can be seen that the experimental buckling loads for the indicator are within the range of 5 to 7 times greater than the theoretical values for an equivalent freely supported hemispherical shell. As expected, this clearly demonstrates that the spikes and flange have a strong stiffening effect. It must be emphasised that these numerical values provide at best an approximate indication of the stiffening effect since, as Brodland and Cohen acknowledge, the inevitable presence of minor imperfections in physical objects will cause the hemispherical shell always to buckle at a lower load than that which may be predicted using their theoretical model. This means that in practice values for the buckling load for freely supported hemispherical shells will be lower than those shown in the table, and so the combined stiffening effect of the spikes and flange will therefore be greater than that indicated here.

This aspect of unpredictability in the relationship between theoretical modelling and real structural behaviour serves to emphasise the requirement for physical making and testing to be retained within an approach that seeks to integrate physical and virtual modelling in design.

6.13 Emotive motion

In addition to the mechanical characteristics of the prototypes described in previous sections, the author found that a further aspect of the indicators' behaviour demanded attention: the objects appeared to be emotive, and to exhibit jewellery-like qualities. This came to light when the author presented the prototype indicators to the others, and was further explored through consultation with an academic specialist whose research focuses on the affective qualities of material objects, and also two jewellery designers.

When presenting the prototypes to others the author was initially surprised by the reactions he observed. In particular the he was surprised by the way people appeared to respond to the "gestures" made by the indicators in motion. The objects appeared to be emotive - people seemed to find them funny or somehow slightly strange. For example, a 26 year old female described the retracting motion of the spikes of the anemone indicator as *"mesmerising"* (02.04.04). Another young female, described the same object as *"...weird, like an alien"* (27.07.04). A middle-aged male commentated that the rotary-action deployable spikes were *"kinky"* (09.03.04).

Curious to investigate the apparently emotive characteristics of the objects, the author consulted Dr Tom Fisher, whose recent research 'What We Touch, Touches Us' (2004) explores the affective qualities of material objects in the human-made world. Fisher was presented with the pneumatically-operated anemone indicator (08.03.04). His responses suggest that the objects might derive its apparent strangeness from its organic shape and *skin-like* material:

"... it's like a seed... it looks like something you'd find if you looked inside a seed pod... when I look at it closed up like that it makes me feel like something's going to happen."

and the tactile qualities of the material from which the object is made:

"... rubbery, viscous, quite skin-like. It's funny because it's a hard shape ... but it's very soft... and it sort of pulsates ... Slightly odd... it brings to mind things that are rather like bits of human body... sort of icky but not quite."

Within the context his own research, Fisher refers directly to the 'distinctly fleshy ... skin-like' qualities of some plastic materials: 'they are seamless; they are warm to the touch.' (Fisher 2003). Here the apparent similarity between human and human-made material may be to some both unexpected and unnerving[12]

---

[12] Definitive values for the elastic properties of human skin and soft tissue are unavailable as these of course vary for different parts of the body and also depend on the age and health of the person from which measurements are taken. However it is worth pointing out that the modulus of elasticity of the silicon rubber of the indicator presented to Fisher is very close to that of human skin measured *in vivo* by Agache et al (1980).

Fisher was presented with the anemone indicator made in 20 Shore A silicon rubber. According to manufacturer's data this material has modulus of elasticity of 0.54 N/mm2 Agache et al. report values for the modulus of elasticity human skin to be within the range of 0.42 - 0.85 N/mm2 measured by applying a torque to the forearm. Also, for the purposes of numerical analysis, the Poisson's ratio of human skin and soft tissue is assumed to be at or around 0.5, as is rubber and rubber-like materials. Comparison between the elastic properties of silicon rubber and those of human skin appear to support Fisher's qualitative evaluation that the material in hand is *skin-like.*

As well as the surprising and seemingly emotive characteristics present in the prototype indicators, a number of people suggested that the objects *"could be jewellery"*. In response to this suggestion, and in order to further explore the emotive, jewellery-like qualities L that appeared to exist in the objects, the author consulted Christoph Zellweger, an artist, designer and maker of jewellery who has received international recognition for his work (08.04.04).

When presenting the prototypes to Zellweger, the author explained that some people seemed to find them emotive, slightly strange and perhaps even *"kinky"*, and also that some had commented that the objects *"could be jewellery"*. Zellweger responded:

Absolutely... it's true - they are sexy in some way... they're funny ... tactile, they're beautiful.

Zellweger continued:

... there are these visual qualities - unexpected beauty. If I were to see jewellery like this I would be quite excited. It's very flowery, that's a traditional theme in jewellery. Also it's interactive, or it can be manipulated, that's very exciting...

Here Zellweger identified that as well as containing visual elements associated with traditional jewellery, the anemone indicators are interactive and for him display an unexpected beauty. He thought these would be exciting qualities to find in jewellery. He continued -

... This is my professional deformation which leads me to think it is jewellery. Maybe others wouldn't think that way [pause] *but no, I think some people would... I think there is a definite aesthetic. I would wear this - I would be delighted to wear this ...*

13 In the literature Downs and Wallace (2004) explore how jewellery can elicit and communicate emotions, whilst Wallace and Press (2004) discuss how jewellery objects can evoke a feeling of beauty and enchantment.

Zellweger also identified that the objects' organic qualities evoke references to the human body.

... one could play on that, which could be a very naughty thing... intimacy exposed in public, or just extremely playful.

The discussion with Zellweger raised a number of significant issues. He recognised that emotive jewellery-like qualities were present in the design of the indicators. He commented that they were funny, tactile, organic and perhaps even sexy, and that these qualities were unexpected. Moreover the language he used to describe the objects - *unexpected beauty, intimacy exposed in public* - is perhaps more easily associated with contemporary avant-garde jewellery than with product design and computer modelling. Zellweger admitted that his professional predisposition as a designer and maker of jewellery may have led him to think of the objects in these terms. In a similar way, Fisher's responses to the *skin-like* material qualities of the objects reflect views expressed in his own research into the affective aspects of materials. Zellweger left the question of whether the objects could be jewellery firmly in the hands of the author as a matter of design intent:

This is the answer to the question if it could be jewellery then yes it can, but the definition has to be recognised by you. We recognise the quality of the aesthetic but the decision has to be yours, on where you want it to be.

In order to further pursue this line of enquiry, the author went on to consult a second practitioner. Julia Keyte is a jeweller, product designer and lecturer at Sheffield Hallam University. Here she describes her responses to the prototype objects.

Reaction to Peter's experiments

My initial response to Peter's pieces was a recognition of qualities with which I am familiar as a jeweller. To me there is an obvious connection to jewellery; the sensitively made and intricate small scale constructions relate to jewellery and to fingers. Particularly the 'sea urchin' experiment, which in my minds eye is already some kind of interactive brooch. I want to stick my finger in it. It is appears tactile and it is visually fascinating. It is asking to be touched and prodded and played with!

... The experiments have been designed for very functional use. Yet they are beautiful. Why not capitalise on this? Does it need to be functional? Can it not just be exquisite? [14]

Whilst the views expressed by Fisher, Zellweger and Keyte represent their personal perspectives as researchers and practitioners, clearly some common features can be identified in their responses, for example, the references to organic forms and tactile material qualities. Both Zellweger and Keyte referred to the objects as having a playful character, and also recognised jewellery-like qualities.

In creating the prototype indicators, the author had not intended them to be viewed as jewellery. The project had been very firmly rooted in the functional considerations of how the indicators were going to work. Therefore to hear them being described in this way by jewellery designers was itself a surprise. It was unexpected, perhaps more a product of accident than design. Recognising and responding to this kind of serendipitous "happy accident" provides a further demonstration of the importance of human judgement as an essential human element in design. Here the author feels he can make no claims on being a jeweller, although he does take it as compliment that someone would be delighted to wear the objects. However the author's personal view is that the objects are not jewellery.

6.14 Discussion

The physical outcomes of this phase of research comprise a series of prototype indicators exhibiting changes in shape in response to external stimuli such as changes in temperature, pressure or with the application of electric current. The aim in creating the prototypes was to demonstrate transferable principles which may in future be applied within product or packaging design. It must be therefore be appreciated that some considerable further effort would be required to develop the indicators to a stage where they are suitable for incorporation into a finished product.

---

[14] E-mail correspondence from Julia Keyte to the author 8 November 2005

For example, future research could focus on the miniaturisation of the linear and rotary spike mechanisms. Research should also investigate further the capabilities of electro and thermo active polymers as a means of actuation. Active polymer technology is still in its infancy, however in future the production of an indicator in a smart polymer material in the form of a single moulded component may be feasible (Ashley 2003). Future research may also explore further the feasibility of using biological agents as a source of actuation.

Production of the prototype indicators was successfully achieved through the use of the "hands-off' design technologies of CAD CAM and rapid prototyping, in particular the computer-controlled laser cutting of small and intricately detailed mechanical parts in plastic, and stereolithography for the production of *direct tooling* to cast small silicon rubber components with complex undercuts. However, the design activity was informed throughout by "hands-on" knowledge of mechanical, structural and material possibilities which was developed through iterative physical prototyping. This was particularly evident in the development of compliant hinge elements incorporated within the indicators with linear and rotary deployable spines. Furthermore knowledge of the structural properties and potential of silicon rubber was developed through moulding a series of bistable spikes in progressively smaller sizes. This process certainly informed the creative development of the anemone indicator.

Following on from the successful production of the prototype shape-changing indicators, the author consulted specialists in computer-modelling and simulation techniques at the Universities of Cambridge and Sheffield. The aim was to explore the feasibility of using finite element analysis to predictively model the structural response of the bistable anemone indicator.

However these investigations - supported by those with specialist knowledge and expertise - were unable to achieve a satisfactory structural simulation. Therefore the author finally had to accept that the feasibility of using virtual methods to simulate such complex structural behaviour was '... pie in the sky' (M Santer, correspondence with the author 22 March 2004). Given that it recently required an extended study in engineering mechanics to simulate structural behaviour significantly less complex than that exhibited by the anemone indicator (Ionita, 2001), the feasibility of the producing a valid predictive model appears to lie beyond the scope of the present study.

Furthermore, finite element analysis is an *approximate* method. Factors influencing the accuracy of the virtual model include the density of the finite element mesh, along with any assumptions made in the formulation of the model, for example, with regard to material properties, loading and boundary conditions. The possible effects of minor imperfections in physical components must also be taken into account. Therefore, even if the behaviour of the anemone indicator were to be modelled virtually, physical testing would still be required in order to establish the accuracy and validity of the simulation.

Regarding the simulation of complex structural behaviour, Santer warned:

> '... The use of finite element analysis is not an exact science ... Even if an analysis appears to have produced a solution, it is by no means certain that the answer is in any way representative of reality.'[15]

In such cases it would clearly be dangerous for designers and engineers to over-rely on finite element analysis techniques, since it may be difficult to anticipate complex real-world behaviour without first having reference to a physical model.

These findings and outcomes appear to be in contrast with the views of those within design and engineering discourse who advocate the virtualisation of product development processes. For example, in 'Designing Better Products with Finite Element Analysis' Adams and Askenazi (1999) describe an 'ideal' design process in which iterative physical prototyping and testing is replaced by predictive modelling and simulation techniques. Similarly Reid (2004) asserts:

> 'To simulate the performance of a product is often easiest, quickest and cheapest using a virtual prototype ... Product designers can now evaluate their intuition and "play" with their [virtual] models giving them a far greater realm of discovery and innovation.'

---

[15] E-mail correspondence from Matthew Santer to the author 9 May 2005

And Kurowski (2004) argues:

> 'With the use of FEA design iterations are moved from the physical space of prototyping and testing into the virtual space of computer-based simulations ... The ultimate objective of using FEA as a design tool is to change the design process from iterative cycles of "design, prototype, test" into a streamlined process where prototypes are used only for final design verification.'
>
> (Kurowski 2004 pp 2, 3)

In Kurowski's statement above, physical prototyping is relegated to the end of the design process where it is used for verification purposes only. Here the physical prototype appears to be viewed as an end result of design, rather than playing an integral role in the creative development and testing of ideas.

Reid (2004) argues that advances in virtual prototyping technologies are bringing simulation techniques typically regarded as the domain of specialist analysts within reach of product designers and engineers. Furthermore, in his recent PhD in industrial design, Evans reports the emergence of "design automation" technologies: '....Neural networks and genetic algorithms are being developed to facilitate the automatic generation of industrial design proposals and engineering detail...' (Evans 2002 p 276-277) Evans goes on to predict that such technologies might be used to automatically perform engineering functions such as finite element analysis on the designer's behalf.

Yet in the present study, Santer points to potential dangers inherent in the use of modelling systems that automatically define finite element analysis steps, particularly in cases involving complex structural behaviour: '...By taking several decisions out of the analyst's hands there are a whole host of potential problems which could be disguised'[16]. The choice of analysis techniques and assumptions is crucial to the validity of a finite element model. In complex cases, the choice of techniques and assumptions may not be obvious, and the task of finding an analytical solution can be an iterative, trial-and-error process. Therefore, there remains an essential requirement to evaluate the validity of the virtual model through comparison with physical test results.

---

[16] E-mail correspondence from Matthew Santer to the author 9 May 2005

Research described within this chapter demonstrates that some design problems may make the limitations of virtual prototyping particularly evident. For example, within the present study, the complex behaviour of the anemone indicator appears to lie beyond that which may adequately of feasibly be described using current predictive modelling techniques alone. Moreover, it is argued that if the scope of the design activity is limited to that which is possible or feasible to simulate using virtual prototyping techniques, then the range of potential physical outcomes may be significantly restricted.

Having been unable to successfully simulate the structural behaviour of the anemone indicator using virtual prototyping techniques, the author turned instead to physical testing to explore the relationship between the critical buckling load of the indicator and the elastic properties of the material from which it is made. The results obtained from these preliminary investigations demonstrated that, as expected, changing the elastic properties of the material has a strong effect on the critical buckling load and pop-out pressure of the indicator. Further experimental investigations are recommended, firstly to obtain results for more samples, secondly to include a broader material range (for example 15 - 60 Shore A hardness) and thirdly to investigate the effects of changing the wall thickness of the component as well as the material properties.

As well as the consideration given to the mechanical characteristics of the prototype indicators, this chapter draws attention to a further significant aspect of human-centred design. The indicators appeared to be in some ways *emotive,* eliciting some quite unexpected responses. Having been absorbed in the mechanical functionality of the indicators, the author was at first surprised by the seemingly emotive characteristics of the objects he had made. Such findings may in some way reflect the kind of unexpected or accidental discoveries which can occur within creative processes, contributing a further dimension to human-centred design practice.

People's responses to the objects included such statements as: "mesmerising" ; "weird ... like an alien";" slightly odd "; "icky - but not quite"; "kinky" ; "unexpected beauty" ; "exquisite"; and "I would be delighted to wear it." Even from this extremely small and informal survey, the selection of responses shown here suggests some complexity - different people responded in different ways to the same set of objects. 'Design and Emotion' is a strongly emerging theme within design discourse (McDonagh et al, 2004; Hekkert and McDonagh, 2003).

For commercial manufacturing companies, it seems to be no-longer sufficient to rely on the creative talents of designers to deliver innovative and emotionally engaging products. Now the trend appears to be moving towards manufacturers deploying psychologists, anthropologists and social scientists to scrutinise the "emotional design" of everything from car body shapes to shampoo bottles (Norman 2004, Desmet et al 2003 McDonagh et al 2004). Researchers working in this context seek to identify methods and techniques to 'predefine' consumers' emotional responses to products (eg 'Designing Emotions' Desmet 2002 pp 163-164; also Weerdesteijn et al 2005).

In his book 'Emotional Design - Why we love (or hate) everyday things' Donald Norman presents an analytical approach to investigating the nature emotion in design. Here he describes three levels of emotional experience in design: *visceral design* is concerned with the immediate emotional impact that is communicated through a product's look and feel; *behavioural design* is concerned with pleasure and effectiveness in use; and *reflective design* is concerned with self image, personal satisfaction and memories. At one point in his discussion of these three levels and how they might be applied in design, Norman asserts '.. if you design according to these rules, your design will always be attractive.' (Norman 2004 p 67).

One might view with some suspicion what appears to be a highly formulaic and somewhat over-simplistic approach to emotional design from Donald Norman. One may instinctively believe that a designer's creative talent, imagination and empathy in handling form and materials all contribute to the development of emotionally-engaging, pleasurable products. That such things might come about through recipe-following and the application of analytical method is perhaps more difficult to accept. However Norman does concede that his system of levels of emotional experience is simplistic, and he recognises that in reality the way in which his three categories interact is complex (Norman 2004 p 39).

Norman's analysis of emotional experience prompted the author to enquire further into the meaning of the word *visceral*, the term he uses when referring to the immediate emotional impact communicated through the look and feel of products. By definition, the term *visceral* can refer to "gut feeling" responses to situations and experiences i.e. those involving instinctive inner feelings ahead of conscious reasoning. According to Norman, 'visceral design is what nature does' (Norman p 65).

Here Norman is referring to the innate ability of humans and other animals to respond to powerful emotive signals in the natural environment. In nature, plants and animals have evolved into a diverse variety of forms according to the demands of the environment and their relationships with other living things. In order to coexist in the environment, animals are required to interpret powerful emotive signals and do so automatically at a visceral level.

Animal signals provided a starting point for this investigation. Therefore, that the bio-inspired indicators appear to exhibit emotive qualities is perhaps not so surprising after all.

7.0 Summary, conclusions and future directions

There is no contradiction between playfulness and pedantry;
the one brings on the other...
Nothing tugs at the heartstrings so much as a quavering mechanical toy;
think of the touching music boxes of bygone times.

Gunter Grass (1965)

This thesis has described in detail an enquiry into the nature and role of prototyping within human-centred design practice. The study has explored the potential of emerging virtual and rapid prototyping technologies in practical investigations in which designers sought to exploit tactile qualities as essential features in design, and also in cases involving complex, dynamic structural behaviour.

This final chapter draws together the diverse themes and activities described in the preceding sections, identifies the theoretical and practical implications of the study, and points to opportunities for future investigation. The chapter will first summarise the methods and outcomes of the research, examining these in light of the aims and objectives that were proposed at the start of the thesis.

The research aims and objectives will be now be restated and research findings reviewed and discussed:

1 To review the literature within the discourses of design, human computer interaction and human factors engineering, to identify approaches to human-centred design adopted by practitioners within these fields.

In a contextual review exploring the significance of the human element in design, *user-centred design* was found to be a strongly emerging theme. User-centred design is an approach to designing that seeks to engage with the experiences, needs and aspirations of end-users. Research identified in chapter two pointed to the need for designers to establish a relationship of empathy and understanding with end-users, in order that this might inform and support the design activity (Brusberg and McDonagh 2003).

Within HCI discourse, Preece et al (2002) asserted that new product development processes should be driven by real user needs and goals, not just technology. Also within the HCI field, Katrovich (2004) reported that user-centred design can lead to improvements in the usability, safety, and performance of products. Usability and product safety were also identified as key concerns within the discourses of ergonomics and human factors engineering (Stanton and Young 1999, Morrissey 1998).

In a review of the emerging user-centred design literature, methodological approaches were identified and discussed. These included design ethnography, participatory design, and scenario-based methods (Rothstein 2000, Ward 2002b, Shaw 2003, Sanders 1999, 2000, Preece et al 2002, Saks-Cohen 1997).

Of particular interest within the present study were methodological approaches in which the making and testing of prototype artefacts played a central role. Practical examples were identified in which designers capitalised on their abilities to articulate ideas through the creation of physical prototypes, which were subsequently evaluated through interaction with end-users. In an iterative process, physical prototypes took on the role of *probe* or *provocative agent* as they were employed to stimulate communication and to elicit further knowledge of the design task and end-user requirements. For example, in Chamberlain's design of vibroacoustic therapy systems, the production of physical prototypes with which users could interact proved to be instrumental in unlocking knowledge of the therapeutic needs of those with profound sensory impairments (Chamberlain et al 1999, Rust et al 2000, Chamberlain and Roddis 2003, Rust 2004, Walters et al 2004)

Whilst the benefits of user-centred design have been widely discussed in the literature, the term *user-centred* design has attracted some notable criticisms. The principle concern is that the term *user-centred* can appear to emphasise purely utilitarian considerations of use and usability, and that by implication the status of the human being is reduced to that of *user* (Buchanan 2001a, Bramwell-Davis 2002).

Human-centred design has emerged from within design discourse as a concept which implies much broader, holistic considerations. By emphasising the significance of the human element in design, human-centred design explores the knowledge, experiences and relationships between the designer and those who depend on the products of creative practice (Walters, Chamberlain, Press and Tomes 2004).

Buchanan points to human-centred design as '...one of the practical disciplines of responsible action ... fundamentally an affirmation of human dignity. It is an ongoing search for what can be done to support and strengthen the dignity of human beings...' (Buchanan 2001a pp 35-37).

Human-centred design is not simply a response to market forces, to fashion or to what is technologically possible. As a discipline, human-centred design seeks to support human needs and affirm human values through practical intervention. This leads the discussion on to the second of the aims and objectives that were set out at the beginning of this thesis:

2 To identify a *paradigm statement* for human-centred design - in this context, a statement of ideas, values or beliefs to guide the theoretic and practical research activity described within this thesis.

The review of literature outlined above led the author to propose a *paradigm statement* in which human-centred design is described as a creative exploration of human needs, knowledge and experience which aims to extend human capabilities and improve quality of life.

Following on from this statement, chapter three proceeded to explore human-centred design within the context of other fields of creative human endeavour, drawing upon literature from the history and philosophy of science as well as the discourses of ait, design and engineering.

In a discussion of relationships between human knowledge, creativity and design, a conflict was identified - Cartesian dualism - in which theoretical reasoning and logical deduction are *set apart* from intuition and practical experience. The philosopher Kant sought to overcome the dualistic schism, when he asserted that human knowledge is only possible through the synthesis of reason and experience. The story of Newton and Hooke was introduced to illustrate how a *coming together* of theoretical and practical approaches can contribute to processes of creative discovery and invention - although sadly in this case the relationship between the two scientists ended in conflict.

The conflict of dualism appears as a recurrent theme in design discourse. For example, in the 1960s the Design Methods movement sought to develop logical, rational, methodological frameworks in an effort to make design respond better to increasing social and technological complexity. However, the movement appeared to have little impact outside the world of academia (Press and Cooper 2003). The methods were criticised for stifling intuition: the logical, deterministic approach appeared to lack the 'vital human element' of design (Heskett, 1980 p 208). The Design Methods approach was eventually abandoned even by the movement's early pioneers, Jones and Alexander (Cross 2001).

Conflicts have continued to emerge between those design theorists who have sought to prescribe rigorous, "scientistic" methodological frameworks, and practitioners who seem to prefer their own tacit methods and designerly intuitions (Friedman and Ainamo 1999, Coyle 1997, Olson 2002). Reconciliation is required, if tensions between theoretical and practical approaches are to be resolved. Here Jones (2004) called on the design research community to '...end the dualism and create integration.' Achieving integration, through a synthesis of theoretical and practical knowledge, is a creative challenge that design must continually seek to address.

Chapter three went on to explore relationships between technology and human knowledge. Heidegger's essay 'The Question Concerning Technology' was introduced, in which the philosopher enquires into the nature of the *essence* of technology. For Heidegger, the essence of technology is nothing technological: it is not to be found in mere machines, nor in those activities through which human beings might be subsumed into the seemingly unstoppable mechanisms of technological progress '... driving on to the maximum yield at minimum expense' (Heidegger 1954 p 321). Heidegger anticipates fears that humanity may *lose itself* to technology in ways that threaten the future humankind and the planet. Yet drawing on the poetry of Holderlin:

> 'But where danger is, grows the saving power also ...
> ... poetically man dwells on this earth.
>
> (Heidegger, 1954 p 340)

Heidegger asserts that as well as great danger, *a saving power* may be found, if the human being is able to grasp the essence of technology.

For Heidegger, the essence of technology is found in *poiesis* - the poetic processes of making, revealing and knowing. Looking back to the Greek origin of the word technology, he identifies the word *techne* is linked with the word *episteme.* Both words are terms for knowing in the widest sense' (Heidegger 1954 p 318). By grasping the essential meaning of technology - in processes of poetic revealing and knowing - the human being opens up the possibility of a *free relationship* with technology.

However, in Aicher's reflection on technology and human experience, the schism of dualism emerged again. Adopting the language of technology, Aicher distinguishes between *digital* - which for him represents abstract logic and dry data; and *analogue* - which represents sensuous human experience. He fears '... digital technology is making man into an increasingly digital being' (Aicher 2001 p 47).

The discussion proceeded to draw on the hypermodem cultural theories of Baudrillard, De Grandpre and Virilio, who warn of a threat presented by emerging technologies - a *theft of reality* - and a descent into digital dystopia; a vapid, virtual, video game world:

> 'Virtuality only gives possibilities virtually, while taking back the reference and the density of things, their meaning. It gives you everything, and subtly, surreptitiously it takes everything away at the same time.' (Baudrillard 1996)

Reflecting upon these ideas, chapter three went on to critically explore relationships between digital and analogue processes in design, focussing on the role of physical and virtual modelling within human-centred design practice. This brings the discussion to the third of the aims and objectives identified at the start of this thesis.

3 To review the literature from within product design and engineering discourse describing the current state of the art in virtual and rapid prototyping.

A survey of literature aimed at the design and engineering professions identified an emerging rhetoric which celebrates the *virtualisation* of design processes. Here proponents of computer modelling and simulation technologies claim virtual prototyping might reduce or in some cases entirely eliminate the requirement for physical prototype iterations in design, thereby greatly increasing the speed and efficiency of new product development processes (e.g. Adams and Askenazi, 1999; Hollerbach et al, 2000; Evans, 2002; Connell, 2004). The chapter went on to identify counterarguments to the designer's total immersion in the virtual design world, challenging the assumption that virtual prototyping technologies might replace physical human input in design.

In his major work 'Being and Time' Heidegger gave primacy to the authentic, 'ready-to-hand' understanding of the world that humans may develop through close engagement in practical concerns:'... not a bare perceptual cognition, but rather that kind of concern which manipulates things and puts them to use; and this has its own kind of "knowledge".' (Heidegger 1927 p 95). In a similar way, within the field of engineering design, Cooley described how skilled engineering technicians develop a deep understanding of structural, mechanical and material possibilities, through direct "hands-on" engagement and manipulation of physical materials: '...All their knowledge of the physical world about them, acquired through years of making things and seeing them break and rupture...' (Cooley 1980 p 81). Cooley feared that this vital practical design knowledge might be lost through the rapid and uncritical adoption of computerised design processes within engineering industries.

Two examples - London's Millennium Footbridge and the B of the Bang sculpture in Manchester - provided evidence that, in spite of increasing capabilities of virtual modelling technologies, there may be no substitute for confronting the physical reality of design problems. In the case of the Millennium Bridge, engineers employed virtual methods to model the structural performance of the bridge prior to its construction. However the problem of pedestrian-induced movement in the bridge deck only came to light when the bridge existed in reality and could be experienced by people. Although for centuries soldiers have been instructed to "break-step" when crossing bridges, it seems the phenomenon of synchronous lateral excitation exhibited by the Millennium Bridge was not sufficiently accounted for in bridge building codes of practice (Newland 2003). The case of the Millennium Bridge has prompted revisions to be made to the British Standard codes for bridge construction, the aim being to help prevent such problems occurring in future.

In the example of the B of the Bang sculpture, computer modelling and small-scale wind-tunnel tests were employed by engineers in an effort to predict wind-induced movement in the structure. However, problems due to "galloping" in the sculpture's steel spikes did not become fully evident until the full-sized structure existed in the physical environment. Following the failure of two of the spikes, the sculpture remains fenced off to the public. According to Michael Burdekin, Professor of Structural Engineering at the University of Manchester Institute of Science and Technology, the B of the Bang sculpture '...is an extreme example of the fact that computer modelling cannot cover all possible occurrences and that physical behaviour has to be checked.'[1]

Practical design problems may be identified and addressed through the making and testing of physical models. Yet it is not only design problems that come to light in this way, since valuable creative opportunities may also be revealed through physical prototyping. Here Myerson (2001) and Kelley (2001) describe the iterative prototyping methods adopted by the US design consultants IDEO, through which designers might literally "make their own luck". As Kelley asserts: 'Call it serendipity or even luck, but once you start drawing or making things, you open up new possibilities of discovery' (Kelley 2001 pp 108-109). So whilst proponents of virtual prototyping promise computer-based simulation techniques will increase in the speed and efficiency of product development processes through a reduction in the requirement for physical modelling, virtual technologies carry with them the danger that designers may *lose touch* with the physical reality of design problems, and also the creative opportunities that may be revealed through discovery-oriented physical prototyping.

Chapter three highlighted one of the most obvious shortcomings of conventional computer aided design systems: in CAD the action takes place behind a glass screen. Virtual modelling deprives designers of opportunities to physically engage with the "task in hand" during the development of their work. In an effort to address this issue, hardware and software manufacturers are developing touch technologies in the form of haptic feedback devices. However, whilst manufacturers promise tangible tactile experiences, the author and colleagues have identified that as yet such systems are unable to provide an adequate substitute for the experience of grasping and manipulating prototype artefacts and materials within the physical workshop (Walters et al 2004). Furthermore, Evans et al (2005) reported that the Sensable Technologies Phantom interface, currently the only commercially-available haptic modelling system, lacks the accuracy and control of surface continuity that is required within industrial design applications.

[1] E-mail correspondence from Professor Michael Burdekin to the author, 24 May 2005

Rapid prototyping was identified as a means through which industrial designers and engineers are able to obtain physical output from virtual modelling systems. A key advantage of rapid prototyping is that it can enable the realisation of dimensionally-accurate physical artefacts which might otherwise be difficult, time consuming, or even impossible to produce using traditional hands-on model-making techniques. For example, hollow parts with complex internal details.

It was noted, however, that despite advances in rapid prototyping technologies, such systems are as yet unable to deliver the rich range of material properties and surface qualities that are typically available to the designer in the real-world workshop. Also rapid prototyping may lack the immediacy of hands-on making and testing in the physical workshop, where prototypes can be created and modified directly and dynamically, and design decisions made "on the fly".

Notwithstanding the limitations identified above, the discussion acknowledged that significant benefits may be offered by virtual and rapid prototyping technologies. For example, virtual methods are widely used for the visualisation of design proposals and can also facilitate communication, collaboration and the sharing of data between those engaged in concurrent design and engineering processes. Virtual technologies can also be employed in the simulation of structural and mechanical performance prior to the construction of physical prototypes, although great caution is necessary to avoid problems already identified which may arise through an over-reliance on such techniques. Furthermore, rapid prototyping can enable the realisation of physical output which might otherwise be difficult or even impossible to create through hands-on workshop-based methods.

The benefits of virtual and rapid prototyping cannot be ignored, nor can the creative opportunities afforded by new forms of making. This points towards a further requirement for reconciliation: between the digital design technologies of virtual and rapid prototyping, and analogue human input in design. The thesis went on to introduce practical investigations, through which the author sought to explore how analogue and digital approaches might together contribute to human-centred design practice. This leads to the fourth of the aims and objectives outlined at the beginning of this thesis:

4 To undertake practical design activities exploring approaches to prototyping within the context of human-centred design.

In the present enquiry into prototyping and human-centred design practice, a methodological approach based upon practice was considered particularly appropriated. It was anticipated that a *practice-centred* approach, in which the researcher's own creative practice played a central role, could yield valuable first-hand insights which might otherwise not be obtained (Rust, Chamberlain and Roddis 2000, Archer 1995). By being in-on-the-action, the researcher might achieve a depth of insight into practice which might simply be unattainable as a "spectator" observing the activities of others.

The practical investigations took the form of an interdisciplinary 'design enquiry' (Rust, 2004), in which experimental 'designing-through-making' was central to the research methodology (Bunnell, 2000; Rust et al 2000). Chapter 4 provided an overview of the methodological approach employed in two practical design projects, which were described in detail in chapters 5 and 6.

The first practical project involved the design, prototyping and testing of a new identification system for medical connectors used in the administration of anaesthetics and other drugs to hospital patients. A number of deaths have resulted from patients being connected up to the wrong drug delivery line. This collaborative project, led by Chamberlain, explored the feasibility of an identification system employing visual and tactile cues: contrasting shapes and textures applied to the outside surface of the connectors, in order that they might be identified by touch as well as sight, the aim being to help make it safer and easier for hospital staff to select and use the correct connector.

This study afforded unique insights into the application of virtual and rapid prototyping technologies when seeking to exploit tactile qualities as essential features in design. 3D CAD modelling was used extensively in the development of the visual and tactile identification system. Because of the extremely small size of the medical connector components, and the intricate surface detailing of the tactile cues, physical sketch modelling was impractical. Therefore, when designing in the virtual environment, it was necessary to rely on an intuitive sense of how the components might feel to the touch. Here the study highlighted the challenge of using hands-off modelling technologies when designing products for hands-on interaction.

Early on in the investigation, Chamberlain and the author attended a demonstration of the Sensable Technologies Phantom haptic feedback interface. Both designers took the opportunity to try out the device in a demonstration activity in which it was possible to carve a block of "virtual clay". The Phantom interface enables the user to "feel" the boundaries of the virtual model through a stylus attached to an articulated arm. However, after just a short period of use, it was clearly evident that the Phantom would be unsuitable for the present study, since the interface does not allow the designer to grasp and manipulate the virtual artefact with the fingers, as would be the case with physical prototypes. Howe has described the stylus-and-arm interface archetype as '...like poking at the world with a stick.' (Hodges 1998). Also, it was quickly apparent that the Phantom system lacked the accuracy and control that would be required for detailed design modelling.

Therefore, in order to evaluate the tactile qualities of the designs, the virtual models were translated into physical prototypes, through the rapid prototyping process of stereolithography, in a series of design iterations. Here the stereolithography process proved ideal since it enabled the accurate and consistent realisation of multiple sets of test components at a "jewellery-like" scale. The prototype identification system was then evaluated in a series of tests conducted by cognitive ergonomists at the Faculty of Psychological Sciences, University of Leeds. Results from the first round of tests, in which participants were psychology students, demonstrated that the prototype connectors could be identified by touch alone with few errors (mean error rate 2.72%).

However, two of the connectors took considerably longer to identify because the tactile features on these components appeared to "overlap". Therefore, following modifications to the design, further prototypes were produced, which were evaluated in tests, this time with participants who were healthcare professionals in intensive care and anaesthetics at Bradford Royal Infirmary. In the second round of tests, the average rate of error dropped to 1.73 %. Whilst the overall rate of error appeared low, in practice it would be unwise to rely on tactile cues alone as a means to prevent misconnection. Chamberlain is now engaged in ongoing research, funded by UK Department of Health and a leading medical device manufacturer, which investigates the integration of a visual and tactile identification system with a mechanically non-interchangeable connection system, in order to help eliminate to possibility of misconnection altogether.

Following on from the investigation into the application of tactile cues within medical device design, a second practical project was introduced, in which the author developed a series of "smart" shape-changing indicators. In future, such devices may be employed as visual and tactile indicators within product or packaging design. For example, consultation with hospital pharmacists revealed the potential opportunity for the development of "smart" safe-storage indicators for pharmaceutical items with temperature and/or time critical storage requirements. Here, a visual and tactile safe-storage indicator could be incorporated into pharmaceutical packaging, to warn if an item has not been stored correctly and is therefore unsuitable for use.

However, because of the anticipated technical complexity that would be involved in the realisation of such a device at a scale small enough to be incorporated into packaging, and also because of the time-constraints of the PhD, the project did not set out to design, prototype and test "smart packaging". Instead the aim of the investigation was to create working prototype devices demonstrating physical design principles which may inform the future development of visual and tactile safety indicators for packaging or other products intended for use in safety-critical applications.

In the development of the shape-changing indicators, the author took inspiration from nature. The pufferfish, which expands and projects spikes to ward off predators when threatened, provided a biological analogy for the design of a series of shape-changing mechanisms which operate in response to changes in temperature, pressure or the application of electric current.

Physical prototypes were constructed comprising linear and rotary arrangements of spines or "hackles" which are raised in response to an increase in temperature. Deployment of the spines is achieved using temperature-responsive shape memory alloy spring actuators.

Also prototyped were a series of "bistable" silicon rubber spikes. These snap between retracted and deployed states when pressure is applied to the underside of the spike, "hands-on" exploration of how the structural properties of silicon rubber might be exploited in this way led the author to develop a further bistable design in which an array of spikes project from the outside surface of a convex hemispherical diaphragm. In order to retract the spikes, the hemispherical diaphragm is inverted and the spikes are drawn inwards, nesting within the concavity created by the inverted diaphragm.

An increase in pressure on the underside of diaphragm causes the structure to revert to its original convex state with spikes deployed. The dynamic behaviour of this design reminded the author of a sea anemone drawing its tentacle within its body.

For the anemone indicator design, pneumatic actuation was achieved using air pressure provided by a small syringe, and electro-mechanical actuation was demonstrated using a miniature robotic servo. The potential of "bio-actuation" was also explored. This was demonstrated using a small quantity of biological material - bakers yeast, sugar and water - contained within capsule mounted behind the diaphragm in its inverted state. Responding to an increase in temperature, the yeast gives off carbon dioxide as it grows, and the resulting increase in pressure causes the actuator to pop-out. Future research will further explore the potential of bio-actuation, including the possibility of encapsulating the active biological material using smart gel coating technologies which melt at a predetermined temperature, in order that the indicator might respond within a specific temperature range (Materials Foresight 2001).

The design and prototyping of the shape-changing indicators involved a combination of hands-on and hands-off processes. The digital design technologies of CAD-CAM and rapid prototyping enabled the production of physical artefacts which would have been difficult if not impossible to create using traditional hands-on modelling techniques. However the design was informed throughout by a hands-on understanding of structural, mechanical and material possibilities developed through the author's exploratory manipulation of physical prototypes and materials. In this way, the development successfully integrated digital and analogue processes in design.

The investigation went on to explore the feasibility of using virtual prototyping techniques to predictively determine the pressure at which the anemone indicator would pop-out, since by modifying the wall thickness and/or the elastic properties of the material from which the device is made, the indicator could be designed to respond at a pre-determined pressure. Several attempts were made to model the structural behaviour of the indicator using finite element analysis techniques. Here research engaged with specialists at the Universities of Cambridge and Sheffield with expertise in computer modelling and complex structural behaviour.

However, due to the indicator's complex, dynamic structural characteristics - the combined effect of the complex shape, non-linear material, large deflection, and high localised strains resulting in critical distortion of the finite element mesh - a satisfactory result could not be achieved using virtual modelling techniques.

Matthew Santer, a specialist in bistable structures at Cambridge University, described the feasibility of undertaking such a complex simulation as 'pie in the sky!'[2]. Moreover, since finite element analysis is an approximate method (Robinson 1981, Kaliakin 2001), even if a predictive simulation of the behaviour of the anemone indicator were to be achieved, it would still be necessary to evaluate the accuracy and validity of the virtual model through comparison with tests carried out on physical prototypes. Factors influencing the accuracy of a finite element model include the density of the finite element mesh, together with any assumptions made in the formulation of the model regarding material properties, loading and boundary conditions. Also, the possibility of physical inaccuracies resulting from the presence of minor imperfections in physical components must also be taken into account.

A predictive virtual model remains a theoretical model that is based on assumptions, the validity of which must ultimately be tested in the real world. In the absence of a physical model, it may be difficult to anticipate complex, real-world behaviour. Santer identified that in complex cases, the choice of analysis techniques and assumptions are not always obvious, and the task of arriving at a solution can be a highly-iterative, trial-and-error process. He asserted:'... finite element analysis is not an exact science ... Even if an analysis appears to have produced a solution, it is by no means certain that the answer is in any way representative of reality.'[3]

Advances in software technologies are bringing finite element techniques once regarded as the domain of highly skilled analysts within reach of product designers and engineers (Reid 2004, Evans 2002). However, some to whom such software becomes available may lack appropriate training and experience in the use of finite element techniques. Clearly such developments could result in further problems.

---

[2] E-mail correspondence from Matthew Santer to the author 22 March 2004

[3] E-mail correspondence from Matthew Santer to the author 9 May 2005

Santer went on to warn of potential dangers inherent in the emergence of CAD software that incorporates automated finite element analysis capabilities: '... it is extremely dangerous to have integrated solvers with 3D CAD software which mesh and define analysis steps on the analysts behalf. By taking several decisions out of the analyst's hands there are a whole host of potential problems that could be disguised.'[4]

Santer's response above suggests to the author that there is a *craft* within finite element analysis, which might be considered analogous to that present in the manipulation of physical material in the hands of a skilled craftsman. Future research may seek to further explore how physical and virtual practices might inform each other in this context.

Having been unable to adequately describe the structural behaviour of the anemone indicator using virtual methods, the author went on conduct physical tests, in order to explore the relationship between the elastic properties of the material from which the indicator is made, and the critical buckling load required for it to snap between each of its two states. Using a tensile testing machine, results were obtained for the critical buckling load of prototype indicators made in 20, 30 and 45 shore hardness rubber, and a "home-made" reservoir manometer was then used to measure the pop-out pressure.

This practical investigation highlighted the essential role of physical prototyping and testing in the design of the indicators, and draws attention to some of the limitations of virtual methods in this context. If the scope of the design activity had been limited to what was possible or feasible to model virtually, then the range of potential physical outcomes could have been significantly restricted.

Advocates of virtual prototyping argue that computer-based simulation techniques can eliminate costly and time-consuming physical prototype iterations, so that physical prototypes are only required for final design verification (eg Kurowski 2004, Adams and Askenazi 1999). Yet this practical investigation demonstrated the value of physical prototyping for the creative development and testing of ideas throughout the design process for the shape-changing indicators.

[4] E-mail correspondence from Matthew Santer to the author 9 May 2005

Having been absorbed in the mechanics of the shape-changing indicators, the author was surprised to find that people seemed *moved* by the apparently emotive, jewellery-like qualities exhibited by the artefacts. The practical investigation into bio-inspired indicators drew to a close by considering the emotional dimension of human-centred design. The discussion referred to Donald Norman's four levels of emotional experience in design - in particular, to the immediate *visceral* response people may have to the look and feel of physical artefacts.

Norman suggests that this immediate, *gut-feeling* response to artefacts is linked to our "animal instincts" - the way in which humans and other animals have evolved to interpret and respond to powerful signals within the natural environment. The author concluded that since the investigation was initially inspired by animal signals, that the shape-changing mechanisms might now appear to exhibit emotive characteristics is perhaps not so surprising after all.

Yet through his poetic insight, Gunter Grass offers an alternative perspective, when he writes:'... Nothing tugs at the heartstrings so much as a quavering mechanical toy...'[5]

Having reviewed the theoretical and practical research described within this thesis, the discussion now returns to the question of technology, and the knowledge which may arise through human making. Earlier it was identified that for Heidegger, the essence of technology is found in poiesis: in poetic processes of revealing and knowing. It is significant here that the word *poet* has as its origin the Greek *poiein* meaning *to make.* Heidegger also referred to the relationship between *techne* and *episteme* '...Both words are terms for knowing in the widest sense. They mean to be entirely at home in something, to understand and be expert in it. Such knowing provides an opening up. As an opening up it is a revealing' (Heidegger 1954 p 318).

In this way, the *essential unfolding* of technology opens up the possibility of new forms of making, revealing and knowing, which together contribute to an ongoing *epistemology of making.*

---

[5] Gunter Grass, from the novel 'Dog Years' 1965 p 225

Following the review of research findings, it is now possible to reflect on the methods and outcomes of the study and to identify conclusions relating to the theory and practice of human-centred design, and the application of prototyping technologies within this context. This research has integrated theoretical and practical approaches, building original arguments around and through innovative creative practice involving novel interdisciplinary engagement. The study has demonstrated that human-centred design can draw upon diverse disciplines and sources: from pufferfish to pharmaceutical packaging, and from spacecraft structures to contemporary jewellery. The enquiry has connected art and science, engaging with specialists in engineering science, as well as academics and practitioners within art and design.

Practical investigations employed both digital and analogue approaches in design. The digital technologies of CAD-CAM and rapid prototyping enabled the realisation of physical artefacts which would have been difficult if not impossible to produce through traditional workshop-based techniques. Yet as well as making use of digital technologies, the design of both the medical connectors and the shape-changing indicators was informed by analogue human input, through hands-on engagement with physical prototype iterations throughout the development process.

The enquiry has drawn attention to some of the limitations of current virtual prototyping technologies, and has highlighted potential problems which may arise through an over-reliance on virtual methods. Therefore knowledge gained through theoretical and practical research leads the author to recommend that an integrated approach is required, in which new technologies go hand-in-hand with tried-and-tested techniques: the analogue and the physical complementing the digital and the virtual, together making a mutual contribution to human-centred design.

This thesis makes an original contribution to the discourse of design. It is anticipated that the study will be of particular interest to academics, researchers and practitioners in the following areas: human-centred design epistemology and methodology; interdisciplinary practice-centred research; and the role of artefacts - physical and virtual - in design research. It is anticipated that the enquiry will also be of interest to design practitioners, educationalists and students concerned with the appropriate application of emerging prototyping technologies in design.

Having examined and reflected upon the research described within this thesis, the following conclusions are now identified:

7.2 Theoretical and methodological conclusions

A contextual review exploring the significance of the human element in design led to the proposal of a *paradigm statement* for human-centred design as follows:

> *Human-centred design is a creative exploration of human needs, knowledge and experience which aims to extend human capabilities and improve quality of life.*

Through a critical review of literature describing emerging prototyping technologies, and through practical investigations described within this thesis, research has demonstrated the following:

- Despite significant advances in computer modelling and simulation technologies, there remain some types of design problem that may only be identified and addressed through the making and testing of physical models.

- It may not be possible or feasible to adequately describe all aspects of a design proposal using virtual methods alone. If the scope of the design activity is limited to what can be simulated using current virtual prototyping techniques, the range of potential physical outcomes may be significantly restricted.

- Creative opportunities can be revealed through discovery-oriented physical prototyping. Conversely, through an over-reliance on virtual prototyping, a designer may fail to grasp the true complexity of real-world physical problems.

- Valuable practical understanding of mechanical, structural, material and ergonomic possibilities may be developed and applied through hands-on physical prototyping. Conversely, if the activities of the designer are confined to the virtual design workshop, then opportunities for the development of this practical *ready-to-hand* knowledge may be lost.

- The digital design technologies of CAD-CAM and rapid prototyping enabled the production of physical artefacts which might otherwise have been difficult if not impossible to realise within the context of this enquiry. Yet the development was informed throughout by analogue human input, through hands-on engagement with prototype artefacts and materials in the testing and evaluation of physical design iterations.

- Moreover, the valuable practical knowledge and experience that may be derived through hands-on engagement and manipulation of physical objects and materials must be retained as an essential human element of design.

7.3 Design outcomes:

The practical outcomes of the research are as follows:

- The design, prototyping and testing of a series of novel shape-changing indicators employing shape memory alloy, electromechanical, pneumatic and bio-actuation systems. The indicators employing shape memory alloy spring actuators respond to an increase in temperature. The pneumatic and bio-actuated indicators are based on a bistable structure which responds to changes in pressure. Alternatively the indicators may be activated electromechanically. These devices demonstrate physical design principals which may in future be developed for use as visual and tactile indicators within safety critical product applications.

- With Professor Paul Chamberlain, the author is co-inventor of a tactile identification system for medical connectors; an outcome of a pilot study that forms part of ongoing interdisciplinary investigation led by Chamberlain into the safety and usability of medical devices. The methods and outcomes of the pilot study have been disseminated at two international conferences (Walters, Chamberlain and Press 2003; Walters, Chamberlain, Press and Tomes 2004) and the identification system has been the subject of UK and international patent applications (PCT/GB2004/001745 Inventors: Paul Chamberlain and Peter Walters).

7.4 Future directions

Research described within this thesis opens up possibilities for further investigation in the following areas:

The shape-changing indicators have attracted the interest of a major manufacturer of pharmaceutical, healthcare and food packaging. Recognising the potential for the future development such devices as safe storage / smart expiry indicators, the manufacturer has offered to support future research in this area, providing technical, manufacturing and marketing expertise and performance testing facilities. Building upon interdisciplinary links established within the present study, an application is to be made for research council funding to support a collaborative investigation which will aim to develop design principles for "smart packaging" to be used for pharmaceutical items with temperature and/or time-critical storage requirements.

In addition to the smart packaging application identified above, the author is keen to explore further the affective aspects of the indicator designs. The potential for designing expressive movement in interactive products was the subject of the First European Workshop on Design Semantics of Form and Movement, which the author attended in November 2005. It is the author's intention that a paper describing the challenges and opportunities encountered in the design and realisation of form and movement in "jewellery-like" objects should be submitted to the workshop next year.

A further area for future investigation that is of particular interest to the author is design education. Writing in the Journal of Design and Technology Education, Evans (2004) considers the future application of virtual and rapid prototyping technologies within the design curriculum. Here he asserts '...the emergence of a virtual workshop appears increasingly viable ... This would lead to a design environment that is largely comprised of computers, haptic feedback devices and rapid prototyping machines' (Evans 2004 pp 7, 6).

Evans goes on to suggest that the introduction of such technologies might '...be seen as liberating in terms of designing, as the student is no longer restricted by what they can make but by what they can design and model using 3D CAD' (Evans 2004 p 13). Evans' virtual workshop prompts significant questions regarding the relationship between designing and making, and the appropriate application of new technologies in an educational context.

Whether such a scenario turns out to be liberating or limiting will depend on how virtual and rapid prototyping technologies are introduced within an educational context. For example, rapid prototyping can enable the realisation of physical forms which might otherwise be difficult or even impossible to make. However, the palette of material properties currently available through rapid prototyping is limited when compared to the richer range of materials that may typically be encountered in the real-world workshop.

In physical model-making, the hands-on manipulation of real materials can contribute not only to a student's three-dimensional visual vocabulary - through form-handling - but can also inform the development of a sound practical understanding of structural, mechanical, material and ergonomic possibilities. Furthermore, hands-on model-making may be effectively employed as a creative tool for problem-solving and innovation. Therefore, the present author argues that within design education, the new technologies should be introduced to complement rather than replace designing-through-making in the physical workshop.

In closing this thesis, the author asserts that whilst it is undoubtedly important for design students to be equipped with skills in the latest technologies and techniques, it is vital that they are not deprived of valuable opportunities to develop practical knowledge through the creative experience of making, in all its forms.

8.0 Bibliography

Adams, V. and Askenazi, A. (1999) *Building Better Products with Finite Element Analysis* published by Onword Press pp 13-14

Agache, P. Monneur, C. Leveque, J. De Rigal, J. (1980) *Mechanical properties and Young's modulus of human skin in vivo* Archives of Dennatological Research Volume 269 Issue 3 pp 221-32

Ahmed, K. (2002) *Milburn eyes no fault system for settling NHS claims* The Observer, 29 December 2002, p 2

Aicher, O. (1*991) Analogous and Digital* published by Ernst and Sohn

Air Force System Command (1980) *Design Handbook 1-3, Human Factors Engineering* 3rd Edition US Air Force

Alexander, C. (1971) *The state of the art in design methods* DMG Newsletter 5:3 cited by Cross, N. (2001) in *Designerly Ways of Knowing: Design Discipline Versus Design Science* in Design Issues Volume 17 Number 3 pp 49 - 55

Anderson, C. (2003) *Violent Video Games: Myths, Facts, and Unanswered Questions* in Psychological Science Agenda Vol 16 No 5

Anderson, C. (2004) *An update on the effects of playing violent video games* in Journal of Adolescence No 27 pp 113 - 122

Archer, B. (1995) *The Nature of Research* in Co-Design 02 pp 6 - 13

Armitage, J. (1999) *From Modernism to Hypermodernism and Beyond - an interview with Paul Virilio* in Theory, Culture and Society Volume 16 Numbers 5-6 pp 25-55

Armitage, J. (2000) *Beyond Postmodernism? Paul Virilio's Hypermodern Cultural Theory* published online at http://www.ctheoiy.net/text file.asp?pick=T33 accessed 3 March 2005

Ashley, S. (2003) *Artificial Muscles* in Scientific American Vol. 289 No. 4 October 2003 pp 52-59

Augustini, G. Borri, C. Niemann, H. (2001) *Is aeolian risk as significant as other environmental risks?* in Reliability Engineering and Safety Vol 74 No 3 pp 227-237

Ayers, J. Yilbur, C. and Olcott, C. (2000) *Lamprey Robots* in Proceedings of the International Symposium on Aqua Biomechanisms, Tokai University www.neurotechnology.neu.edu/lampreyrobots.pdf accessed 20 November 2005

Baker, E. H. Kovalesky, L. and Rish, F. L. (1972) *Structural Analysis of Shells* published by McGraw-Hill pp 254 - 255

Bar-Cohen, Y. and Breazeal, C. (2003) *Biologically Inspired Intelligent Robots in the Proceedings of the SPIE Smart Structures Conference* San Diego, CA March 2003

Barthlott, W. (accessed April 2005) *Lotus Effect* University of Bonn http://www.botanik.uni-bonn.de/system/bionik_flash_en.htinl

Basdogan, C. De, S. Kim, J. Manivannan, M. Kim, H. Srinivasan, M (2004) *Haptics in minimally invasive surgical simulation and training* in IEEE Computer Graphics and Applications Volume 24 Issue 2 pp 56- 64

Basdogen, C. and Srinivasan, M (2002) *Haptic Rendering in Virtual Environments* in Handbook ofVirtual Environments, Stanney, K. Ed. published by Lawrence Earlbaum, London pp 117-134

Baudrillard, J. (1995) *The Gulfwar did not takeplace* Power Publications

Baudrillard, J. (1996) *Baudrillard on the New Technologies: An interview with Claude Thibault* trans. Falcone, S, European Graduate School www.egs.edu/faculty/baudrillard/baudrillard-baudrillard-on-the-new-technologies.html accessed 23 November 2005

BBC Documentary (2005) *Thomas Heatherwick and Britain's Biggest Sculpture* broadcast 12 January 2005

BBC News (2003) *Antibiotics crisis looming* published online 28 September 2003

BBC News 7 March (2005) *Bang Sculpture in Safety Scare* www.news.bbc.co.uk

BBC News 20 May (2005) *Bang Sculpture in Fresh Scare* www.news.bbc.co.uk

BBC Newsnight Friday 7 January 2005 report of first spike failure on The B of the Bang

Beavon, R. (2001) *Robert Hooke, Natural Philosopher* available online at: http://www.bbc.co.uk/history/discovery/revolutions/hooke robert beavon Ol.shtml accessed 26 April 2004

Bennett, J. Cooper, M. Hunter, M. and Jardine, L. (2003) *London's Leonardo: The Life and Work ofRobert Hooke* Oxford University Press pp 105 - 162

Bennett, O. (2003) *Set in emotion* in Design Week, 11 December 2003 pp 22, 23

Berwick, D. M. (2001) *Not Again* in British Medical Journal No 322, pp 247-8

Bickford-Smith, P (2001) *Designing safer medical devices needsfinancial and political support* in British Medical Journal 3 March 2001 322, P 548

Biggs, J. and Srinivasan, M (2002) *Haptic Interfaces* in Handbook of Virtual Enviromnents Stanney, K. Ed. published by Lawrence Earlbaum, London pp 93-116

Blackburn, S. (1994) *Oxford Dictionary ofPhilosophy* published by Oxford University Press

Blincoe, R . (2002) *Design: Plastic Rocks* British Council Culture Lab UK URL: http://www.culturelab-uk.com/site/templates/issuel/archive_item_culturelab.asp?ID=l 15 accessed 15 March 2005

Blunt, A. (1959) *The Art of William Blake* published by First Icon Edition 1974 p 60

Boeing (1995) *Boeing 777 Digital Design Process Earns Technology Award* press release June 14, 1995 www.boeing.com/comniercial/777fainily/news/index.htinl accessed 20 February 2006

Bocking, C. (2003) Editor's Introduction to the *Proceedings of the Fourth National Conference on Rapid and Virtual Prototyping and Applications* Lancaster University June 2003 Professional Engineering Publishing

Borst, C. and Volz, R. (2003) *Preliminary Report on a Haptic Feedback Technique for Basic Interactions with a Virtual Control Panel_* in the Proceedings of Eurohaptics 2003 Trinity College Dublin 6-9 July 2003

Boswell, B. (1998) *Digital Prototyping Unplugged* in Time Compression Technologies Volume 6 Number 3 pp 37-43

Bothwick, J. (2003) *Power to the People* in New Design January/February 2003 pp 34-37

Boyd-Whyte, I. Baxter, C. MacDonald, A. (1997) *John Fowler, Benjamin Baker Forth Bridge* published by Axel Menges

Brainerd, E. L. (1994) *Pufferfish inflation: functional morphology of post cranial structures in Diodon holocanthus (Tetraodontiformes)* in Journal of Morphology, 220: 243-261.

Bramwell-Davis, P (2002) interviewed in MacDonald, N. *The Missing Link* in New Design January/February 2002 http://www.spy.co.uk/Articles/NewDesign/IDE21/

Brand, S. (1994) *How Buildings Learn* published by Phoenix p 188

Broadbent, G. (1984) *The Development of Design Methods,* in Cross, N. (Ed) Developments in Design Methodology, published by Wiley pp 337-345

Broadbent, J. (2003) *Generations in Design Methodology* in The Design Journal Vol 6 Issue 1 pp 2-13

Brodland, G. W. and Cohen, H. (1987) *Deflection and Snapping of Spherical Caps* International Journal of Solids and Structures, Vol. 23, No. 10

Bruseberg, A. and McDonagh-Philp, D. (2001) *New product development by eliciting user experience and aspirations* in International Journal of Human Computer Studies 55 pp 435-452

Bruseberg, A. and McDonagh-Philp, D. (2003) *Focus Groups in New Product Development: Designers' Perspectives* in Langford J and McDonagh D (eds) Focus Groups Supporting Effective Product Development published by Taylor and Francis London p 63

Bryant (2001) *Talking Medicine Identifiers* in Voice of the Diabetic http://www.nfb.org/vod/vodsum0111.htm accessed 14 December 2005

Bryman, A. (2001) *Social Research Methods* Oxford University Press pp 475-485

Buchanan, R. (2001a) *Human Dignity and Human Rights: Thoughts on the Principles of Human-Centred Design* in Design Issues Volume 17 Number 3 Summer 2001 pp 35 - 39

Buchanan, R (2001b) *Design Research and the New Learning* in Design Issues: Volume 17, Number 4 pp 3 - 23

Buchanan, R. (1995) *Wicked Problems in Design Thinking,* in Margolin, V. and Buchanan, R. (eds) *The Idea of Design* published by MIT Press pp 3 - 20

Bullock, A. Stallybrass, O. and Trombley, S. ed. (2000) *New Fontana Dictionary of Modern Thought* published by Fontana Press

Bunnell, K. (1998) *The Integration of New Technology into Ceramic Designer-Maker Practice* PhD thesis Robert Gordon University

Bunnell, K. (2000) *Designing Through Making* in The Design Journal Volume 3 Issue 3 pp 1-3

Burnett, G. and Porter, J. M. (2001) *Ubiquitous computing within cars: designing controls for non-visual use* in International Journal of Human Computer Studies 55 pp 521-531

Bussler, M. (2003) *FEA-based simulation technologies are defining virtual prototyping in* Time Compression Technologies Volume 11 Issue 5 pp 52-56

Butterfass, J. Hirzinger, G. Knoch, S. Liu, H. (1998) *DLR's Multisensory Hand Part 1: Hard and Software Architecture* in the Proceedings of the IEEE International Conference on Robotics and Automation Leuven Belgium 1998 pp 2081-2086

Castro, I. and Graham, J. (1999) *Numerical wind engineering: the way ahead?* in the proceedings of the Institute of Civil Engineers, Structures and Buildings 134 pp 275-277

Catchpole, H. (2004) *Knitting in nanometres* ABC Science Online 19 November 2004 www.abc.net.au accessed 12 May 2005

Chamberlain, P. Roddis, J. (2003) *Making Sense: A case study of a collaborative design-led new product development for the sensorily impaired* in The Design Journal Volume 6, Issue 1, pp 40 - 51

Chamberlain, P. Roddis, J. and Press, M. (1999) *Good Vibrations* in Proceedings of the Third European Academy of Design Conference, Sheffield Hallam University, UK Vol 3 pp 18 - 39

Chapman, A. (1996) *England's Leonardo: Robert Hooke (1635 - 1703) and the art of experiment in Restoration England* from Proceedings of the Royal Institution of Great Britain 67 pp 239 - 275 www.rod.beavon.clara.net/leonardo.htm accessed 20 Februaiy 2006

Christmass, C. (2004) *Sing me a song* in Music in Action volume 1 issue 3

Clarke, C. (2002) *Troubled bridge over water* in C3 Magazine March 2002 http://www.c3mag.com/news/focus/bridge march02.htm accessed 21/01/2004
Collins Lexicon (2002) Harper-Collins CD-ROM

Collins, J. and Selina, H. (1999) *Introducing Heidegger* published byTotem Books USA pp 55-57

Connell, A. (2004) *The rise and rise of virtual prototyping* in Time Compression Technologies Volume 12 Issue 3 pp 44-49

Cooley, M. (1980) *Architect of Bee? The Human Technology Relationship* Hand and Brain Publishers, Slough p. 5, p. 22

Cooley, M. (1988) *From Brunelleschi to CAD/CAM in Thackara Design After Modernism* published by Thames and Hudson, London pp. 197 - 207

Cooper, R (2003) *Concepts, Theory and Practice* in The Design Journal Volume 6 Issue 1

Coyle, P. (1997) *The Madness in my Method* in Proceedings of the Second European Academy of Design Conference, Stockholm 23-25 April 1997 www.svid.se/ead/ead-coyle.htm accessed 15 May 2003

Coyne, R. D. and Snodgrass, A. D. (1991*)_Is designing mysterious? Challenging the dual knowledge thesis* in Design Studies, Vol. 12, No.3, pp. 124-131

Cross, N. (2001) *Designerly Ways of Knowing: Design Discipline Versus Design Science* in Design Issues Volume 17 Number 3 pp 49 - 55

Davey, A. (2003) *Model Behaviour* in Design Week 27 Feb 03

DeGrandpre R (2001) *The Great Escape* an extract from Digitopia: The New Look of the Digital You published by Random House, also in Adbusters: Journal of the Mental Environment March/April 2001 pp 21-31

Department of Health (2000) *An Organisation with Memory* published by Her Majesty's Stationary Office, London

Desmet, P. (2002) *Designing Emotions* PhD Thesis, Delft University of Technology

Desmet, P. Hekkert, P. and Hillen, M. (2003) *Values and emotions; an empirical investigation in the relationship between emotional responses to products and human values* in the Proceedings of the Fifth European Academy of Design Conference, Barcelona University, April 2003

Dewey, J. (1929) *The Quest for Certainty: a study of the relation of knowledge and action* published by Milton Balch, New York

Dowling N (2005) *B of the Bang Prang* and *New fears over B of the Bang* in Manchester Evening News, Manchester Online 21 and 23 May 2005

Downs, J. and Wallace, J. (2004*) Making Sense: Using an experimental tool to explore the communication of jewellery* in McDonagh, D. Hekkert, P. Van Eip, J. and Gyi, D. (eds) Design and Emotion: The Experience of Everyday Things published by Taylor and Francis, London pp 131 -136

Dreyfus, H. and Dreyfus, S. (2003) *Using Computers as Means, Not Ends* in Ennann, M. and Shauf, M. Ed. Computers, Ethics and Society third edition published by Oxford University Press

Dreyfuss H (1955) *Designing for People* published by Grossman, New York p 62

Duerig, T. Pelton, A. and Stockel, D. (1997) *Superelastic Nitinol for Medical Devices* in Medical Plastics and Biomaterials Magazine, March 1997

Epstein, R. (1996) *Capturing Creativity* in Psychology Today July/August 1996 pp 41-43, 75-78

Evamy, M. (1998) *Learning to Harness the Forces of Nature* in Design Week 18 Sept 1998 pp 22-23

Evans, M. (2002) *The integration of rapid prototyping within industrial design practice* PhD Thesis, Loughborough University

Evans, M. A. (2004) *An Investigation into the Capabilities of a Virtual Workshop* in The Journal of Design and Technology Education Volume 9 Number 1 pp 6 - 13

Evans, M. A. Wallace, D. Cheshire, D. Sener, B. (2005) *An evaluation of haptic feedback modelling during industrial design practice* in Design Studies, Volume 26, Issue 5, September 2005, Pages 487-508

Finney, J. (2000) *Curriculum Stagnation: the case of singing in the English National Curriculum* in Music Education Research Vol 2 No 2

Fireman, J. (2004) *Modeling Libeskin's WTC* in Architecture Week 21 April 2004

Fish, K. J. (2001) *Human Error in Medicine: Promises and Pitfalls* in Annals of Emergency Medicine April 2001 issue 37(4) pp 419-20

Fisher, T. (1997) *The Designers Self Identity - Myths of Genius and the Management of Teams* in Creativity and Innovation Management Volume 6 Number 1 pp. 10-17

Fisher, T (2003) *What We Touch, Touches Us: Materials, Affects, and Affordances* in the Proceedings of the 5th European Academy of Design Conference, University of Barcelona, April 2003

Fisher, T. (2004) *What We Touch, Touches Us: Materials, Affects, and Affordances* Design Issues Volume 20 Number 4

Foster, N (2005) *Norman Foster: Catalogue* Prestel Publishing

Friedman, K. and Ainamo, A. (1999) *The Problem Comes First: Establishing Design as a Science- Based Profession* in Proceedings of the Third European Academy of Design Conference Sheffield Hallam University 30 March - 1 April 1999 pp 294 - 316

Friemart, C. and Bruttel, T. (2003) *Tomas Maldonano: From Buenos Aires to Ulmjn* Form und Zweck 20 pp 15 -21

Gaver, B. Dunne, T. and Pacenti, E. (1999) *Cultural Probes* in ACM Interactions Magazine January and February 1999 pp 21 - 29

Getzels, J. and Cszikszentmihalyi, M. (1976) *The Creative Vision - A Longitudinal Study of Problem Finding in Art* published by John Wiley and Sons New York pp 67 - 82

Gharib, M. Kremers, M. Koochesfahani, M. Kemp, M. (2002) *Leonardo's vision of flow visualization* in Experiments in Fluids 33 (2002) 219-223

Ghee, S. (1998) *The Virtues of Virtual Products* Mechanical Engineering Vol 120 issue 6 p60

Gibson, J. J. (1962) *Observations on Active Touch* in Psychological Review Vol 69 No 6 pp 477-491

Gibson, J. J. (1977) *The Theory of ajfordences* in Shaw, Robert and Bransford Perceiving, Acting and Knowing: Towards a Ecological Psychology published by John Wiley, London pp 67 -82

Gibson, J. J. (1979) *The Ecological Approach to Visual Perception* published by Lawrence Erlbaum Associates p 127

Gilbertson, R. (2000) *Muscle Wires Project Book* 3rd Edition, Mondotronics, San Rafael CA pp 1.1 - 1.22

Gledenryd, H. (1998) *How Designers Work - making sense of authentic cognitive activities* PhD Thesis, Lund University

Gleick, J. (2003) *Isaac Newton* Fourth Estate pp 11 - 12, 18, 64, 100, 119-124

Graham-Rowe, D. (2005) *Armed, yes, but not very dangerous* in The Guardian 10 March 2005

Grass, G. (1965) *Dog Years* translated by Ralph Manheim, published by Vintage pp 9, 225 quotation also appears in Mitchell, D. and Nicholson, A. (2002) The Mahler Companion published by Oxford University Press

Gray, J. (2004) *Herecies - Against Progress and Other Illusions* published by Granta, London pp 49-56

Green, S. and Bavelier D (2003) *Action video game modifies visual selective attention* in Nature Volume 423 May 2003 pp 534-527

Guba, E. (1990) *The Paradigm Dialogue* published by Sage pp 17-27

Hadid, Z .(2004) *Zaha Hadid Complete Works* published by Thames and Hudson

Hamlyn, R. and Phillips, M. (2000) *William Blake* Tate Gallery Publishing Limited p 212

Harris, J. (2000) *The Aesthetic Fabrication of Digital Textiles - The Design and Construction of 3D Computer Graphic Animation* PhD Thesis, Royal College of Art

Hawking, S. (2002) *On the Shoulders of Giants* published by Running Press p 731

Heidegger, M. (1927) *Being and Time* trans. Macquarrie, J and Robinson, E (1962) published by Blackwell

Heidegger, M. (1954) *The Question Concerning Technology* trans. Lovitt, W in Farrell Krell, D ed. (2002) 'Basic Wrings: Martin Heidegger' published by Routledge

Hekkert, P. and McDonagh, D. (2003) *Design and Emotion* in The Design Journal Volume 6 Issue 2 pp 1-4

Heskett, J. (1980) *Industrial Design* published by Thames and Hudson pp 206-208

Hodges, M. (1998) *It Just Feels Right* in Computer Graphics World 1998 Volume 21 Number 10 pp 48 - 58

Hohl, M. (2004) *Examples for transforming data of live real world activities into meaningful visual and sensuous output and vice versa* in the proceedings of Pixel Raiders 2, Sheffield April 2004 see also http://www.hohlwelt.com/en/interact.html

Hollerbach, J. Cohen, E. Thompson, W. Freier, R Johnson, D. and Thomson II, T. (2000) *Virtual Prototyping for Human-Centric Design* Proceedings of the NSF Design Manufacturing Research Conference, Vancouver Jan 2000 http://www.cs.utah.edu/gdc/publications/papers/hollerbachOOa.pdf accessed 14 Dec 2005

Hollinghurst, A. *(2004) At home with the creator spiritus* The Guardian, Saturday 30 October 2004

Howard, I. C. Patterson, E. A. and Yoxall, A. (2003) *On the opening mechanism of the aortic valve: some observations from simulations* in Journal of Medical Engineering and Technology Volume 27 Number 6 pp 259-266

Huebner, K. Thornton, E. Byrom, T. (1995) *The Finite Element Method for Engineers* 3rd Edition Wiley New York pp 3 - 13

Hughes, B. and Jansson, G. (1994) *Texture perception via active touch* in Human Movement Science No 13 pp 301-333

Hunter, M. (2003) *Hooke the Natural Philosopher* in Bennett, J. Cooper, M. Hunter, M. and Jardine, L. (2003) *London's Leonardo: The Life and Work of Robert Hooke* Oxford University Press pp 105 - 162

Ignatius, A. (2001) *Hands On* in Time Magazine Volume 157 No 22

Ionita, A. (2001) *Finite Element Analysis of the Deformation of a Rubber Diaphragm* PhD thesis Virginia Polytechnic Institute and State University

Inwood, M. (1997) *Heidegger: A Very Short Introduction* published by Oxford

Inwood, S. (2002) *The Man Who New Too Much - The Strange and Inventive Life of Robert Hooke 1635-1703* published by Macmillan pp 5, 219

Ittzes, M. (2004) *Zoltan Kodaly 1882-1967* in International Journal of Music Education Volume 22(2) pp 131-147

Jackson, B. (1995) *Supra Art: Towards a New Paradigm of Creative Education* in Co-Design No. 3

Jardine, L. (2002) *On A Grander Scale: The Outstanding Career of Christopher Wren* published by Harper Collins pp 294, 420 - 424

Jenkins, W. O. (1947) *The tactual discrimination of shapes for coding aircraft type controls* in Fitts P. M. (ed) Psychological research on equipment design, research report 19, US Army Air Force Aviation Psychology Program

Johnson, S (2005) *Everything Bad Is Good For You: How Popular Culture Is Making Us Smarter* published by Allen Lane

Jones, J C (2004) Contribution at *Designing Design Research 4: Reflecting, Refreshing, Reuniting and Renovating* held at the Royal College of Art, London, UK. Date: Saturday 20th March 2004 http://nelly.dmu.ac.uk/4dd/DDR4/DDR4-frame2.html

Jones, J. C. (1970) *Design Methods: Seeds of Human Futures* published by John Wiley and Sons

Jones, J. C. (1991) *Designing Designing* published by Architecture Design and Technology Press, London pp 15-27

Kaliakin, V (2001) *Introduction to Approximate Solution Techniques, Numerical Modeling and Finite Element Methods* Published by CRC

Kalpakjian, S. (1992) *Manufacturing Engineering and Technology* published by Addison Wesley (Second Edition) pp 16, 17

Kant, I (1787) *Critique of Pure Reason* A 51/B 75 trans Meiklejohn, J (1964) Everyman's Library, London pp 62 - 63

Kant, I. trans. Kemp-Smith, N. ed. Caygill, H. (2003) *Critique of Pure Reason* published by Palgrave Macmillan

Kantrovich, L. (2004) *To Innovate or Not to Innovate* in Interactions Jan/Feb 2004 pp 25-31

Kelley, T. (2001) *The Art of Innovation* published by Harper Collins Business, London pp 37 - 39, 103 - 118

Kemp, M. (2004) *Leonardo* published by Oxford University Press pp 126 - 130

Kimbell, R. et al (1990) *The Assessment of Performance in Design and Technology* Published by the School Examination and Assessment Council pp 18-25

King, R. (2001) *Brunelleschi's Dome: The Story of the Great Cathedral in Florence* published by Pimlico p 43

Kneebone, R. Scott, W. Darzi, A. Horrocks, M. (2004) *Simulation and clinical practice: strengthening the relationship* in Medical Education 38: 1095-1102

Knight, W. (2002) *Thread spun from pure carbon nanotubes* in New Scientist 23 October 2002 www.newscientist.com accessed 12 May 2005

Knight, W. (2004) *Mars rovers set to scale new heights* in New Scientist 12 June 2004 p21

Kuhn, T. (1962) *The Structure of Scientific Revolutions* third edition published by The University of Chicago Press

Kuniavsky, M. (2003) *Observing the user experience* published by Morgan Kauffman pp 28 - 42

Kurowski, P. M. (2004) *Finite Element Analysis for Design Engineers* published by SAE International

La Grange, H. and Weiss, G. (ed) (2004) *Gustav Mahler: Letters To His Wife* published by Cornell University Press p 179.

Lamson, L (2004) *Wren: the man who built Britain* BBC Documentary

Laurel, B. (2003) *Design Improvisation* in Laurel, B (ed) Design Research: Methods and Perspectives published by MIT Press pp 49 - 54

Lederman, S. and Klatzky, R. (1998) *The Hand as a Perceptual System* in The Psychobiology of the hand Connolly, K (ed) published by Cambridge University Press, pp 16-35

Li Wan Po, A. Su, X. Y. (1996) *Over the counter drugs* in BMJ 313:115

Lidwell, W. Holden, K. and Butler, J. (2003) *Universal Principles of Design* Published by Rockport

Liu, T. L. (2005) *Beyond PhD, Expectations from American Industrial Design Industry* proceedings of Joining Forces - University of Art and Design Helsinki 22-24 September 2005

Livio, M. (2002) *The golden ratio: the story of phi, the the Extraordinary Number of Nature, Art and Beauty* Published by Broadway

Maciel, A. Sami, S. Buchwalder, O. Boulic, R. Thalmann, R. (2004) *Multi-Finger Rendering of Deformable Objects* proceedings of Eurographics Symposium on Virtual Environments The Eurographics Association

Macquarrie, J. (1968) Martin Heidegger published by Lutterworth Press

Magee, B. (1973) *Popper* published by Fontana Wm Collins and Co, London pp 65-67

Magee, B. (1998) *The Story of Philosophy* published by Dorling Kindersley, London pp 84 - 87, 102 - 108

Manzini, E (1995) *The Prometheus of the Everyday* in Buchanan R and Margolin V (ed) Discovering Design University of Chicago Press pp 219 - 243

Mahoney, D. (2000) *Innovative Interfaces* Computer Graphics World 2000 Volume 23 Number 2 pp 39 - 46

Malley, C. and Saunders, J. (1952) *Leonardo da Vinci on the human body* published by Schuman pp 265 - 273

Margolin, V. (1997) *Getting to know the user* in Design Studies Vol 18 No 3 pp 227-236

Marzano, S (1998) *Creating value by design: thoughts andfacts* published by Lund Humphries

Materials Foresight (2003) *Smart Materialsfor the 21st Century* Institute of Materials, Minerals and Mining www.iom3.org accessed 4 November 2005

McCullough, M (1998*) Abstracting Craft: The Practiced Digital Hand* published by MIT Press

McDonagh, D. Hekkert, P. Van Erp, J. and Gyi, D. (eds.) (2004) *Design and Emotion, the experience of everyday things* published by Taylor & Francis, London

McDonagh-Philp D and Lebbon C (2000) *The emotional domain inproduct design* The Design Journal Volume 3 Issue 1 pp 31-43

McDonagh-Philp, D. (1998) *Gender and Design: Towards an appropriate research methodology* in Proceedings of the 5th National Conference on Product Design Education Glamorgan University July 1998 (No Page Numbers)

McRobie, A (2000) *Millennium Bridge* entry in_University of Cambridge 125 Years of Engineering Excellence URL: www-g.eng.cam.ac.uk/125/noflash/now/millennium bridge.html accessed 22/04/2004

Morrissey, M. (1998) *Human-Centric Design* in Mechanical Engineering Vol 120 Issue 7 pp 60 - 63

Mumby, V. (2003) *Designfor Technology* in Time Compression Technologies volume 11 issue 5 October 2003 pp 20 - 24

Myerson, J. (2001) *IDEO Masters of Innovation* published by Laurence King, London, p 89

Negroponte, N (1996) *Being Digital* published by Vintage

Newland, D. (2003) *Vibration of the London Millennium Footbridge: Cause and Cure* International Journal of Acoustics and Vibration 8, 1, x-y 2003 also in Proceedings of 9th International Congress on Sound and Vibration, Orlando, Florida (on CD Rom) also available online at http://www2.eng.cam.ac.uk/~den/ICSV9_06.htm and http://www2.eng.cam.ac.uk/~den/ICSV9_04.htm accessed 22/04/2004

Nicholl, C. (2004) *Leonardo da Vinci - the Flights of the Mind* published by Penguin pp 32, 150 - 151

Nikitin, I. Nikitina, L. Frolov, P. Goebbels, G. Gobel, M. Klimenko, S. Nielson, G. (2002) *Real-time simulation of elastic objects in Virtual Environments usingfinite element method andprecomputed Green's functionsjpxotQQ&mgs* of Eighth Eurographics Workshop on Virtual Environments (200) S Muller and W Sturzlinger Eds The Eurographics Association

Nishi, K. et al (2004) *Development of an Implantable Anal Artificial Anal Sphincter Using a Shape Memory Alloy* Journal of Pediatric Surgery Vol 39 No 1 pp 69-72

Norman, D. (1999) *The Invisible Computer* published by MIT Press paperback edition

Norman, D. (2001) *The Design of Everyday Things* Fourth Edition MIT Press p 9

Norman, D. (2004) *Emotional Design: Why we love (or hale) everyday things* published by Basic Books, New York pp 22, 39, 63-89

Norman, D. A. (1988) *The Psychology of Everyday Things* published by Basic Books, New York pp 9, 95

Norman, E. Heath, R. and Pedgley, O. (2005) *The framing of a practice-based Ph.D. in design* URL: www.core77.com/research/thesisresearch.html accessed 24 November 2005

Okasha, S. (2002) *Philosophy of Science - A Very Short Introduction* published by Oxford, pp 77 - 94

Olsen, G. (2002) *The emperor has no labcoat* in Interactions Vol. 9, No. 4 , Pages 13-17

Otake, M. Kagami Y, Inaba, M. and Inoue, H. (2001) *Dynamics of Gel Robots made of Electro-Active Polymer Gel* in Proceedings of the 2001 IEEE International Conference on Robotics and Automation Seoul, Korea May 2001 pp 1457 - 1462

Ottoson, S. (2002) *Virtual reality in the new product development process* in the Journal of Engineering Design Volume 13 Number 2 pp 159 - 172

Ottewell, G. (2005) *Bang sculpture fenced off for repairs* in Manchester Evening News Monday 7 March 2005

Papanek, V. (1984) *Design for the Real World - Human Ecology and Social Change* second edition published by Thames and Hudson

Pering, C. (2002) *Interaction Design Prototyping of a Communication Device* in Interactions November/December 2002 pp 37 - 46

Petrovski, H. (1992) *To Engineer is Human: the role of failure in successful design* published by Vintage Edition, New York p 195

Petrovski, H. (1996) *Invention by Design* published by Harvard University Press pp 169-171

Philips Design (2000) *The New Nomads* www.design.philips.com Accessed 23 April 2003

Polanyi, M (1962) *Tacit Knowing: its bearing on some problems of Philosophy* Review of Modem Physics No 34 pp 601-605

Poole, S. (2005) *What Zelda Did* review of Johnson, S. Everything Bad Is Good For You in Observer July 2 2005 www.books.guardian.co.uk accessed 3 September 2005

Popper, K. (1963) *Conjectures and Refutations*, Routledge London (7th Edition) p 68

Popper, K. (1976) *Unended Quest* Routledge Revised Edition 2002 pp 63, 228

Preece, J. Rogers, Y. and Shaip, H. (2002) *Interaction Design: Beyond Human-Computer Interaction* published by Wiley, New York

Press, M. and Cooper, R. (2002) *The Design Experience* published by Ashgate

Press, M (2000) ,4 *sense of wonder* opening address to the Association of Contemporary Jewellery, International Conference, Birmingham UK 19-22 July 2000

Press, M. (1995) *Buddy, can you spare a paradigm?* in Co Design S3 03 pp 78 - 83

Press, M. (1996) *To bee or not to bee* in Co Design S3 07 08 pp 94 - 97

Purves, L. (2000) *Bouncing in step to the rhythm of life* in The Times, 15 August 2000 http://www.times-archive.co.uk/news/pages/tim/2000/08/15/timopnope01005.html accessed 22/04/2004

Quinton, A. (2003) entry for *Holism* in Bullock, A. and Trombley, S. (ed) The New Fontana Dictionary of Modem Thought paperback edition published by Harper Collins p 400

Raemer, D. and Feinstein, D. (1998) *Simulating Crisis as a Means of Evaluating a Medical Device* in FDA Minimizing Medical Product Errors: A Systems Approach, Bethesda, MD, January 1998

Raine, K. (1970) *William Blake* published by Thames and Hudson, London pp 18, 50, 72, 76

Ramm, E. and Wall, W. A. (2004) *Shell Structures - a sensitive interrelation between physics and numerics* in International Journal of Numerical Methods in Engineering Volume 60 Issue 1 pp 381 - 427

Ramsden, C. and Yen, C. (1999) *Design Culture Within UK Medical Equipment Industry* in Proceedings of the Third European Academy of Design Conference Sheffield, UK, 30 March - 1 April 1999 pp 210 - 234

Ranky, P. (1994) *Concurrent/Simultaneous Engineering (Methods, Tools and Case Studies)* published by CIMware, Guildford pp 21-23, 30, 31
Reason, J. (2000) *Human error: models and management* in British Medical Journal 18 March 2000, pp 768-770

Rees, H. (1997) in Dormer P ed *The Culture of Craft* published by Manchester University Press pp 116-136

Reid, D. (2004) *The expanding use of simulation software to develop superior products in Time Compression Technologies* Volume 12 Issue 3 pp 36 - 41

Richards, P. (2005) *Computers widen gender gap for boys* in The Guardian Monday August 29, 2005 p 5

Richardson, T. (2003) *U T. Dallas Scientists Spin Carbon Nanotube Fibres with Record Strength and Toughness* in Nanotechnology Now 11, June 2003 www.nanotech-now.com accessed 12 May 2005

Rittel, H. and Webber, M. (1972) *Wicked Problems* in Cross, N. Elliott, D. and Roy, R. (ed) (1974) Man-Made Futures The Open University/Hutchinson London pp 272-280

Robinson, J. (1981) *Understanding Finite Element Stress Analysis* published by Robinson and Associates

Rothstein, P. (2000) *Ethnographic Research: Teaching a young profession old tricks* in Innovation Winter 2000 pp 33 - 38

Ruckert, F *Blicke mir nicht in die Lieder* (Do not look at my songs!) translation The Decca Record Company, London (1979)

Rust, C. (2004) *Design Enquiry: Tacit Knowledge and Invention in Science* in Design Issues Volume 20 Issue 4 pp 76 - 85

Rust, C. Whiteley, G. and Wilson, A. (1999) *First Make Something - Principled, Creative Design as a tool for multi-disciplinary research in Clinical Engineering* Proceedings of 4th Asian Design Conference, Nagaoka, Japan, October 1999, 733-743

Rust, C. Whiteley, G. and Wilson, A. (2000a) *Experimental Making in Multi-Disciplined Research* in The Design Journal Volume 3 Issue 3

Rust, C. Hawkins, S. Whiteley, G. and Roddis, J. (2000b) *Knowledge and the Artefact* in the Proceedings of the Conference on Doctoral Education in Design La Clusaz France published by Staffordshire University Press pp 395 - 404

Rust, C. Chamberlain, P. and Roddis, J. (2000) *A Practice-Centred Approach to Research in Industrial Design* Proceedings of Design plus Research Conference, Politecnico di Milano, May 2000

Sadie, S. and Latham, A. (1990) *The Cambridge Music Guide* published by Cambridge University Press pp 261-280

Saks-Cohen, J (1997) *Learning from experience* in Innovation Volume 16 Number 3 (Fall 1997) pp 37-39

Sanders, E. (1999) *Postdesign and Participatory Culture* in the Proceedings of Useful and Critical: the position of research in design University of Art and Design Helsinki Finland available online at www.sonicrim.com

Sanders, E. (2000) *Generative tools for co-designing* in Collaborative Design Scrivener S Ball L Woodcock A (eds) published by Springer-Verlag London available online at www.sonicrim.com

Sanders, M. and McCormick, E. (1993) *Human Factors in Engineering and Design* 7th edition published by McGraw Hill Inc, pp 184 - 196 and pp 334 - 344

Sandhana, L. (2004) *Is That a Pilot in Your Pocket* Wired News 23 October 2004 www.wired.com/news accessed 9 November 2005

Santer, M. and Pellegrino, S. (2005) *Asymmetrically-Bistable Tetrahedra* in the proceedings of AIAA-2005-2104 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 13th AIAA/ASME/AHS Adaptive Structures Conference, Austin, Texas, 18-21 April 2005

Santer, M. J. and Pellegrino, S. (2004) *An Asymmetrically-Bistable Monolithic Energy-Storing Structure* in Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC Structures. Structural Dynamics and Materials Conference, Palm Springs, CA, April 2004 American Institute of Aeronautics and Astronautics

Scanlan, R. (2002) *Observations on Low-speed Aeroelasticity* in Journal of Engineering Mechanics Vol 128 Issue 12 pp 1254-1258

Schioler T and Pellegrino S (2004) *Multi-Configuration Space Frames* Proceedings 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Palm Springs California, USA, April 2004

Schmidt, K. (2004) *The future of biotech* in New Scientist 10 July 2004 pp 50 - 53

Schon, D. (1983) *The Reflective Practitioner: How Professionals Think In Action* published by Ashgate Arena (Second Edition) pp 171 - 176

Scruton, R (2001) *Kant - A Very Short Introduction* published by Oxford University Press p 27

Sener, B. and Van Rompuy (2005) *In touch with consumers: Freeform® as a co-design tool for real-time product modification* in The Design Journal Volume 8 Issue 1

Sener, B. Wormald, P. Cambell, I. (2002) *Towards 'virtual clay modelling' - challenges and recommendations: a brief summary of the literature* in the proceedings of Design 2002, Dubrovnik May 14-17 2002.

Seymour, R. (1990) *Engineering Polymer Sourcebook* McGraw Hill Publishing

Shaw, N. (2003) *Emergency Service* in New Design January/February 2003

Sheil, B. and Packman, R. (2005) *Making a Bang* in AD Volume 75 Number 4 July-August 2005 pp 70 - 77

Shelley, T. (2004) *Dolphin tail doubles fluid efficiencies* in Euraka Magazine May 2004, pp 26-27

Sherman, L. M. (2004) *3D Printers Lead Growth of Rapid Prototyping* in Plastics Technology URL http://www.plasticstechnology.com/articles/200408cu3.html accessed 3 March 2004

Shillito, A. Scali, S. and Wright, M. (2003) *Haptics: for a more experiential quality in a computer interface* in the Proceedings of the 5th European Academy of Design Conference, University of Barcelona, April 2003

Shillito, A. Wright, M. Gauldie, D. (2004) *The TACITUS experience: a new spatial, multi-sensory digital interface supporting creativity* in the Proceedings of Pixel Raiders 2, Sheffield Hallam University, 6-8 April 2004 (CD ROM)

Sim, W. Y. Yoon, H. J. Jeong, O. C. and Yang, S. S. (2003)^4 *phase-change type micropump with aluminumflap valves* in Journal of Micromechanics and Microengineering 13 pp 286-294

Singmaster, D. (2003) *St Pauls Cathedral* in The British Society for the History of Mathematics Gazetteer - London Part Three
WAvw.dcs.warwick.ac.uk/bshm/gazetteer.html (accessed 13 July 2005)

Soller, M. (2004) *Be all thatyou can be - virtually* in Los Angeles Times June 11 2004

Stanton, N. and Young, M. (1999*) A Guide to Methodology in Ergonomics - Designingfor Human Use* published by Taylor and Francis, London
Stephen, M. (2005) *Designs on Nature* BBC Radio 4 broadcast March 16, 2005

Strogatz, S. Abrams, D. McRobie, A. Eckhardt, B. and Ott, E. (2005) Theoretical mechanics: Crowd synchrony on the Millennium Bridge in Nature 438 pp 43-44

Subrahmanyam, K. Greenfield, P. Kraut, R. Gross, E. (2001) *The impact ofcomputer use on children's and adolescent's development* in Applied Development Psychology No 22 pp 7 -30

Subrahmanyam, K. Kraut, R. Greenfield, P. Gross, E. (2000) *The Impact ofHome Computer Use on Children's Activities and Development* in The Future of Children: Children and Computer Technology Vol 10 No 2 p 123 - 144

Suchman, L. (1987) *Plans and Situated Actions: The Problem ofHuman-Machine Communication* pubished by Cambridge University Press

Sudjic, D. (2001) *Blade of light the story ofLondon's Millennium Bridge* published by Penguin Books, London 88-93

Summers, A. & Bensusen, S. J., (2001) *A Fish Story. The spinypuffer's means of defence is hard to swallow* Natural Histoiy Magazine, American Museum of Natural History, October 2001 pp 86-87

Toft, B. (2001) *External inquiry into the adverse incident that occurred at Queens Medical Centre, Nottingham on 4 January 2001*
Avww.doh.gov.uk/qmcinquiry/index.htm Accessed: July 18, 2002

Torrens, G. (1998) *User-Centred Design* Loughborough University http://www.lboro.ac.uk/departments/cd/docs_dandt/research/ergonomics/dil/Research4.htm accessed March 2005

Vincent, J. (2002) *Stealing ideasfrom nature* in Deployable Structures ed. Pellegrino, 5. published by Springer, Vienna pp. 51-58

Vincent, J. and Parr, A. (accessed April 2005) *What is Biomimetics?* transcript of an interview originally broadcast on New Zealand Radio http://www.bath.ac.uk/mech-eng/biomimetics/nzradint.htm

Virilio, P (2000) *The Information Bomb* published by Verso Books

Virilio, P (2005) *City ofPanic* published by Berg

Wallace, J. and Press, M. (2004) *All This Useless Beauty: Finding beauty through craft and digital technology* in the proceedings of Pixel Raiders 2 International conference on craft and digital technologies, Sheffield Hallam University, April 2004

Walters, P. Chamberlain, P. and Press, M. (2003) *In Touch - An investigation of the benefits of tactile cues in safety critical product applications* in the Proceedings of the 5th European Academy of Design Conference, University of Barcelona, April 2003

Walters, P. Chamberlain, P. Press, M. and Tomes, A. (2004) *Designing by Numbers - Keeping the Human in Human-Centred Design* in the proceedings of Pixel Raiders 2 Sheffield Hallam University April 2005

Warburton, N. (2001) *The impact of three dimensional digital modelling media on the modes of communication used by industrial designers PhD thesis Northumbria University*

Ward L (2004) *Computer games "can help children learn"* in The Guardian Education Supplement October 27, 2004 www.guardian.co.uk

Ward, A. (2002a) *Sixth Sense* in New Design, January-February 2002 pp 36-39

Ward, A. (2002b) *The bigger picture* in New Design March-April 2002 pp 58-60

Wears, R. (1999) *Human Error in Emergency Medicine* in Annals of Emergency Medicine September 1999 issue 34(3) pp 370-372

Weerdesteijn, J. Desmet, P. and Gielen, M. (2005*) Moving design: to design emotion through movement* in The Design Journal Vol 8 Issue 1

White, M. in Bothwick, J. (2003) *Power to the People* in New Design January/February 2003 pp 34-37

Whiteley, G. (2000) *An Artificial Skeletal Analogy of the Human Upper-Limb* PhD Thesis Sheffield Hallam University

Whyte, J. (2002) *Virtual Reality and the Built Environment* published by Architectural Press

Woods, K. (2001) *The Prevention of Intrathecal Medical Errors: A Report to the Chief Medical Office* http://www.doh.gov.uk/imeprevent/ Accessed January 22, 2003

Yacoub, M. Cohn, L. (2004) *Novel Approaches to Cardiac Valve Repair* in Circulation 109 pp 942-950

Zhang, M. Atkinson, K. Baughman, R. (2004) *Multifunctional Carbon Nanotube Yarns by Downsizing an Ancient Technology* in Science Vol 306, 19 November 2004 pp 1358 - 1361

Appendix 1

Well Connected Part 2

Visit to the Centre for the Integration of Medicine and Innovative Technology, Cambridge, Massachusetts

In Boston Public Gardens stands a monument. On top of the monument is a sculpture depicting the parable of the Good Samaritan; the biblical story of an injured traveller who receives help from a stranger. The monument, dating from the mid nineteenth century, commemorates the revolutionary discovery made by surgeons in Massachusetts General Hospital of the anaesthetic properties of ether.

In September 2003, the author travelled to Boston, Massachusetts to present preliminary findings of research into the design of medical connectors to Professor Daniel Raemer of the Harvard/MIT Centre for the Integration of Medicine and Innovative Technologies. Professor Raemer is Associate Professor of Anaesthesia at Harvard Medical School and is also leading expert on the use of simulation technologies in medical training. The aim of the meeting was 1) to elicit feedback from Professor Raemer on the project and its outcomes so far and 2) to discuss the feasibility of using a medical simulator for product testing in realistic medical scenarios.

The Centre for Medical Simulation (CMS) is a fully equipped clinical facility based at the Centre for the Integration of Medicine and Innovative Technology, Cambridge, Massachusetts. The simulation centre has two state-of-the art medical simulators each consisting of a realistic mannequin “patient”, hardware actuation system and computer workstation. The simulation system provides extremely realistic physiological responses to numerous clinical procedures and medications.

The centre provides training to physicians in the principles of crisis resource management (CRM). The training courses consist of a series of scenarios where medical events are simulated. Trainees and CMS staff act out the roles of clinical personnel, in scenarios that simulate adverse clinical events. Following the scenarios, trainees review the videotaped simulations with CMS staff as part of a debriefing session.

Figure 1 View from the control room at the Harvard-MIT Centre for Medical Simulation

Peter Walters presented preliminary findings of the investigation into the design of a new identification system for medical connectors which aims to help prevent potentially fatal misconnection errors in the administration of anaesthetics and other drugs to hospital patients. Professor Raemer was extremely encouraging about the progress made on the project so far. He recounted a number of cases having occurred in the US involving both misconnection errors, and also misidentification of drug “cassettes” used in pump delivery systems. He described the problem as a ***brainer*** ” and identified the fact that as yet there is not a standardised identification system to distinguish between drugs for spinal and intravenous delivery.

He was not aware of any similar studies being carried out by researchers elsewhere, and he said that the work presented was certainly worthwhile. He noted that one delivery system manufacturer had introduced a coloured stripe on the drug delivery line to distinguish between epidural and intravenous routes. However, other means of visual and/or tactile identification had not been explored. Professor Raemer is not in favour of relying on colour coding as a means of identification, since this can lead to confusion due to the various colour coding systems already used in hospitals. Drug misidentification and misconnection scenarios have been included in simulator training at CMS.

Regarding prototype testing, Professor Raemer stressed the importance of testing in a realistic user environment. Citing a recent research paper:

> *“the power of realistic simulation to uncover problems in the medical device design prior to clinical use that would be difficult to discover by casual observation... the realistic context and urgency of the simulation highlight design problems that may not be apparent in the typical device design and review phases. ”*

(Raemer and Feinstein, 1998 www.harvardmedsim.org/FDA_oo_l.htm)

Professor Raemer recommended contacting the Medical Simulation Centre in Bristol, UK, since it would provide a practical location for conducting end-user testing. Professor Raemer has worked with staff based at the Bristol simulator, and said he was sure they would be interested to help with the project.

Professor Raemer also suggested that the international conference of the Society would be an appropriate platform for dissemination of the research to a medical audience, and would provide a means of attracting support for the project from other interested parties.

Subject to obtaining funding for future research, the project team led by Professor Chamberlain plan to work with a medical simulation centre in the UK. It is hoped that, with the support of experienced healthcare specialists, a programme of realistic testing of the prototype medical connectors will be undertaken. Furthermore, the Society for Technology in Anaesthesia conference may provide an ideal opportunity to present the outcomes of future research.

Designing by numbers?
Keeping the *human* in human-centred design

Peter Walters, Paul Chamberlain, Mike Press, Anne Tomes
Art and Design Research Centre,
Sheffield Hallam University

Abstract

> *'The feel of the physical about us is being lost due to the intervention of computerised equipment and work is becoming an abstraction from the real world... knowledge has been abstracted away from the labour process and has been rarefied into mathematical functions... In my view, profound problems face us in the coming years due to this process.'*
>
> Cooley (1980)

Virtual reality technologies play an increasingly significant role within new product development processes. Advocates of these rapidly emerging technologies claim that computer-based product simulations provide significant benefits, including shorter development times and a reduction in the number of prototype iterations required to get a product concept off the virtual drawing board and onto the production line.

This paper argues that physical prototyping should be retained as an essential element of the human-centred design strategy. Designing for physical action requires both the designer and the end-user to develop an intimate understanding of the *task in hand*, experienced through all of the human senses. This highlights the multi-dimensional nature of design, where opportunities for innovation are revealed through discovery-oriented physical prototyping.

Case studies are presented from the field of medical and healthcare product design. These demonstrate the effective use of multiple prototyping methods in parallel; designers used a combination of *hands-on* physical prototyping, alongside virtual and rapid prototyping techniques, to develop and communicate the multisensory qualities of products. The paper highlights the complex, evolutionary nature of the design activity, and the role of physical prototyping within human-centred design practice.

Walters, P; Chamberlain, P; Press, M and Tomes, A (2004) 'Designing by numbers? Keeping the human in human-centred design' in the proceedings of *Pixel Raiders* 2, Sheffield Hallam University, UK 6-8 April 2004

Designing by numbers?
Keeping the *human* in human centred design

1 Introduction

This paper highlights the human element in design. Through case studies, we explore the evolutionary nature of the design activity, and the role of physical prototyping within human-centred design practice. Designing for physical interaction requires both the designer and the end-user to develop an intimate understanding of the *task in hand,* experienced through all five of the human senses. This highlights the multi-dimensional nature of design, where opportunities for innovation are revealed through discovery-oriented physical prototyping.

The benefits of user-centred design have been widely discussed, within Product Design discourse, and also in the disciplines of Human Computer Interaction (HCI), Human Factors Engineering and Ergonomics (Norman 1988, McDonagh-Philp 1998, Preece, Rogers and Sharp 2002, Stanton and Young 1999).

Human-centred design is a broader concept; a holistic approach that explores the relationships between the designer, the end-user(s), and the other ‘stakeholders’ within the system of production and consumption. This may include those who manufacture, transport, sell, carry out maintenance, or dispose of the product or system at the end of its useful working life. The role of the designer becomes that of'advocate', within a system of production and consumption that is socially and ethically responsible (Papanek, 1971).

2 The historic case of the Design Methods movement versus Heskett’s ‘..vital human element...’

Heskett (1980, 2002) and Friedman (2000) introduce design as an activity common to all humans; the ability of humans to shape their surroundings and to create objects that extend their capabilities and improve quality of life. From the earliest shelters and tools used for hunting and the preparation of food, through the pre- industrial, industrial and post-industrial revolutions, patterns of designing have evolved (Heskett, 2002, Broadbent, 2003).

This evolution in the patterns and processes of designing might begin with the individual objects that were the products of craftwork and skilled artisans, through design by drawing, mechanisation and industrial-scale mass production, to the rapid development of information and communication technologies and flexible manufacturing systems in the late twentieth century, that enable the creation of products and services to meet the needs of individual consumers.

The Design Methods movement, introduced by academics in the 1960s, was an attempt to make design respond better to the increasing complexity of social and technological structures.

Heskett (1980) describes Design Methods as *'a rational, analytical sequence intended to identify the fundamental nature of any given design problem, enabling a solution to be devised to meet defined needs.'* This positivistic ‘Hard Systems’ approach was rejected by the design community as a whole since it did not fit with the often intuitive activities of practicing designers, and failed to provide what Heskett (1980) refers to as the '... *vital human element* ’of designing.

The ‘Hard Systems’ of the Design Methodologists gave way to a ‘Soft Systems’ approach, which draw on methodological frameworks from the social sciences, in an effort to bring design ‘closer to the users’, and other stakeholders in the process of production and consumption.

Preece, Rogers and Sharp (2002) describe a *'participatory approach'* applied by usability specialists working in human computer interaction (HCI):

'.... *users are actively in involved in development. The intention is that they* (the users) *become an equal partner in the design team, and that they design the product in co-operation with the designers'*

One criticism of this approach is that, in most cases, users are not designers. Whilst end-users can inform the design process in a uniquely valuable way *'... they do not necessarily know the best solution to the problem'.* (White, in Bothwick, 2003); *'the Skill of the designer is first to abstract consumer needs and aspirations, and then to give them material form.'* (Rees in Dormer ed. 1997).

Designers are not in the business of simply providing what users say they think they want; innovation requires designers to interpret user research in a creative and intelligent way. Proponents of developing areas such as design ethnography and user-participatory design often come from areas outside of design, and so perhaps find it difficult to understand the informal, intuitive “methods” at work within creative design practice.

And so, just as the products of design activity are continuously changing, the patterns of designing continue to develop and evolve. Broadbent (2003) describes this evolution in his ‘Generations of Design Methodology’, proposing an ‘Evolutionary Systems Methodology’ for design. Drawing on the evolutionary theories of Ervin Laszlo, Broadbent describes an approach to designing that is embedded within the complex, dynamic nature of social and technological systems.

3 Evolutionary Design

The Design Methods movement was widely criticised for its reductionalistic approach, and for failing to address ‘higher-order’ questions (eg Heskett 1980, Mitchell 1993, and Broadbent, 2003). More recently, similar criticisms have been voiced against so-called ‘usability methods’, particularly those employed within the fields of Human Computer Interaction and Human Factors Engineering (eg Olson 2002, and Gaver 2003)

Human activities are complex and unpredictable. Therefore the processes of endeavour aimed at improving quality of life and extending human capabilities are likely to be both unpredictable and non-algorithmic[1] in nature.

---

[1] Algorithm: A sequence or set of rules to be followed in problem solving activities (adapted by the author from the Oxford English Dictionary).

(See also Taylor 2001, Amabile 1990)

Chaos theory and the sciences of complexity are embraced by Ervin Laszlo (1996) in his General Theory of Evolution. Laszlo describes how social and technological changes come about through a combination of iterative “stepwise” developments (Popper’s ‘Conjectures and Refutations’), and dramatic revolutions or ‘Paradigm Shifts’ (Kuhn). In his Evolutionary Systems Methodology, Broadbent (2003) considers the processes of social and technological change that influence design, describing these in terms of Laszlo’s evolutionary theories.

In order to cope with complexity and the accelerated pace of social and technological change - the driving force behind the quest for innovation - designers may use multiple methods in parallel. Quick and dirty methods (rapid ethnography; user-participatory design with soft-modelling materials; the iterative making and testing of low-fidelity prototypes) may be employed both intuitively and informally, designing “on the hoof’. By doing this, designers hedge their bets and literally ‘make their own luck’, creating opportunities for unexpected, serendipitous discoveries. (Kelly 2001, Myerson 2001).

L*avo*

Darwin's Finches
ADAPTIVE RADIATION!

■Stubs

Tool Using Finch

*"**Patches**from dal&pagos Archipelago." Variations on the Ceuspaa. from Charles Darunn.* The Vevapr of (he Beadle */Colin **ni„ 1909).***

Figure 1 **Darwin’s finches**

The evolutionary nature of design mirrors evolutionary design in nature (images from Hardison, 1989)

4 Designing: Real or virtual?

The abacus, one of the earliest "computers", has a multi-sensory interface. The human senses of sight, sound, and touch provide the user with a multidimensional experience of the mathematical activities performed with this "simple" physical tool (Ishii and Ulmer, 1997).

As the technologies, patterns and processes of designing evolve, virtual reality plays an increasingly significant role within new product development processes. Advocates of these rapidly emerging technologies claim that computer-based product simulations provide significant benefits, including shorter development times and a reduction in the number of prototype iterations required to get a product concept off the virtual drawing board and onto the production line. (Davey 2003, Ghee 1998, Hollerbach, et al 2000)

However, a counter-argument to the designer's "total immersion" in the virtual design environment is that physical prototyping should be retained as an essential human element in the product development strategy. Designing for physical action requires both the designer and the end-user to develop an intimate understanding of the *task in hand,* experienced through all five of the human senses. This highlights the multi-dimensional nature of design, where opportunities for innovation are revealed through discovery-oriented physical prototyping. Since the products they create will ultimately exist in the real world, designers need "hands-on" interaction with real physical prototypes in the real physical world. Designers literally construct their own realities, which later become the realities of other people.

In the United Kingdom, the art school tradition of design education embodies the constructivist paradigm (Guba, 1990) of problem-based "learning through doing". Students are encouraged to ask the question: "What happens if I do this?" and, at the same time as learning to make and learning how things are made, experience for themselves the act and art of "making to learn" (Kimbell et al, 1990).

Prototypes unlock design knowledge by providing a tangible bridge between the designer and the end-user (Chamberlain, Roddis, Press, 1999; Rust, Whitely et al. 2000). The physical prototype becomes a probe or "provocative agent", through which the designer elicits knowledge of the design task, end-user requirements and context for design.

The emergent "time compression technologies", including so-called desktop rapid prototyping (RP) provide physical outputs from virtual design systems. Such systems go some way towards the accelerated craft evolution of designed objects, as predicted by Broadbent (2003) and others. However, in many cases it is still more efficient in design terms to "hand-make" a large number of quick low fidelity prototypes than just a few higher-fidelity prototypes via CAD and desktop RP. With CAD-based prototyping, the designing literally takes place behind a glass screen. Whilst interfaces are often counter-intuitive, even to the most lucid of CAD-savvy designers, the level of control available within the software acts to suppress the kind of happy accidents that occur in real-world prototyping. Recently introduced 'haptic' interfaces are a still a long way off representing what it is like to manipulate real materials in the workshop.

Wilson (2001) describes an experience he had when teaching furniture students at the Rhode Island School of Design. One of Wilson's students had stated that he could not imagine being a designer without having a computer '... to make work easier.' Wilson asked the student what he considered the purpose of computer technology to be, and the student reiterated the view that the purpose of technology in this case was to make designing easier and to enable products to be manufactured quicker and cheaper.

Wilson then asked the student if he considered the piano to be an example of technology, and, if so, what the purpose of the technology was. The student answered that the piano might not be the best example of a 'labour saving device', but that advancement in piano technology would probably improve tone production or make the instrument easier to play. Wilson suggests that the student' ...might not fully appreciate the long history of co-evolution of technology and technique... observing that '...until quite recently one always expected that a machine implied a machinist to operate it, just as a piano implied a pianist to play it. And no matter how well a piano might be constructed, it was just an over-engineered paperweight without a pianist.'

Wilson continues 'Your computer.... certainly can produce more notes but it isn't likely to stimulate the creation of more pianists. And while there certainly are many (mostly untrained) pianists looking for computer technology that that will make it easier for them to get music out of a keyboard, such an idea is an anathema to the vast majority of artists. Their public ambition is to please audiences. Their private ambition is to see their own artistry and musical understanding increase.'

He goes on to state:

> 'My interviews with people who work with their hands (not just at the piano) have convinced me that some people, at least, look forward to not less work but to more satisfying and personalized work and to those days when they find themselves becoming something other than what they were before.'

The cerebral processes of learning, understanding and knowing are often discussed in metaphorical language that describes the physical actions of the hands. For example:

> "have you grasped that... ?"
>
> "Are you in touch with your true feelings?"
>
> "We like to encourage hands-on teaching and learning."

In design, there is a direct relationship between knowledge and discovery, and physical prototypes made with the hands.

Figure 2 Watson and Crick

Physical modelling informed the discovery of the double helix
structure of DNA (Rust 2004, Kelley 2001
Image: www.nature.com/nature/dna50/index.html
accessed 21 February 2006)

However, as the technologies become ever more sophisticated, virtual prototyping continues to develop. Already proven in the design of products and systems containing a large number of complex elements, manufacturing systems built around these technologies will provide customisable designs that are flexible enough to meet the requirements of individual users. But users of “tailor made” sports products and fashion items are not the only likely beneficiaries. The technologies are proving to be especially valuable in medical applications, since they enable complex surgical procedures (for example, those involving prosthetic implants) to be trialled virtually before being conducted on real patients. (Rosner, 2002)

But, from a designer’s perspective, there may be no substitute for hands-on prototyping. In many cases this continues to be used to support design work undertaken in CAD, providing further supporting evidence for the use of multiple “design methods” in parallel. The authors therefore advocate an approach designing that is flexible and adaptable enough to accommodate the benefits of both physical and virtual techniques.

5 Case studies in multisensory design from the medical and healthcare sector

A traditional view of the industrial design profession is that it tends to be preoccupied with *visual* appearance, at the expense of other factors. In America, the first industrial designers were known as "stylists", since their chief concern was the cosmetic appearance of products (Chamberlain et al 1999, Margolin 1997, Rothstein 2000). However, a change of direction appears to be taking place, as Moggridge (in Myerson, 2001) Heskett (2002) and Ward (2002) identify a demand from end-users for products that satisfy all five senses, not just the visual.

The following case studies present projects from the medical and healthcare sectors that explore the multisensory qualities of products. The case studies, carried out by industrial designers working in an academic context, demonstrate a human-centred approach using different design “methods” in parallel, and how this approach has resulted in successful design outcomes

Case Study 1 Vibro-acoustic furniture

Chamberlain (in Chamberlain and Roddis, 2003, Chamberlain, Roddis and Press, 1999 and Rust, Whiteley and Roddis 2000) describes the development of vibro-acoustic furniture to be used therapeutically by children who are profoundly deaf, or both deaf and blind. The furniture allows people with sensory impairments to experience sounds and music, through the vibration of loudspeakers enclosed within furniture.

Early on in the project, the designers were able to discuss ideas with therapists who had expertise in working with children with sensory impairments, and also with loudspeaker technologists and potential manufacturers. However, because of their disabilities, the end users (i.e. the children) could not actively participate in the research until the designers produced working physical prototypes with which they could interact. The prototypes allowed the children to control their own sensory experiences.

The designers found that the working prototypes acted as a bridge between themselves, the therapists and the children, revealing new knowledge about the therapeutic needs of the end user, and also as a catalyst for further research and investigation.

The vibro-acoustic furniture developed by Chamberlain is manufactured and distributed in the UK by Rompa Limited. In 2000 the “Tactile Sounds System” received two Millennium Product Awards from the UK Design Council.

Figure 3 **Tactile Sounds System**

Chamberlain, 2003

Case study 2 Multisensory learning aid

Anderton and Purcell (2003) have developed a novel computer interface for use by children with physical disabilities or who have special educational needs. The product uses barcode scanning technology to enable users who would find it difficult or impossible to operate a conventional personal computer to control specially-developed multimedia learning activities.

Physical objects (such as toys or common household objects) can be fitted with a barcode tag, which, when placed on the interface, will trigger responses such as sounds, words or pictures from learning software on a standard multimedia PC. The interface provides a link between the 'real' and 'virtual' thus engaging the user with a greater sensory experience and understanding.

Anderton established a supportive network of schools and day centres, where he undertook observational research and discussion with end-users including teachers, therapists and carers, as well as the children themselves. Throughout the development process, Anderton worked closely with the user group, involving them in the design of the learning activities and introducing early working models as well as more developed ‘pre-production’ prototypes in order to elicit feedback on his designs.

The response from end-users was very positive. Therapists and carers reported that children whose behaviour was often withdrawn and distant appeared excited and animated when using the new interface.

Purcell continues to develop the product in partnership with Rompa Limited and staff at Sheffield Hallam University. The designers are currently exploring how the device might interact with Rompa’s other products, such as the “Tactile Sounds System” described above, as well as other possible applications for the learning technology.

Figure 4 **Multisensory learning aid**

Anderton and Purcell, 2003

Case study 3 Tactile identification system for medical connectors

Chamberlain and Walters (2003) have undertaken research that explores the potential benefits of tactile cues within safety-critical product applications (Walters, Chamberlain and Press, 2003). The project, carried out in collaboration with psychologists from the University of Leeds and healthcare professionals from Bradford Royal Infirmary, investigates how contrasting shapes and textures might be applied to medical connectors, to help prevent potentially fatal misconnection errors.

Current drug delivery systems utilise the universal ‘Luer’ connector. Within this system, there is no distinction between connectors used for different drugs or different delivery routes into the body (eg spinal, intravenous, respiratory). A number of fatalities have occurred because patients have been connected to the wrong drug, or because a drug has been mistakenly administered through the wrong delivery route. The project aimed to develop an identification system for medical connectors exploiting a combination of visual and tactile cues, to help prevent misidentification. The new identification system would be used in conjunction with a “failsafe” mechanical system, designed to prevent misconnection.

Initially, the designers undertook observational research and discussion with staff working in both the intensive care and anaesthetics departments at Bradford Royal Infirmary. This helped designers develop their own understanding of the context for design, and their knowledge of some of the specific design problems to be addressed within the project.

Design of the prototype connector components took place within a 3D CAD environment. Because of the small scale of the components, and the intricate nature of the surface details, it was very difficult to produce accurate physical sketch models of the tactile shapes. Up to this point in the development process, the designers had to rely on tacit knowledge; an intuitive sense of how the shapes might feel to the touch, based on previous experience handling 3-dimensional form and materials (Rust, 2004).

Q ^ O O O #

Figure 5 **Tactile medical connectors**

3D CAD models (Chamberlain and Walters 2003) ill

vanous surfao* toriurw*

longdudirsl ribs

w ocm vdn

t'ansversa r<»

diagonal new

orO® triangle add tq jare crow Mdiorts

chaquarad tiianpa

000006
o o o o o o
ôôôôôô
hem spbenui bumps

Figure 6 **Contrasting shapes and textures**

(Chamberlain and Walters, 2003)

Drug Package

Tubing —

Spinal Needle

Mating Elements

Mating Elements

Figure 7 **Systems Approach:**

The elements of the drug delivery system are linked by mating components that have a distinctive shape and surface texture. These can therefore be matched like-for-like with the other elements in the system.

(Chamberlain and Walters, 2003)

It was only through the production of a series of prototype component sets that the tactile qualities of the components could be evaluated. These were produced by rapid prototyping on a stereolithography (SLA) system. The physical models formed the basis of "blind" identification tests conducted by psychologists from the Human Factors Research Centre at the University of Leeds. Early findings from the study were extremely encouraging. The tests showed that participants could identify the tactile components using only the sense of touch, even when wearing surgical rubber gloves.

Figure 8 **Prototype connector components**

(Chamberlain and Walters, 2003)

Figure 9 **"Blind testing"**

Carried out by the Human Factors Research Group, University of Leeds. Early results showed rates of error in tactile identification were extremely low, even when participants wore surgical gloves.

The project has now been presented to the European Safety Standards Advisory Committee for medical devices (CEN), and the UK Government Department of Health. Proposals for future research include integrating the tactile identification system with the failsafe mechanical system described earlier, and also an investigation of tactile object differentiation through contrasting materials as well as shape and surface texture.

6 Discussion and Conclusions

Human centred design is an approach to designing that engages with end-users and other stakeholders in the process of production and consumption.

In the case studies, designers worked with a range of stakeholders, who actively participated in the development process. In all three examples, the designers were instrumental in providing a link between disciplines, for example, between healthcare professionals, technology specialists, psychologists as well as end-users. However, whilst the knowledge elicited through stakeholder intervention was essential to the successful development of the products, it was the designers who took ownership and responsibility of the creative decision-making.

The case studies explored the multisensory qualities of products. This highlighted the need for physical prototypes, and the multidimensional nature of the design activity. The products themselves *evolved* through a series of prototype iterations, which enabled stakeholders to respond by giving ongoing feedback to the design team.

In the development of a tactile identification system for medical connectors, designers informally made use of multiple design methods in parallel. The methods included observation, discussion and end-user participation in the designing activity, as well as iterative making and testing of physical prototypes.

The project *connected* real and virtual design worlds. Whilst the design of the tactile connectors was carried out in 3D CAD, the designers relied on an intuitive sense of how the components might feel to the touch. Through the production of a series of physical prototypes from the 3D CAD data, the tactile qualities of the test components could be evaluated with end-users. The case studies illustrate the use of multiple design methods, and how designers had to make decisions based on instinct and intuition.

Designing requires human judgement; instinct, intuition and tacit knowledge *'the things we know but cannot tell'* (Cooley, 1988, after Polanyi). Knowledge that is difficult to express in words can be revealed through the physical action of designing, and the interaction of end-users with the products of the design activity. In a design culture that increasingly emphasises the *virtual,* the need for *physical* making and testing of objects that will ultimately inhabit the *real physical world* must not be neglected.

The role physical modelling within human-centred design practice has been explored, and also the analogous models of design activity that help to explain the methods at work within the design activity.

We do not advocate an extension of the reductionalist Design Methods movement, which Heskett (1980) described as *'a rational, analytical sequence intended to identify the fundamental nature of any given design problem, enabling a solution to be devised to meet defined needs.'*

Heskett continues:

> *'For many designers, rational analysis alone is too deterministic and impersonal… an intuitive synthesis and instinctive feeling for the "rightness" in form is regarded as necessary to ensure individuality of expression and a vital human element in design'*

Similarly, Rust (2004) reminds us that the significant discoveries that often lead to innovation in design are not solely the product of logical reasoning or iterative development. Rust refers to the work of Michael Polanyi (1958) when describing the *'logical gap'* between existing knowledge and a new discovery or *inventive step,* and the leap of *'illumination'* that takes place when the discovery is made:

> *'Illumination … is the is the plunge by which we gain a foothold in another shore of reality'*
> (Polanyi, 1958, p128)

A personal interpretation of this view is expressed in the following way:

Successful design is a strategy of innovation and creativity that requires a leap of faith and imagination, underpinned by knowledge.

Human centred design embraces the *vital human element,* by exploring the relationships between the designer, the users, and other stakeholders; those who depend on the *products* of creative design practice.

7 Bibliography

Amabile (1990) 'Within You, Without You - The Social Psychology of Creativity, and Beyond' in 'Theories of Creativity' ed. Runco and Albert pp 62-63

Broadbent (1984) ‘The Development of Design Methods’, in N Cross (Ed) Developments in Design Methodology, Wiley, pp 337-345

Broadbent (2003) 'Generations in Design Methodology’ in The Design Journal Vol 6 Issue 1 pp 2-13

Chamberlain and Roddis (2003) 'Making Sense: A case study in collaborative design-led new product development for the sensorily impaired' in The Design Journal Vol 6 Issue 1 pp 40-51

Chamberlain, Roddis and Press (1999) 'Good Vibrations' in Proceedings of the Third European Academy of Design Conference, Sheffield Hallam University, UK Vol 3 pp 18 - 39

Cooley (1980) ‘Architect or Bee? The Human/Technology Relationship’ Hand and Brain Publishers, Slough, England

Cooley (1988) ‘From Bunelleschi to CAD-CAM’ in Design After Modernism Thackara Thames and Hudson pp 197-207

Davey (2003) ‘Model Behavior Design’ Week 27 Feb 2003

Friedman (2000) 'Creating Design Knowledge: From Research into Practice' In the Proceedings of the International Conference on Design and Technology Education IDATER 2000, Loughborough University, UK pp 5-32

Gaver et al (2003) 'Abiguity as a Resource for Design' www.equator.ac.uk/technology/ambiguity/ documents/ambiguity.pdf

Ghee (1998) ‘The Virtues of Virtual Products’ in Mechanical Engineering Vol 120 issue 6 p60

Guba (1990) The Paradigm Dialogue' Sage pp 17-27

Hardison (1989) 'Disappearing Through the Skylight: Culture and Technology in the Twentieth Century' Viking Books

Heskett (1980) ‘Industrial Design’ Thames and Hudson pp 206-208

Heskett (2002)' Toothpicks and logos: Design in eveiyday life' Oxford University Press ppl3-16

Hollerbach et al (2000) ‘Virtual Prototyping for Human-Centric Design’ Proceedings of the NSF Design Manufacturing Research Conference, Vancouver Jan 2000

Ishii, H. and Ullmer, B., ‘Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms’ Proceedings of Conference on Human Factors in Computing Systems (CHI '97), ACM, Atlanta, March 1997, pp. 234-241.

Kelley (2001) ‘The Art of Innovation’ Harper Collins Business, London pp 37 - 39, 103 - 118

Kimbell et al, (1990) ‘The Assessment of Performance in Design and Technology’ Published by the School Examination and Assessment Council pp 18-25

Laszo (1996) 'Evolution: The General Theory' Cresshill, NJ, Hampton

Magee (1973) ‘Popper’ Fontana Wm Collins Sons and Co London pp 65- 67

Margolin (1997) 'Getting to know the user' in Design Studies Vol 18 No 3 pp 227-236

McDonagh Philp (1998) 'Gender and Design: Towards an appropriate research methodology' in Proceedings of the 5th National Conference on Product Design Education, Glamorgan University, July 1998

Mitchell (1993)' Redefining Designing' Van Nostrand Reinhold, New York pp 35-60

Myerson (2001) 'IDEO Masters of Innovation' Laurence King, London, pp 10 and 89

Norman (1988) 'The Psychology of Everyday Things' Basic Books, New York

Olson (2002) 'The emperor has no labcoat' from Interactions Journal Volume 9, Issue 4 (July 2002)

Papanek (1971) 'Design for the Real World - Human Ecology and Social Change' Thames and Hudson, London

Polanyi (1958) 'Personal Knowledge: Towards a Post-Critical Philosophy' Routledge, London p i28

Popper (1963) 'Conjectures and Refutations' Routledge, London (7th edition) p 68

Preece, Rogers, Sharp (2002) 'Interaction Design: Beyond human-computer interaction' Wiley, New York'

Rees, H (1997) in Dormer (ed) 'The Culture of Craft' Manchester University Press, pp 116-136

Rosner (2002) 'Plastics Surgery' in 'Wired' June 2002, p 36 see also www.buffalo.edu/research/9virtualmed.shtml

Rothstein (2000) 'Ethnographic research: Teaching a young profession old tricks' in Innovation, Winter 2000 pp 33- 38

Rust (2004) 'Design Enquiry: Tacit Knowledge and Invention in Science' Design Issues Volume 20 Issue 4 November 2004

Rust, Whiteley, Roddis et al (2000) ‘Knowledge and the artefact’ in the Proceedings of the Conference: Doctoral Education in Design, La Clusaz, France 2000, Staffordshire University Press, pp 395 - 404

Stanton and Young (1999) 'A Guide to Methodology in Ergonomics - Designing for Human Use' Taylor and Francis, London

Taylor (2001) Thesis 'As easy as ABC? An inquiry into the nature of jazz pedagogy' Leeds College of Music, University of Leeds, pp 11, 39

Walters, Chamberlain and Press (2003) ‘In Touch: an investigation of the benefits of tactile cues in safety-critical product applications’ in Proceedings of the Fifth European Academy of Design Conference, April 2003, Barcelona University, Spain - in press

Ward (2002a) 'Sixth Sense' in New Design, January/February 2002 pp 36-39

Wilson, F (2001) ‘What is the purpose of a piano’ in ‘How to Handle Hands?’ Form und Zweck 18, pp 16-23

White, M, in Bothwick (2003) ‘Power to the People’ in New Design Jan/Feb 2003 pp 34-37

Whiteley (2000) PhD Thesis ‘An Articulated Skeletal Analogy of the Human Upper-Limb’, Sheffield Hallam University pp 2.2 - 2.7

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

WO 2004/097994 A1

(43) International Publication Date
11 November 2004 (11.11.2004)

PCT

(10) International Publication Number
WO 2004/097994 A1

(51) International Patent Classification7: H01R 13/46, 13/645

(21) International Application Number: PCT/GB2004/001745

(22) International Filing Date: 23 April 2004 (23.04.2004)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) Priority Data:
0309451.3 25 April 2003 (25.04.2003) GB

(71) Applicant *(for all designated States except US):* **SHEFFIELD HALLAM UNIVERSITY** [GB/GB]; City Campus, Howard Street, Sheffield SI 1WB (GB).

WO 2004/097994 A1

(72) Inventors; and

(75) Inventors/Applicants (*for US only):* **CHAMBERLAIN, Paul** [GB/GB]; Sheffield Hallam University, City Campus, Howard Street, Sheffield SI 1WB (GB). **WALTERS, Peter** [GB/GB]; Sheffield Hallam University, City Campus, Howard Street, Sheffield SI 1WB (GB).

(74) Agents: FRANKS, Robert, B, et al.; Franks & Co, 9-10 President Buildings, Savile Street East, Sheffield S4 7UQ (GB).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available):* AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, **JP,** KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available):* ARIPO (BW, GH,

[Continued on next page]

(54) Title: IDENTIFICATION SYSTEMS FOR COMPATIBLE COMPONENTS AND APPARATUS FOR USE WITH SUCH SYSTEMS

(57) Abstract: A set of identifier members in which at least two of said identifier members s are configured such that they can be unambiguously matched together by at least one common tactile feature.

{©)