Experimental making in multi-disciplinary research

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Abstract

For the past 3 years, Graham Whiteley has been using making in a project to develop a mechanical analogy for the human skeletal arm to inform the future development of prostheses and other artefacts. Other aspects of the work such as use of drawings and the use of a principled approach in the absence of concrete design goals have been documented elsewhere, this paper concentrates on the central role of making in the process.

The paper will discuss the role of making in multi-disciplinary research; craft skills and resources appropriate to each stage of a practice centred research project in this area; the use of models in an iterative experimental investigation and the value of models in eliciting knowledge from a broad community of interested parties and experts.

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Introduction

The Art and Design Research Centre at Sheffield Hallam University has participated in a number of multi-disciplinary research projects using design practice as a central part of the investigation. An overview of three such projects has been provided earlier by Rust et al (2000, a). This paper is concerned with a specific project which addresses questions in the field of medical physics/clinical engineering.

A designer, Graham Whiteley, who has taken a leading role in the research, identified part of the research problem while working on the design of animatronic devices for museum exhibition. He was seeking mechanisms to allow the construction of a realistic moving human arm and had reviewed the design of prosthetic arms in the belief that suitable prototypes would exist. Instead, he found that existing prostheses did not follow a close analogy with human anatomy and thus were unlikely to have potential for natural motion (Fig 1).

A more detailed review of prosthesis research and development showed that current prosthesis designs were largely unsatisfactory (Burger & Marincek, 1994)(Kejlaa, 1993) and that there had been no significant improvements for users for many years. It was proposed that the lack of potential for natural motion was a barrier to the improvement of existing designs and a research project was established with the specific aim of discovering and demonstrating a set of mechanical design principles for an analogous skeletal arm. While this would not be a prosthesis in itself it could be an important building block for future designs and could also inform design in other areas.

In choosing to take this approach, the researchers were aware that most recent research into prostheses had concentrated on problems of control. The thinking of scientists and engineers in this field appeared to overlook the possibility that the mechanical configuration was a central issue and that most designs were based on simplistic functional analogies developed in the 1960's (eg Jacobson et al 1982). In the light of this evidence that existing approaches were not yielding significant improvements, it was proposed that a completely fresh start with an emphasis on practical design work might be beneficial.

The research has continued for three years and has resulted in a complete set of mechanical analogies for the joints of the hand and arm, embodied in a model skeletal arm (Fig 2) which has been batch-produced for use in related research projects in other universities, such as artificial muscle and control system development.

This paper describes the extensive use of craft making in this research. Earlier papers have addressed the use of a principled approach in the absence of concrete design goals (Rust et al, 1999); the use of drawings for learning, analysis and development (Rust et al, 1998, b); technical outcomes and context of the research (Whiteley et al, 1999)(Rust et al 1998, a).

Skills and Resources

Graham Whiteley, is an industrial design graduate with excellent skills and experience in mechanism design developed through his work on museum exhibits. His experience has been complemented in the project by supervisors with a broad knowledge of industrial design and of clinical engineering. The development activities of the project have been located in a research studio/workshop which is part of a large, well-equipped modelmaking workshop used by students in 3D design. Researchers are provided with Windows NT graphics workstations and software for 3-D computer modelling and Computer Aided Manufacturing (CAM)

There is a full range of general equipment and machine tools for working in wood, metal and plastic plus some small scale Computer Numerically Controlled (CNC) machines (Router, Lathe and Milling) for CAM. Researchers also have access to external CAM resources including large scale CNC machine tools in the Engineering School and Stereo-Lithography prototyping equipment part-owned by the University at the REACT Centre, which provides technical support for local companies. During the project the researchers have constructed some specialized equipment for vacuum-casting of prototypes in resin and wax and local manufacturers have been used for batch-production of precision castings and machined parts.

Making in the Context of Research

The investigation included a wide range of research activities including a detailed review of the state of the art; engagement with users, manufacturers, prosthetists and clinicians; detailed examination of anatomy, especially the construction and action of joints; and quantitative analysis of joint motion. However practical design activity was at the centre of the research project and was the main distinguishing feature of the project in comparison with work being carried out by colleagues in Medical Physics. This emphasis reflects ideas about directions for Design Research expressed by Frayling (1993), Archer (1995) and Glanville (1998).

Drawing provided the main technique for understanding the anatomy and synthesizing analogous mechanisms. Making provided the means to refine, evaluate and demonstrate the mechanisms and investigate their implications for other aspects of prosthesis design. The other research activities described above provided a great deal of useful knowledge which underpinned the work but the designing activities were the main source of new knowledge, in the form of mechanical principles for an analogous arm.

Some past research has focused on analogies for actuation and control (eg Hannaford et al 1995) but has been hampered by the lack of a robust mechanical "platform" for an analogous arm. One aim of the research was therefore to meet this need and enable such research, It was thus essential for prototypes to be produced in batch quantities to a high standard of accuracy, to be durable and to be suitable for future experimental work.

A second reason for an emphasis on making is the belief, shared by members of the Art and Design Research Centre at Sheffield, that artefacts provide the most reliable bridge between the communities concerned with a multi-disciplinary research project. Not only do they facilitate communication but they can be instrumental in eliciting knowledge in a research project. Chamberlain (1999) has argued for this and Rust et al (2000, a) have described examples of artefacts which communicate or elicit knowledge.

The third reason for valuing making in the research is the degree to which experimental work relies on the quality of the test devices employed. Minimal lashups produced to carry specific tests can be helpful but they do not allow for a holistic review of the ideas embodied in them. Using design knowledge and craft skills to produce a robust model which looks forward to potential products can allow a wide range of evaluation and, in the opinion of the authors, is likely to provide recognition of issues and problems much earlier in the research.

The making techniques used are familiar in industrial design practice, where the production of high quality prototypes is a normal method of advancing the product development process. However this approach is relatively unusual in the context of medical physics research where emphasis is placed on the analysis of data, often through mathematical models. The use of practical craft skills to represent a hypothesis and allow a rich set of evaluations could be regarded as a lost art in many fields of the physical sciences today.

Making Activities

There have been three main cycles of development and review in the project: A first iteration of a hand design (Fig 3), a more complete design for the elbow/wrist rotation mechanism (Fig 4) and a design for a wrist flexion/extension mechanism (Fig 5). Together these provide analogies for a complete set of joints for the hand and arm although the hand requires further development to be true to the original.

In considering the hand, it was recognized that modularity was an important feature to support manufacturing of future products and adapt to the needs of individual users. The design was based on principles described by Mather (1988) in which the designer takes responsibility for creating a standard product platform which can be rapidly adapted to provide a wide range of products to meet individual customer's needs at the point of delivery. This was one reason for adopting CNC production at this point.

In support of this, Soddu & Colabella (1997) have pointed out that 'Digital manufacturing technology allows one to realize, at the same operational cost, unique objects or repeated objects'. Although some parts of the modular designs for the hand and arm lend themselves to moulded plastic or cast metal production, CNC techniques could provide an essential element of the production process, allowing individual elements to be tailored to match the anatomy of users quickly and locally. This feature of digital manufacturing is a powerful argument for its adoption by craftspeople seeking means to produce high quality objects in very small numbers or individually customized without excessive cost to the user.

More immediately, CNC provided a useful means of working rapidly through several iterations of a design. Early versions of the joints of the hand were machined cheaply and quickly in medium density fibreboard (Fig 6) and provided a check on fit and function, allowing refinements of the design which were quick to implement through detail changes in CNC machining data (using a simple CAD system built into the CNC software) before producing final versions in an engineering plastic.(Fig 7) The CNC process provided a batch of several joints and allowed the design to be varied between the two main types of joint in the fingers. It also provided a means to make accurate jigs for assembling and drilling the joints.(Fig 8) The CNC software available at the time did not lend itself to soft forms but at that stage this was not regarded as a priority.

Iteration has been one of the key principles of the research (Rust 1999). Glanville (1998) describes the circular, iterative nature of the design process and goes so far as to say that 'I believe this circularity to be so important that I am willing to use it, prescriptively, as a requirement'. Local equipment which is cheap to run and well-understood by the designer reduces the opportunity cost of iteration, ensuring that the design can be revisited as often as necessary. Later versions will be developed using stereo-lithography which will provide more appropriate external shapes but this would have been restrictive in the initial stages.

When developing the hand a large number of quick mock-up models were made to explore ideas (Fig 9). For example, many of the problems were concerned with routing fine wire 'tendons' to operate the finger elements. In exploring means to pass tendons through the wrist, compensate for wrist movement which lengthens and shortens the tendons and provide an opposed action between tendons opening and closing the grip, a complex test rig was constructed (Fig 10).

This completely failed to meet any of the functional needs and demonstrated the limits of a purely mechanical design. In fact it was quickly recognized that this contraption failed because it bore no relation to the way in which these problems are dealt with in the original anatomy. This alerted the researchers to the probability that this problem should be addressed through analogous control systems which replicate some of the internal sensing and control systems of the muscle. This was a significant event in the research as it crystallized the principle of pursuing a close analogy which became a central part of the research hypothesis.

Thus an attempt to address a complex problem through making a complex prototype demonstrated a flawed approach. Arguably a series of small test devices which dealt with each of the design ideas on its own might have indicated that the solutions could work, not allowing recognition of the unreasonable complexity of the whole package which emerged when the ideas were combined and interacting.

When the project moved on to the forearm and elbow a different approach was adopted. There were fewer joints but they were more complex and interacted in a subtle way. Also the bones of the forearm traverse past each other and are interconnected by muscles, calling for a complex form. Essentially, more subtle forms were called for and CNC would not provide them easily or quickly. A combination of hand work, conventional machining, and fabrication were used to produce patterns for the main components, the bones were cast in resin from original bones.

A means of replication and batch production was needed for this process and the researcher investigated the possibility of vacuum casting of thermosetting resins. The commercial equipment required for this cost around UKP20,000 which was not realistic for the project or the research centre. A visit to a local design company provided information about the technology and a redundant vacuum pump and chamber were found in the university and refurbished, Within a short time from its introduction, the vacuum casting system became an established resource in the workshops. As well as producing the prototypes required for this project it has become an important tool for other researchers and design students. Fig 11 shows moulds, vacuum mouldings and lost wax castings generated by this process. This illustrates the value of developing one's own resources since the benefits to the whole community of designers in the University have repaid the effort of finding/refurbishing the equipment and developing techniques many times over.

Evaluation

In order to verify the design of the forearm it was necessary to compare it with the movement of a real arm. Measuring rigs were therefore constructed to measure the movement of the model (Fig 12) and the original (Fig 13). Each of these was a design challenge in itself, especially as the measurement of bone movement in the original anatomy is inevitably hampered by the intervening soft tissue, a problem facing many researchers in the field of Medical Physics.

Fortunately, the availability of a complete hand, wrist and forearm assembly allowed a separate form of qualitative evaluation by palpation (manipulation) of the arm model by people who regularly palpate human arms in their professional work, for example surgeons. This process is described in detail elsewhere (Rust 2000, a) and provided triangulation for the quantitative evaluation which would not have been available with a less complete model or a computer simulation (which is increasingly the medium chosen by engineers for such work.)

Quality of Making

It is natural for a designer from the art school tradition to be concerned with the quality of execution of 3-Dimensional work. Arguably this concern has taken up a considerable proportion of researcher's time and, in some respects, does not support the core purpose of identifying a functional analogy. However the quality of the prototypes has served several purposes which are important to the research.

As has been indicated already, the quality of the prototypes is important in allowing their use in the widest possible context. The first issue is recognition - when the model hand was discussed with a manufacturer he was able to recognise the modularity and manufacturing implications of the design within a very short time, when it was handled by an osteopath as part of the quantitative review she found the external forms of the joints to be close enough to her experience of human anatomy to cause no distraction in assessing the motion of the arm.

A second issue is robustness. The original model arm and hand have clocked up a substantial number of air miles, having been taken to several conferences and other events where it was passed round and manipulated by many people. Very few scientists routinely take their lab test rigs on the road with them.

The third issue is concerned with credibility. The immediate reaction of most people to the prototypes is to comment on their appearance and the quality of construction. It has been clear to the researchers that this has allowed many people who might have been sceptical or uninterested to recognise that the work is serious and that there is something here that is worth becoming involved with. While this cannot be a substitute for good research, it is important for designers who are seeking collaborations to ensure that potential partners are able to take them seriously and become sufficiently engaged with the work to understand its potential for them.

When the project moved on to creating a batch of prototypes for other researchers the opportunity was taken to evaluate the use of carbon-fibre reinforced plastic since this material has been proposed as suitable for artificial bones. This process, together with an evaluation to ensure the repeatability of the design in batch production provided models which were substantially lighter, stronger and less expensive to produce. It also provided the research centre with experience in working with carbon fibre and we anticipate that the process will find its way into general use in the school, for example in furniture design projects.

A benefit of this improvement in the “veracity” of the test rigs is that the arms can now be evaluated with some forms of artificial muscle technology which can only exert very slight forces at present. The original model would have been too heavy. Attention to detail and seeking to move the research as close as possible to a manufacturable design has therefore widened the usefulness of the models in research.

Discussion and Conclusions

In this paper we have set out to show how the making skills of the designer can enhance research in a field dominated by the analytical approaches of science and engineering. We have also described some of the methods used and some of the issues which have arisen in developing this approach.

In giving this partial view of a complex, long-term project it is not possible to describe the processes of evaluation and the outcomes of the project in any detail, some aspects of evaluation have been referred to briefly and the principle outcomes, in scientific terms, have been published elsewhere (eg Rust 1998, a)(Whiteley 1999).

In this project the designing activities and outcomes are similar to those which might be encountered in normal professional practice and the concept of designing as a research activity may be difficult to recognise given this similarity. As already pointed out, the designer, working as a researcher rather than professional practitioner, has the opportunity to use their skills to represent and develop a hypothetical proposition in a form which is widely accessible and suitable for many forms of evaluation.

The designer's understanding of the wide social and technical implications of the research allows the hypothetical device to be embodied in a form which has many of the characteristics of a "product". Nevertheless it is intended to be a tool for evaluation of a proposition which goes much further than a specific product. The "realism" and richness of the designer's hypothetical device allow for a very full evaluation of its character and implications by a wide community of interested people and this depends heavily on the quality and appropriateness of making.

Some specific issues have arisen in this project:

It is important to use making techniques which reflect the design process as well as considering the problems of producing the final artefact.

Willingness to engage directly with novel production techniques (CNC, Vacuum Casting, Carbon Fibre) has had multiple benefits for the research and student communities in the University.

Concern for quality of making and a wish to produce complete artefacts which look towards an eventual product (rather than dealing with discrete problems within the research) allow the work to support a wide range of research activities and allow recognition of issues of complexity and interaction between parts of a proposed solution. Quality of making can also enhance the credibility of designers in multi-disciplinary research.

To summarise, Engineers and Scientists frequently comment to us that they have lost the art of making things and we suggest that this aptitude for and willingness to engage with making is the single most valuable contribution which designers can bring to multi-disciplinary research. As we address increasingly multifaceted questions in the physical and social sciences, the ability to embody a complex proposition in an intelligible artefact may become the only way that some questions can be properly understood and addressed by the whole community, rather than from a limited disciplinary viewpoint.

Figures

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