THE IMPACT OF IN-HOUSE RP UPON FINAL YEAR INDUSTRIAL DESIGN STUDENT PROJECTS

R. I. Campbell and A. R. Hodgson
Department of Design and Technology, Loughborough University, LE11 3TU, UK
Reviewed, accepted August 13, 2003

Abstract

A vital part of the Industrial Design and Technology degree course at Loughborough University is the development of appearance and functional prototypes. Previously, the use of rapid prototyping (RP) has been fairly limited because of the high cost and problematic timing issues of using external facilities. However, during 2003, the availability of an in-house FDM 2000 machine has greatly increased the use of RP models. This paper identifies the impact this has had upon a) the design approach, b) the characteristics of the models produced and c) the use of the models with user evaluation trials. Conclusions drawn show that RP has brought major benefits but that there are some pitfalls that must be avoided.

Introduction

The Industrial Design and Technology degree course at Loughborough University is characterised by an integrated treatment of the aesthetic, ergonomic and functional aspects of product design. Final year students are encouraged to incorporate all three into their major design project and to validate their product design through user evaluation. This necessitates the use of appearance models and functional prototypes within user evaluation trials. Conventionally, appearance models will be used to convey aesthetics and some ergonomic aspects to the user while functional prototypes are used to convey the remaining, more technical features. In industry, rapid prototyping (RP) has been used to help produce both appearance models and functional prototypes, often yielding significant time and cost savings. However, recent research at Loughborough [Evans, 2003] has shown that the greatest benefit of RP to industrial design is the ability to create an integrated appearance model/functional prototype, often called an appearance prototype. When used in this manner, it can not only reduce time and costs but also improve the designer's confidence in the results of user trials because of the increased realism of the prototypes used. Therefore, it has become an aim of the Department of Design and Technology (DDT) at Loughborough to encourage the use of RP whenever possible and beneficial.

If rapid prototyping (RP) is to become a widely used tool within the field of industrial design, it is necessary for students of the subject to be completely familiar with its capabilities and limitations. To this end, DDT set up close relationships with local RP service providers, initially in a nearby RP bureau, and more recently, in another department at Loughborough. However, the uptake of RP remained rather low, with less than 10% of final year students making use of it during their major design project. This was partly due to the relatively high cost of using the RP bureau and some scheduling problems with the other university department. However, it was also believed that there may have been a lack of willingness to use RP techniques because they were seen as "engineering only" tools. At the beginning of the 2002/03 academic year, DDT acquired FDM 2000 and ThermoJet RP machines for its own use. Although quite old, the FDM machine worked well, once a new deposition head had been fitted. It was hoped that the addition of an in-house facility would promote greater student familiarity with RP techniques in general and break down any perceived barriers. This paper describes the effect that in-house RP has had within DDT and the impact it has had upon the students' design process. The overall aim of the paper is to present results and draw conclusions that will help industrial design departments in other universities who find themselves in a similar situation.

Background

The Industrial Design and Technology course at Loughborough is a three year undergraduate programme that can lead to a BSc or BA, depending on which optional modules are taken. It is one of only a few university courses in the UK which place major emphasis on both the outward, aesthetic properties of a product together with the internal technology required to provide the product's function. Therefore, the students cover a wide range of subjects including sketching, manual model making, product semantics, multi-media presentation, engineering drawing, electronics, mechanics, materials, computer-aided design (CAD) and design for manufacture. Great importance is attached to a hands-on approach to design. Students undertake project work in all three years aimed at assimilating and applying the knowledge they have gained from other modules. Graduates from the programme have been known to embarque on careers in engineering design as well as industrial design.

The major design project undertaken by all final year students is the culmination of all their practical activities. It runs across both semesters and has a nominal student time input of 500 hours, in total. The first semester concentrates on finding a potential market for a product, developing a product design specification, generating several concept designs and selecting one for further development. During semester two the students are expected to convert the chosen concept design into a fully detailed design, produce a functional prototype, have it evaluated by potential users and consider design for manufacture issues. If the functional prototype does not reflect the actual appearance of the final product then a student will be expected to produce an appearance model also. It is during this "prototype manufacture" stage of the project that students will employ their model making skills. Traditionally, this has involved manual modelling in blue foam, medium density fibreboard (MDF), various plastics, aluminium, steel and occasionally, textiles. The techniques used include machining, forming, welding, filling, sanding and painting. Computer numerical control (CNC) milling and routing is sometimes used for both component and tool manufacture, and more recently, vacuum casting has been used to replicate models in more representative materials. In the past, the predominant use of manual techniques has often made it difficult for students to combine both an organic form and intricate internal details within a single appearance prototype.

Throughout the duration of the project, students are expected to attend weekly seminars that cover both organisational aspects of the module and various skills and knowledge they will need to apply. RP is introduced to the students during one of these seminars. They are given an overview of how it works, the techniques available, its pros and cons, and the importance of having a high quality CAD model to drive the RP process is stressed. All of the students will have covered 3D CAD in both their first and second year but mostly this is confined to solid modelling techniques. It should be noted that around half of the students will already have had a more detailed introduction to RP during an optional final year module entitled "Computer-aided Modelling and Manufacture" (CAMM). This module also exposes them to more advanced CAD/CAM techniques such as freeform surface modelling and three axis CNC machining. Therefore, the CAMM students tend to have acquired more skills and knowledge in regard to the "digital" design process. It is interesting to note that 85% of the students who used RP during their project had attended the CAMM module.

Data Collection

The aim of this research was to determine the effect that the introduction of in-house RP has had within DDT and, in particular, the impact it has had upon the students' design process. To do this it was necessary to gain an insight into how and why students had used RP. This was undertaken in two ways. Firstly, a questionnaire was given to all the final year students asking specific questions about their use (or non-use) of RP. The aim of the questionnaire was to obtain some quantitative data regarding the use of RP. The questionnaire generally followed the same format as one that had been used with industry-based designers in a previous research project [Campbell, 1998]. However, it had to be tailored to the different circumstances faced by students. The questions are listed in the Appendix. Secondly, to gain more qualitative data on the impact that RP had had upon students' design process, several student projects were treated as case studies. Their use of RP was tracked throughout their projects and the resulting prototypes analysed to see what benefits RP had yielded. The results obtained from both strands of the research are now presented together with some preliminary analysis.

Questionnaire Results and Analysis

The questionnaire was issued to all 90 final year Industrial Design students who had just completed their major individual design project. 35 students completed the questionnaire, equivalent to a response rate of 39%. Of these 35 students, 20 had used RP during their project whereas 15 had not. It is known that a large majority of those who did not respond had not used RP. Therefore, it can be estimated that approximately 25% of the final year had used RP this year, a big increase over the previous year when only around 10% had used it. A range of reasons where given for not using RP with just under half of the responses being “not appropriate to project”. This is a fairly vague phrase but other students were more specific. Virtually equal numbers cited “lack of know-how”, “unsuitable materials”, “product too large”, “RP too expensive” and “simpler to use conventional techniques” as reasons for not using RP. In regard to RP being too expensive, the students were charged at a rate of 25 pence (40 US cents) per gramme for FDM models. This was much less than a commercial rate but could still result in larger models having a significant cost. The “lack of know-how” most likely refers to a deficiency in CAD skills rather than a lack of knowledge about RP techniques. This can be assumed because only half of the students took the optional final year CAMM module.

Of the 20 students who did use RP, the predominant reason given (cited by 14 students) was “the ability to create more complex or more organic product forms”. Other reasons were “improved accuracy”, “better surface finish”, “faster process”, “more convenient” and “to gain experience”. None of these was cited by more than four students. It should be understood that the majority of the students were comparing RP to conventional, manual techniques for model making rather than to CNC machining or other final production processes.

Half of the students required only a small number of RP models (five or less) and the distribution for the remainder can be seen in Figure 1. The largest number of models made for any one student was 26. 11 of the students made use of the in-house FDM machine, whereas the numbers who used SLA, ThermoJet and SLS were 8, 4 and 2 respectively (7 students used more than one machine). Although the cost of using FDM was greater (SLA, ThermoJet and SLS models were provided for free), the convenience of using locally located facilities seemed to be more important to many. Other reasons given for usage of particular techniques were accuracy, strength, surface finish and suitability for investment casting. Indeed the fact that several students used more than one technique showed that they had gained an understanding of the relative merits of the various systems available.

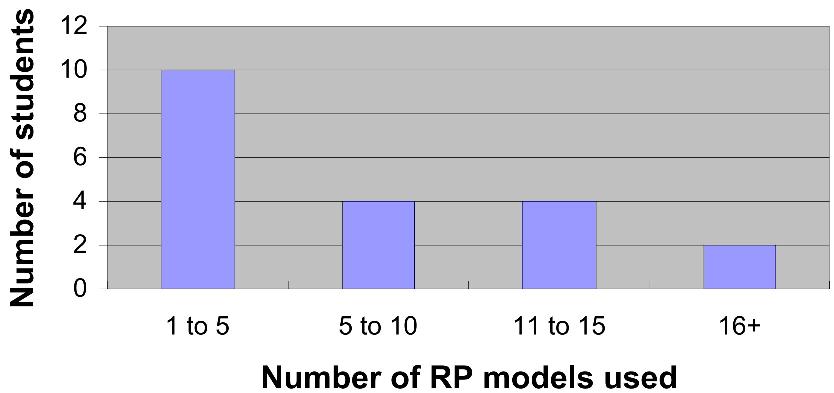


Figure 1: Number of students against numbers of models used.

75% of the students used their RP models as functional components within their prototype whereas only 20% used models for purely visualisation purposes. This shows that the majority of students had recognised the ability of RP to create models that have similar characteristics to final production components. 25% of students used their RP models for vacuum casting, again the aim being to arrive at functional components. Other uses for the models where investment casting (1 student), assembly checking (2 students) and ergonomic testing (1 student). Several students used different models for different purposes, again showing a good understanding of RP system capabilities.

In an attempt to determine if RP had opened up new design possibilities for the students, they were asked if they would still have made the same models if RP had not been available. Unfortunately, nine of students answered "not sure" which does not give much indication of their thought processes. However, four students said they would have made do without a physical model, perhaps using 2D images or a CAD animation instead of an appearance model. Obviously, for these students, RP had enabled them to produce a more tangible output from their design process. For the seven students who said they would definitely have made the same models, all of them said they would have used manual modelling techniques with three saying they would also have used CNC machining. Following on from this, the students were asked if they had used conventional modelling techniques alongside RP. 85% of them had done so and the number of students using each of a wide range of techniques is shown in Figure 2. This shows that the traditional skills of industrial designers compliment well the capabilities of RP. The students were entirely at ease with creating a high quality prototype from an RP model with stair-stepping and supports. Furthermore, the technological capabilities of the students enabled them to combine this model with others created using plastic and metal-forming techniques.

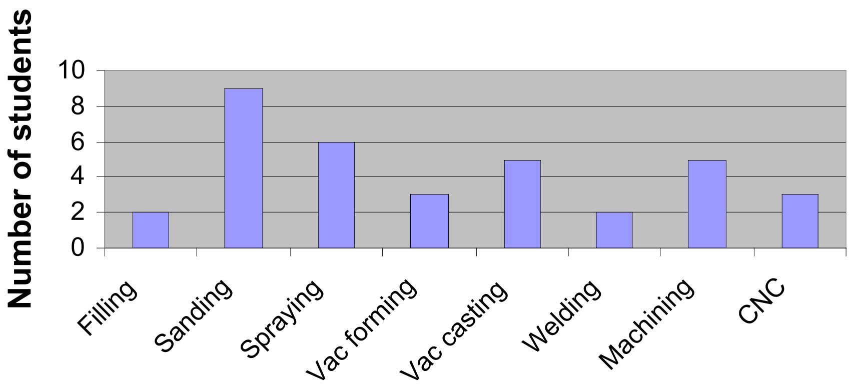


Figure 2: Conventional modelling techniques used alongside RP

The students reported a variable degree of success with using RP. The proportion of RP models that were deemed "satisfactory" by each student varied from 100% to zero. Figure 3 shows the wide distribution of satisfaction levels. Most students have had a reasonably favourable experience in using RP but one student was dissatisfied with all the models produced. This was partly due to different expectations from the models and partly from the different RP techniques used. 70% of the students judged the quality of their RP models by the level of accuracy, 50% by appearance and 40% by surface finish (Most students listed more than one criteria). However, the strength, functionality and surface texture of the RP models were also considered important by some students. RP models produced by some techniques do not measure up well against all of these criteria. The two predominant reasons given for lack of satisfaction were "poor surface finish" (cited by eight students) and "poor accuracy" (cited by seven students. Considering that some students had used RP specifically to improve upon these two factors, it is possible they held some rather unrealistic expectations that have not been met.

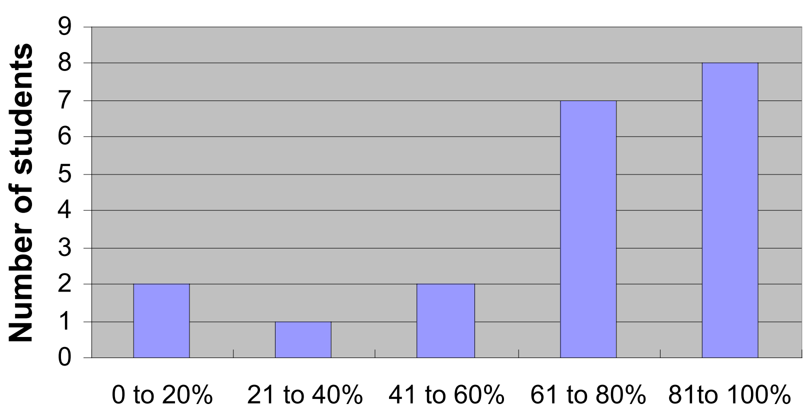


Figure 3: Proportion of RP models judged satisfactory by students.

The last question tried to gauge what impact RP had had upon the design process employed by the students. They were asked how RP had changed their approach to design. 25% of students said that RP had enabled them to produce a more realistic prototype. A further 10% stated that they had been able to produce a single appearance prototype. When taken with the 15% who cited "more complex shape possible" the result is that half of the students had been able to change their physical modelling strategy because of RP. The only other change in design process that was cited by more than one student was that model making had been quicker. This may also refer to the fact that only one set of models was required rather than both an appearance model and a functional prototype.

The results of the questionnaire demonstrated that RP had been used intelligently by many students and had proved beneficial to their design project. However, little indication was given as to the extent that RP can change the way students work. To determine this, three of the highest ranked student projects were taken as case studies and analysed in more detail.

Case Studies

Three student projects used as case studies to probe further into issues that had been raised by the questionnaire. These were a) changes in the design approach followed, b) changes in the characteristics of the models produced and c) the enhanced use of the models within user evaluation trials. Each of the three case studies is now discussed in turn.

Case study 1 – Michael's Glue Gun

Michael's product was a re-design of a glue gun that was aimed at the 'hobbyist' and 'craftsman' who wanted more sophisticated control of the glue as it is dispensed. His final design integrated mechanical, electronic and visual elements in order to meet his intended design specification (see Figure 4).

Figure 4: Final design of glue gun

Early design development raised major problems concerning his aim to incorporate a motorised glue delivery system into a small pen-like product. Instead, it was decided that a separate motor housing should be coupled to the pen via a drive cable, since the required purpose-built motors and mechanical components were outside the scope of his project work. He also decided that his product would be evaluated using two different prototypes. Firstly, an appearance model that would represent the aesthetics and "feel" of the final design, and secondly, a functional prototype that would represent the functional operation of the product – a key part of the 'added value' for this new product.

Towards the later stages of the design project, Michael developed two parallel designs using CAD modelling to create a detailed assembly of parts. One design was to represent the new glue gun as it would be commercially manufactured, with custom designed electrical and mechanical parts. The model for this design was to be made using SLA parts. The other design included a similar (though slightly different) dispenser, a simple drive unit that would house a prototype motor drive (from a cordless screwdriver) and prototype electronics circuit. His intention was to deliver the glue with varying speed, to sense when the user has finished and retract the glue stick to prevent it dripping, and also to vary the heating element power depending on the intended gluing operation. The system required significant development and so a large drive unit, with substantial space for further development, was built in the stronger FDM 2000 material. Figure 5 shows the two different prototypes side by side, and their differences are quite apparent.

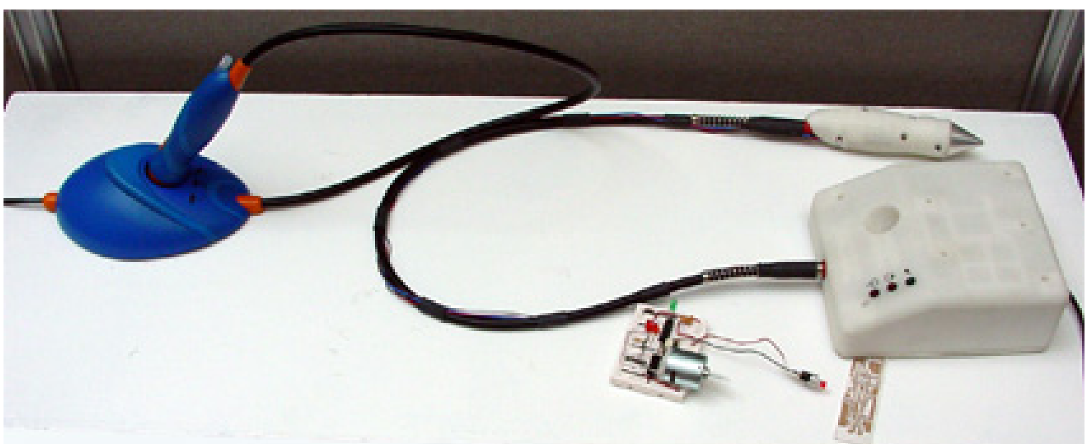


Figure 5: Appearance model (on left) and functional prototype (on right).

Michael made no attempt to finish the surface of the FDM parts used to make the functional prototype. However, the SLA parts for the appearance model of the final design were hand finished and painted. Although not as robust as the FDM model, the purpose of this prototype served only to illustrate form and appearance, and it complemented the functional prototype well. The main conclusion to be drawn here was:

that RP processes can be carefully selected to produce different prototype outcomes.

Case study 2 - Jon's CD Player

Jon used a variety of different RP processes at different phases of his design development work, all linked to his significant CAD modelling capability with Pro/ENGINEER software. He designed a domestic CD player, which included speakers that could be separately located, and also allowed remote control of the CD player volume and track (see Figure 6). The product comprised a main body (that included the CD player itself and the speaker battery chargers) and two symmetrical speaker ‘pods’ (that included audio receivers and control transmitters, together with batteries and NXT sound exciters so that the speaker cases acted as sound boards). This allowed the CD player to be used in wet environments, like showers, since the speaker ‘pods’ could be completely sealed.

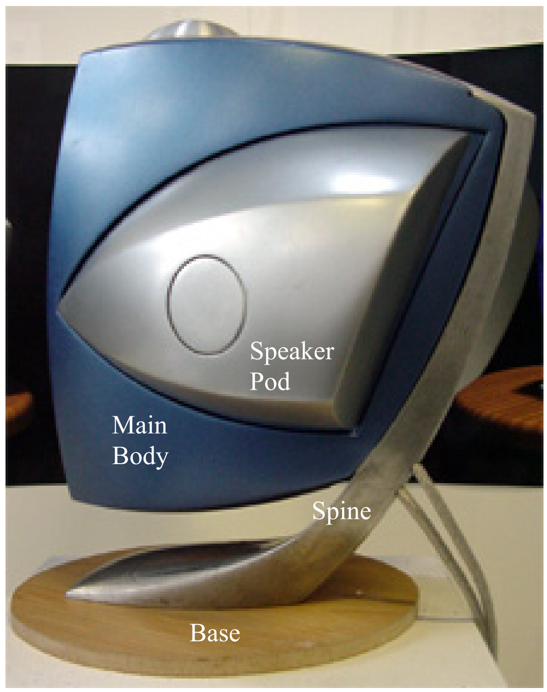


Figure 6: CD Player with various features indicated.

Jon made use of ThermoJet wax models for proving the fit of the pods to the main body, and went through a number of design iterations to prove the initial concepts as the shape and form of the product developed. The product functionality took longer than anticipated to complete, so instead of using SLA models and vacuum casting to produce prototype polymer shells, he chose to use FDM models and then finish/paint their surfaces. He considered that the extra time needed to finish the FDM surface would be less than the time required to make silicone moulds and cast resin parts.

The two plastic mouldings that formed the main body were attached to a cast aluminium ‘spine’. Although Jon considered modelling the spine by hand (which would have sufficed for such an early prototype), he decided to use a ThermoJet wax model of the part to make an investment casting in aluminium alloy, made as a one-off part. This provided a rigid framework onto which the less substantial RP parts could be fastened, and so the CD player could be effectively evaluated as a fully working, appearance prototype.

that the faster, less functional RP techniques enable rapid and copious design iterations,

that the need for separate appearance model and functional prototype can be eliminated via the combined use of RP and secondary processes.

Case study 3 – Kelly's Food Preparation Device

Like Jon, Kelly made use of a several RP techniques at different phases of her design project. She was developing a food preparation product that exploited a new textured plastic within what was aimed to be a "cooking is fun" context. As with all students of the Industrial Design and Technology course, she started by analysing the potential market and considering the needs of users, helping her to generate initial ideas, concepts and design specifications. During this time, some mechanical parts were modelled in CAD, and evaluated through mechanical simulation, but she still felt the need to physically model the mechanism.

The shape and form of the different parts were developed using a combination of sketch work and CAD modelling, and then built in wax using the ThermoJet process (an example part is shown in Figure 7). These helped Kelly to evaluate the overall appearance of her design together with the comfort and other related ergonomic factors of the hand-held parts in particular. These parts could have been modelled in foam, either by using 3-axis CNC routing, or by hand. However, the wax RP model was an accurately formed prototype part that very closely followed the CAD model and Kelly's intended design. It required minimal finishing and was quickly achieved using an STL file generated from Pro/ENGINEER. The ability of the model to build internal features in the casing parts was particularly beneficial, since it allowed Kelly to check for fit and location of mechanical parts. Several versions of wax-modelled prototypes were produced during the concept development phase of the project, alongside continuing sketch and CAD modelling work. It is thought that the use of quick and easy RP output enabled a more effective design to be developed through a number of early design iterations.

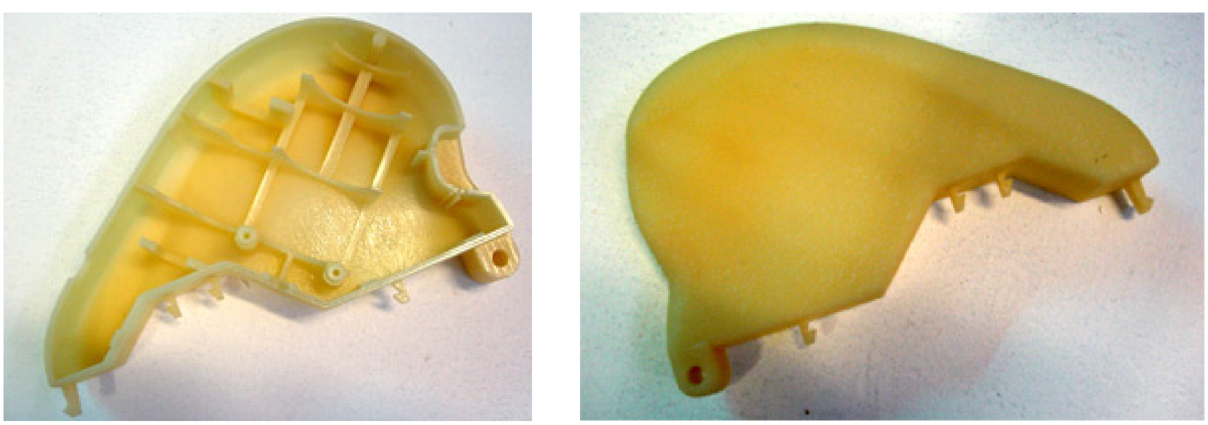


Figure 7: One of the ThermoJet models used for aesthetic, ergonomic and assembly evaluation.

As the project progressed, more robust components became necessary for full assembly and testing purposes and so FDM was used. Kelly decided to hand-finish these parts to in order to present her progress to her external "client company" (see Figure 8).

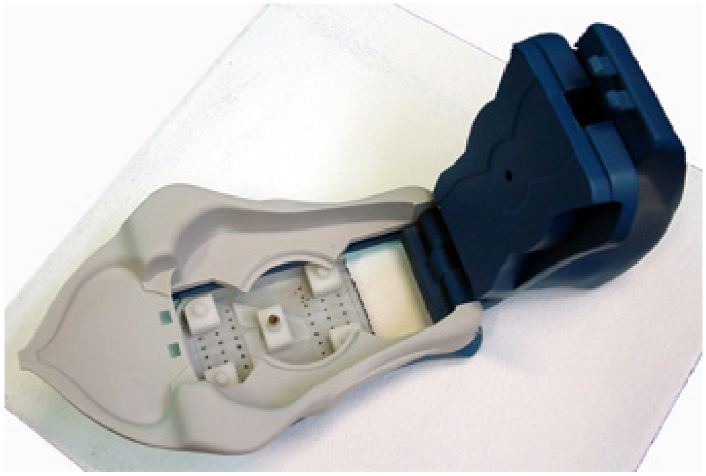
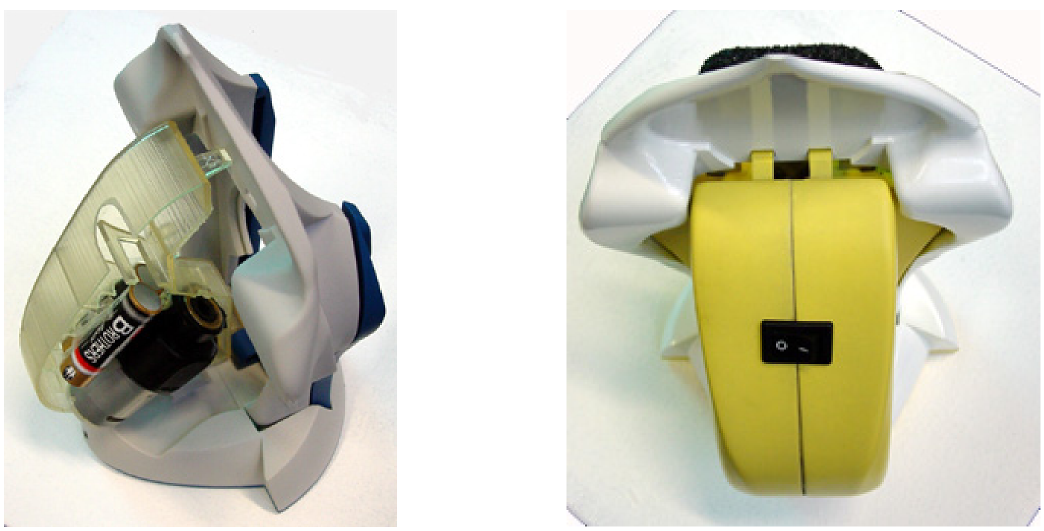


Figure 8: Hand-finished FDM parts

However, the quality of surface finish and detail was not considered to be sufficient for a final appearance prototype. Following some minor re-design after evaluation of the FDM models, Kelly used SLA models with subsequent vacuum casting for this purpose. Figure 9a shows a combination of SLA and vacuum casting parts prior to final finishing.



(a) (b)

Figure 9: Appearance prototype before and after finishing.

The SLA models required less finishing than FDM would have needed, and were vacuum cast in an ABS-replicating resin with appropriate colouring pigment to minimise finishing requirements. This resulted in an appearance prototype that was robust enough to be used by a number of people in a typical food preparation context (see Figure 9b). The resulting evaluation provided very effective feedback on the user acceptance and operation of the product. The main conclusions to be drawn from this project were:

- that the use of RP at different stages in the design process enabled more design iteration and resulted in a higher quality product,
- that the combination of RP with conventional modelling techniques provided a high quality appearance prototype that was suitable for extensive user trials in a realistic environment.

Conclusions

The availability of an in-house FDM machine served to raise the general profile of RP within the department. As a result, the student use of other RP techniques increased over previous years. Aligned to the increased availability of RP modelling was the development of increased CAD modelling capability. Students were able to capture their design intent in Pro/ENGINEER through a combination of solid modelling, surface modelling and freeform surface modelling (using ISDX). This was a pre-requisite for their RP work, and vital to the successful implementation of RP in both appearance models and functional prototypes.

The questionnaire captured data from most of the students who had used RP for their design project. RP was primarily adopted to achieve more complex and more organic forms that would otherwise be difficult and time consuming. This was only beneficial because the traditional model making skills of industrial designers were used to produce high quality model finishes. Different RP systems were used for different outputs and it was highly desirable that a range of complimentary techniques were available. Some students had unrealistic expectations of what RP could achieve. It is therefore essential that students are well informed about various system capabilities. Most significantly, half of the students stated that RP had changed their strategy for creating physical models.

These results were supported by the case studies, which showed that RP processes had been carefully selected to achieve different outcomes. They also showed that the rapid and copious design iterations facilitated by RP result in more optimised designs. The most important change in modelling strategy was the combination of aesthetics and functionality within a single prototype. This led to more realistic user trials, which in turn, should give more reliable feedback on the product design.

References

Evans, M.A. and Campbell, R.I. (2003), "A Comparative Evaluation of Industrial Design Models Produced Using Rapid Prototyping and Workshop-Based Fabrication Techniques", accepted for publication in Rapid Prototyping Journal.

Campbell, R.I. (1998), "Using Feature-based Product Modelling to Integrate Design and Rapid Prototyping ", PhD thesis, Manufacturing Engineering and Operations Management, University of Nottingham, UK.

Appendix: Questions asked in the questionnaire

1. Did you use one or more rapid prototyping (RP) models for your design project?

(If yes, please go to question 5.)

2. Did you consider using RP during your design project?

(If no, please go to question 4.)

3. Why did you decide not to use RP? Thank you for completing the questionnaire.

4. Why did you not consider using RP? Thank you for completing the questionnaire.

5. Why did you decide to make use of RP models?

6. How many RP models did you have made for your design project?

7. Which RP system(s) were used and why did you select them?

8. What design or prototyping purpose did you use your RP models for?

9. Would you still have made these models if RP had not been available?

10. If yes to question 9, how would you have made your models?

11. Besides using RP, did you still make use of other model-making techniques (e.g. to make other parts or to finish your RP models)?

12. If yes to question 11, which technique(s) did you use?

13. What criteria did you use when evaluating the quality of your RP models?

14. What proportion of the RP models you had built were of satisfactory quality for your purpose?

15. What were the reasons for any of your models not being satisfactory?

16. How has the availability of RP changed your approach to your design project?

Thank you for completing the questionnaire.