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Real time integration of user preferences into virtual prototypes

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Abstract

Within new product development (NPD), both virtual prototypes and physical prototypes play important roles in creating, testing and modifying designs. However, in the current design process, these two forms of prototyping methods are normally used independently and converted from one to the other during different design phases. This conversion process is time consuming and expensive and also introduces potential information loss/corruption problems. If the design process requires many iterations, it may simply be impractical to generate all the conversions that are theoretically required. Therefore, the integration of virtual and physical prototyping may offer a possible solution where the design definition is maintained simultaneously in both the virtual and physical environment. The overall aim of this research was to develop an interface or a tool that achieves real time integration of physical and virtual prototyping. "Real time integration" here means changes to the virtual prototypes will reflect any changes that have been made contemporaneously to the physical prototypes, and vice versa. Thus, conversion of the prototype from physical to virtual (or vice versa) will be achieved immediately, hence saving time and cost.

A review of the literature was undertaken to determine what previous research has been conducted in this area. The result of the review shows the research in this area is still in its infancy. The research hypothesis was developed through the use of a questionnaire survey. Totally 102 questionnaires were sent to designers, design directors or design managers to address the issue: will industrial designers want to make use of real time integration and if so, how? The outcome from the literature review drove further development of the research hypothesis and an initial pilot experiment to test this. The pilot trial was designed to address the research questions:

- Can real time physical and virtual prototyping integration be conveniently demonstrated?
- Will designers and users be comfortable using the integration method?
- Will users recognise the benefits of the integration?

The results showed that real time integration between physical and virtual prototyping is necessary in helping designers develop new products and for getting users more closely involved. The future research suggested is that more investigations and experiments are needed to explore a proper method that

simultaneously employing these two types of prototyping in product development process.

Keywords

Physical Prototyping; Virtual Prototyping; Integration; Real Time.

Within new product development process prototyping is the pivotal activity that structures innovation, collaboration, and creativity in design (Hartmann & Klemmer, 2006). Repeated, efficient, and extensive use of prototypes is a vital activity that can make the difference between the successful and unsuccessful entry of new products into the competitive world market (Zorriassatine et al., 2003). Generally speaking, all types of prototyping can be categorized into physical prototyping (PP) and virtual prototyping (VP).

As a conventional prototyping method, physical prototyping still plays a very important role in process and product development. Particularly, it supports a concurrent, time-oriented approach and helps collaboration in teams composed of people from different functions and backgrounds (Vandevelde et al. 2002). Virtual prototyping is an up-to-date concept in the design and NPD cycle. Due to its strength in reducing the design cycle time and cost, virtual prototyping has replaced physical prototyping in many areas and will be used more widely in the future (Huang & Chen 1999). However, physical and virtual prototyping are not competitive but complementary technologies (Grimm, 2005).

Campbell (2003) proposed that research is undertaken in the area of "the real time integration of virtual and physical prototyping." He suggested that it is valuable to test, modify or verify both virtual and physical prototypes simultaneously. "Real time integration" here means changes to the virtual prototype can reflect any changes that have been made contemporaneously to the physical prototype, and vice versa. It is believed that the "real time integration" would improve the traditional use of the two types of prototyping technologies and consequently contribute to the progress of new product development.

The main problem to solve in this research is to develop the method that could be used to simultaneously convey the changes in the virtual and physical prototypes to each other. By understanding how physical and virtual prototyping technologies work and connect with each other, it will be possible to develop tools that enable industrial designers to apply them simultaneously in their design and evaluation activities.

Therefore, the overall aim of the research is:

- To develop an interface or a tool that can achieve the real time integration of virtual and physical prototyping.

The research questions to be answered include:

- What are the characteristics of physical prototyping and virtual prototyping?
- Will virtual prototyping replace physical prototyping?

- What are the gaps between the current integration technologies and the research aim?
- What benefits will the real time integration of physical prototyping and virtual prototyping bring to new product development?
- What are the main challenges to achieving real time integration?

The paper begins by presenting an overview of physical and virtual prototypes and prototyping. It goes on to describe related work in the research and industrial arenas. Next, a questionnaire survey and pilot trial are presented. Finally, the paper draws some conclusions and presents future research directions.

Prototypes and prototyping

Prototypes can be classified into two main types: physical prototypes and virtual prototypes. Hence, as it involves the construction and testing of prototypes, prototyping can also be distinguished as physical and virtual prototyping. In this paper, the terms PP and VP stand for physical prototyping and virtual prototyping, respectively.

In the product development process, there are some situations where physical prototyping is more beneficial, while others where virtual prototyping is preferred. A physical prototype usually allows human beings' sensory evaluation of a product, such as, form, feel, fitness, and so on. Virtual prototyping applications will be those where physical prototyping is impractical, impossible or inefficient (Grimm, 2005). The two types of technologies are not competitive, the strengths and advantages of one technology will address the weakness and limitations of the other. Physical and virtual prototyping are valuable techniques that can join together to form a powerful tool for rapid development of complex products (Campbell et al., 2004). Industry has access to both technologies and has the ability to select the best one for the task at hand (Grimm, 2005) or even to combine their strengths together. This leads to the need for the integration of physical and virtual prototyping.

After summarizing the findings from the literature review, a checklist of factors where either virtual or physical prototyping is more suitable is shown in figure 1.

	Virtual prototyping	Physical prototyping
cost	√	
time	√	
Ability for iteration	√	
Evaluation of ergonomics		√
Exploring aesthetics	√	
Tactility		√
Dynamic analysis	√	
Complex product	√	

Product with simple structure		√
Functional testing		√
User communication		√

Figure 1 checklist of factors where either virtual or physical prototyping is more suitable

In summary, either physical or virtual prototyping has its own advantages and disadvantages. To optimize the application of these two types of prototyping technologies, a way to integrate them is needed. As Jain (2005) stated the integration of physical and virtual would yield shorter development cycles, fewer late-stage errors, and a higher return on intellectual property such as design, simulation, and testing data.

Conversion Technologies

The research on related work is mainly focused on the existing technologies relevant to the conversion between physical prototyping and virtual prototyping, such as computerised numerical control (CNC) machining, Rapid Prototyping (RP), Reverse Engineering (RE), Parametric Prototype, and so on. Although all of them integrate PP and VP in some way, some problems still need to be solved to meet the requirements of real time integration.

Two typical technologies for converting virtual prototyping to physical prototyping are CNC machining and Rapid Prototyping. Both of them use a finished virtual model to produce a physical part. Therefore, they are also recognized as being a physical prototyping process.

CNC machining is the process of cutting material from a solid block of metal or plastic to obtain a finished physical prototype. In the application of CNC machining, the operator must deal with every feature in a part, and this can add time and cost (Wohlers & Grimm, 2003). In contrast to the subtractive process of CNC machining, Rapid Prototyping is a process of material deposition (Grote et al 2001). It is the automatic construction of physical objects using layered fabrication. The data transfer method in rapid prototyping is the STL (Stereo-lithography tessellation language) file. The CAD model must be converted to the STL format for the build program to analyze and process through RP.

A typical method that converts a physical object to a virtual prototype is Reverse Engineering (RE). It is a process that employs various scanning system, such as Coordinate Measurement Machine (CMM), 3D Laser Scanner (LS), to measure the existing physical object and represent the measured data as a data cloud. The data cloud usually lacks topological information and needs to be processed by 3D software packages, such as DesignWorks, Imageware, PolyWorks, Rapidform, etc, into STL or IGES (initial Graphics Exchange Standard) format for CAD, CAM or CAE applications.

CNC machining, Rapid Prototyping and Reverse Engineering have made significant progress in producing high quality prototypes, shortening prototyping time and combining virtual prototyping and physical prototyping technologies. However, with these technologies, the processes of virtual and

physical prototyping are still used in different stages, and the iteration between them is slow. For example, Rapid Prototyping, which has been recognized as one of the fast prototyping methods, usually needs hours or days to convert a virtual model to a physical part. This means the designers will have to wait for a long time to get these parts, then assemble them and test the physical prototype. After finishing the evaluation of the physical prototype, the designer needs to go back to modify the CAD model again. This iteration between the two types of prototype might happen many times.

Since time and cost are becoming more and more crucial in the product market, it is necessary to re-evaluate these existing technologies. Why is the iteration so ineffective? In the authors' opinion, the ultimate reason is that they are still one-directional technologies. For instance, CNC and RP is a process from virtual prototyping to physical prototyping, while reverse engineering is a process from physical prototyping to virtual prototyping. All these processes are one-directional and irreversible. This requires PP and VP to be used at different times (rather than simultaneously) and hence they become time consuming. Based on these analyses, we propose the research topic of real time integration. The idea is that after the designers evaluate and make changes to a physical prototype, the changes will be applied to a corresponding virtual prototype immediately, and vice versa. It could be called a real time and bidirectional process. If this aim can be achieved, the effectiveness of prototyping will be improved, and the time for new product development could be reduced significantly.

Despite the range of technologies and methods that could be used to integrate virtual prototyping and physical prototyping, the real time and bidirectional integration of physical prototyping and virtual prototyping has still not been achieved by industry. Initial findings can be summarized as follows:

- In the marketplace, there have been various technologies related to the integration between virtual and physical prototyping. These technologies have different emphasises, some concern the conversion from physical prototyping to virtual prototyping, some concern converting from PP to VP and others concern the bidirectional convert.
- The data transfer that bridges physical prototyping and virtual prototyping is usually achieved through the STL file format or others based on STL. However, the lost of design intent is still one of the biggest problems within the data transfer process.
- Non of these technologies can completely match the stated requirement of real time integration of physical prototyping and virtual prototyping

Related research

Recently, some researchers have identified the significance of bidirectional conversion between physical and virtual prototyping. Anderl et al (2006) have developed a tool called "parametric prototype" for integrated parametric and physical shape representation to optimize styling and design (see figure 2). They defined the parametric prototype as "the set-up of a physical mock-up and a virtual model which are linked by an interface." This prototyping technology uses a physical prototype, which has been divided into several

parts. Every separate physical part links with a corresponding virtual part in a personal computer through a hardware interface. The changes to the virtual part can be converted to the corresponding physical one through electrical, mechanical and control components. The changes to the physical part can be converted to the corresponding virtual part through outputting data to the computer.

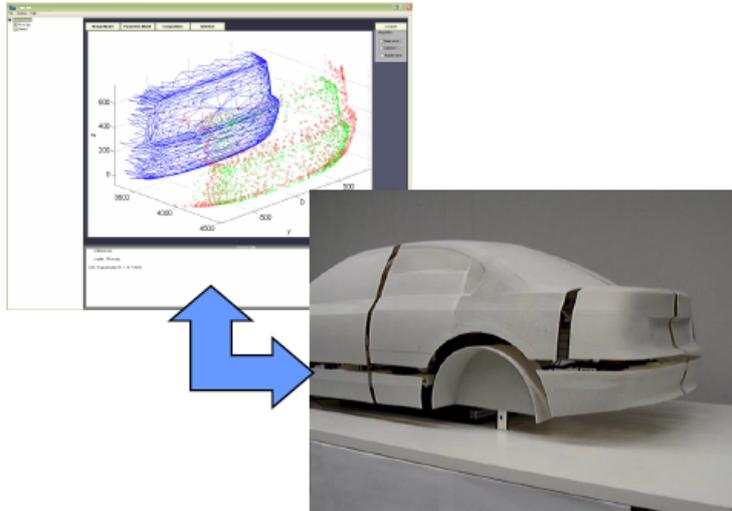


Figure 2 Virtual model with physical parametric prototype (Anderl, 2006)

The development of this tool comprises a method that converts changes to the CAD model and the physical model in a bidirectional manner. This method has matched several requirements of the integration between VP and PP, such as data transitions between a virtual system and a physical prototype, and the bidirectional conversion of shape and size changes. However, this technology is limited to developing the styling of a prototype and the changes are limited to the motion of the parametric parts in horizontal and vertical directions. Other elements, such as aesthetics, material and ergonomics of a product are difficult to test with this tool. As can be seen from the picture showed in the figure 2, the virtual model is still quite rough; it can not simulate the property of material, colour, texture, environment, etc. For the physical prototype, it still cannot be used to test ergonomics element. In addition, when one part is moved, the outline of the car body will be interrupted. Hence, it is necessary to improve the quality of the virtual prototype and the functionality of the physical prototype to make it more practical for actual new product development.

Questionnaire survey and pilot trial

The outcome from the literature review drove further development of the research hypothesis through a questionnaire survey and an initial pilot experiment to explore some of the issues raised.

The questionnaire survey

The research hypothesis was developed by a questionnaire survey that specifically addressed the issues:

- What limitations and benefits of physical and virtual prototyping have industrial designers experienced?
- Will industrial designers want to make use of real time integration and if so, how?

The questionnaire consisted of three main categories: the background, respondent's personal details and the main questions. The "background" gave the respondents an overview about the research and the purpose of the survey. All the questions were designed in the format of "open-ended questions", since the answers might cover a wide range and were difficult to predict.

This survey started from the middle of April 2007 to the end of July 2007, lasted around three months. A total of 102 questionnaires were sent out to consultancies and institutions that have business in industrial design or product design and manufacture. The respondents consisted of industrial designers, design management directors, senior engineers, product designers, design consultants, and so on. Seventeen valid questionnaires were collected and analyzed. This was quite disappointing but the quality of the data received was useful.

To investigate the situations of the use of virtual prototyping and physical prototyping in industry, the respondents were asked what kinds of virtual prototyping tools and physical prototyping methods they use, and the types of product they use these tools or methods for. The respondents presented various virtual prototyping tools being popularly used for a wide range of products, from small electronic product to transportations; from medical device to furniture, etc. The respondents also introduced many types of physical prototyping approaches, ranging from traditional hand made modelling to advanced Rapid Prototyping, that are used in various product design and manufacture activities. From their answers, it was seen that prototyping technology plays one of the most important roles in a wide range of industry areas. Research in this area is therefore significant to new product development.

The next group of questions was designed to explore the benefits and limitations of physical and virtual prototyping. All the respondents gave their opinions on this issue according to their experience obtained from design activities. In summary, compared to virtual prototyping, physical prototyping was seen as more beneficial in the following areas:

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

Compared to physical prototyping, virtual prototyping was seen as more advantageous in terms of:

- Accuracy
- Lead time

- Cost
- Modification
- Flexibility

These answers indicate that both physical and virtual prototyping play important roles. In some situations, physical is more beneficial while in others virtual prototyping is more preferable. Virtual prototyping still cannot replace physical prototyping in many circumstances.

The last group of questions was about in the situations in which the simultaneous use of virtual and physical prototyping has been desirable and how has this been accomplished. About half of the respondents claimed that they had never experienced the simultaneous use of these two types of technologies. Most of these suggested that virtual and physical prototyping were usually used sequentially. However, the other half of the respondents said that they had experienced this or else realized the necessity of real time integration. There are two main categories of the situations where they used (or would use) virtual and physical prototyping together:

- Presentation: present CAD model and physical prototype simultaneously to the clients.
- Test: use FEA and physical prototyping in parallel to test strengths and other elements.

These answers show that in some design consultancies, designers have realised the way in which integrating both types of prototyping will be more effective in developing new products.

Overall, the findings of the questionnaire survey supported the results from the previous literature review that physical and virtual prototyping would not replace each other; each of them having its own benefits and limitations. In addition, some consultancies and designers have recognized the real time integration of both would be helpful for both designers and users during product design. However, the simultaneous use of them is still in its infancy.

Pilot trial

Introduction

Based on the theoretical knowledge and the analysis of the questionnaire survey, a pilot trial was designed to address the following research questions:

- Can real time PP/VP integration be conveniently demonstrated?
- Will designers and users be comfortable using the integration method?
- Will users recognise the benefits of the integration?

The pilot trial can be simply described as a proposed method to simultaneously use a CAD model of a chair (created in Pro/Engineer) to test its appearance and a corresponding physical mock-up to evaluate the ergonomics aspects, combined with the ability to quickly modify both types of models.

The trial involved creating a physical prototype of a basic office chair (see figure 3) that could be modified by the user for backrest angle, seat height and seat angle. These three dimensions were measured with straight ruler and goniometer. Since this is a pilot trial to initially test the proposed method, the accuracy of the measurement was not a key point in this stage. The measurements were then input into Pro/ENGINEER where they were used to drive a parametric CAD model of a highly stylised chair (see figure 4). The user was then able to simultaneously evaluate the comfort and appearance of the chair design by referring to the physical prototype and virtual prototype, respectively.



Figure 3 The physical mock-up



Figure 4 The CAD model of the chair

Trial process

There were six groups of people involved in this test. In each group, the author acted as a "director", another person (industrial design student) acted as a "designer" and the third person acted as a "customer". As the "director", the author told the designer and customer how to use the method to finish this trial.

For each group, the trial process followed five steps:

1. The designer asked the user to try the chair and collected a group of data of the three evaluated elements.

2. The designer entered a group of data into the Pro/E feature “family table” associated with the CAD model that modified the CAD model immediately. Figure 5 shows when the backrest angle was adjusted to position 1, 2 and 3, how the CAD model was changed correspondingly.

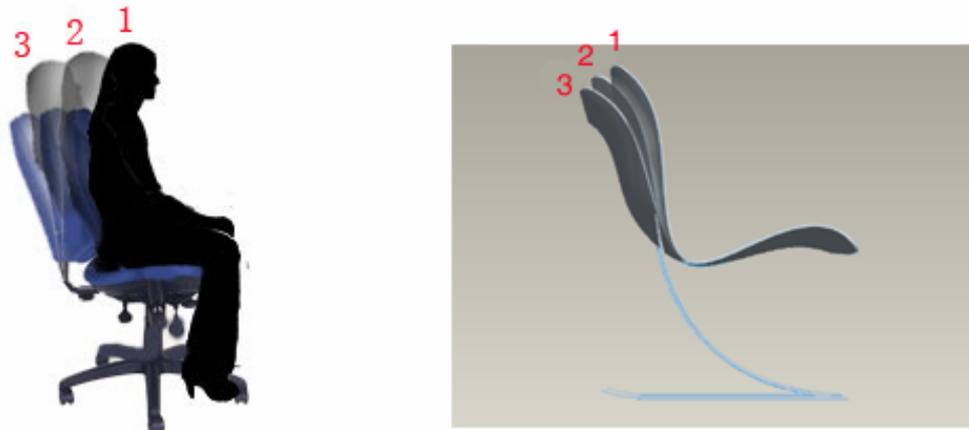


Figure 5 The corresponding changes of physical and virtual chair model

3. The designer showed the changed model (the CAD model image was projected to make it easier for the user to see (see Figure 6)) to the user who provided feedback about the aesthetics of the design so that the designer could update the CAD model again.



Figure 6 The evaluation of the chair with both virtual and physical models

4. The designer could use other features of Pro/E to evaluate other elements of the CAD model, such as, the volume of the material, the strength of the structure, the dynamics, etc. After all the required evaluations, the designer would have a new version of the chair design.

Summary of findings

This trial explored an approach on how the two types of prototypes were used at the same time to help the designer develop their design and help the user become more involved. In terms of technology, the most important and difficult part was the building of the CAD model before the trial. It should be built properly by using key Pro/E features, such as relations, family table, etc., to make sure the shape changes of the chair in the CAD model could stay smooth when the backrest angle, seat height and angle were changing.

After the trial, the designers and users were asked to complete a questionnaire to show their opinions on this method. The main results from the trial were that designers saw it as a method that was helpful in terms of quick modification of models, reducing testing iteration time and hence reducing costs. They also gave some suggestions about the method as following:

- The complexity of the method should vary for different products. Since there are more complex products with more variables and there are more simple products with less.
- More vectors should be added to the test, such as a texture, feeling, and environment.

The users claimed that this method was helpful for them to understand chair design. However, some aspects would be needed to improve the user involvement. For example, the physical mock-up needed to be easier to adjust and it should look more like the CAD model as it was difficult for the users to match them together.

Conclusions and future work

Physical prototyping has a long history in contributing to new product development. On the other hand, thanks to the development of computer technology, virtual prototyping has enjoyed a significantly rapid development and has replaced physical prototyping in many aspects. However, physical prototyping will not be completely replaced by virtual prototyping. It still shows its advantages in many ways, such as ergonomics evaluation, the test of material texture, etc. Therefore, it is necessary to combine the advantages of both types of prototyping technologies.

In the current market, there are some technologies useful for combining physical and virtual prototyping. Some of them are used to generate physical prototype from virtual model, such as Rapid Prototyping and CNC machining; others are used to establish a virtual prototype from a physical object, for instance, Reverse Engineering. These technologies have shown the significance of the integration of physical and virtual prototyping. However, the process of generating prototypes with them is usually time-consuming. In addition, these technologies cannot be seen as a real and complete integration of virtual prototyping and physical prototyping.

The literature review and questionnaire survey have shown that some designers and researchers have identified the necessity of using PP and VP in parallel and have even developed a new prototyping approach, called, the parametric prototyping technology. The theory of this technology is close to the authors' research aim, which demonstrates the significance and

importance of the parallel and synchronous use of virtual and physical prototyping. However, this technology just focuses on the styling development of a product and is still at an early stage.

The results of the pilot trial have shown that simultaneously applying physical and virtual prototyping is useful for getting users more involved and for reducing testing time. However, the method used in the trial is still rough. More work is needed to improve the quality of both the physical and virtual prototyping used. For instance, applying advanced measurement equipment to obtain accurate data for the physical prototype's dimensions; making the virtual prototype more realistic to help the user understand the design. In addition, apart from developing this method, other possible integration approaches need to be explored. For example, employing motion capture technologies to translate the movement of the physical prototype into a computer program, while using robotic technologies to control the movements of the physical prototype. Then a comparative study will be needed to evaluate all these methods, choose a best one and recommend directions for further development.

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In 2003, Bingjian Liu finished his undergraduate study in Industrial Design and was awarded Bachelor of Engineering at Shandong University in China. In 2006, he obtained his Masters degree in the Department of Design and Technology at Loughborough University. In the same year, he was awarded a university studentship and started his full time PhD research supervised by Dr R.I. Campbell. The research interest of Bingjian Liu is "the real time integration between physical and virtual prototyping".