

Visualization of Surface Accuracy for Virtual Prototyping

S.H. Choi and A.M.M. Chan

Department of Industrial and Manufacturing Engineering
The University of Hong Kong

Abstract

This paper introduces a virtual prototyping (VP) system that simulates a RP process to produce a virtual prototype of a product, which facilitates visual study of the surface quality of the physical prototype that the RP machine will subsequently fabricate. The virtual prototype displayed in a computerized virtual environment allows the designer to analyze the surface texture and accuracy of a product prototype conveniently. It may be super-imposed on its original design so that all dimensional deviations are clearly highlighted. The system can further pinpoint the areas in which the dimensional deviations are out of the acceptable range. The designer can hence improve the accuracy of the prototype well before physical fabrication by optimizing the RP fabrication parameters, such as the layer thickness, hatch space and build orientation, in the system. In this paper, the simulation principles will be described and case studies will be given to illustrate how the system works.

Introduction

1.1 Rapid Prototyping and Virtual Prototyping

Rapid Prototyping (RP) is a prototype-making technology, which helps explore the potential problems of a product design prior to actual production by fabricating prototypes in short time and then carrying out design analyses on them. A wide variety of RP systems (Xue, 1996; Pham, 1998) are now commercially available. Although they are much more advanced than conventional methods, current RP technology is plagued by some problems that undermine the accuracy and quality of the prototypes. Virtual prototyping (VP), however, can get rid of these problems because digital models are mostly used for testing and evaluation of the specific characteristics of a product or a manufacturing process in a virtual reality environment.

Dedicated VP systems have been developed and are used by automobile and aerospace companies. Ressler presented a summary of applications of virtual reality in manufacturing projects (Ressler, 1995). The task performed at the Boeing's Huntsville laboratories is to model lunar rover radiation effects, especially during a solar proton event. The VR world developed allows a designer to insert a model to evaluate the dosage levels of radiation based on their position. The work at University of Michigan and the Naval Research Institute focused on experiments in shipboard firefighting to verify the effectiveness of virtual reality as a mission-planning tool (Roseblem, 1996). The researchers also used VR as a visualization tool in the preliminary design of new naval ships. Volkswagen employed VR to accelerate their car design process (Purschke, 1997). The engineers used life-sized virtual models for ergonomic analysis and surface inspection instead of building clay models, which are costly and time

Despite the above VP developments, RP still plays an irreplaceable role in manufacturing. For example, RP makes master patterns for molds and dies used in injection molding and investment casting. Fabricating these tools rapidly facilitates speeding up the whole production process. However, relatively few researchers have adopted the advantages of VP to enhance RP technologies. Gibson *et al.* investigated the contributions of VR and RP towards a more efficient product development in ergonomic, aesthetic and functional aspects of design (Gibson, 1993). Morvan *et al.* linked virtual reality with the rapid prototyping process to visualize the support structures of a part and to aid the designer to identify improper support structures (Morvan, 1996). They further coupled RP with VR by developing the Interactive Virtual Environment for Correction of STL files (IVECS) system. The system detects errors in STL files and allows triangular facets to be added, removed, reversed or offset. Jee *et al.* developed a visual simulation system for 3D printing as a visual tool to examine surface textures of relatively simple objects (Jee, 1998).

1.2 A new approach to virtual prototyping

To conclude, VP is well developed and used in automobile and aerospace industries for replacement of large and expensive physical mock-ups. However, VP applications for general manufacturing industry have been overlooked. Indeed, VP may provide a test-bed and much valuable information that might otherwise have required time-consuming and expensive physical experimentation. Suppose that VP is used to study the quality of the prototypes before physical fabrication and thus tune up the process parameters for RP, it definitely reduces the number of physical iterations and thereby the associated manufacturing overheads that results in faster and cost-effective development of products.

Indeed, prototype quality is major problem in RP. Many researchers have developed systems for this purpose. They generally adopted the computational approach, in which prototype quality is presented in numeric values. Thomson *et al.* estimated the volumetric error between the intended part and the layered approximation (Thomson, 1995). Zhao *et al.* quantified the surface accuracy by the relative surface area deviation between the successive slices (Zhao, 1998), and Hur *et al.* evaluated the part accuracy by the projected staircase area with the cross-sectional cusp area (Hur, 1998). The computational figures, however, only indicate the overall quality of the prototype, but not give detailed quality assessment of any specific parts of the prototype. Choi *et al.* have recently developed a virtual prototyping system that adopts the VP approach and simulates RP process to fabricate a product prototype in a virtual environment (Choi, 2001). The virtual prototype facilitates design validation, as well as and the optimization of process parameters with regard to key requirements, which include accuracy, build-time and efficiency. Despite the advantages of this system in facilitating product development, most of the results are still presented in numeric terms. The benefits of virtual prototypes have yet to be fully exploited.

This paper describes the enhancements of the VP system. The new system builds a virtual prototype with either rectangular strips of solid or solid layers depending on which RP process is being modelled. These two modelling approaches resemble the physical fabrication processes of most powder-based and laminated sheet-based RP systems. The system simulates an RP process to create a virtual prototype, which allows a designer to perform analyses of the surface accuracy conveniently. The virtual prototype may be superimposed on the original product model to provide a

clear visualization for direct comparison of the product design and the resultant prototype that the RP machine will subsequently deliver. This is particularly useful for point-to-point analyses of the surface texture and the dimensional accuracy of the prototype. Specific areas of the prototype where the dimensional deviations are beyond the design limits can be easily identified and highlighted for subsequent improvement. With such a virtual prototype in the computer, process parameters can be tuned during analysis carried out on the virtual prototypes and a qualified prototype can be obtained in the first time fabrication. The following sections describe the implementation of the VP system.

Virtual prototypes

2.1 Modelling approaches

To perform an accurate analysis of physical prototypes in VR is not a simple task. An essential and prerequisite criterion is that a virtual prototype should accurately represent its physical one. Having so many RP processes commercially available in the market, it is impossible and uneconomical to develop individual modelling approaches for each of them. Therefore, common RP processes are classified into two major types, the ones that fabricate prototypes hatch-by-hatch and the ones that fabricate prototypes layer-by-layer. With respect to these types of processes, there are two separate modules, dixel-based and layer-based, provided by the system for appropriate virtual simulation.

2.1.1 Dixel-based virtual simulation

Physical prototypes made by powder-based RP processes, such as SLS, FDM and 3DP, may be regarded as being made up of strips of material that are solidified/sintered by the laser or binder head. To model this effect, a dixel-based virtual simulation is proposed. In the simulation, dexels behave as the hatch lines and represent the head trajectory where rectangular solid strips formed by the head represent the volume blown up by the dexels. This is a new approach to virtual prototyping in that arrays of dexels, which are finite strips, are laid to form a layer, and subsequently stacked up to form a virtual prototype.

2.1.2 Layer-based virtual fabrication

For laminated sheet-based RP processes those fabricate prototypes layer-by-layer, such as the LOM and Solid Ground Curing (SGC), the dixel-based simulation is not fully applicable. Smooth edges in every layer of the real prototypes cannot be achieved by dexels. To solve this problem, another simulation approach, a layer-based virtual fabrication, is proposed. It extrudes all the contours in a slice in one time to build a proper layer directly. Since each layer is extruded, instead of being composed of rectangular solid strips, the build-time for the virtual prototype by this approach is a lot shorter than by the dixel-based approach.

2.2 Visualization of RP

The proposed VP system facilitates the analysis of surface accuracy through visualization of the RP process and the resultant virtual prototype. Indeed, visualization is important in every kind of analyses. For example, a car model may be built virtually and then projected on a large screen, and the design team can share a virtually realistic 3D image of the product by wearing stereo-glasses. and discuss and

solve any design problems conveniently.

Visualization also helps designers understand what will happen to a particular part of the prototype. It is common that not all features in the model are required for a specific analysis and the average quality presented by numeric values is not enough to fulfill the actual requirements. On the contrary, a clear visualization of the prototype is particularly helpful for making objective decisions.

2.2.1 Superimposition of product model on virtual prototype

For this purpose, the proposed VP system can display the virtual prototype and the product model simultaneously. These two images are superimposed for direct comparison of the resultant prototype and the original design. This allows point-by-point investigation of any discrepancy in the characteristics of the prototype. Any specific areas with dimensional errors beyond the tolerance limits may be clearly identified and highlighted for subsequent improvement.

2.2.2 Staircase effects and optimization of process parameters

Due to the working principle of RP processes, the resultant prototypes cannot be produced in the same dimension as the CAD model. At least, they suffer from the vertical staircase effect and may be also the horizontal staircase effect. The surface texture and the dimensional accuracy of a prototype may be improved by reducing the layer thickness and the hatch spacing. However, the fabrication time will be increased accordingly. Indeed, the quality and the build-time of a prototype are significantly affected by some major process parameters, particularly the orientation, the layer thickness and the hatch spacing, etc. Therefore, an optimal combination of process parameters must be carefully chosen for efficient production of prototypes of the required quality.

Visualization of RP will be very useful to help choose a proper set of process parameters for optimal production of prototypes. The designer can clearly see the effects on the prototype quality by changing the process parameters. Subsequently, an optimal set of process parameters may be chosen quickly for efficient production of prototypes.

The proposed virtual prototyping system

The main objective of the proposed VP system is to facilitate visualization and optimization of RP processes, and thus faster product realization. Based on a product model designed on a CAD package, the system simulates the characteristics of an RP process to perform virtual fabrication of the product prototype. The virtual prototype may then be used in various analyses. As shown in Fig. 1, the proposed VP system consists of three main steps, namely (1) Creation of a product model; (2) Virtual fabrication; and (3) Visualization and tuning of process parameters.

3.1 Product model

Creating a product model is the first step to provide the necessary information of the design, which includes the geometry and the attributes of material and colour, etc. Mostly, the product model is designed on a CAD package and then converted to a STL model.

3.2 Virtual fabrication

According to the RP process being modelled, a proper simulation approach is chosen. Before performing virtual fabrication, preparation work is carried out in several modules, including a model viewer, a slicer, a hatcher and a part fabricator. The Model Viewer Module reads a STL model and displays it in the virtual world (VW) to allow the designer to have an idea of the original model first. The Slicer Module slices the STL model to produce the contour information in each layer. The Hatcher Module performs hatching in all layers to generate the laser/binder path. If layer-based simulation approach is chosen, this step can be omitted. The Part Fabricator Module reads in necessary information and simulates the fabrication process to

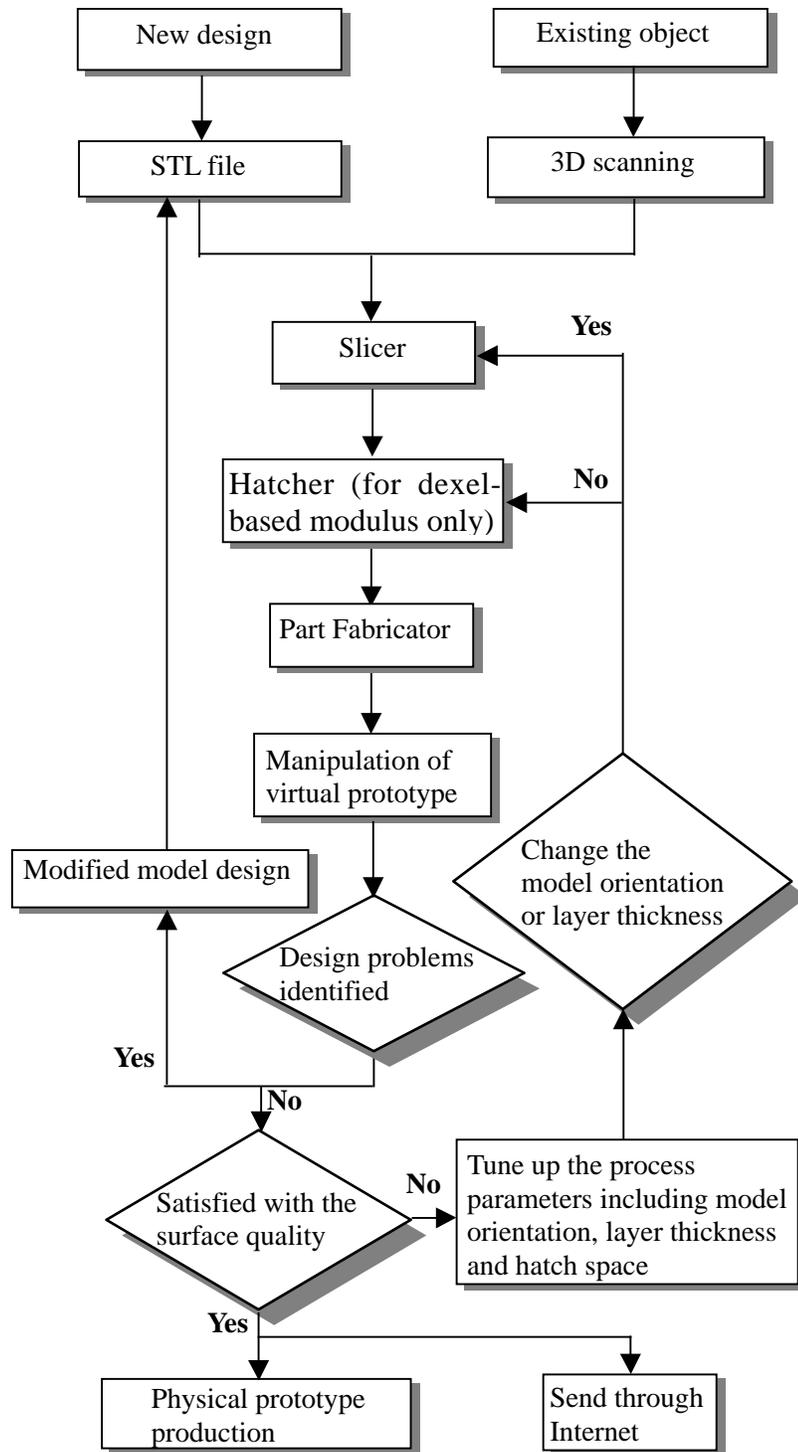


Fig. 1. Flow of the virtual prototyping system

form a virtual prototype in the VW created by WorldToolKit (WTK) from Sense 8. It allows the designer to visualize the process by displaying the modelled results, such as the surface quality, with respect to the process parameters to show the effect of different process parameters on the prototype in real-time.

3.3 Visualization and tuning of process parameters

Once the simulation process is completed, the designer can manipulate the virtual prototype by the functions provided to visualize the quality of the product

prototype that the RP machine will subsequently deliver. The designer can navigate around the internal and opaque structures of the prototype to investigate the product design. At the same time, model deviations are indicated by superimposing the STL model on its virtual prototype. The system calculates the maximum and the average cusp heights that indicate overall accuracy of the prototype. If the cusp heights are found unsatisfactory, a tolerance limit may be set for the dimensional deviations. Any location with a deviation beyond the limit will then be clearly highlighted. The designer may thus identify and focus on the parts that most need modifications. To improve the accuracy and the surface quality of specific features of the prototype, the orientation of the model, the layer thickness or hatch space may have to be optimized.

Case study

4.1 Dimensional accuracy study – model deviations

A toy spider was chosen as an example to illustrate how the VP system facilitates the study of dimensional deviations between a prototype and its STL model. Fig. 2 shows two spiders, one of which was the STL model and the other was the virtual prototype produced by the layer-based modulus. In the real world, it is difficult to study the dimensional deviations even if a physical prototype was available. However, when they were superimposed in a virtual environment, as shown in Fig. 3, the surface texture and the dimensional deviations were clearly shown.

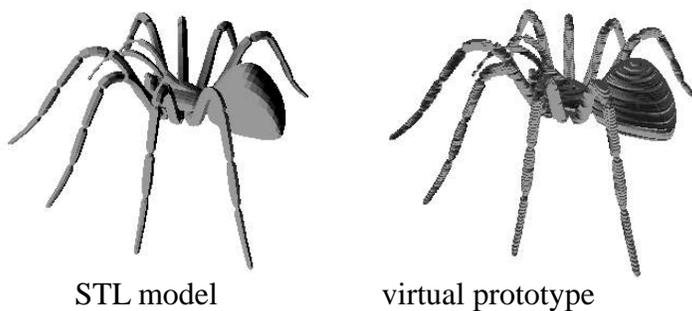


Fig. 2 Spider in STL model and a layer-based virtual prototype

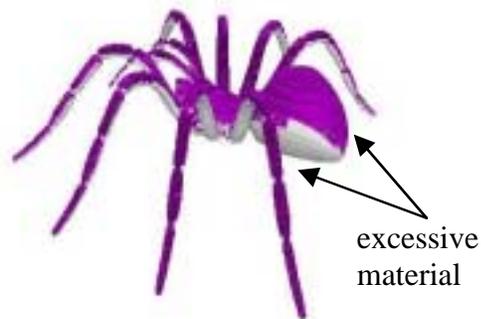


Fig. 3 Superimposition of the spider on its virtual prototype

The solids in gray located on the spider indicate the excessive material formed in fabrication. Before visualization analysis, the system firstly calculates the cusp heights to evaluate the overall accuracy of the prototype. In this example,

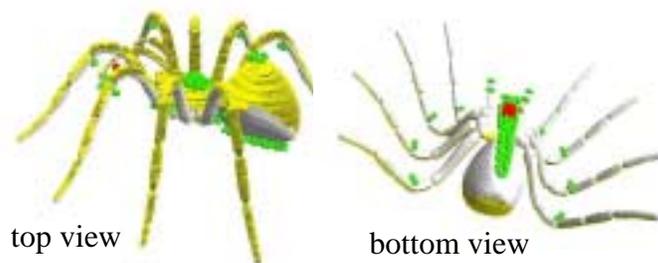


Fig. 4 Areas on the spider with dimensional deviations beyond design limits

the average and the maximum cusp heights were 0.401mm and 0.852mm respectively. Suppose that any deviations more than 0.762mm were not acceptable, the designer

investigation of these important features. Fig. 4 shows the same spiders with some pins on them. The pins actually pointed to the facets of the STL model with cusp height more than 0.762mm. If unsatisfactory deviations were located on the important parts of the model, the designer might choose either changing the model orientation to shift the deviations or reducing the layer thickness to improve the cusp heights. Here, the latter corrective action was made. A smaller layer thickness was used in the second simulation. Fig. 5 shows a comparison of the two virtual prototypes formed with a different layer thickness. It can be visualized that the excessive material was less than before, and at the same time, the average and maximum cusp heights were reduced to 0.241mm and 0.511mm respectively.

4.2 Surface texture study – staircase effects

A gearbox was used to demonstrate the analysis of surface texture. It was sliced into 5mm thick layers and hatched with 4mm. Fig. 6 shows the prototype that fabricated in the first simulation by the dixel-based modulus of the VP system.

This prototype indeed provided a preview for the surface roughness of the physical prototype. It demonstrated the possible appearance of the surface if the same process parameters were used in the physical fabrication.

In this case, the surface roughness appeared to be far from acceptable. Therefore, both the layer thickness and hatch space were reduced to improve the surface quality. The second simulation was conducted with a layer thickness of 2.5mm and a hatch space of 2mm. The resultant prototype was compared with the previous one. Significant improvement was noticed in the staircase effects, as shown in Fig. 7. However, if the improvement was not yet satisfactory, the simulation might be repeated by tuning the parameters until satisfactory surface texture was obtained.

Conclusions

This paper proposes a virtual prototyping system that builds a virtual prototype with two simulation approaches, the dixel-based and layer-based. Dixel-based virtual prototypes may truly represent the surface texture of the

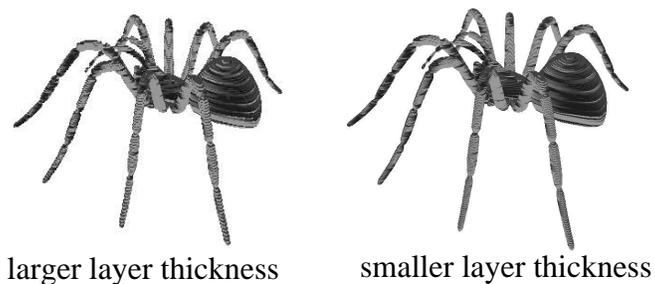


Fig. 5 Comparison of spider prototypes with different layer thickness

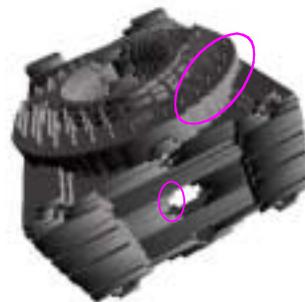


Fig. 6 Staircase effects on prototype

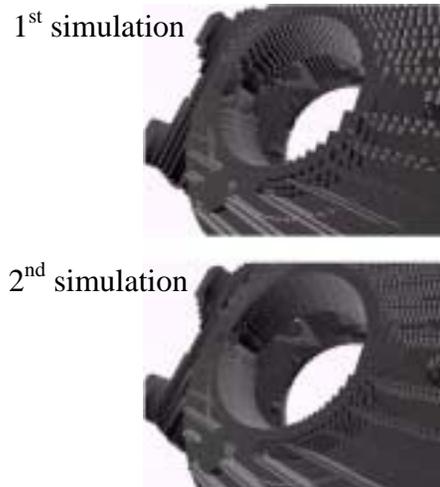


Fig. 7 Prototypes of gearbox with improved horizontal

physical ones fabricated by powder-based RP processes whereas layer-based virtual prototypes represent the prototypes fabricated by laminated sheet-based RP processes. The system may superimpose a product on its virtual prototype for visual investigation that facilitates surface accuracy analysis and process parameters optimization. The system helps reduce considerably the number of physical prototypes and the associated manufacturing overheads, hence realization of rapid product development may become possible in an economic way.

Acknowledgements

The authors would like to acknowledge the Research Grant Council of the Hong Kong SAR Government and the CRCG of the University of Hong Kong for their financial support for this project.

References

- D.C. THOMSON and R.H. CRAWFORD, *Optimising part quality with orientation*, Solid Freeform Fabrication Symposium, (1995), p.362.
- D.T. PHAM and R.S. GAULT, *A comparison of rapid prototyping technologies*, International Journal of Machine Tools & Manufacture, (1998), Vol. 38, p.1257.
- F. PURSCHKE, R. RABATJE, M. SCHULZE, A. STARKE, M. SYMIETZ and P. ZIMMERMANN, *Virtual reality (VR) – new methods for improving and accelerating vehicle development*, Virtual Reality for Industrial Applications, Springer, (1998), p.105.
- H.J. JEE and E. SACHS, *Visually simulated surface texture models for 3D printing*, Proceedings of the 7th European Conference on Rapid Prototyping and Manufacturing, (1998), p.49.
- I. GIBSON, D. BROWN, S. COBB and R. EASTGATE, *Virtual reality and rapid prototyping*, Virtual Reality in Engineering, (1993), p.51.
- J. HUR and K. LEE, *The development of a CAD environment to determine the preferred build-up direction for layered manufacturing*, The International Journal of Advanced Manufacturing Technology, (1998), Vol. 14, No. 4, p.247.
- ROSEMBLEM, *Shipboard VR: from damage control to design*, Naval Research Laboratory, IEEE Computer Graphic Applications, Nov., (1996), p.10.
- S. RESSLER, *Applying virtual environments to manufacturing*, NISTIR, (1995), 5343.
- S.H. CHOI and V. SAMAVEDAM, *Visualisation of rapid prototyping*, accepted for publication in Rapid Prototyping Journal.
- S.M. MORVAN and G.M. FADEL, *IVCES, Interactive correction of .STL Files in a virtual environment*, Solid Freeform Fabrication Symposium, (1996), p.491.
- W.K. CHIU and S.T. TAN, *Multiple material objects: from CAD representation to data format for rapid prototyping*, Computer-Aided Design, Vol. 32, (2000), p.707.
- Y. XUE and P. GU, *A review of rapid prototyping technologies and systems*, Computer-Aided Design, Vol. 28, No. 4, (1996), p.307.
- Z. ZHAO and L. LAPERRIERE, *Adaptive direct slicing of the solid model for rapid prototyping*, Proceedings of the First Conference on Rapid Prototyping and Manufacturing, Beijing, (1998), p.470.