An Interactive Virtual System for Simulation and Optimization of Rapid Prototyping

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Abstract
The paper describes the development of a computer system for simulation and optimization of rapid prototyping (RP) processes. The system provides a test-bed for virtual prototyping by integrating product design and RP with simulation and realistic visualization techniques. It enhances the dimensional accuracy and reduces the build-time of product prototypes. The virtually fabricated parts may be exported in VRML format over the Internet for effective communication between the manufacturer and the customer. The designer may use the system to *design-build-break* as many parts as required at a relatively low cost and in a short period of time. Therefore, virtual simulation of RP processes facilitates tuning of the control parameters according to the requirements, and hence reduces the number of physical prototypes needed to produce a part.

1.0 Introduction

Innovative products and shorter *time-to-market* cycles are essential for the success of every company. A typical product development cycle (concept->design->evalutaion->redesign) consists of several sub-processes, such as prototyping, simulation and optimization. An important way to reduce the product development cycle time is to accelerate the prototyping processes. This is often achieved by using rapid prototyping (RP) techniques. A typical RP process, as shown in Fig. 1, includes pre-processing, physical processing and post processing stages. The pre-processing stage involves creation of 3D CAD models and process planning. The process planning stage generates appropriate laser path signals based on the control parameters specified by the designer. The physical processing stage drives the laser to build the part in layers. The method of achieving this differs amongst various processes. The post-processing comprises a few operations, which include removal of support structure, and curing and cleaning and of the part, as needed for the RP process.

The process planning stage is almost identical to all the RP processes. However, it significantly influences the quality of the part, which can be measured by the accuracy, build-time, efficiency and strength. It involves part orientation, slicing of the CAD model and laser path generation. For liquid-based processes, support structures are required. All these steps affect the part quality. The orientation of an RP part affects its accuracy, build-time and strength. For example, orienting the part with minimum z-height possible will result in fewer slices, and hence a reduction in build-time. Layer thickness affects the accuracy and build-time. The accuracy may be improved when the part is built with a smaller thickness, but the build-time will increase inversely. Hatch spacing refers to the distance between the laser paths. It affects the build-time and strength. Typically, the user has to determine these process planning parameters. Thus the quality of the part depends on the users' experiences, which are often inconsistent. To overcome this problem, several semi- or fully automatic algorithms have been proposed to optimise the process planning to enhance part quality [1-4]. However, most of these methods choose only a single criterion as the objective function, while other criteria are treated as constraints or ignored altogether. Also these methods do not reconstruct the part for verification before manufacture. A system that provides a convenient means for the designer to tune the control parameters and to visualise the desired part before manufacture will reduce the prototype development time. Virtual reality (VR) addresses this need. It mainly consists of a suite of 3D graphics and real-time simulation software that allow the user to interact with a computer-generated environment. Simulating an RP process in VR may result in accurate determination of the control parameters. The simulated part can be quickly regenerated and easily modified and transported over the Internet. This may reduce the need for physical prototypes to a larger extent.

An integrated virtual system for optimisation of pre-processing parameters is now being developed. Fig. 2 illustrates the main modules of the system. It includes the model generator, the model viewer, and the virtual simulator. The model generator accepts the digitised data of the part and processes it to generate a tessellated CAD model. The model viewer accepts the model created either by the model generator or a CAD model in STL format. It allows the designer to visualise the part in virtual environment and to interact with it. The virtual simulator module orientates the part based on the user-defined criteria and simulates the RP process. This module quantifies the accuracy, build-time and efficiency. It also facilities visualisation of the desired part before physical fabrication is committed. The integrated virtual system enables the user to design a part in STL format or digitised data. These CAD models can also be used to simulate the RP process to optimise the control parameters. Subsequently, the system helps materialise the final part in digital format for analysis and effective communication. The system was developed on Window NT, WorldToolKit (WTK) and Visual C++, with interfaces with AutoCAD and Solidworks. A semi-immersive virtual reality system with shutter glasses and a 21" monitor are used. The shutter glasses are used to obtain stereoscopic visual effect.

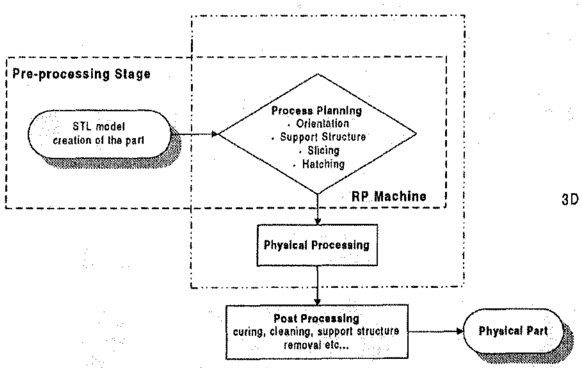

Fig. 1 Rapid Prototyping Process

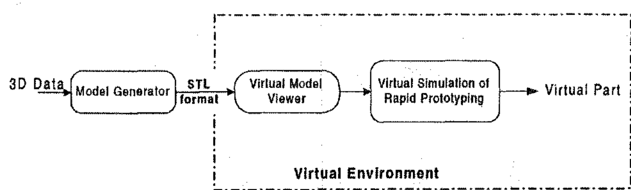

Fig. 2 The Modules of the Virtual System

2.0 Model Generator

This module generates a 3D CAD model from digitised data [5]. It involves digitising the surface data of a part by using a mechanical or laser scanner. The surface data are filtered to eliminate redundant points. The algorithm employed calculates the change of the slopes between successive points and compares it with the user-specified tolerance. If the change of slope falls within the tolerance, the corresponding point is eliminated. Employing this approach, the regions with high curvature are approximated with a large number of points, while flat surfaces with fewer points. The filtered points are considered as control points of spline curves, which are created both longitudinally and transversely to reconstruct the surface of the part. The designer can also alter the control points to manipulate the geometry locally. These surfaces are approximated with a given tolerance to generate a CAD model in STL format. The model generator can also generate male and female cavities of the part for rapid tooling purposes.

3.0 Model Viewer

This module reads in a product model in STL format, such as the dolphin in Fig. 3, and displays it in the virtual environment. The main element of VR is its stereoscopic presentation, which generates a compelling illusion of the product. The stereo-viewing ability allows the designer to gain *'being there'* feeling. This creates an impression to the designer that he or she is acting upon a real object. The model viewer thus provides a real-time tool for the designer to explore and enhance the features of the part. The ability to view a model from different perspectives helps the designer analyse it by inspecting both the external geometry and the interior structure. For complex prototypes, it may be necessary to analyse the interior of the part for layout, visibility, and accessibility etc. The designer can view and analyse with a realistic feeling the interior of the virtual prototype. Furthermore, the aesthetic evaluation of a product can be performed in VR by mapping a combination of texture and colours to it. Lighting and illumination effects may also be created for better assessment of the part. Thus virtual parts not only represent the geometry but also material properties like colour, texture and reflectivity, which are not completely supported by CAD systems. Indeed, visualisation of STL models in VR interactively may help the designer check its validity [6].

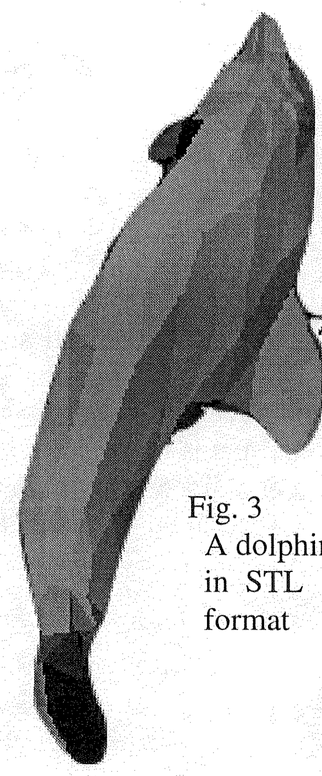

Fig. 3 A dolphin in STL format

The module allows the designer to interact naturally with the virtual part with 3D mouse. The designer can view it in stereo, rendered or wireframe mode and navigate around and into the part. Visualisation of the CAD models in a realistic display enhances the designer's imagination upon viewing and manipulation, which facilitates refining the design.

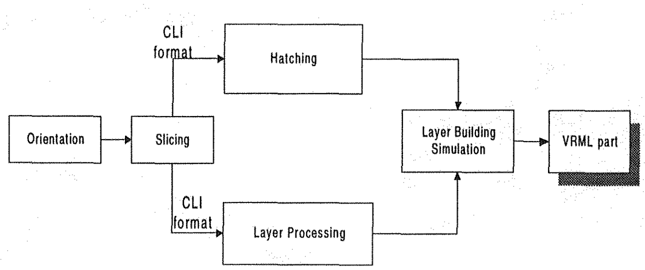

Fig. 4 The flow of Virtual Simulation

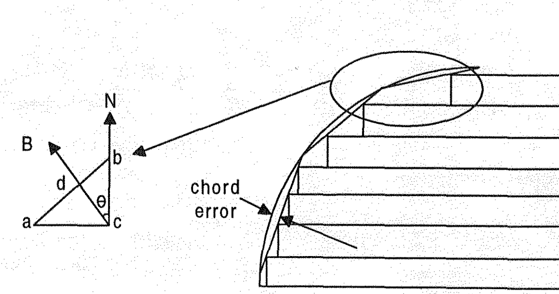

Fig. 5 The stair-step effect of layer thickness

4.0 Virtual Simulation

This module simulates the rapid prototyping process. Fig. 4 illustrates its sub-modules and the detailed structure can be found in [7]. The orientation module determines the optimal orientation. The slicing module employs uniform slicing to slice a part. The layer processing module process the slice data to generate layers, while the hatching module determines the laser paths. The layer building simulation module generates the part. It also calculates the build-time, efficiency and accuracy of the part for a given orientation. The methods used to determine these criteria are discussed below.

Accuracy

Accuracy can be defined as the geometric deviation of the part from the progenitor CAD model. In process planning stage, the loss of accuracy is mainly due to the generation of layers by extrusion of planar contours. This results in stepped approximation of the boundary of the original CAD model. Consequently, all the parts generated by layer manufacturing technique exhibit "stair-step" effect, as shown in Fig. 5. This effect is more significant on slanted and curved surfaces. This error can be quantified by cusp height, which is the distance between the intended and approximated surface at each facet. For each facet, the surface normal indicates the angle that the facet makes with the build direction. If the surface normal is not perpendicular to the build direction, the facet will exhibit some stair-step effect. For a given facet, with a, b, c as vertices in Fig. 5 and the notations at the end of the paper, the error can be evaluated as follows:

$$\text{Cusp height } (h_c) = bc\cos\theta \quad (1)$$

$$\text{Maximum cusp height (MCH)} = \max(h_c) \quad (2)$$

$$\text{Average cusp height (ACH)} = \frac{\sum_{i=1}^{N_f} h_{ci}}{N_f} \quad (3)$$

The average cusp height represents the mean of the linear deviation of the facets, while the maximum cusp height is the maximum linear deviation among the facets. The cusp height estimation predicts the linear deviation of the surface on geometry. Hence in the present approach, cusp height for measuring the dimensional error is adopted.

Build-Time

Build-time can be defined as the time required to build the part physically. The system aims at developing a generic build-time estimator for RP processes using optical laser heads. It evaluates the time as a function of laser velocity, scan distance and layer thickness. The velocity for SLA can be obtained from literature [8]. For SLS the laser velocity derived from [9] is shown in Eq. 4.

$$\text{Velocity (V)} = \frac{P \times (1-R)}{\rho \times d_b \times \ell_m \times \left[C_p\left(T_m - T_b\right) + k L_h\right]} \quad (4)$$

The build-time of a part can be obtained by summing up the time taken for each layer, as shown in Eq. 8, which is derived from Eq. 5. The time taken for a layer can be divided into the scan time and the set-up time. The set-up time can be obtained from the machine manual and it is normally constant for all layers. The time required for scanning a layer varies along the z-axis and can be obtained as a ratio of the scan distance to the scan velocity from Eq. 6.

The total scan distance within a layer can be obtained from the hatch file. The velocity can be estimated based on the process. For example, it can be estimated from Eq. 4 for SLS process. The elements in the set-up time for the SLS process are given in Eq. 7.

$$\text{Build-time of a part} = \sum_{i=1}^{N_\ell} T_{\ell i} + (T_s \times N_\ell) \qquad (5)$$

$$\text{Scan time } (T_\ell) = \frac{L_d}{L_v} \qquad (6)$$

$$\text{Setup time } (T_s) = t_{pd} + t_m + t_r + t_{pr} + t_d \qquad (7)$$

$$\text{Therefore, Build-time of the part} = \frac{h}{\ell_m} T_s + \frac{\sum_{i=1}^{N_\ell}\left(d_{si} \times \frac{\ell}{\ell_m} \right)}{\ell v} \qquad (8)$$

The scanning pattern differs from process to process. The laser scans the layer in horizontal and vertical directions. A hatching algorithm was developed to evaluate the total scan distance of each layer. The laser velocities can be obtained from the power equation of the process involved. The power equation of the RP includes process parameters, such as the laser beam diameter, the slice height for SLS, and the overcure depth for SLA. The present approach allows the user to evaluate build-times for different process parameters. The algorithm developed is mainly targeted at SLS machine, though it may be subsequently modified for other processes. For standard DTM materials, it estimates build-time with approximately 93% accuracy.

Efficiency

Efficiency can be measured by in terms of material utilisation. It can be obtained as a ratio of volume of the parts with the total volume of the workspace. However, in most cases the parts may not be completely filling the build chamber and may contain only a limited part. Hence, the volume of workspace that a part uses is different when compared to the total volume of the workspace. The volume occupied by a part can be obtained as the product of the height of material deposition and the surface area of the work platform. The maximum material height may vary with parts orientation. For example, the volume occupied by a rectangular box when oriented at 45° is more than when it is oriented at 90° or 0° to its base. Thus the volume occupied by a part can be approximated with its bounding box for a given orientation. Even if the parts are packed in the workspace, the packing algorithms usually pack them by building bounding box around each part. The enclosing bounding box to the volume of the workspace in use indicate the maximum material utilised for a given orientation of the part. The relative efficiency is given in Eq. 9.

$$\text{Efficiency } (\eta) = \frac{\sum_{i=1}^{N_p} V_{pi}}{h_m \times A_w} \qquad (9)$$

4.1 *Orientation*

This module orients the STL model in the build direction. The optimal build orientation is determined based on the minimum build-time or the maximum accuracy criterion. For the minimum build-time criterion, the part is enclosed in a bounding box and oriented such that it has the minimum z-height in the build-direction. This reduces the number of layers required and hence the build-time. The build-time is estimated from Eq. 8.

For the accuracy criterion, the part is rotated about the x- and y- axes within a given range at specific intervals. The rotation of the part about the z-axis will not change the angle between the facet normal and the build-direction. For each rotation, the average cusp and the maximum cusp heights are estimated. If the maximum cusp height exceeds the given value, that orientation is not considered. The orientation that gives the minimum average of these values is the preferred orientation of the part for the maximum accuracy criterion. For each rotation the build-time and the relative efficiency indicating the material utilisation are also estimated. From these data the designer may fine tune and subsequently select the preferred set of process parameters.

4.2 ***Slicing and Layer Processing***

Once the part is oriented it has to be sliced. A uniform slicing algorithm is employed to slice the CAD model. All the slice contours have to be processed for displaying the layer in the virtual system and for hatching to generate for build-time estimations. The layer processing module processes the layer data for display purposes. It determines the contour hierarchy within a layer, i.e., to place all the contours within a contour in a tree structure. The contour that surrounds a set of contours is considered as the parent contour. For faster display and rendering purposes, all the contours in a parent contour are joined with imaginary lines to form a closed contour. After arranging the contours, each parent contour is extruded to form a certain portion of a layer or a layer itself. Each parent contour is treated as a child node within the layer node.

4.3 ***Virtual Simulation***

This module simulates the building process of layers in the system. The designer can interactively view the building of a single layer or multiple layers. Once the simulation is completed, the designer can rotate the part to view it or to map surface texture to visualise the physical part that the RP machine will subsequently deliver. Visualisation, in general, is a method of extracting meaningful information from complex data sets through the use of interactive graphics and imaging. It facilitates navigating through the unseen. For example, navigation around a virtually fabricated mould cavity of the logo of the University of Hong Kong in Fig. 6 allows the designer to explore the interior of the mould for design improvements. It also provides mechanisms that facilitate exploring the internal and opaque structures of the part.

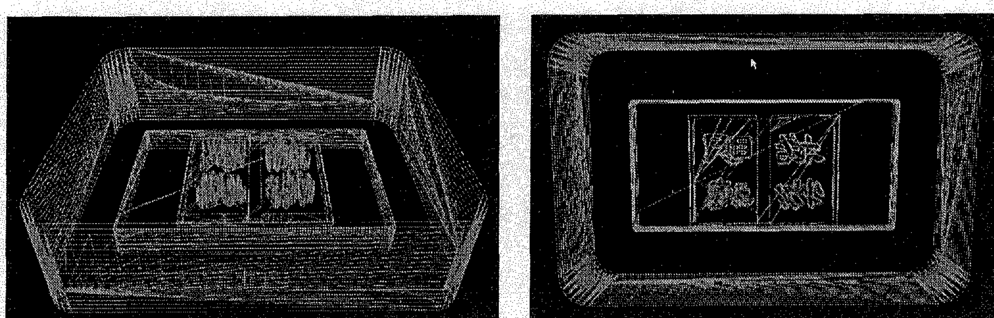

Fig. 6: A set of mould cavities for the University logo

The system evaluates the accuracy, build-time and relative efficiency based on Eqs. 3, 8, and 9 respectively. Fig. 7 illustrates a virtually fabricated dolphin. It is fabricated using fine nylon on SLS 2000 with a layer thickness and hatch spacing of 0.1mm. The preferred orientation for maximum accuracy is shown Fig. 7A. The maximum cusp height (MCH) and the average cusp height (ACH) were .099mm and .032mm respectively. The ACH for minimum build-time orientation was 0.045mm, which was higher than the ACH of maximum accuracy orientation due to the angle between the facets' normal with the build-direction. The minimum build-time was 2.1 hours with the orientation shown in Fig. 7B. This is because of the minimum z-height and hence the minimum number of layers. The build-time for maximum accuracy criterion is 3.9 hours, since the number of layers required were 534, whereas there were only 184 for minimum build-time criterion. The actual laser-scan times for both cases were the same. However, the variations in the build-times were mainly due to the time required for the machine to prepare for the extra number of layers.

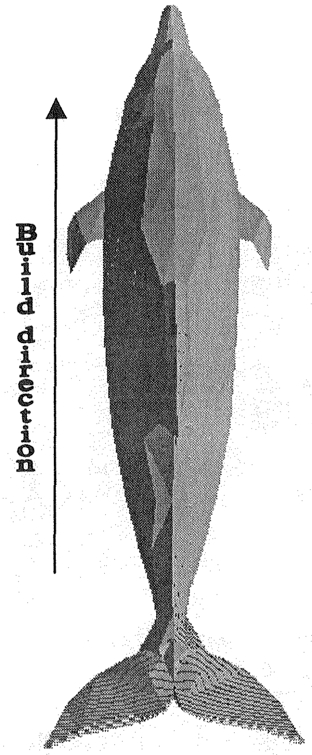

Fig.7A Preferred orientation for maximum accuracy criterion

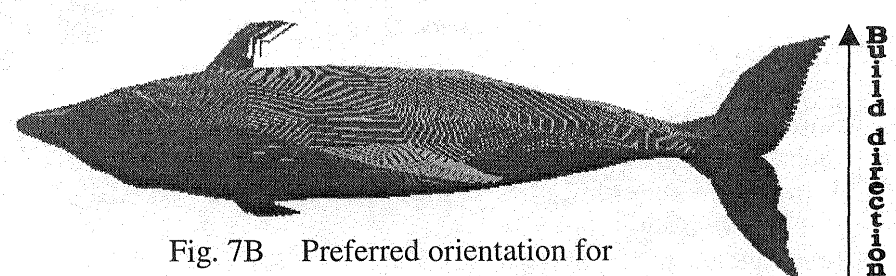

Fig. 7B Preferred orientation for minimum build-time criterion

If the cusp height of a facet is higher than the tolerance level, that layer is marked with a different colour. Visual presentation of the part along with the numerical values of the accuracy gives the designer a better illustration of the stair-step effect. Efforts are also underway to superimpose the actual STL model on the fabricated one. The actual translucent model of the part is superimposed on the virtually fabricated one. This enables the designer to realise the difference between the intended model and the virtually fabricated part. The designer can parametrically modify the virtual part to match the intended model, and thus make qualitative judgement about the product by manipulating the virtual part and viewing its geometric changes. If the RP part is an assembled or a merged part, visualisation facilitates analyse of its fitting. The system can export the virtually fabricated part in VRML format for effective communication between designers at various locations. Thus, virtually fabricating the part helps avoid manufacturing bottlenecks and facilitates tuning the control parameters for physical fabrication. This reduces the manufacturing costs and the development time involved. The responsiveness to customer demands is therefore significantly enhanced.

5.0 Conclusions

A virtual environment for faster prototype development has been developed. It allows the designer to design a part either with STL or digitised data. It facilitates optimisation of the rapid prototyping process parameters. The mathematical models developed predict the accuracy, build-time and efficiency of a part for a given orientation. It allows the designer to visualise the desired part in a virtual environment before committing to manufacture. Work is now underway to develop a layer format that can incorporate colour information along with the laser path data to facilitate fabrication of multi-coloured parts.

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Notations:

P	power (W);	η	relative efficiency;
h_c	cusp height (mm);	A_w	surface area of workspace (mm^2);
N_f	total number of facets;	V_p	enclosing box volume of a part (mm^3);
N_p	total number of parts;	t_{pd}	time required to move the platform down (s);
N_ℓ	total number of layers;	t_m	time required for material deposition (s);
T_ℓ	scan time of a layer (s);	t_r	roller movement time (s);
T_s	setup time of a layer (s);	t_{pr}	time required for the platform to rise (s);
ℓ	layer thickness (mm);	t_d	time delay between these operations (s);
ℓ_m	machine layer thickness (mm);	ρ	material density (g mm^{-3});
h	total height of the part (mm);	d_b	laser beam diameter (mm);
d_s	scan distance of a layer (mm);	C_p	specific heat (J $g^{-1}K^{-1}$);
L_d	laser scan distance (mm);	Tm	melting temperature (K);
L_v	laser scan velocity (mm s^{-1});	T_b	bed temperature (K);
ACH	Average Cusp Height;	k	sinter factor;
MCH	Maximum Cusp Height;	L_h	latent heat (J g^{-1});
B	build direction;	R	reflectivity of the mirror;
		h_m	maximum material height (mm);