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USING REVERSE ENGINEERING TO SUPPORT PRODUCT DEVELOPMENT ACTIVITIES

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1. Introduction

Concept design is the first step in the process of creating a new product. Early stages in this process generally involve the divergent development of many alternatives, focussing on innovation, structure and function. Information gathering and brainstorming are typical activities at this stage, and there is considerable emphasis on the designers creative skills [Otto and Wood 2001]. With very few exceptions, notably aero and ship design, initial concept design is more the domain of the artist than the engineer.

Concept designers often prefer to work with traditional design tools, rather than computer-based ones. They perceive that traditional methods are less restrictive of the creative design process, and that sketches and physical models complement development and design evaluation activities. One of the major tools in concept design is the prototype model and one consequence of this is that engineers are faced with the challenge of converting prototype concept models into CAD models at the appropriate stage in the product development/manufacturing cycle.

Design prototypes may be very complex, incorporating both analytic and free-form geometric entities on fully three-dimensional models. For example, Baranek [Baranek 2002] presents a case study based on the re-design of Ford's GT40 super car. The process started with design and concept drawings, based on the original GT40 produced in 1966, then the production of sculptured clay models. The clay models were full scale but represented just one half of the car, that is one complete side up to the centre-line. These were modified and developed to represent current trends in proportion and aerodynamics. The resulting design was a combination of aerodynamic and aesthetic features incorporating many complex, free-form, surfaces. The challenge then was to generate a CAD representation of the geometry of the sculptured half-model, and to use this to develop CNC cutter paths to mill the matching half in order to produce a complete model of the concept car. The CAD model could also be used for subsequent engineering activities.

Producing geometric representations of free-form, or sculptured, parts from scratch is a time consuming and expensive process. CAD workstations with advanced curve and surface modelling capabilities, such as B-Spline and NURBS facilities, are used to develop three-dimensional geometric representations of sculptured parts, but even with these tools ab-initio modelling of complex parts is a lengthy process. It is not unusual for engineering designers to spend weeks, or months, developing CAD models of such parts. It would probably have taken many months to develop a geometric model of the GT40 concept car from scratch. Consequently, Ford used reverse engineering tools to develop the CAD model.

2. Reverse engineering

In the most general sense, reverse engineering entails the prediction of what an existing product should do, followed by dissection, modelling and analysis of its actual characteristics. Redesign follows reverse engineering, where a product is developed to its next level. Within the context of this paper, reverse engineering is limited to the process of generating CAD models of existing products. This is in contrast to conventional engineering design which starts with a CAD model and ends with a product.

2.1 Digitisation

The reverse engineering process starts with the capture of three-dimensional data from existing parts. Traditional methods would involve the physical measurement of a limited number of key features on the part and interpolating a model based on these. More recent techniques employ digitising systems to generate masses of three-dimensional position vectors, known as point-cloud data, which are then used to aid the development of CAD models. A point-cloud data set for a relatively small component may consist of tens of thousands of individual data points (figure 1). Whereas a large complex part may require many millions of points. The density of points depends on the level of detail to be captured; plain flat areas will require few points, highly curved areas and fine detail will require many points.

The method of digitisation used for a particular application will largely depend on the size of the part to be digitised and the accuracy required. An overview of three different methods is given below.

2.1.1 Digitising with co-ordinate measuring machines

Co-ordinate measuring machines (CMM) have been used to measure analytic and free-form features for several decades. The initial approach was to use touch-trigger probes to gather discrete position data. This data could be very accurate, systems with sub-micron resolution are available, but the process of collecting data with such probes is relatively slow.

Many factors are involved in limiting the speed of data capture, significantly the need to back-off and reset touch trigger probes and the inertia of moving parts of the CMM limit the rate of data collection. A typical CMM with touch trigger probe could gather data at about the rate of 200 points per minute. Recent developments in CMM technology and contact scanning probes have improved this situation. Inertia has been reduced considerably and there is no requirement to back-off and reset scanning probes. Consequently, scanning rates may be increased to the region of about 800 points per minute.

The high accuracy, but low data collection rate, tends to limit the application of CMM digitisation to geometric inspection rather than reverse engineering.

2.1.2 Digitising with scanning machines

The requirement to capture geometric surface data led to the development of dedicated three-dimensional scanning machines. In principle these are similar to CMM but the controlling software and scanning heads are purpose designed for the collection of point-cloud data. Systems range from those based on analogue contact scanning, such as the Renishaw Cyclone machine [Renishaw 2002], with resolutions in the order of 10 microns collecting data at the rate of 400 points per second, to those based on laser digitisation with higher scanning rates but lower resolution, such as the Lectra Digilast [Lectra 2002] with a resolution of about 100 microns.

Scanning machines typically have a working volume in the range of a 400 mm cube. This makes them well suited to scanning small to medium sized parts.

2.1.3 Digitising with optical systems

Optical systems for the digitisation of three-dimensional parts generally employ some form of stereo-imaging. This involves capturing two images of the part and using these to generate a set of three-dimensional vectors representing the surface geometry. Such systems may use either ambient or structured light. Optical systems are capable of digitising large areas very rapidly. Commercial systems are available with the capacity to capture areas up to a square meter in a few seconds.

One of the more successful optical digitising tools is ATOS from Gom [Gom 2002]. This employs two cameras and a fringe projection system to capture three-dimensional data. It is capable of measuring up to 1,300,000 points in seven seconds. Accuracy depends on the measuring area and varies between about 30 to 250 microns. Areas up to 1200 x 960 mm can be captured in one set up, and the system is free-standing so very large parts can be digitised as a series of sections. Baranek [Baranek 2002] describes the digitisation of the GT40 concept car using ATOS.

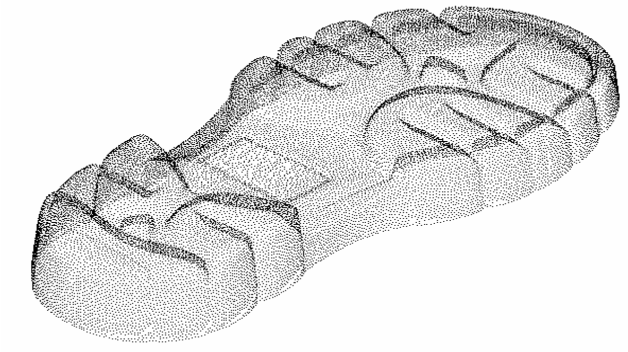

Figure 1. Point-Cloud Data

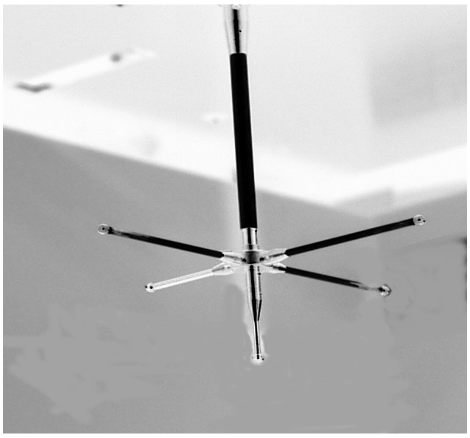

Figure 2. Star Stylus

2.2 Multiple Sets of Point-Cloud Data

Digitising parts which can be viewed, scanned or probed from one direction is a relatively routine activity. Such parts, subject to limitations on physical size, may be represented by a single point-cloud data set. Large parts and parts with re-entrant features pose more of a challenge. Re-entrant features will necessitate scanning from more than one direction, large parts will need multiple scans to cover the entire area. Large parts with re-entrant features will need many scans from several directions. This will necessitate either changing the part orientation during scanning or changing the orientation of the scanning device.

The general principle adopted in machine shops for decades is that it is better to keep changes in part orientation to a minimum. Changes in orientation will require additional fixturing and result in some loss of accuracy. For parts with fixed orientation, accuracy will be dictated by the machine's motion control systems. Changing part orientation introduces another set of variables relating to the efficiency and accuracy of jigs and fixtures. It is also apparent that some parts, for example the clay models used in concept car design, are inherently difficult to move. These factors mitigate against changing part orientation when digitising.

Scanning parts from different orientations is also problematic because it necessitates the collection of multiple sets of point-cloud data then assembling these into one three-dimensional model. Miss-alignment of point-cloud data sets may result in ambiguities and unwanted holes in the assembled model. These can cause serious problems for subsequent activities such as the generation of machining data, STL files or the development of surface models.

Many sculptured parts have no obvious datum points, and points of reference between different scans can be difficult to determine. Gom [Gom 2002] address this problem by employing a two-stage process for the digitisation of large parts. This involves photogrammetry to determine the co-ordinates of a set of reference targets placed at strategic positions on the part. These targets define the part co-ordinate system. Digitising is then carried out from as many positions as necessary to cover the scanned area. Each scan must include at least three reference targets. The position of these targets is transformed onto the global co-ordinate system, and the point-cloud data is then transformed onto the part co-ordinate system. Hence, the reference targets provide a common co-ordinate system for all sets of point-cloud data, facilitating their assembly into a single model.

Renishaw [Renishaw 2002] adopted a different strategy involving the use of a fixture to hold the part vertically on the Cyclone Scanning machine, then scanning from multiple directions using a star stylus (figure 2). The process starts with the calibration of each arm of the stylus against a reference sphere so that the precise geometry of the star is known. The part is then sectioned and each section is scanned using whichever arm of the stylus is most appropriate. There is a common reference between each scan because of the fixed co-ordinate system and the known geometry of the star stylus. The common co-ordinate system facilitates the assembly of point-cloud data sets into a single model.

The authors have carried out extensive tests with the Cyclone and star styli. Full three-dimensional models have been created by assembling multiple sets of data (figures 3 and 4). It has been established that this approach facilitates the assembly of point-cloud data sets with sufficient accuracy to facilitate subsequent machining, the generation of STL files and the development of valid surface models without unwanted holes or ambiguities. The main restrictions of this system are the limited scanning volume (600 x 500 x 360 mm), the need for long styli to scan deep overhangs, and the inaccessibility of the area held by the fixture.

Figure 3. Three Sets of Data

Figure 4. Assembled Data

3. Geometric modelling

Point-cloud data is the most basic form of three-dimensional geometric information. It gives an incomplete representation, but it is relatively easy to generate and it can be very accurate. Any subsequent modelling activities based on point-cloud data may increase the completeness but will almost certainly reduce the accuracy. For example, fitting splines and surfaces to point-cloud data can give a complete representation of the surface of a part, but the process of creating these will add further approximations to the model.

The process of constructing surface models based on point-cloud data consists of: trimming to remove excess data, tolerancing to remove unnecessary data, triangulation to create a tessellated model, segmentation to split the data into logical subsets, boundary creation and finally surface fitting. Boundary curves and fitted surfaces may take many forms, but Bezier and B-Splines are by far the most common for free-form modelling.

The use of reverse engineering to create models may appear lengthy, but it is generally much quicker than ab-initio modelling for parts with complex geometry. For example, the triangulated surface model shown in figure 4 was scanned and created in less than 8 hours. It would have taken weeks to produce such a model from scratch. Baranek [Baranek 2002] describes the digitisation and modelling of the

GT40 concept car. This process was completed in three days, compared to three weeks without the aid of point-cloud data.

3.1 Surface Fitting

The processes of fitting surfaces to data points and boundary curves are well established. They generally involve some form of least squares approximation to give the best fit surface to a set of data points. The resulting network of curves and patchwork of surfaces are combined to give a smooth, or fair, representation of the modelled part. Such representations are achieved by applying tangent plane ($\mathbf{G}^1$) or curvature ($\mathbf{G}^2$) continuity conditions over the entire surface. Complex parts are thus represented by a set of surface patches, rather than as individual points or triangles. Sarkar [Sakar and Menq 1991] and Milroy [Milroy et. al. 1995] give consideration to the development of smooth surfaces in the reverse engineering process.

Segmented surface models support localised modifications, such as the alteration of individual patches or boundary curves, and the control of continuity between adjacent surfaces. From a design perspective, this makes them far more useful than basic point-cloud data or triangulated surface representations.

The authors have attempted to evaluate the accuracy of curve and surface fitting techniques based on the triangulation, segmentation and surfacing of a series of moulding tools. A mould would typically be represented by between six and twenty surface patches with $\mathbf{G}^1$ continuity. Two approaches were considered, one based on the segmentation of point-cloud data along arbitrary boundary curves, the other based on segmentation along curves corresponding to areas of very high curvature. In practice, areas of very high curvature may correspond to functional features, such as parting lines on moulding tools. Any nominal sharp-edge will be represented as a region of high curvature on triangulated point-cloud data. Software routines were developed to identify points in areas of high curvature, these points were sorted into sets and splines were fitted through them. The splines were used as boundary curves in the segmentation process. An arbitrary approach was adopted for segmentation in areas of lower curvature.

Error maps were produced by projecting surface models onto the original point-cloud data. The results of segmentation along arbitrary curves are shown in figure 5, results for segmentation along curves corresponding to regions of high curvature are shown in figure 6. There is clear evidence that segmentation along boundaries corresponding to high curvature gives more accurate results than arbitrary segmentation. It is also more logical to segment models along functional features, such as parting lines, because this will facilitate subsequent design revisions.

Figure 5. Surface Developed by Arbitrary Segmentation

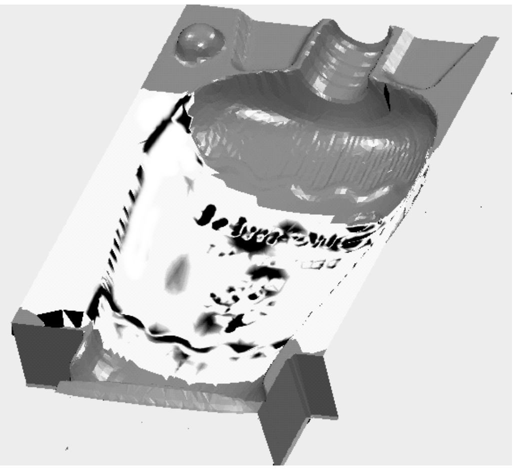

Figure 6. Surface Developed by High Curvature Segmentation

4. Conclusions

Case studies have been presented to support the case that the reverse engineering approach to geometric modelling has some advantages over ab-initio modelling. Digitised data, from concept models, can considerably reduce the time taken to develop CAD representations.

The difficulties associated with digitising large parts and parts with re-entrant features have been discusses. The conclusion that it is generally advantageous to fix part orientation and scan/digitise from different positions was presented. Strategies for combining point-cloud data sets obtained from different scan positions have been discussed. It has been shown that multiple point-cloud data sets can be assembled to give full three-dimensional representations of complex parts. These representations have sufficient accuracy/validity to support subsequent activities such as rapid prototyping, CNC machining and surface modelling.

Alternative strategies for the segmentation of point-cloud data sets have been presented. Arbitrary segmentation and segmentation along lines of high curvature were considered. Projecting constructed surfaces back onto the original point-cloud data tested the relative accuracy of each approach. It was shown that segmentation along lines of high curvature can give significantly more accurate results.

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