Free-Form Surface Models Generation Using Reverse Engineering Technique - An Investigation

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Abstract

This paper presents an investigation of reverse engineering technique to generate free-form surface models in a computer-aided design system from physical objects. This technique involves data acquisition from the physical objects, registration of the data acquisition, data pre-processing, polygon mesh, segmentation, surface fitting and surface model generation. From surface modelling perspective, the applications of this technique can be widely used in many areas of research and industry such as surface models generation for space suits in aerospace industries, prostheses in medicine, antique parts in archaeology, car bodies in automotive industries, turbine blades in nuclear power generators etc. Furthermore, the surface models generated can be used thereafter for engineering analysis, inspection in metrology, solid modelling, design and manufacture of new products. The advantages of employing this technique lead to reduction of product design times, easiness of product design modifications and rapid product developments.

Keywords: *Surface modelling; Reverse engineering; Computer-aided design; CAD.*

1. Introduction

In modern manufacturing industries, a new product is generally manufactured according to the computer-aided design (CAD) model that has been created by engineers. This process is known as conventional engineering [18, 20, 23, 25]. The opposite of that is termed as reverse engineering [7, 18, 23, 25] which is the process of existence product (i.e. physical object) is transformed into a CAD model. Several example of the physical object that can be used for reverse engineering are such as casing of mobile phone, human bone, train body, aeroplane compartment, turbine blade, teapot etc.

In practice, a CAD model is designed as a solid or surface model which is depends on the manufacturer requirement. A solid model can be created directly by using solid modeller tool or can be produced by merging a complete set of surface models. To create a solid model from the surface models, a closed volume model must be formed by the surface models before it is converted to the solid model. Since the surface models are independently employed to create the CAD model, hence only the surface models are concentrated in this work. On top of that, the surface models generation by using a reverse engineering technique is focused because reverse engineering is a fairly new technology that recently becomes very attractive and it is incredibly demanded in the latest manufacturing world.

From surface modelling perspective, the applications of reverse engineering can be widely used in many areas of research and industry such as surface models generation for space suits in aerospace industries, prostheses in medicine [13, 24], antique parts in archaeology, car bodies in automotive industries [21], turbine blades in nuclear power generators [8] etc. Furthermore, the surface models generated can be used thereafter for engineering analysis, inspection in metrology, solid modelling, design and manufacture of new products. The advantages of employ this technique lead to reduction of product design times, easiness of products design modifications and rapid product developments.

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As an impact and awareness of all the circumstance that have been mentioned before, hence an objective of this work has been setup i.e. to investigate a versatile reverse engineering technique that has been used for generating free-form surface models from physical objects. This investigation is concentrated on basic principles, common issues and benefits of using the reverse engineering technique. Thus, the investigation of the reverse engineering technique is presented in Section 2 and finally it is followed by Section 3 for the conclusions.

2. An investigation into reverse engineering technique

From surface modelling point of view, the main purpose of reverse engineering is to redesign existence surface of a product so that similar or new surface models of the product can be reproduced. Traditionally, reverse engineering technique that has been used for surface model generation requires a lot of manual process by experienced engineers. For instance, a combination of ruler, measuring tape or calliper is required to measure dimensions of a physical object for data acquisition. Then, the obtained data will be used in conventional engineering way to create the surface model in any CAD systems. This technique gives disadvantages which are lack of accuracy and uncertainty because of human interaction, it is very time consuming to acquire the data and the work is very tedious especially when dealing with free-form surfaces.

Therefore, new techniques of reverse engineering have been introduced few years ago in order to overcome the disadvantages. In principle, a complete task for reverse engineering system consists of data acquisition, registration, data pre-processing, polygon mesh, segmentation, surface fitting and surface model generation [19, 23, 25]. To implement the reverse engineering system, combination of hardware and software are required. Currently, there is a lot of hardware and software are being developed by researchers and commercialised by well-established companies to cooperate with reverse engineering systems. For examples, the available hardware for reverse engineering systems such as 3D laser scanner [5], Magnetic Resonance Image (MRI), Computer Tomography (CT) scanner [17, 24], Coordinate Measurement Machine (CMM) with mechanical probe [7, 9] etc. While the available software for reverse engineering systems such as Paraform, CopyCAD, RapidForms, Geomagic Studio etc. The consequence of that, reverse engineering nowadays become more versatile technology in the advanced manufacturing world.

However, the latest techniques to generate surface model are some how in many different ways. For example, techniques to acquire data from the physical object requires hardware which can be obtained by using contact method, non-contact method or a hybrid of contact and non-contact method [19, 25]. Another example is the free-form surface model can be represented by parametric form surface representations such as Non-Uniform Rational B-Spline (NURBS), B-Spline or Bezier surface depend on the software whether it has been employed these type of surface representations or not. Therefore, a versatile technique that can be used for surface modelling is investigated and presented as follow:

In this technique, there are six stages will be investigated based on the principle that has been mentioned earlier i.e. (i) data acquisition, (ii) registration, (iii) data pre-processing, (iv) polygon mesh, (v) segmentation, (vi) surface fitting and surface model generation. All the stages will be described in Section 2.1 to 2.6 including the related basic principles and some common issues regarding each stage are highlighted.

2.1. Data acquisition

Data acquisition, which begins the process of reverse engineering, requires hardware which is generally referred as a 3D scanner to scan the physical object. The scanning methods can be classified into two i.e. contact (e.g. CMM with mechanical touch probe) and non-contact (e.g. 3D laser scanner, MRI, CT scanner, ultrasonic, digital camera etc). The contact methods involve mechanical contact between the physical object and the probe during the scanning operation.

While non-contact methods, there is no mechanical contact between the physical object and probe during the scanning operation. A good overview and classification of 3D scanners can be found in the works of Motavalli [19] and Varady *et al* [25]. Compared to contact methods, non-contact methods have short scanning time, can obtain thousands of measurement points simultaneously, can capture the complete data point of the component and have long measurement range but they are less accurate (0.3 mm compared to 0.01mm for contact method), more error prone when the physical objects have shiny surfaces and are more costly. Therefore, a laser scanner is more preferable for this technique because in stead of vast capability from the comparison mentioned before, it is also widely used in industries [5], it is relatively a small device, easy to handle it and it has more flexibility which can attach to robot arm or CMM so that it can have freedom of movement to scan the object from multiple views.

Clark [11] and Varady *et al* [25] have identified common issues that occur in data acquisition. These include accuracy of data point, accessibility of the scanner, occlusion due to shadowing, obstruction or fixturing of the physical object, effect of object's surface such as shining object. Some solutions to these issues have been reviewed by Varady *et al* [25] such as calibrating any sensing device in order to get accurate data, use of multiple scanning devices and multiple views to solve problems arising from accessibility and occlusion. Clark [11] suggests coating the target object in powder or paint to prevent high reflectivity of optical light from shiny objects which will generate noisy data.

2.2. Registration

Since the data are acquired from different views, the data need to be registered in order to merge them into a complete set of points in a single view. To achieve that, a single view (i.e. fixed view) represents one set of points and the other sets of points which are represented as multiple views (i.e. floating view) have to be merged. This process involves transformation sets of data from the floating views to the set data of a fixed view [9]. A set of points coordinate P_b in a floating view b can be converted to the equivalence set of points coordinate P_a in a fixed view a by using equation 1.

$$P_a = P_b\, T\, M \qquad (1)$$

where T is the transformation matrix for a translation set of points from b to a, while M is a rotational matrix about an arbitrary axis and can be obtained by a translation set of points S to the origin followed by rotation Rx, Ry and Rz (with the angles of α, β and θ respectively) about the x, y and z axes and finally inverse transformations Ry^{-1}, Rx^{-1} and S^{-1}. Thus M can be written as equation 2.

$$M = S\, Rx(\alpha)\, Ry(\beta)\, Rz(\theta)\, Ry^{-1}(\beta)\, Rx^{-1}(\alpha)\, S^{-1} \quad (2)$$

2.3. Pre-processing

After registration, pre-processing takes place to remove the noisy points and remain the points required. To achieve that, noise in the acquired data is filtered. It is important to remove the noisy points to prevent error in the surface generation in the subsequent stages. The noisy points can be removed manually if the noisy data is already known. Otherwise, there are different filtering approaches that can be used presented by Varady *et al* [25] such as dimensionality filtering applied by Benko *et al* [3] for noisy data.

2.4. Polygon mesh

For polygon mesh, the points from the pre-processing stage are joined together to form a triangular mesh. Polygon mesh is done to produce a rough surface of the outer skin defining the shape of an object. This polygon mesh is shown in form of facets after joining the points. In order to generate the polygon mesh, several triangulation algorithms can be used, the most known of which is Delaunay triangulation [3, 6, 26]. Two ways to apply Delaunay triangulation are the Voronoi and the circumcircle approaches. The first approach begins with generating the Voronoi diagram which is also known as Direchlet tessellation or Theissen tessellations of the points acquired. The Voronoi diagram will have only one point in the middle of each polygon. The Delaunay triangulation is then created by connecting all points. In the circumcircles approach, circumcircles that do not contain any other points in their interior are created through three points. The Delaunay triangulation is then created by joining the three points from the circumcircles.

While scanning a complex shape of physical object for the data acquisition, it may sometime miss out some part of the scanned object. Thus the missing scanned data is arises a problem of holes in the polygon mesh generated. If this problem is not solved at this stage, it will affect the result in the next subsequent stages and definitely will generate a poor surface model which contains the holes. Recently, one of the available solutions to solve this problem was presented by Jun [12]. He has proposed a methodology that can be used to fill the holes automatically with a piecewise manner.

Since the polygon mesh is shown in form of facets, hence a stereolithography (STL) file format can be generated which is the standard file used for rapid prototyping. Typically, the STL format contains only the coordinates of triangle vertices and the normals of triangle facets. For instance, Liu *et al* [1] was employed the STL format within their work for integrating a system of cross-sectional imaging based reverse engineering and rapid prototyping for reproducing complex objects.

2.5. Segmentation

Next, segmentation is done to divide the polygon mesh into surface patches. Segmentation is carried out to partition the original point set into patches, one for each natural surface, so that each patch contains just those points sampled from a particular natural surface. Basically, there are two different methods that can be used for segmentation i.e. face-based and edge-based methods [2, 25]. Face-based methods infer connected regions of points with similar properties as belonging to the same surface patch. For example, a group of points having the same normal (using the normal to the triangles) is belongs to the same plane. Then, edges of each patch (boundary of the patch) can be derived by intersection from the surface patches. While edge-based methods, boundaries are determined in the point data representing edges (either sharp or smooth) between surface patches. For instance, if sharp edges are being sought, places where the normal of surface patch estimated from the point data suddenly change the direction are identified. If smooth edges (tangent-continuous) are being considered, places where surface curvatures or other higher derivatives have discontinuity are identified.

2.6. Surface fitting and surface model generation

In order to fit a surface to a set of points, several methods have been proposed [4, 7, 9, 10, 14, 15, 16, 22, 23], one of which is the least square method. Various types of surface models are used to model the segmented data. To model standard engineering surfaces (i.e. analytical surfaces) such as cylinder, conical and others, implicit polynomial functions are used. While to model free-form surfaces, parametric representations such as NURBS, B-Spline and Bezier surfaces are used. For fitting a parametric surface, the least square method is defined as equation 3.

$$\min \sum_{i=1}^{n} \| (f_x(u_i, w_i), f_y(u_i, w_i), f_z(u_i, w_i))^T - p_i \|^2 \quad (3)$$

where f_x, f_y and f_z are functions defining x, y and z coordinates in terms of parameters u and w, while n is the number of points and p_i is the actual data points from a scanning operation. For example, when the type of surface is a Bezier surface, f_x, f_y and f_z can be expressed as equation 4.

$$F(u,w)=\sum_{i=0}^{m}\sum_{j=0}^{n} B_{im}(u)\ Q_{ij}\ B_{jn}(w) \qquad (4)$$

where $F(u,w) = \{f_x(u,w), f_y(u,w), f_z(u,w)\}$, m+1 and n+1 are the number of control points, $B_{im}(u)$ is blending function in u direction i.e. ($0 \le u \le 1$), Q_{ij} position of the control points and $B_{jn}(w)$ the blending function in w direction i.e. ($0 \le w \le 1$). To fit a bicubic Bezier patch, equation 3 can be written as equation 5.

$$E(F)=\sum_{i=0}^{N}\left\|F(u,w)-p_i\right\|^2 \qquad (5)$$

where the function E of $Q_{11}, Q_{12}, \ldots, Q_{44}$ will have a minimum when $\partial E/\partial Q_{ij} = 0$ for i = 1,2,3,4 and j = 1,2,3,4. By solving that, all the control point Q_{ij} can be determined. To simplify the calculation, the values of u and w, which are input values, are assumed to have equal increments and the grid lines coincide with scan paths. Thus if there are 11 grid lines in the u direction, the values of u will be 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1. The assumption that u and w values are equally spaced is based on a further assumption that the spacing between the scanned data is uniform and the slope of the surface does not change drastically. Therefore, once the control points are obtained and the grid are determined, hence the x, y and z coordinates for every point on Bezier patch can be determined by using equation 4, where $F(u,w) = \{f_x(u,w), f_y(u,w), f_z(u,w)\} = \{x, y, z\}$. As a result, a surface model with Bezier representation is generated.

Unfortunately, the local control of surface shape is not possible for the Bezier surface [23]. Unlike B-Spline and NURBS surfaces, the Bezier surface does not have ability to add control point without increasing the degree of the surface. Consequently, it limits the availability of the surface fitting optimisation and also because of that ability, B-Spline and NURBS have been the standard for representing free-form surfaces in current commercial CAD systems. However, the NURBS surface is differs from B-Spline surface because it has a weight and denominator to represent smoother surface. Similarly, the basic concept presented before can be applied for B-Spline or NURBS surface. Lin *et al* [16] employed an existence B-Spline surface fitting as comparison to their method i.e. surface lofting method. Their method begins with fitting each row of data points to obtained B-spline curves and then the section curves are fitted into a lofted surface. The B-Spline surface, f_x, f_y and f_z used can be expressed as equation 6.

$$B(u,w)=\sum_{i=0}^{m}\sum_{j=0}^{n} P_{ij}\ N_{ip}(u)\ N_{jq}(w) \qquad (6)$$

where $B(u,w) = \{f_x(u,w), f_y(u,w), f_z(u,w)\}$, P_{ij} are position of the control points, m+1 and n+1 are the number of control points, $N_{ip}(u)$ and $N_{jq}(w)$ are the normalized B-Spline basis functions of degree p and q in two parametric directions which are in u i.e. ($0 \le u \le 1$) and w i.e. ($0 \le w \le 1$) directions respectively. While Chivate *et al* [10] employed NURBS surface fitting using a least squares data approximation method in which the NURBS surface, f_x, f_y and f_z can be expressed as equation 7.

$$S(u,w)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n} v_{ij} P_{ij} N_{ip}(u) N_{jq}(w)}{\sum_{i=0}^{m}\sum_{j=0}^{n} v_{ij} N_{ip}(u) N_{jq}(w)} \qquad (7)$$

where $S(u,w) = \{f_x(u,w), f_y(u,w), f_z(u,w)\}$, v_{ij} represent the weight, P_{ij} are position of the control points, m+1 and n+1 are the number of control points, $N_{ip}(u)$ and $N_{jq}(w)$ are the normalized B-Spline basis functions of degree p and q in two parametric directions which are in u i.e. ($0 \le u \le 1$) and w i.e. ($0 \le w \le 1$) directions respectively. Since NURBS surface has more advantages, therefore it is more favoured to be used for this technique.

In addition, the different between this technique and the others are one or more stages have been skipped except data acquisition, surface fitting and surface model generation. The consequent of that is the generated surface model may not have a very good quality, especially when dealing with a complex physical object which requires segmentation to define the patches. Also, there are feedbacks from each stage so that some of the stages can be repeated to edit and modify previous results such as point cloud, polygon mesh, segmentation or surfaces model generation. For example, a feedback to data acquisition may be necessary if a surface fitting stage indicates that there are holes, error or noisy points in the data set.

3. Conclusions

Although there is a number of reverse engineering techniques currently available in the advanced manufacturing world, this investigation has given an attention to a versatile technique of reverse engineering for generating free-form surface models from physical objects.

To have a very good reverse engineering system, the system must have all the presented stage i.e. data acquisition, registration, data pre-processing, polygon mesh, segmentation, surface fitting and surface model generation.

The output from polygon mesh i.e. data in STL file format can be used for rapid prototyping which leads to the rapid product development.

Whilst the result from surface fitting and surface model generation can be used for surface modelling and solid modelling which thereafter the design of products can be easily modified. Then, it can be used for other purposes.

Since the surface models can be generated from the physical objects by obtaining the digitised data rapidly, hence, the product design times can be definitely reduced.

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