Reverse Engineering of Sculptured Surfaces by Four-Axis Non-Contacting Scanning

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Reverse engineering can be divided into four steps: surface data extraction; extracted data processing; surface reconstruction; and CNC part program generation. The goal of this research is to deal with data extraction from complex sculptured surfaces, redundant data elimination, and surface reconstruction problems of reverse engineering.

To deal with the complex-sculptured-surface data extraction problem, an efficient four-axis non-contacting surface data scanning system, which integrates a PC-based XYZ table, a laser displacement meter (LDM), and a personal computer is developed. In this four-axis system, an LDM, an XYZ table and a PC are used as a displacement sensor, sensor carrier and central controller, respectively. In extracted data processing, we apply the medium filter technique to smooth data points, and propose a simple algorithm to discard efficiently those redundant measured points according to the required degree of accuracy. While in the surface reconstruction, we first try to convert all eliminated column or row data into spline curves. Methods for 2D spline (u, v directions) curve construction are described. Non-meshed 2D spline curves are then blended to a spline surface in terms of a sparse matrix data structure.

Experimental results show that the proposed four-axis surface data scanning machine can be programmed to measure most of the complex sculptured surfaces which is not possible using a three-axis machine. The proposed extracted data-processing method can reduce the surface reconstruction time substantially, for only the cost of a little extracting time and minor modelling errors.

Keywords: Four-axis non-contacting scanning; Redundant data elimination; Reverse engineering; Sculptured surface reconstruction

1. Introduction

Advanced CAD/CAM technology developed in the 1990s has become increasingly popular in the design and manufacturing of products. When the shape of a desired product is relatively simple, engineers can easily design and manufacture it with commercial CAD/CAM techniques. However, it is not satisfactory to use only simple templates such as lines, circles and ellipses to build products whose shapes contain free-form or sculptured surfaces. It is thus not surprising that copy milling still deals with 80–90% of the surface machining work in tool and mould related industries [1]. Copy milling can only produce a new product exactly the same as the original prototype model. As modifications of shape or size are desired, a new prototype model needs to be built. Copy milling thus does not satisfy the demands of today’s industry. To overcome this inflexibility, reverse engineering, which can convert measured data into mathematical representations of a surface model or a solid model, is becoming more and more attractive to the CAD/CAM community. Reverse engineering can be divided into four steps:

1. Surface data extraction.
2. Extracted data processing.
3. Surface reconstruction.
4. CNC part program generation.

Data extracting procedures are usually performed on a coordinate measuring machine (CMM) by contact measuring techniques [2–4]. High accuracy and insensitivity to variations of material properties and colours are its main advantages. However, time consumption and the inability to sensor small corners are the disadvantages. Additionally, the cost of CMMs is always high. Therefore, alternative sensing instruments such as the laser displacement meter (LDM) have been employed recently [5–8], and some useful results have been obtained. The application of LDM based scanning systems is limited, owing to disadvantages such as the accuracy of measurement depends greatly on the material and colour of the measured
parts, and the difficulty of measuring surfaces with large inclinations.

Very limited work has been undertaken on data processing of the extracted data. Most of the reverse engineering related work skips this step and concentrates on how to optimise the surface reconstruction error [9,10]. In general, the more data points measured, the more closely is a surface model approximated. However, a large number of data points can be a serious problem for any practical CAD/CAM software in surface reconstruction. It is thus desirable to have an algorithm that can efficiently extract the minimum number of data points without affecting the accuracy. Intuitively, areas with a large curvature require more measured points, whereas uniform or smooth regions need only a small amount of data.

The purpose of surface reconstruction is to build a mathematical surface model by using the measured data. Many algorithms and methods have been proposed for surface construction. Among them, B-Spline, Bezier and Cubic-Spline are the most commonly used. Most of the commercial CAD/CAM systems possess these functions for the designers’ convenience, rather than for reverse engineering. A least-squares-fitting-based B-spline surface reconstruction method for reverse engineering was proposed by Seiler [11]. In their work, both mean and maximum modelling errors were reduced by interior net vertex adjustment. However, equal knot spacing and meshed data format were still employed. This may lead to some modelling errors when applied to a complex sculptured surface. The large amount of computing time required is also a problem. Moreover, comparisons between B-Spline, Bezier and Cubic-Splines in the application of reverse engineering have not yet been reported.

The goal of this research is to deal with the surface data extraction, the redundant data elimination, and the surface reconstruction problems of reverse engineering. To deal with the complex sculptured surface data extraction problem, an efficient four-axis non-contacting surface-data-scaning system which integrates a PC-based XYZ table, a laser displacement meter (LDM), and a personal computer is developed. To solve the redundant data elimination problem, we propose a simple algorithm that can efficiently discard those redundant points according to the required degree of accuracy. While in the surface reconstruction, we try first to convert all eliminated column or row data into spline (B-Spline, Beizer and Cubic-Spline) curves. Relative cross-direction spline curves are then blended based on the parallel curves already generated. Column and row spline curves are then blended to a spline surface. Comparisons among B-Spline, Bezier and Cubic-Splines on data structure, computing time and accuracy are then carried out.

In Section 2, the proposed four-axis LDM measuring system is described. An efficient data-processing method for the extracted data is discussed in Section 3. In Section 4, we describe the details of the B-Spline, Bezier and Cubic-Spline based surface reconstruction procedures. In Section 5, experimental results and discussion are provided. Conclusions are given in Section 6.

![Fig. 1. The measuring principle of the LDM.](Image)

**2. Four-Axes LDM Based Measuring System**

The measuring principle of an LDM is shown in Fig. 1. When the laser beam illuminates an object, the sensor head uses the reflecting scattered light, received by the light receiving lens, to detect the distance from the laser head to the measured object. However, when there is a large incline or curvature on the measured object, the reflected scattered light received by the light receiving lens may not be strong enough and a measuring error results. Experimental results shown in Fig. 2 can help to illustrate this phenomena. In this experiment, we selected four objects with different inclination angles (10°, 20°, 50°, 75°). For each object, we focused the LDM on a certain point on its incline and gradually raised the LDM, with the displacement signal taken at every 0.5 mm. The plot of the measured vertical displacement by the LDM versus the real displacement obtained from the Z-axis of the XYZ table are shown in Fig. 2. From Fig. 2, we find that the larger the incline is, the greater the degradation of the accuracy. However, this drawback can be overcome if the LDM is rotated such that its emitting light is as perpendicular to the incline as possible.

A four-axis LDM based surface-data extracting system, as illustrated in Fig. 3, is then developed. In this four-axis system, an LDM, a precise XYZ table (10 μm/60 cm repeatability) to which is attached an additional rotating axis, and a PC based controller are used as displacement sensor, sensor carrier and

![Fig. 2. The effect of inclination on the accuracy of LDM.](Image)