EXTREMELY LOW COST SCANNING SYSTEM FOR FREE FORM SURFACES

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ABSTRACT

Reverse engineering is the process of reconstructing a computer model for a physical object based on 3D data point captured from the surface of the object. This work presents a low end and extremely cost effective technique for representing the free form surfaces of physical objects in a CAD model.

An analogue signal was used to acquire the free form surface data unlike conventional methods like laser scanners or Coordinate Measurement Machines (CMM). The surface was scanned using a Linear Variable Differential Transducer (LVDT) as position sensor for measuring the data from the surface of the object. The analogue signal was acquired through a data acquisition system in a continuous fashion to PC. Solid works CAD/CAM software was used to obtain the free form surface from the acquired 3D data using spline technique.

A dedicated system was constructed to collect data using vertical milling machine. The benefit of this scanning technique is the ability to scan the target free form surface of the physical object in the following aspect: cost effective scanning technique, low end acceptable accuracy, speed and ease of calibration. Special software was built to minimize the data acquired during the scanning operation for reducing modeling time.

KEYWORDS

3D digitizing; reverse engineering; surface modeling; line scan.

1. INTRODUCTION

Reverse Engineering (RE) is a methodology for reconstructing the 3D CAD model for an existing physical part by various digitizing processes. The digital data obtained from the digitizing technique usually can be imported into a CAD system for subsequent redesign and manufacturing. Unlike the traditional manufacturing process in which conceptual designs is being transmitted into physical products, RE remodel the CAD design of an existing objects for remanufacturing, modifying, analyzing, and digitizing products [1-4]. Due to the growing number of parts, for which no CAD models exist, there is a growing interest in representing the surface geometry of physical objects in CAD model. There are two main challenges to develop a fully automated reverse engineering system: the digitization of the scanned surface object, and the conversion of the 3D scanned data into a form, compatible with CAD/CAM software packages. Minimizing number of data representing the surface of the object enhances the speed of constructing the CAD
model. The reverse engineering procedure can be characterized by the flowchart in figure 1. These phases are often overlapped instead of sequential process.

![Flowchart](image)

**Figure 1: Steps in reverse engineering (Varady et al., 1997)**

RE is necessary when working from a physical prototype rather than starting from a CAD concept model. This is also particularly useful for the product development where CAD was not used in the original design and a part must be replicated. RE can significantly reduce the production lead time and the costs of the part duplication processes. The three primary steps in the RE process are part digitization, features extraction and CAD model reconstruction [5]. They can be classified into two broad categories: contact and non-contact. The CMM is the most commonly used contact digitizing device equipped with a touch-triggered probe, and can usually produce 3D point coordinates of external part surfaces with high-level accuracy. However, its digitizing speed is relatively slow compared with most non-contact optical measuring systems. Due to the contacting force, the process is not suitable for soft or fragile objects. Another approach is the non-contact digitization of surfaces using optical techniques, which are usually much more efficient in measuring speed and human labor. A number of systems based on optical methods have been developed, such as laser scanners and camera-based vision systems. Laser scanners have a very high measuring speed and adequate resolution [6], but they are so sensitive to the ambient lighting that the digitizing process usually has to be performed in a specially dedicated or well-conditioned lighting environment, and the digitizing accuracy can also strongly depend on the brightness, texture and curvature of the part surfaces. Vision systems can capture millions of data points simultaneously over a large spatial range without moving the optical head [7]. Although industrial computer tomography (ICT) and magnetic resonance imaging (MRI) are able to image the internal structure of a part, they are quite expensive and poor in accuracy, and usually require a well-trained person to operate them. Furthermore, MRI is not suitable for various metallic parts.

Chang and Chiang [8] presented a method of three dimensional image reconstructions for complex objects by an abrasive computed tomography apparatus. The apparatus uses an abrasive process to remove the inlaid object, layer by layer, and to capture the cross-sectional image of each layer with a CCD camera. A numerical scheme is applied to obtain the Bezier curve of the contours for each layer. Yang and Chen [1] described a new reverse engineering methodology based on haptic volume removing. Liu et al. [9] proposed an integrated system of cross-sectional imaging based on reverse engineering and rapid prototyping for reproducing complex objects. Chow et al. [10] developed a laser-based reverse engineering and machining system that would significantly reduce time for CAD model creation and NC code generation. Aoyama and Yun [11] described a system to autonomously measure the shape of an unknown physical object for constructing the computer model of a physical object. Li et al. [12] presented a reverse engineering system for rapid modeling and manufacturing of products with complex surfaces. The system consists of three main components: a 3D optical digitizing system, a surface reconstruction software and a rapid prototyping machine. CGI has developed a cross-sectional imaging and digitiz-
ing system based on a milling machine for simultaneously capturing both the external and internal geometry of any complex parts [13], where the milling process is performed successively to capture the planar image of each cross section. However, CGIs cross-sectional scanning system is actually a dedicated machine tool, and rather expensive, and the vibration of mechanical components may affect the measuring accuracy of its imaging components. A number of related studies, such as the cross-sectional imaging process, interpolation, data reduction, 3D model reconstruction, and error analysis have also been investigated profoundly [14-21]. The probe performance depends on numerous factors such as its internal design, stylus bending, and qualification on the master ball to name a few [22]. In addition, since the tip center point coordinates are recorded and not the contact point on the surface, radius correction is necessary to find an appropriate point on the surface, potentially introducing errors. While Jeong and Kim [23] proposed to slice the 3D CAD model to obtain a number of 2D contours, and then offset the contours with discrete distance maps in order to obtain the NC cutter path. In order to avoid gouging during NC cutting, Chen and Ravani [24] stated one should first identify the intersecting surfaces, and then use these to obtain the offset surface. With understanding of the above-mentioned problems, this research proposes a simple, yet complete way to set-up surfaces directly from a large quantity of 3D data points.

2. CONSTRUCTION OF THE PROPOSED SCANNING SYSTEM

A small milling machine with 800 x 300 mm moving table was used as the base for the prototype machine. Two encoders (MINERTIA MOTOR F SERIES UGF MED-B9ECY11 326945-1) were supported to the movable table axes to measure the distance in the horizontal plan (X-Y plan). An LVDT (CTA plus Co., Ltd, Model: LPS-505, Capacity: 50mm, Serial no.: 7051717; Made in Korea) was used as vertical position sensor (Z direction). The scanning technique includes beside the LVDT a hardware low path filter to eliminate signal noise. It was attached to the head of the milling machine. Figure 2 shows the complete assembly of the proposed 3-D measuring system. Motion is generated through two motors attached to the two spindles of the moving table however it can be produced manually using the hand micrometers of the two spindles. A software was built to acquire the 3D data points with National Instrument's data acquisition board USB-6221 (NI USB-6221, 16 analogue input channel, 250 KS/s, 16-bit resolution, Multifunction I/O USB board).
The proposed scanning system contains a special software program that was built to control the rate of the data acquired from the LVDT sensor and to measure the moving distances from spindles encoder.

The LVDT is placed directly above the part, with the head of the milling machine fixed perpendicular to the direction of travel of movable table. An LVDT and two encoders are connected to a National Instrument's motion control board USB-6221 data acquisition board. A low path filter to restrict the signal noise of data reaching the data acquisition board. An infinity data text file is processed within C sharp using the Proposed Reverse Engineering Scanning software. This program can pick millions of data points that represents the surface, eliminate the undesirable data, and save one text file that contains the data points that represents the surface.

In mechanical engineering, backlash, sometimes called lash or play, is clearance between mating components, sometimes described as the amount of lost motion due to clearance or slackness when movement is reversed and contact is re-established [25]. Theoretically, the backlash should be zero, but in actual practice some backlash must be allowed to prevent jamming. It is unavoidable for nearly all reversing mechanical couplings, although its effects can be negated. Depending on the application it may or may not be desirable. Reasons for requiring backlash include allowing for lubrication, manufacturing errors, deflection under load and thermal expansion. The greater the accuracy the smaller the backlash needed. Backlash is most commonly created by cutting the teeth deeper into the gears than the ideal depth. Another way of introducing backlash is by increasing the center distances between the gears. To compensate the backlash distance, a number of pulses will be automatically added or subtracted to the X pluses or Y pluses, these values are constant for each machine, so it will be blotted in the setting options.
In order to scan an object, the LVDT sensor sled is traversed in the X-direction with predetermined steps. At each step, data is collected by the data acquiring board and the scanning software by adjustable rate of number of data collected per second, these data indicates and presents X, Y, and Z values. The file saved consists of three columns the first column indicates the number of pluses collected by encoder X, these pluses multiplied by the X calibration factor, by the same way the second column indicates the number of pluses from encoder Y, these pluses multiplied by the Y calibration factor, The third column indicates the voltage of the LVDT output these voltage values multiplied by the Z calibration factor.

The primary objective of this research work is to devise a low-cost reverse engineering tool to reconstruct a fairly accurate CAD model of a physical object with minimal user assistance. Such a re-configurable digitizing system for reverse engineering offers a number of advantages, such as the functional extension of an existing NC milling machine, low costs, rapid construction and high accuracy.

3. DATA PROCESSING

Analogue signal always combined with an inevitable noise signals, there for a technique for reducing this noise were constructed. This noise always degrade the accuracy of surface reconstruction. In addition, large amounts of redundant data make the surface reconstruction a time-consuming process and can be a serious problem for any practical CAD/CAM software. It is thus desirable that the original surface data extracted be pre-processed before surface reconstruction. Two methods are provided to process the extracted data efficiently.

3.1 SMOOTHING PROCESSING

Owing to variations of measurement process of the measured object, impulse-like noise as may occur during measurement. This impulse-like noise should be eliminated to avoid modeling errors. First of all, a hardware low path filter with a suitable frequency in order to reduce the signal noise. A software filter, as used in signal processing, is a useful tool for eliminating the impulse-like noise. A filter is a data domain filter with a very strong capability for reducing the impulse like signals while there is no influence on other signals. Therefore, most of the measured data, except those impulse signals, remain the same when passed through the filter.

Error analysis and error charts were constructed in the three directions. The main source of error happen due to the LVDT noise effect during the measuring process. These noise effects should be eliminated before saving the 3-D data points. Figure 3 presents the scanning process of a straight line and the curved line in a physical object before and after eliminating noise using proposed noise elimination techniques.

Figure 3: the scanning process of a straight line and the curved line during noise elimination processes.
3.2 REDUNDANT DATA ELIMINATION

The principle of this algorithm can be briefly described as: a point can be eliminated from the data list if this point, have a very small change in all directions, if a change larger than a certain displacement in any direction (coordinate) the point will be saved, otherwise, the point will not be saved if the difference between the point coordinate and the previous point coordinates in all direction less than the desired change in all directions of motions. Prior to the eliminating process, users can select a desired displacement according to the required degree of accuracy. According to the preset accuracy, the elimination process is then carried out.

3.3 PROBE RADIUS COMPENSATION

However, the point data gathered by the proposed technique often are probe-centre data, rather than the surface data of the measured object. It becomes a need to compensate the probe radius before the measured data point can be used to undertake various tasks in reverse engineering. The compensation of the point data with the value of probe radius is performed in order to find the contact points between the probe and the measured object. The primary task is to compensate the value of probe radius for the 3-D data points is to determine the normal vector for each point. It is, thus, proposed to offset each point in its normal direction with the value of probe radius. So, the spline curves should be offset in the direction of the surface to compensate the probe radius of the LVDT as a curve compensation. We can use the raw splines to present the surface and offset the surface as a method to the surface compensation.

3.4 SURFACE RECONSTRUCTION

In this research, a systematic surface reconstruction method using the acquired data was used. First, the data acquired was used to build spline curves. Secondly, the resulting splines were blended to spline surface. Since different surface representations require different data structures, the data structure of the processed data points must be rearranged to satisfy different requirements. This will be explained in case study shown later.

4. ERROR ANALYSIS AND ACCURACY ASSESSMENT

The accuracy of a RE digitizing system represents the deviation in dimension, position and surface quality between a reconstructed 3D CAD model and the original. Various sources of errors contributing to overall error in accuracy and repeatability of the system can be divided into three major parts: digitizing process, hardware system, and software system. Based on previous investigations, the influencing factors from the hardware system primarily include the repeatability precision of the milling machine, the vibration affecting the machine, and the noise due to the LVDT. The errors derived from the software system mainly consist of the calibration and accuracy loss of reconstructing the CAD model process due to fitting curves and splines constructions.

An experiment was conducted to test the accuracy of the RE system. A set of standard block gauges were used to perform the experimental study. A variety of evaluating indicators are frequently used to assess the digitizing accuracy of a RE process. Namely, in the experiment, dimensional comparisons of the sample parts between the original and the measured value were performed to assess the digitizing accuracy.
5. CASE STUDY

A free form surface of a telephone hand body surface was used as a typical part to better demonstrate the application of the RE digitizing system. However, the proposed LVDT reverse engineering imaging process provides an ideal solution to digitize the part. The Proposed LVDT Reverse Engineering imaging system together with solid works software packages can be applied to digitize and reconstruct the 3D CAD model of the telephone hand body. Fig. 4, presents the graphical user interface of the software driving the system and acquiring the data point files.

5.1 RECONSTRUCTING THE 3D CAD MODEL

The data points acquired after processed were stored in a special format by a special software developed by the authors. These format should be combatable with the software package that will be used for constructing the surface, In order to draw the spline representing the file for the following CAD model reconstruction.

On the basis of the scanned data point files acquired, reconstructing the 3D CAD model for the object involves were created. Several commercial software packages which can implement the above function can be used to aid the reconstruction of the 3D CAD model.

In this work Solid works software package was used for reconstructing the spline surface of the physical object. This package has the ability large amount of surface data point to build or reconstruct surfaces. And this technique was not used because of its time consuming. Therefore, the other technique which is used in this study is to capture the scanned surface as a set of curves. Each curve of them was saved in a different file and imported in solid works program separately.
For this case, Solid works was employed to reconstruct the 3D CAD model of the telephone hand body surface. In order to reconstruct the 3D CAD model using Solid works software includes two steps: Step 1 create the spline curve due to input the txt file in order to using the tools of curves through XYZ points. Based on the step above, Step 2 Create the 3D CAD model of the PC mouse body using the boundary surface options. The reconstructed 3D CAD model is shown in Fig.5. In order to obtain better surface quality of the reconstructed CAD model, Solid works surface options was used to smooth the surface of the CAD model.

![Image of reconstructed CAD model](image)

Figure 5: The 3D CAD model of the surface created by solidworks software.

6. VALIDATION PROCESS

A part of telephone hand as a case study used as a typical part to better demonstrate the application of the RE digitizing system. The part which is divided into certain points shown in figure 6. This part has been measured using coordinate measuring machine in the national instate for standards which belongs to the ministry of scientific research – Egypt.

![Image of measured part](image)

Fig. 6: The part of telephone hand which is used to validate the system.

The cross-sectional line imaging system together with solid works software packages can be applied to digitize and reconstruct the 3D CAD model of the measured surfaces. The measuring tool
of the analysis menu in solid works software is employed to measure the dimensions of the surface of the CAD models constructed. Different positions for each CAD model are selected to measure their corresponding dimensions.

The reconstructed 3D CAD model is shown in Fig.7. In order to obtain better surface quality of the reconstructed CAD model, free-form surfaces can directly create from curves, surfaces, or measured data. It has three basic functionalities: point processing, curve and surface generation and entity analysis. The completed 3D CAD model of the surface is shown in Figure 7 demonstrates all RE processes for the comparison between the surface measured by the proposed technique and the data measured using Coordinate measuring machine in the national instate for standards which belongs to the ministry of scientific research – Egypt. A comparison between the original and the reconstructed 3D CAD model are made to determine the digitizing accuracy and efficiency of the case. The comparison results indicate that the global accuracy of the RE case is within acceptable tolerance. The output surfaces are divided into equal displacements to get points of measurements.

Figure 7: The comparison between the surface measured by the proposed technique and the data measured using Coordinate measuring machine.

7. RESULTS AND DISCUSSION:

A comparison between the original and the reconstructed 3D CAD model was made to determine the digitizing accuracy and efficiency of the case. The comparison results indicate that the global accuracy of the RE case is within a tolerance of ±0.05 mm. Based on the analysis, the increment in the Y direction and basic orientation have a significant effect on the accuracy of a reconstructed CAD model. The accuracy of a RE digitizing system can be effectively improved by optimizing the increment in the Y direction and basic orientation. The global accuracy of the RE system can reach approximately ±0.05 mm.
8. CONCLUSIONS:

In this work an approach has been proposed for reconstructing a CAD model of a physical object. The proposed approach has been implemented for reconstructing simple engineering objects and requires minimal user assistance. It has been shown that the implemented technique can reconstruct simple engineering objects with an acceptable accuracy. This paper presents a RE digitizing system based on an existing milling machine which can simultaneously capture the line scan contours of a part with line scan of the surface. A new combined device which consists of two encoders, a LVDT sensing displacement sensor and a data acquisition card is proposed to capture the cross-sectional line images of a free form surfaces. The combined device together with a computer control unit can be considered as a high compliant accessory which would be integrated closely with a milling machine to form quickly a cross-sectional imaging system for reverse engineering. Such a digitization system has a number of advantages including extending the function of an existing milling machine, low costs and rapid construction. The system also has the ability to reduce time with minimal user assistance. In the extracted data processing, a filter is used to smooth the raw data points. Then, we proposed a simple algorithm to efficiently discard those redundant measured points according to the required degree of accuracy. In this research, solutions for complex sculptured surface data extraction, redundant data elimination, and surface reconstruction problems of reverse engineering are provided.

9. REFERENCES


