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Representing Surfaces in Reverse Engineering Using Analogue Signals

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Abstract

Reverse engineering is the process of reconstructing a computer model of a physical object based on the 3D point cloud data captured from the surface of the object. This work presents a novel and extremely cheap approach of reverse engineering for reconstructing a CAD model of the physical object. Unlike conventional data acquiring dimensions methods using laser scanners and Coordinate Measurement Machines (CMM), we use a (Linear Variable Differential Transformer), LVDT position sensor for measuring the data from the surface of the object. Solid works CAD/CAM software has been used to obtain a carrier for the unorganized set of measured data. A dedicated system was constructed to collect data using a 2-axis milling machine. The benefit of this scanning system is the ability to scan the target object surface completely in the following aspect: extremely cheap, measurement accuracy, speed, ease of calibration, and estimation of measurement uncertainties. This system allows for quick scanning of any object while minimizing the number of data points in the resulting scan data.

Keywords: 3D digitising; reverse engineering; surface modelling; Points registration; geometric modelling; line scan.

1. Introduction

Reverse engineering (RE) is a methodology for constructing the vectored 3D digital model for an existing physical part by various digitizing processes. The digital model can usually be imported into a CAD system for subsequent redesign and manufacturing process planning. Unlike the traditional manufacturing philosophy about conceptual designs being transmitted into physical products, RE digitizes, analyses, modifies and fabricates products based on the existing objects (Yang et al., 2005; Sansoni and Docchio, 2004; Varady et al, 1997; Lee and Woo, 2000). Due to the growing number of legacy parts, for which no CAD models exist, there is a growing interest in the representation of the surface geometry and topology of physical objects. There are two main challenges to develop a fully automated reverse engineering system: the digitization of the scanned object image, and the conversion of the 3D scanned data into a compact form, compatible with CAD/CAM packages.

The reverse engineering procedure can be characterized by the flowchart in Fig 1. These phases often overlap, and instead of the sequential process depicted, several iterations are required. The outline presented serves as a basis for organizing the content of the subsequent paragraphs which gives a description of each phase.

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 (Motavalli, 1998).

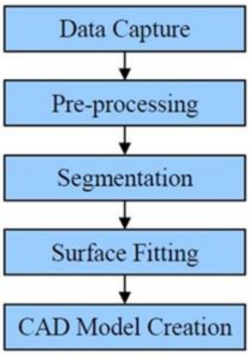

Figure1: steps in the reverse engineering (Varady et al., 1997)

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 (Chan et al., 1997), 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 (El-Hakim and Pizzi, 1993).

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 (2003) 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 (2005) described a new reverse engineering methodology based on haptic volume removing. Liu et al. (2006) proposed an integrated system of cross-sectional imaging based on reverse engineering and rapid prototyping for reproducing complex objects. Chow et al. (2002) developed a laser-based reverse engineering and machining system that would significantly reduce time for CAD model creation and NC code generation.

Feng, (2003) addressed a methodology of Internet-based reverse engineering, and provided a case study to illustrate its applications in integrating CAD and CAM. Aoyama and Yun (2001) 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. (2002) 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, surface reconstruction software and a rapid prototyping machine.

CGI has developed a cross-sectional imaging and digitizing system based on a milling machine for simultaneously capturing both the external and internal geometry of any complex parts (CGI, 2005), 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 (Park and Kim, 1996; Lim et al. 1997; Yau, 1997; Chen et al., 1999; Wu, et al., 2004; LW et al., 2004; Giri et al., 2004; Yen et al., 2005).

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.

2. Construction of the Proposed Reverse Engineering Scanning System

A small milling machine with 800 x 300 mm moving table was used as the base of the prototype machine. Two encoders were supported to the movable table axis to measure the distance in the horizontal plan that the table moves in X and Y directions. An LVDT was used as vertical position sensor (Z direction). 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 applied motors or manually (if we can manually use the milling machine table driving hand to drive the table in the direction of X and Y using the hand micrometre). In our application we use C sharp to build up our software with National

Instrument's motion control board USB-6221 (NI USB-6221, 16 analogue input channel, 250 kS/s, 16-bit M Series device, Multifunction I/O with correlated digital I/O for USB). An C sharp virtual program has been written to control the Proposed Scanning System motion or to count encoder pluses or sense LVDT variable voltage. Implementing the program for all three motions, all motions of the scanner can be controlled by the software.

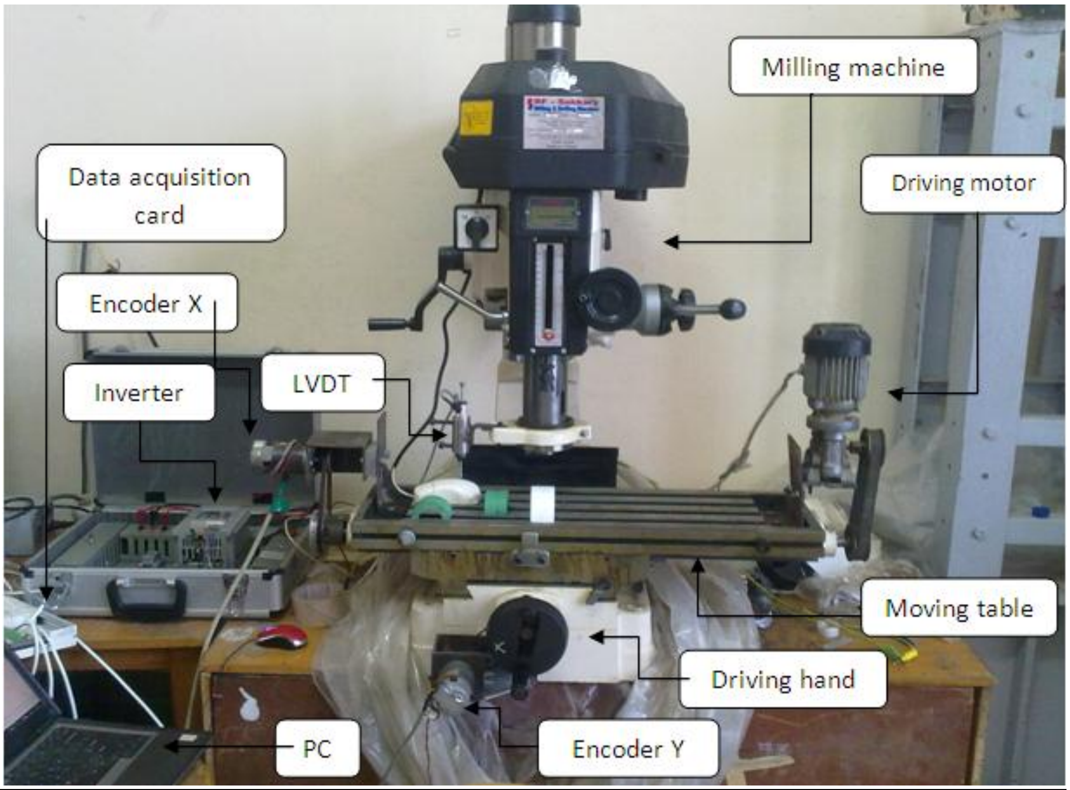

Figure 2 photo of the constructed LVDT scanning system

2.1 Scanning Sensors

The scanning sensor is comprised of a LVDT and low path hardware filter to eliminate signal noise. 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. A LVDT (CTAplus Co., Ltd, Model: LPS-505, Capacity: 50mm, Serial no.: 7051717; Made in corea) and two encoders (MINERTIA MOTOR F SERIES UGFMED-B9ECY11 326945-1) 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.

2.2 Backlash compensation hardware

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 [23]. For example, in a pair of gears, backlash is the amount of clearance between mated gear teeth as shown in fig.3. 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.

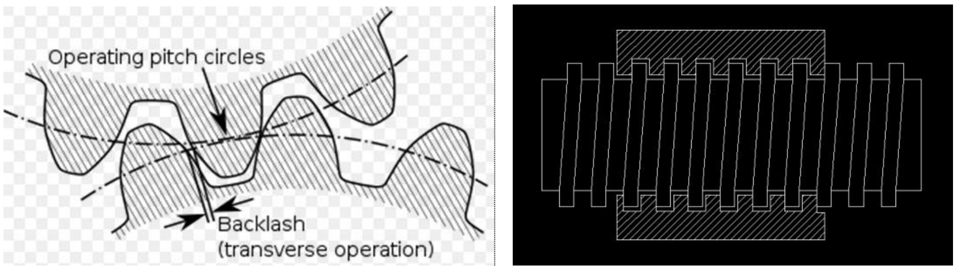

Fig.3 shows gear backlash

Factors affecting the amount backlash required in a gear train include errors in profile, pitch, tooth thickness, helix angle and center distance. 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.

2.3 Conversion of digital Values to XYZ Coordinates

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.

3. Calibration process

From the above, X, Y, and Z calibration factors can be calculated as follows: First, in the setting options we can input a distance in the place assigned to the input distance, then we use the rotating hand with its micrometer to move the movable table by the input distance in the direction required, we notice that the number of pluses rewarding the input distance appears in the place assigned to the pluses, calibration factor can be calculated. Also the X backlash and Y backlash are plotted to be added or subtracted to Compensates the value of pluses due to backlash. The overall research algorithm that controls the system motion, the encoders and the LVDT generates two output files. The first contains the points collected from the object surface in text (TXT) format while the second file have the same points stored in AutoCAD (DXF) format or solidworks (SLDPRT) format.

4. Efficient Extracted Data Processing

Inevitable noise signals during measurement 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.

4.1 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 filters 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.

4.2 Redundant Data Elimination

The principle of this new 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 pervious 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.

5. Surface Reconstruction

In this research, a systematic surface reconstruction method using the non-uniform processed data is proposed. First, each non-uniform processed data vector is converted into a spline curve. Secondly, the resulting splines are then blended to a 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. Data structures for B-spline curves, error analysis, Accuracy assessment and Reconstruction of CAD models are described as follows.

5.1 **B-spline curves**

The B-spline curve algorithm is applied to each row or column of processed data vectors to generate isoperimetric B-spline curves. The other set of B-spline curves in the cross-direction are then constructed by extracting data points from those generated curves. To prevent the redundant data problem from re-occurring, the redundant data elimination process has to be executed simultaneously when the second set of isoperimetric curves are being constructed.

5.2 **Error analysis**

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.

5.3 Accuracy assessment

An experiment was conducted to test the accuracy of the RE system. Three same circular aluminum sleeves were used to perform the experimental study. In the experiment, dimensional comparisons of external diameter, height and wall thickness of the sample parts between the original and the reconstructed CAD model were performed to assess the digitizing accuracy of the RE system.

5.4 **Reconstruction of CAD models**

The 3D CAD models of the measured parts were reconstructed by using solid works software. It can import any 2D splines and allows 3D reconstruction from them.

6. Case study

A free form surface of a computer mouse 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 the solid works software packages can be applied to digitize and reconstruct the 3D CAD model of the computer mouse body. Fig.4, presents the graphical user interface of the software driving the system and acquiring the data point files.

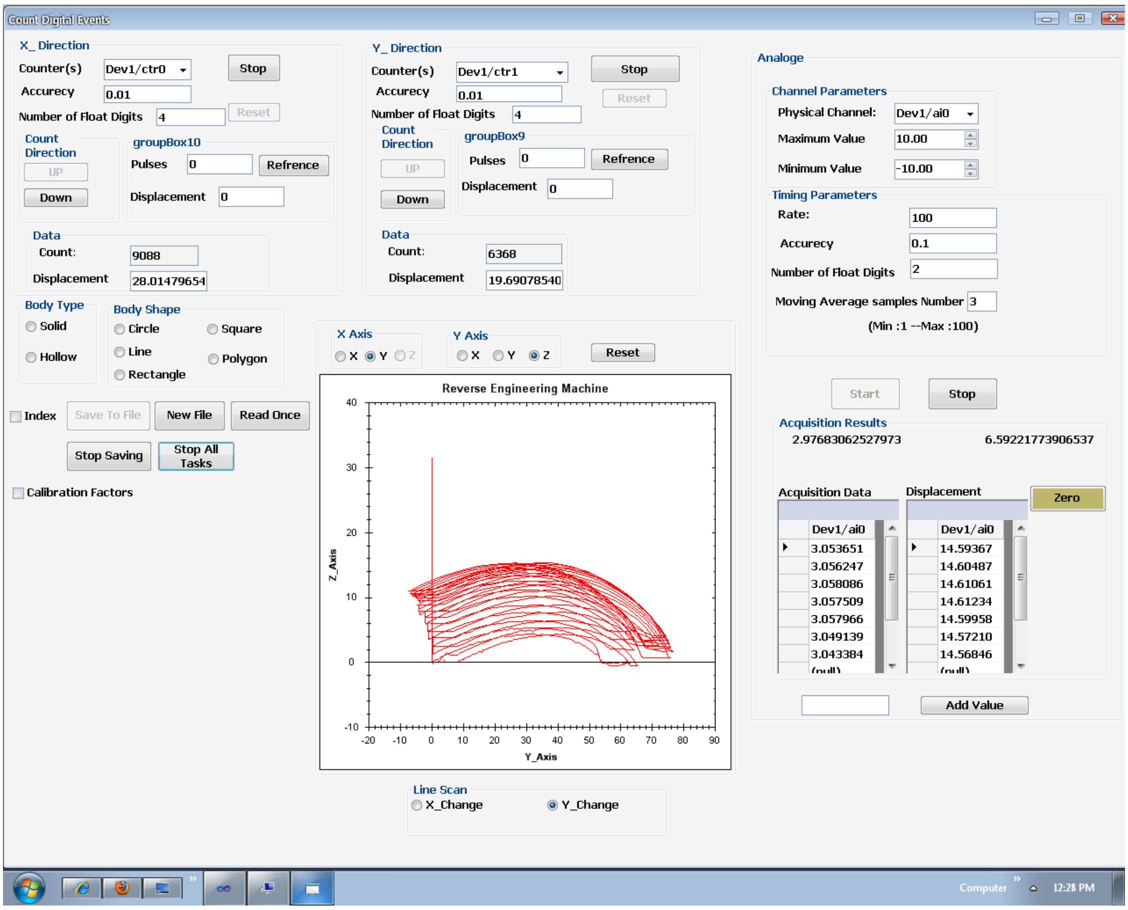

Fig.4, the software driving the system and acquiring the data point files

6.1 **Capturing line scan files**

After the data points acquired were processed by a special software developed by the authors, these data points are transformed and stored in the text format. In order to draw the spline representing the file for the following CAD model reconstruction.

6.2 **Data processing and reconstructing the 3D CAD model**

On the basis of the scanned data point files acquired, reconstructing the 3D CAD model for the object involves created. Several commercial software packages which can implement the above function can be used to aid the reconstruction of the 3D CAD model. For this case, Solid works was employed to reconstruct the 3D CAD model of the PC mouse body. Reconstruction of the 3D CAD model by using the Solid works software includes two steps: Step 1 create the spline 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.

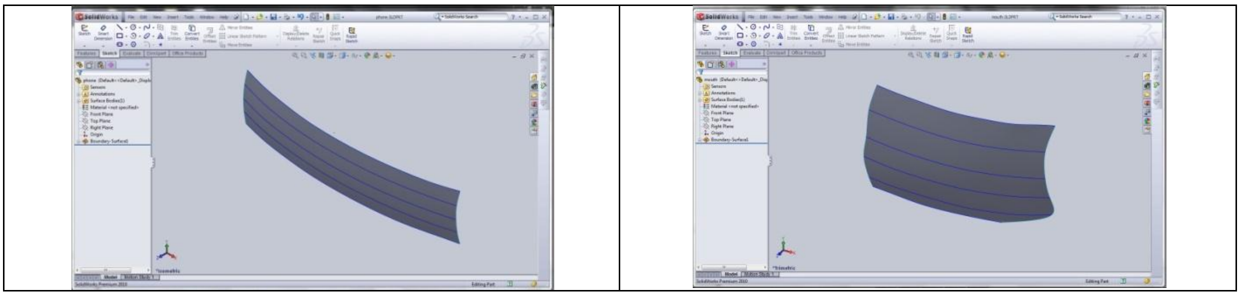

Figure 5: The 3D CAD model of the surface created by solidworks software.

7. Results

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 a novel 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 accuracy of (0.05 mm). 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 impulsing 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.

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