Development of a non-contact multi-axis reverse engineering measurement system for small complex objects

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Abstract: This study presents the development of a non-contact multi-axis measurement system, which consists of a circular triangulation laser probe system, a multi-axis CNC engraving machine, and a PC, to digitize the 3D profile of small workpieces. The information in the whole measuring system, comprising a personal computer, a CNC engraving machine controller, and a controller of the circular triangulation laser probe, was integrated technically. Three scanning methods for the developed measurement system were proposed to configure the scanning path, namely the multiple-fold scanning method, the rotational scanning method, and the radial scanning method. The homogenous transformation matrix method was used to calculate the data registration of different digitized data sets. The measurement error of the development system was analyzed by digitizing a designed 3D test carrier. The root mean square error was about 0.028 mm and was obtained through a comparison between the digitized, reconstructed data and the measured data obtained with a CNC coordinate measuring machine (CMM). The developed system was applied successfully to the reverse engineering measurement of some small complex models, such as a tooth model and a toy model.

1. Introduction
Reverse engineering (RE) has played an important role in many engineering fields for quick product design. Reverse engineering mainly consists of four parts, namely (1) a measurement system used to digitize a sample part or a prototype model, (2) data processing software of the digitized point data, (3) construction of a CAD model, (4) CAE and/or CAM based on the constructed model. The measurement systems used in the reverse engineering process can basically be divided into the contact type (a coordinate measuring machine equipped with a scanning probe) and the non-contact type (laser assisted scanning system). Non-contact type equipment, due to its high measuring speed, lack of contact force and absence of probe radius compensation, etc., is nowadays the dominant tool used for reverse engineering measurement. Non-contact type measurement equipment can basically be divided into three categories: first, a measurement machine integrated with a triangulation laser probe [1-4]; second, a measurement machine integrated with a laser line projector and two CCD cameras [5-6]; third, a measurement machine integrated with a structured light projector and two CCD cameras [7]. In general, a measurement machine integrated with a laser line or with a structured light projector and two CCD cameras, is appropriate to digitize objects with dimensions larger than about 30 mm. To digitize small complex objects, with dimensions smaller than about 30 mm, a measurement machine integrated with a triangulation laser probe is a good solution, due to its small spot size. The widely used standard triangulation laser probes and circular triangulation laser probes are commercially available. The circular triangulation laser probe has been developed in recent years to improve on, principally, the
drawback of the standard triangulation laser probe, i.e., shading-effects at steps or other shape discontinuities [8-9].

This study developed a multi-axis non-contact measurement system, in which a circular triangulation laser probe was integrated with the z-axis of a CNC engraving machine, so that the automatic measurement of full surface models of small complex objects was possible. Possible measuring procedures, using the developed multi-axis measurement system, are also proposed.

2. Informational integration of NC-controller, control unit of laser probe, and PC
The information in the whole measurement system, including a personal computer (PC), a CNC controller of the multi-axis engraving machine, and a controller of the circular triangulation laser probe, were integrated technically (Figure 1), so that automatic measurement was possible. The laser probe used in this research was a model OTM-3A30 made by Wolf & Beck Co. [8]. The working distance of this laser probe type is 85 mm and the measuring range is 20 mm. Resolution of two microns can be obtained with this probe. The developed 5-axis PC based measurement system comprised x-y-z axes, a rotary axis W, and an index table V of the rotary axis W. Each linear axis was integrated with a linear encoder and the rotary axis was integrated with a rotary encoder, to ensure accurate positioning. A serial interface (RS232 interface card) was used in the computer to send special commands for different operation modes for the laser probe (e.g. trigger operation) to the laser probe controller. A trigger signal was generated from the counter card inserted in the PC main board, which received impulses from the linear encoder, whenever an interval passed according to the predefined distance. The trigger event was also the signal for the laser probe to take a measurement, so that all coordinates of the measured location were exactly known. The measured data of the laser probe was transferred to the computer by means of a serial interface. A set of measuring software programmed using C++ language was developed to configure the scanning path, to process the control commands of the laser probe, to generate NC commands, search for the origin and the rotational center of the auxiliary fixture used to fix the object to be digitized, and to process the digitized data points. Two methods were proposed to search for the rotation center of the auxiliary fixture, namely the rotational offset method and the least square circle method. After configuring the measuring range, the scanning pitch etc., the digitizing of small complex objects was possible through the developed measurement program.

Three possible measurement procedures were proposed to measure the freeform surface of complex objects for the developed multi-axis measurement system, namely (1) the multiple-fold x-y plane reciprocal scanning procedure for the rotary axis, when it is in the horizontal position (V-axis = 0°), (2) the rotational scanning measurement procedure for the rotary axis, when it is in the horizontal position,
(3) the radial scanning procedure for the rotary axis, when it is in the vertical position (V-axis = 90°). The multiple-fold x-y plane reciprocal scanning measurement procedure is appropriate to digitize thin-flat workpieces, whereas the rotational scanning measurement procedure is suitable to digitize workpieces with roughly cylindrical profiles. By utilizing the rotational scanning procedure and the radial scanning procedure sequentially, two sets of digitized data with same angular spacing (increment) can be registered together using the homogenous transformation matrix method.

3. Data registration of the digitized data with the homogenous transformation matrix method

The 3D profiles of small complex objects should basically be combined and registered together from multiple sets of digitized data so no regions of the profile can not be digitized. The homogenous transformation matrix method was used to calculate the data registration of two different digitized data sets, namely the digitized data set \( P \) measured when the rotary axis was in the horizontal position and the digitized data set \( P' \) measured when the rotary axis was in the vertical position (Figure 2). So as to have comparable data, the vertical position measurements should be subjected to the matrix operations below to yield one set of \( P' \) measurements.

\[
P' = M_F \cdot M_R \cdot P
\]

\[
M_R = M_{EX} \cdot M_{EY} \cdot M_{EZ}
\]

\[
M_F = \begin{bmatrix}
1 & 0 & 0 & d' \\
0 & 1 & 0 & e' \\
0 & 0 & 1 & f'
\end{bmatrix}
\]

where

\( d', e', \) and \( f' \), are the coordinate translation of the origin of the fixture

\( \alpha, \beta, \) and \( \gamma, \) are the rotation angles with respect to the x-, y-, and z-axes, respectively.

![Figure 2. Coordinates transformation](image)

4. Application of the developed system

The measurement error of the development system was analyzed by digitizing a designed 3D test carrier. To evaluate the measurement error of the developed system, a 3D test carrier was designed and manufactured. The coordinate origin of the auxiliary fixture was determined by using the derivative method after the laser probe scanned along the x-axis and the y-axis respectively. The B-spline curve method was used to interpolate the vacancy region after carrying out the data registration of different digitized data sets. The root mean square error result was about 0.028 mm and was obtained through a comparison between the digitized, reconstructed data and the measured data obtained using a CNC CMM. The developed system was applied successfully to the reverse engineering measurement of some
small complex models, such as a tooth model and a toy model. Figure 3 shows the reverse engineering of a full ceramic coping. A tooth plaster model was mounted in an auxiliary fixture (Figure 3 (a)). The model was first digitized by the 4-fold x-y plane reciprocal scanning procedure for the rotary axis in the horizontal position (V-axis = $0^\circ$), then by the radial scanning procedure for the rotary axis in the vertical position (V-axis = $90^\circ$) (Figure 3 (b)). Through the application of the homogenous transformation matrix, multiple sets of digitized data can then be merged and registered (Figure 3 (c)). The CAD model of the registered data can be constructed by using Pro/E software (Figure 3 (d)).

5. Conclusion
A multi-axis measurement system and software has been newly developed, successfully, to digitize small complex objects. Three scanning procedures, namely (1) the multiple-fold x-y plane reciprocal scanning procedure for the rotary axis in the horizontal position (V-axis = $0^\circ$), (2) the rotational scanning measurement procedure for the rotary axis in the horizontal position, (3) and the radial scanning procedure for the rotary axis in the vertical position (V-axis = $90^\circ$), were proposed for the developed system. The root mean square error was about 0.028 mm and was obtained through a comparison between the digitized, reconstructed data and the measured data obtained using a CNC CMM.

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