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MULTIPLE-SENSOR INTEGRATION FOR EFFICIENT REVERSE ENGINEERING OF GEOMETRY

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ABSTRACT

This paper describes a multi-sensor measuring system for reverse engineering applications. A sphere-plate artefact is developed for data unification of the hybrid system. With the coordinate data acquired using the optical system, intelligent feature recognition and segmentation algorithms can be applied to extract the global surface information of the object. The coordinate measuring machine (CMM) is used to re-measure the geometric features with a small amount of sampling points and the obtained information can be subsequently used to compensate the point data patches which are measured by optical system. Then the optimized point data can be exploited for accurate reverse engineering of CAD model. The limitations of each measurement system are compensated by the other. Experimental results validate the accuracy and effectiveness of this data optimization approach.

Keywords: Hybrid system, CMM, Reverse engineering.

1 INTRODUCTION

Even though tactile and optical sensing technologies are widely used in data acquisition in dimensional metrology, it has been shown that each technique has its own characteristics and limitations, which lend them to particular applications. On the other hand, due to the different measuring techniques and their physical working principles, different interactions between the workpiece and sensor occurs and different surfaces are captured (Weckenmann *et al.* 2000). The reduction of the lead time in RE, and the increased requirements in terms of flexibility as well as accuracy have resulted in a great deal of research effort aimed at developing and implementing combined systems based on cooperative integration of homogeneous sensors such as mechanical probes and optical systems (Chan *et al.* 2000, Carbone *et al.* 2001, Bradley *et al.* 2001, Sladek *et al.* 2011). However, until now no relevant study has been found about how to efficiently handle integrated measurement data in reverse engineering, in other words, how to use more accurate measurement information to improve the overall measurement accuracy.

This paper describes a flexible and effective approach for the integration and optimization of a 3D structured light system with dual CCD cameras and a CMM with a contact-probe to perform the reverse engineering of geometry. A sphere-plate artefact is developed for unification of the hybrid system and it does not need the physical integration of the two sensors onto the CMM, but includes their combination at the measurement information level. The system unification is achieved by measuring the spheres calibration board and then measurement results from combining all of the optical sensors and the CMM probe head into one set. With the coordinate data acquired using the optical system, intelligent feature recognition algorithms can be applied to extract the geometric elements of the object. These key features of elements can be re-measured using a small number of points by the tactile CMM and described by mathematical and numerical methods. The obtained information can subsequently be used to optimize the vast amounts of point cloud data measured by the optical sensor.

2 HYBRID SYSTEM CONFIGURATION AND CALIBRATION

2.1 Elements of The Hybrid System

The integrated system (see Fig. 1) is designed and manufactured with the following components as shown in Table 1:

Table 1: The Components of The Integrated System.

A	High accuracy CMM	Zeiss PRISMO system
B	Two CCD cameras	IDS UI-1485LE-M-GL, the CCD resolution is 2560(H)×1920(V), the dimension of a pixel is 2.2 μm ×2.2 μm
C	Lens	Fujinon HF12,5SA-1/1,4 5 Megapixel C-Mount Lens, the focal length is 12.5 mm
D	Projector	Panasonic PT-LB60NTEA projector with 1,024×768 pixels
E	Planer calibration board for optical scanner calibration and sphere-plate standard for unification of hybrid system	



Figure 1: The integrated system

2.2 Hybrid System Calibration

The CMM and optical scanner need to be calibrated separately before measurement to reduce uncertainty within their own coordinate frames. A master stylus is used for qualifying the CMM on a reference sphere and then a new stylus system must be qualified. The maximum permissible error of length measurement (MPE) is $(1.9+L/300)$ μm (ISO 10360-2:2009).

There are many studies concerning modelling and calibration of CCD cameras (Atkinson *et al.* 2003, Sheng-Wen *et al.* 1996, Sagawa *et al.* 2008). Camera calibration in the context of 3D optical measurements is the process of determining the transformation from 2D CCD image to 3D world coordinate system. In this paper Zhang's (2000) method is exploited to calibrate CCD cameras, the accuracy of 3D structured light system is up to 45 μm .

3 HYBRID SYSTEM COORDINATES UNIFICATION

3.1 Geometric Transform Method for Hybrid System Unification

The optical scanner and the CMM work in their own separate coordinate systems. If the integrated system is to produce useable results, these two coordinate systems have to be unified. The same

position surface data of a workpiece scanned from an integrated system can be seen as a kind of rigid body movement, so the geometric transformation method can be used to deal with coordinate unification. Since three non-collinear points can express a complete coordinate frame, data fusion of the two systems will be achieved simply with three different reference points and a three-point alignment coordinate transformation method. Therefore, the data fusion problem for an optical system and CMM is converted to a coordinate transformation problem, the coordinates of multiple scan data from both system can be transformed to one coordinate system.

Coordinate transformation of 3D graphics includes geometric transformations of translation, proportion, rotation and shear. The coordinate transform method by three points is derived by Mortenson and presented by Tao (2007).

3.2 Calibration Board Design

While using this method the question arises of how to select optimal match datum-points from two different sensors. It is usually very difficult to obtain the same reference point from two different sensors (CCD cameras and CMM in this case) because of the different measurement principles and methods of two systems as well as different point cloud density. If we take a reference feature point as the calibration reference point every time, the possibility of occurrence of system error, human errors and accidental errors will increase greatly. Because three points can establish a coordinate frame, we can consider calculating the centroid of a standard calibration ball and then use the sphere centre coordinate as the datum reference point coordinate to achieve data fusion and reduce fusion errors.

A ball-plate calibration board with three spheres attached to it is created for data fusion of the hybrid system. Three spheres form an approximate equilateral triangle and are made of solid polypropylene with a matt finish and have good roundness and sphericity with nominal diameter $\Phi=25.4\text{mm}$ and form error no greater than $\Phi=30\text{ }\mu\text{m}$. The coordinates of spherical centres measured by CMM and optical scanners can be calculated by least squares best fit method.

3.3 Mathematical Model of 3D Cartesian Coordinate Transformation

Suppose two 3D Cartesian coordinates $O-XYZ$ and $O_T-X_TY_TZ_T$, in space Cartesian coordinates transformation process, first the origin O is translated to another origin O_T along the direction of X , Y and Z subsequently, then two coordinates that have same origin can be transformed into the same one through three rotations. The transformation relation can be described by equation (1):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_T = \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} + kR \begin{bmatrix} x \\ y \\ z \end{bmatrix}_O \quad (1)$$

Where $\begin{bmatrix} x & y & z \end{bmatrix}_O^T$ is the coordinate in $O-XYZ$ and $\begin{bmatrix} x & y & z \end{bmatrix}_T^T$ is the coordinate in $O_T-X_TY_TZ_T$; $\begin{bmatrix} x_o & y_o & z_o \end{bmatrix}_O^T$ is three translation parameters, R is rotation matrix and k is scale factor.

$$R = \begin{bmatrix} \cos \beta \cos \gamma & -\cos \beta \sin \gamma & \sin \beta \\ \cos \alpha \sin \gamma + \cos \gamma \sin \alpha \sin \beta & \cos \alpha \cos \gamma - \sin \alpha \sin \beta \sin \gamma & -\cos \beta \sin \alpha \\ \sin \alpha \sin \gamma - \cos \alpha \cos \gamma \sin \beta & \cos \gamma \sin \alpha + \cos \alpha \sin \beta \sin \gamma & \cos \alpha \cos \beta \end{bmatrix} \quad (2)$$

Then there are 7 parameters x_o , y_o , z_o , α , β , γ and k , at least three pairs of coincidence points (9 known values) are needed to solve these parameters. The fitting function of spatial coordinate transformation 7 parameters problem is a matrix function, we can consider convert it into a non-linear over determined equation group, take space coordinates of 3 reference points to compose 9 over determined non-linear equations, then exploit non-linear least squares method to solve these 7 parameters.

4 DATA OPTIMIZATION BASED ON CMM MEASUREMENT RESULTS

4.1 Proposed Solution

After coordinate system unification, the optical and CMM measure in the same absolute coordinate system. However, two data sets measured by different sensors are unlikely to coincided absolutely, which means there must be a measurement error between the optical and tactile system. To overcome this problem, a data optimization method is proposed to enhance the measurement accuracy of the optical structured light sensor for RE. We are only interested in industrial samples.

After a part is measured, the acquired point cloud data should be divided into several smooth regions for surface fitting purposes, which is called the segmentation process (Woo *et al.* 2002). A segmentation that extracts the edges and partitions the 3D point data plays an important role in fitting surface patches and applying the measured data to the manufacturing process.

Planes, spheres, cylinders and cones are ubiquitous in the shapes of industrial components. In fact, more than 70% of the functional parts in precision machines can be modelled using these simple shapes (Zhang *et al.* 2012). In RE, the final CAD model accuracy depends on the measured point data. Then, a small amount of discrete point data measured by the CMM can be used to ‘optimize’ massive point cloud data that has been measured by the optical scanner to improve the overall measurement accuracy. The specific method follows these steps:

- 1) Use the optical system to scan the workpiece to digitize the entire surface; and then a segmentation algorithm is exploited to obtain the point data patches with geometric features;
- 2) Use the CMM to re-measure these geometric features with a small number of points, and then use the least square method to best-fit these geometric elements and derive an equation to describe these elements;
- 3) Substitute x and y coordinates of points measured by the optical sensor into this equation then the new z coordinate can be derived; and then use x , y and new z coordinates as new point data coordinates to reconstruct the CAD model.

The new workflow of an RE workpiece by using hybrid contact-optical measuring system can be expressed as in Fig.2.

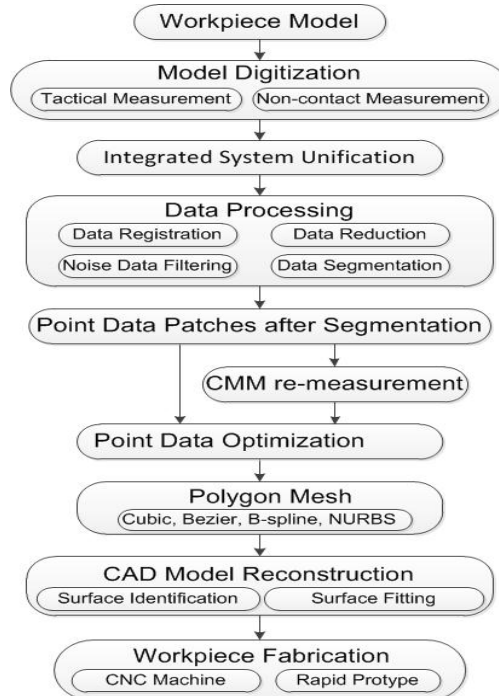
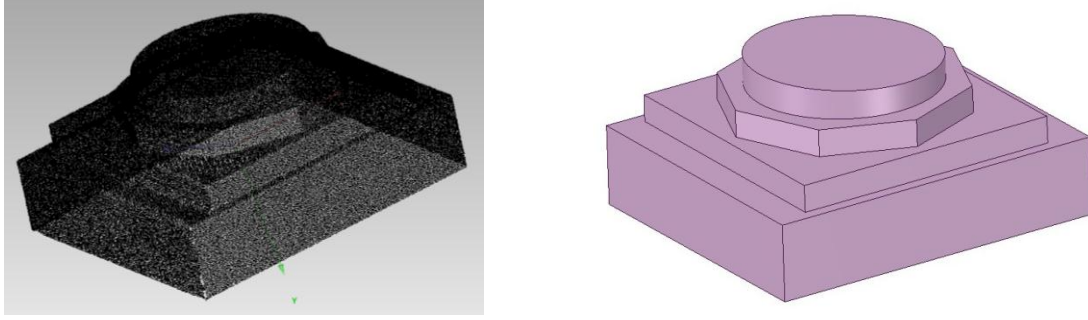


Figure 2: Workflow of RE by using hybrid contact-optical measuring system

4.2 Example Application

The method was applied to optimize point data measured by an optical sensor to reconstruct the workpiece CAD model in RE (see Fig.3).



(a) Points data measured by optical sensor (b) CAD model reconstruction after optimization

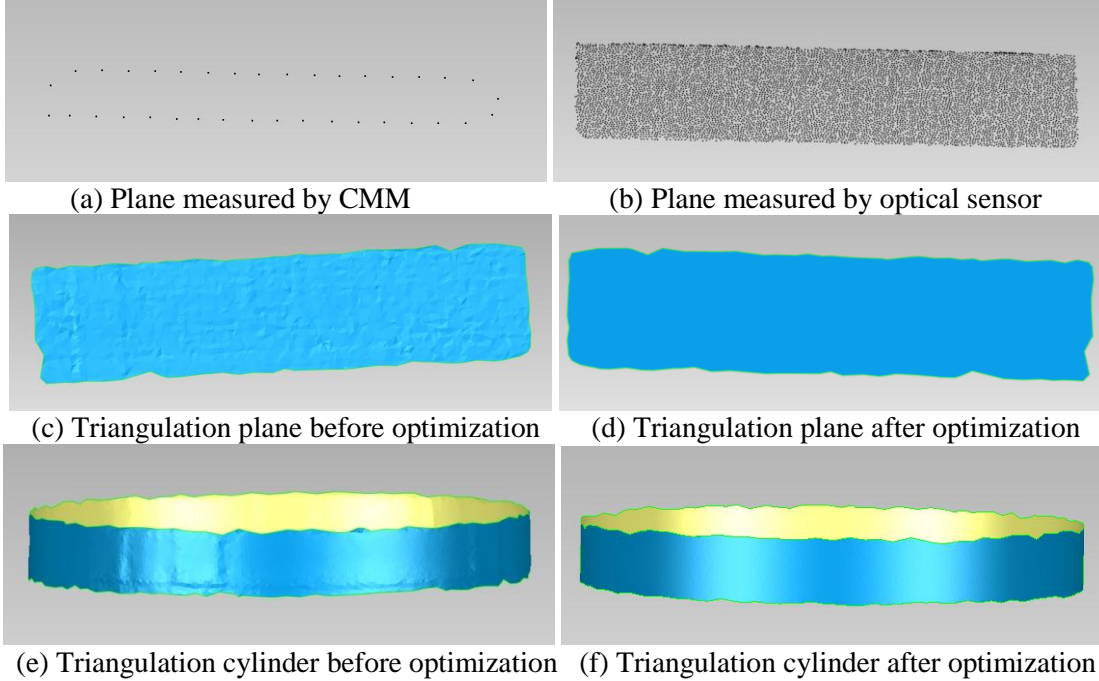
Figure 3: RE of workpiece by using hybrid contact-optical measuring system

After data segmentation, this model contains only two types of geometric elements: plane and cylinder.

A spatial plane is specified by

$$Ax + By + Cz + 1 = 0 \quad (3)$$

There are three unknowns in this equation. By using the point data measured by CMM (see Fig.4 (a)) and using the least square method, these parameters can be solved. To substitute x and y coordinates of points measured by optical sensor (Fig.4 (b)) into this equation (3), then the new z coordinate can be derived and new point data coordinates are used to reconstruct the polygon model.



(e) Triangulation cylinder before optimization (f) Triangulation cylinder after optimization

Figure 4: Point data optimization

Fig.4 (c) shows the triangulation mesh plane generated by original un-organized point cloud data which is scanned by the optical sensor, Fig.4 (d) shows the new triangulation mesh plane after optimization. The new polygon model is very smooth as every point falls exactly onto the plane according the equation (3).

A cylinder is described by the direction cosines of its axis (m, n, l) , a point on the axis (x_o, y_o, z_o) and the radius r . We use the Levenberg-Marquardt algorithm (Shakarji *et al.* 2012) to obtain estimates of these parameters. Fig.4 (e) and Fig.4 (f) show the triangulation mesh cylinder before and after optimization, respectively. The accuracy and quality of point data on the surface have been greatly enhanced. The rough edge on the cylinder (Fig.4 (f)) could then be improved by constraining with projection of the measured planes.

5 CONCLUSIONS

The development of a multi-sensor integrated coordinate measuring system for rapid and high-precision reverse engineering has been introduced. In current implementation, the multisensory system consists of a high-precision scanning CMM and structured light scanning system. A sphere-plate artefact with three spheres has been developed for unification of the hybrid system. With the millions of points acquired using a structured light optical scanning system, intelligent feature recognition and segmentation algorithms can be applied to extract the global surface information of the object. Then the CMM is used to re-measure the geometric features with hundreds of sampling points. The obtained information can be subsequently used to optimize the point data patches which are measured by the optical system. Theoretically, after optimization the data measured by optical sensor has same accuracy as the CMM (depending on the accuracy of geometric characteristics of sample pieces). The experiment results show this novel approach is accurate, convenient and reliable. The principles presented can be further extended to include other geometric features, such as cone, torus and elliptical cylinder etc.

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