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A study of fiducial aided calibration and positioning for precision manufacture of freeform surfaces

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Abstract
Precision manufacturing of freeform surfaces requires accurate positioning of workpiece on the machine tool and measurement instrument with high repeatability during the manufacturing cycle. However, the geometric complexity of ultra-precision freeform surfaces brings considerable challenges in precisely localizing the workpiece for different processes including the machining process and the measurement process. This paper presents a study of a Fiducial Aided Calibration and Positioning (FACP) method to achieve better accuracy and efficiency in manufacturing of the ultra-precision freeform surfaces. The FACP method makes use of fiducials to purposely design high precision fiducial fixtures to form a Fiducial-aided Computer Aided Design (FA-CAD) of the freeform workpiece which not only calibrates the geometric error of the volume of the machine tool where machining is undertaken but also establishes an intrinsic reference datum of the workpiece for precise location on the machine tool and the measuring instrument so as to link the machining and the measurement process for form characterization and compensation of the form errors of the workpiece. Some preliminary experiments are conducted to realize the capability of the method.

Keywords: Freeform Surfaces, Precision Manufacture, Fiducial, Precision Surface Measurement, Ultra-precision Machining.

1. Introduction

It is well known that the use of ultra-precision freeform surfaces (UPFSs) considerably improves the performance of optical and other systems: the number of elements is reduced, the weight and size is reduced and material is conserved [1]. However, the high accuracy requirement and the geometric complexity of UPFSs bring considerable challenges for the control of manufacturing process and the quality assessment, which hinders the explosive growth of the application of these surfaces.

The process chain for the manufacturing of a UPFS includes machining, measurement, and evaluation. As the components passing from design through machining process to measurement, there are a number of coordinate systems involved in the manufacturing cycle among which the coordinate transformations should be determined precisely. However there still exists a significant gap between the manufacturing and the measurement process for UPFSs due to a lack of high precision and robust positioning method for unifying the coordinate frames of the measuring instruments and the machine tool [2, 3]. On-line/machine metrology is an enabling technique to address the problem. However, most of the current on-line/machine metrology system is either limited to 2D measurement for rotationally symmetry surfaces [4].

One of the promising approaches is the use of fiducials on the freeform surface as points of reference or measure [5]. As a result, this paper presents a framework of a fiducial aided positing method for precise positioning of freeform workpiece on multi-axis machine tools in order to improve the accuracy and the efficiency in the manufacturing of ultra-precision freeform surfaces.

2. Fidicial aided calibration and positioning method

One of the major difficulties in locating freeform surfaces is that these surfaces are lack of inherent surface features. Considering the on-machine probing capability of modern machine tools, a fiducial fixture is designed to address this problem by using standard geometries such as ball artefact as basic elements which are served as inherent features of the freeform workpiece in the manufacturing cycle.

Fig. 1 shows the architecture of the FACP. Taking the CAD of the designed surface (DS), the characteristics of the machine tool and the measuring instrument as input, a fiducial fixture is designed using standard geometries such as sphere as elements. The freeform workpiece is assembled on the designed fiducial fixture which is measured by a high precision measuring instrument in a thermal control environment. The CAD of the DS is then fitted into the measured surface of the workpiece and hence a fiducial aided-CAD (FA-CAD) of the DS is generated by integrating the CAD of the DS with the measured fiducials. Hence the fiducials are serve as intrinsic features of the FA-CAD which are used to guide the precision positioning in later machining and measurement processes.

In the machining process, the fiducials of the FA-CAD are also used as reference datum to evaluate the geometric error of the volume of the machine tool where the machining of the workpiece will be undertaken so as to minimize the effect of the machine tool error. In the measurement process, the quality of the machined workpiece is assessed by a precision measuring instrument. It is emphasized that the form error of the machined workpiece is evaluated by comparing the measured surface with the FA-CAD of the DS. Hence, the localization of the measured data on the coordinate frame of the DS is conducted based on the fiducials. As a result, the form characterization of ultra-precision freeform surfaces undertaken in FACP system is no longer based on the traditional least square based best fitting process [3]. Hence, the technical merit of the proposed method towards the previous work is that FA-CAD will not only be used to position the workpiece but also link the manufacturing process and the measurement process. By making use of proposed method, it is feasible to perform the corrective machining of the freeform workpiece. The uncertainty associated in the FACP system are analyzed based on Monte Carlo method. Several uncertainty contributors should be considered, including but not limited to, the error of the measuring instruments, the geometric error of the machine tool, the error of the machine probing error, the deflection of the fixture and the workpiece due to temperature variation and gravity.

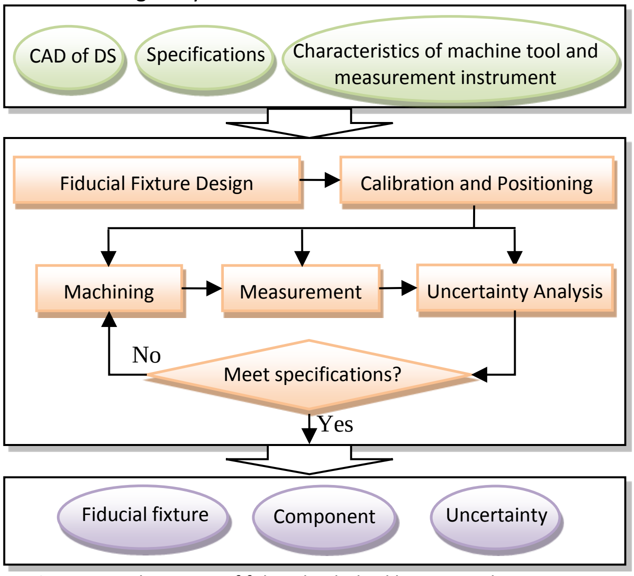

Figure 1. Architecture of fiducial aided calibration and positioning method

3. Experimental study

Experimental study has been conducted on a sinausoidal freeform surface as given by Eq. (3) as follows:

$$z = 5\sin(0.1x) + 5\sin(0.1y) \quad (3)$$

The radius of the workpiece is 60mm. A fiducial aided fixture is designed as shown in Fig. 2. A total of 8 calibrated balls are uniformly mounted around the edge of the fixture with different height. The coordinates of the ball centres are (100, 0, 5), (70, 70, 5), (0, 100, 35), (-70, 70, 35), (-100, 0, 5), (-70, -70, 5), (0, -100, 35), (70, -70, 35), respectively. All the units are in mm. According to the principle of the FAP method, Five uncertainty contributors are considered in the presented study, including: calibration error of the fiducials (u=0.8, normal distribution); error of the probing system mounted on the machine (u=1, normal distribution), error in determining the centres of the balls (u=0.3, normal distribution), the deflection of the fixture in temperature variation (u=0.4, normal distribution), geometric error of the machine tool.

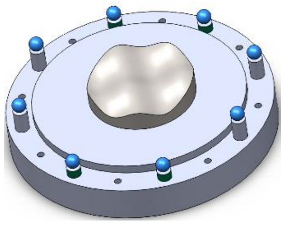

Figure 2. Designed fiducial aided fixture

Considering that the geometric error of the machine tool would be the major error contributor the proposed method, a wide range of the magnitude of errors 1~9 are imposed into the simulation for different case studies. It is also assumed that the residule geometric errors have normal random statistics after compensation process. The uncertainty is evaluated by Monte Carlo method with 3000 trials. In each Monte Carlo trial, the original coordinates of the fiducials are transformed to an arbitrary coordinate frame with known spatial parameters, then the random errors are added to the transformed coordinates of the fiducials. Fig. 3a shows the simulated surfaces. The accuracy of the FAP method is characterized by the accuracy of the method in evaluating the six spacial parameters of the coordinate transformation matrix. Fig. 4 shows positioning uncertainty of the proposed method, i.e. the standard deviation (Std) of the evaluated six spatial parameters for coordinate transformation, with respect to the magnitude of the geometric errors of the machine tool. rx, ry, and rz refer to the rotational angles, and tx, ty, and tz refer to translational offsets along to X, Y, and Z axis respectively. It is interesting to note that the proposed method is able to achieve a scaling of approximately 1 in 10 positioning accuracy respect to the magnitude of the geometric error of the machine tools.

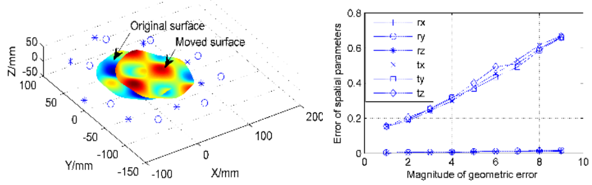

Figure 3. (a)Simulated surfaces; (b) Uncertainty of the proposed method in positioning freeform surfaces (scaling analysis with respect to the magnitude of the error)

4. Conclusion

This paper presents an initial attempt for the development of a fiducial aided calibration and positioning method for precisely positioning of freeform surfaces in manufacturing cycle. The method makes use of fiducials to add reference datum to the freeform workpiece which is used to compensate the geometric error of the machine tool and determine the coordinate transformation between the coordinate frame of the workpiece and the machine in the machining process and the measurement process. Hence it is able to establish a link between the machining and the measurement process. Experimental study indicates that the proposed FAP method and apparatus are capable of achieving a scaling of 1 in 10 positioning uncertainty with respect to the geometric error of the machine tools.

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