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A self-calibration rotational stitching method for precision measurement of revolving surfaces

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A B S T R A C T

When measuring revolving objects, it is often desired to obtain not only the geometrical form of the workpiece, but also the topography of the surface, as they both affect the performance of the part. However, holistic measurement of the entire three-dimensional surface of a revolving part is challenging since most surface measurement instruments only have limited measurement ability, where the bottom and the side surfaces cannot be measured. One solution to obtain geometrical form and surface topography information simultaneously is to add a precision axis to rotate the object while performing surface topography measurement. However, this solution requires a high-cost precision rotation stage and adjustable mounting and alignment aids. Moreover, errors in the rotation will be added to the measurement result, which can be difficult to compensate. Stitching is a method often used for measuring revolving surfaces without the need for precision motion axes, as the method is applied at the software level, and errors in the rotation can be compensated by the stitching algorithm. Nevertheless, the overall accuracy of stitching is limited when the number of sub-surfaces is large, since the measurement and stitching error accumulate along the stitching chain. In this paper, a self-calibration rotational stitching method is presented which can compensate for the accumulated error. The self-calibration method utilises the inherent nature of a revolving surface and compensates for the registration error by aligning the last dataset with the first dataset. The proposed method is demonstrated by measuring grinding wheels with a coherence scanning interferometer and simultaneously rotating the grinding wheels with a low-cost stepper-motor. It is demonstrated that the proposed stitching measurement method is effective in compensating for accumulated registration error. The proposed self-calibration rotational stitching method can be easily extended to a wide range of applications for measuring revolving surfaces using various measuring instruments.

1. Introduction

Revolving surfaces, such as precision rollers [1], shafts [2] and grinding wheels [3], are widely used in precision engineering. They are usually produced by a machining process that involves the rotational motion of spindles or motors, such as turning and grinding. There is an increasing demand for precision not only in the geometrical form of the machined part, but also in the surface texture, in applications such as producing microlens arrays on a roller stamper in order to replicate them onto a continuous flexible substrate [4] and optimising the micro-topography on a diamond grinding wheel for improved grinding performance [5]. To holistically obtain both geometrical form and surface texture requires measuring the revolving surface with a surface measuring instrument and extracting both large-scale and small-scale information from the measurement. Measuring a revolving surface with a surface measuring instrument is a challenging task as most surface measuring instruments, such as coherence scanning interferometers (CSIs) and focus variation microscopes (FVMs), only have 2.5-dimensional (2.5D) measurement capability, where the bottom surface or the surface with high slope angle cannot be measured. In order to achieve three-dimensional (3D) measurement of the revolving surface, an additional precision rotational axis can be used to rotate the object, so that the entire surface can be measured. However, this method requires a high-cost precision rotational axis, and sometimes additional devices for tilting and alignment adjustment, which are not available to most surface measuring instruments, especially when large workpieces, such as precision roller drums in the roll-to-roll industry, are involved [6].

Measurement accuracy is often affected by the motion error of the rotational axis such as runout, angle error, misalignment between the workpiece and the rotational axis, and misalignment between the

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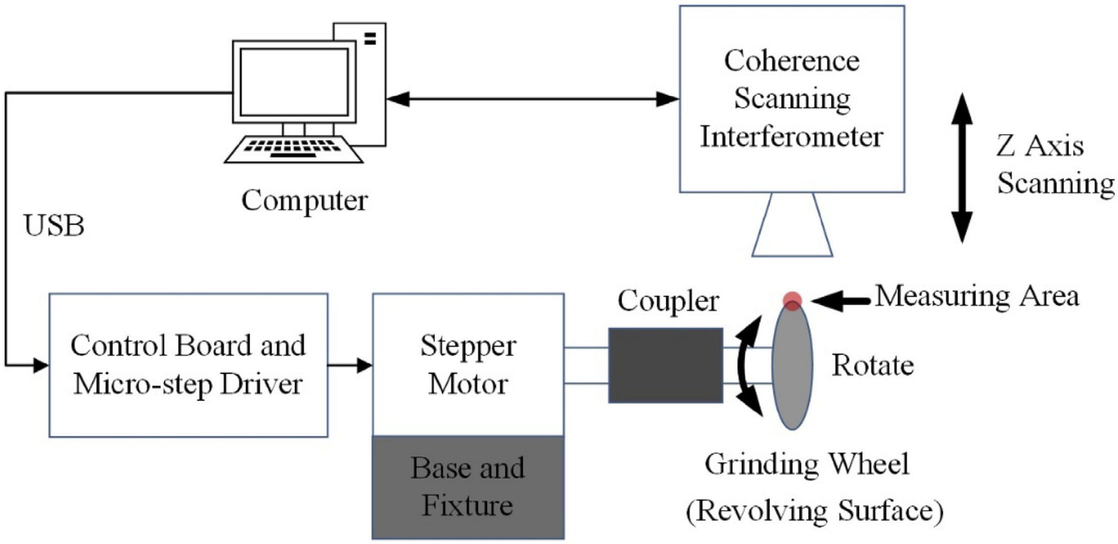

Fig. 1. Schematic diagram of rotational stitching measurement of revolving surfaces.

measuring probe and the rotational axis. The measurement error caused by the misalignment between the workpiece and the rotational axis is also subject to human errors and, therefore, cannot be easily controlled. One promising method to minimise this error is stitching, which utilises the common features in the overlapping region between two neighbouring fields of view to minimise alignment error. The stitching method is applied at the software level, independent of the instrument hardware setup. Several studies have focused on planar stitching, such as sub-aperture stitching interferometry for relatively flat surfaces [7,8], and spherical and aspherical surfaces [9,10]. Some studies have explored the measurement of revolving surfaces - specifically cylindrical surfaces. For example, stitching measurement of a full cylindrical surface has been studied by Peng et al. [11,12], with a method based on a Fizeau type interferometer and a computer generated hologram (CGH) null. The method achieves sub-micron accuracy, but it was only applicable to high precision cylindrical surfaces with a specific diameter, since different CGH nulls would be needed when the size of the cylinder changes. Weckenmann et al. [13] developed grazing incidence interferometry for high-precision measurement of cylindrical form deviations. The method utilised the incident laser beam to project to the measured cylindrical surface and the interferogram was recorded by the CCD camera. The interferogram could then be used to determine the cylindrical form deviations. Guo and Chen [14] developed a multi-view connection technique for 360° 3D measurement using fringe projection, where the object was placed on a precision rotary stage and two sets of fringe patterns were projected onto the overlapped regions at different angles. The measured topographies were then stitched together using an iterative least-squares algorithm. However, the accuracy of the method was not determined. Vissiere et al. [15] developed a cylinder measuring machine with a dissociated metrology technique (DMT)-based architecture using a modified multi-step error separation method to eliminate the spindle errors. To achieve the ultimate 5 nm measurement uncertainty level, the machine was designed with sophisticated hardware. Neugebauer et al. [16] developed a comparator for the measurement of diameter and form of cylinders, spheres and cubes. With a two-probing system adhering to the Abbe principle and a form reference ring, the measurement uncertainty was as low as 20 nm. Most of the above mentioned revolving measurement instruments were specially designed machines dedicated for measuring specific types of revolving surfaces but not for generic revolving surfaces. Most of these instruments also involved sophisticated hardware and are not widely available in industry.

This paper presents a self-calibration rotational stitching (SCRS) method for precision measurement of generic revolving surfaces that can be applied to any surface topography measuring instrument. The proposed SCRS method utilises a traditional 2.5D surface topography measurement instrument, such as CSI. Instead of using a high-precision rotational axis, this method only requires a low-cost rotating motor, such as a stepper motor for rough positioning of the measured revolving surface. Measurement of the entire revolving surface is divided into multiple sub-surfaces with overlapped regions; the sub-surfaces are stitched together initially using the surface registration method. The accumulated measurement and registration error is minimised by the SCRS method which makes use of the first and the last sub-surface in the stitching loop. The proposed method is presented in detail, demonstrated by measuring precision diamond grinding wheels, and is shown to be effective. Due to its generality, the proposed method can be applied to measure various types of revolving surfaces such as cones, spheres and cylinders. The SCRS method can be easily implemented to existing 2.5D surface measuring instruments to enable true 3D measurement of revolving surfaces. In addition, a software user interface (UI) is developed to synchronise rotation of the object with measurement, without the need for an application program interface (API) to the instrument software, making the proposed method truly independent of measuring instruments.

2. Self-calibration rotational stitching (SCRS) method

The schematic diagram of the proposed SCRS method for measuring revolving surfaces is shown in Fig. 1. The method is demonstrated on a CSI with a rotational axis driven by a stepper motor. The SCRS method is divided into two steps. The first step is data acquisition of the revolving surface topography by synchronised measurement while the sample is being rotated. For every measurement, only a small part on the top of the revolving surface is measured because of the limited field of view (FoV). The number of required sub-surfaces is determined by the FoV of the measuring instrument, the dimension of the revolving surface and the percentage of overlapped region. After each measurement, the stepper motor rotates by a specific angle so that the sub-surfaces are overlapped by the required percentage of region for registration purposes. Automatic measurement is implemented using purposely designed software running on the personal computer (PC) that controls the CSI. Since the topographical accuracy of the measurement is ensured by the CSI and the registration process, the motion error of the rotational axis and the misalignment between the revolving surface and the rotational axis are minimised using the proposed SCRS