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Analysing and evaluating a dual-sensor autofocusing method for measuring the position of patterns of small holes on complex curved surfaces

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ABSTRACT

This paper proposes and discusses an active dual-sensor autofocusing method for measuring the positioning errors of arrays of small holes on complex curved surfaces. The dual-sensor unit combines an optical vision sensor and a tactile probe and is designed to achieve rapid automated measurements in a way that can be adapted to be suitable for deployment on a manufacturing machine tool. Mathematical analysis is performed to establish the magnitude of the deviation from the optimal focal length that is induced by the autofocussing method. This evaluation is based on the geometrical relationship and interaction between the radius of the tactile probe with both the measured holes and the complex-curved surface. A description is provided of a laboratory-based standalone dual-sensor autofocusing unit and test rig that was built to perform experimental validation of the method. This system is estimated to have a focusing uncertainty of 11 μm deriving mainly from the inaccuracy of the *X*–*Z* translation stage and the maximum permissible error of the tactile probe.

A case study is presented which evaluates the accuracy of a pattern of Ø 0.5 mm small holes on an elliptic cylinder. A mathematical analysis of that problem and practical results from both the tactile and optical sensors are provided and discussed. It is estimated that the deviation in optimal focusing induced by this automated method is between −23 μm and +95 μm. This is sufficiently accurate to ensure that the optical device can capture the entire space outline of each of the small holes on the complex curve surface clearly and can therefore identify its centroid from the image to provide a measurement of the position.

1. Introduction

The inspection and measurement of small holes on complex curved and freeform surfaces is a demanding problem in precision manufacturing. Such surfaces are commonplace within the automotive, aviation and space industries, where cooling holes with diameter less than Ø 1 mm are commonly found. One type of aero-engine blade is designed with arrays of 79 air-cooling holes of Ø 0.3 mm and Ø 0.5 mm that need to be orientated within ±11′. The latest generation of aero-engine blade has as many as 470 such small holes that need to be positioned accurately.

Measurement of such a large number of small features is impractical, if not impossible, using standard tactile probes that are commonly mounted on a coordinate measuring machine (CMM) or a computer numerical control (CNC) machine tool. Other probes that are designed for nano- and micro-metrology [1], especially the tactile optical-fibre probe [2] for the measurement of the diameter of small holes, are too fragile and costly to measure such a large number of small holes in a production environment.

An optical vision sensor that consists of a high-resolution digital camera and an optical microscope (a set of microscopic objective lenses) allows such measurements to be performed by means of image processing and vision inspection. This technology is broadly applied in various contour-related metrology fields, such as the inspections and measurements of hole orientation and position [3,4] on regular geometric shapes and surfaces of equal curvature such as a flat, a circular cylinder, a sphere, etc.; the form and profile of a workpiece [5,6]; the discovery and measurement of the surface defects [7]; wheel steer angle detection [8]; etc.

A clear image is necessary when using an optical vision system for measurement and inspection. Autofocussing is essential for efficient measurement and repeatable results. The autofocusing techniques currently used mainly rely on the various optical evaluation functions (OEFs) [9–11]. In practise, the optical microscope

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Nomenclature

a,b	major radius and minor radius, respectively (mm)
CAD	computer aided design
CCD	charge coupled device
d	horizontal distance between dual sensors (mm)
DCT	discrete cosine transformation
DOF	depth of field (μm)
OEF	optical evaluation function
L	vertical distance between forefronts of two sensors (mm)
L_0	object distance of optical microscope (mm)
R,r	radii of tactile sensor and small hole, respectively (mm)
$u_c(f)$	positioning uncertainty of the testing rig (μm)
XOZ	measurement coordinate system
xoz	coordinate system of the workpiece
(X_i,Y_i)	image centre of nominal hole in CCD panel (pixels)
(X_i',Y_i')	image centre of drilled hole in CCD panel (pixels)
$(X_i - X_i')$	centroid position change in circumference (pixels)
$(Y_i - Y_i')$	centroid position change in axis (pixels)
Δz	focusing error caused by tactile probe radius (μm)
$\Delta z'$	Focusing error caused by position error of small hole (μm)

is driven to move from a short distance below the focal plane to a short distance above the focal plane while a series of images are captured at different planes. The corresponding series of OEF values are calculated and the plane whose image corresponds to the maximum of the OEF is approximately the focal plane. The procedure uses a hill-climbing search algorithm [12] that is ultimately limited by the resolution of the separation of the planes. The evaluation functions and algorithm are not mathematically complicated, and no additional hardware is required. CMMs equipped with an optical vision sensor usually employ such autofocusing methods.

2. Problem of single optical vision sensor autofocusing

OEF-based methods can be successfully applied when autofocussing on features on a flat surface. However, the method is less successful when focusing on features such as small holes drilled on the steep slope of a complex curved surface. The method is highly sensitive to the illuminating light intensity, the reflectivity of the illuminated workpiece surface and the depth of field (DOF) of the optical microscope. These and other factors combine to mean that the OEF-based focusing method can find a false focus. In this case, the focus positions have to be manually selected, which is time-consuming and less repeatable since it is subject to the skill-level of the operator.

An example of the limitations of OEF-based autofocussing is the inspection of a small hole on a turbine blade. The light-reflecting condition on the surface of the turbine blade introduces a significant level of noise, while the illuminating light reflects at different angles along the surface depending upon the curvature at each point. The OEF-based autofocusing method can find false solutions, as shown in Fig. 1, where ambiguity exists while autofocussing on the outer border of a small hole drilled on the more skewed slope of the blade. If the optical microscope lens moves vertically to position C_1, the lower half of the ellipse image is clear and upper half of it blurs; if the optical microscope lens moves vertically to position C_2, the upper half of the ellipse image is clear while the lower half of it blurs. Between positions C_1 and C_2, the location of the focal plane is uncertain, with the uncertainty increasing as the steepness of the slope increases.

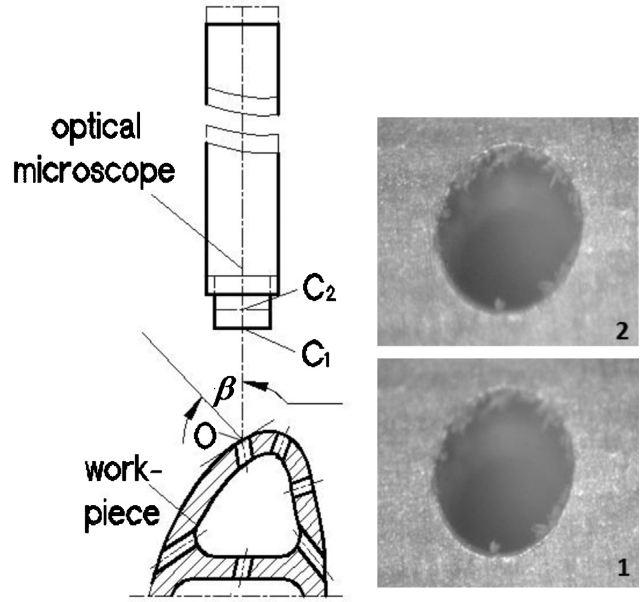

Fig. 1. Ambiguity by only optically focusing the small hole on an engine blade surface at lens position C1 and C2: corresponding images 1 and 2 are blurred in upper/lower semicircle and clear in the opposite semicircle.

To provide a benchmark for this work, typical OEF methods were tested to focus on small holes on an elliptic cylinder and a Brinell hardness indentation on a flat workpiece. Several evaluation functions including image entropy function [12], image gradient variance evaluation function [13] and image discrete cosine transformation (DCT) evaluation function [14] have been tested using the hill-climbing search procedure. A series of images were captured in the procedure where the illuminating light intensity (LI) was tuned to be strong, medium and weak for the elliptic cylinder and medium for the flat workpiece, respectively. The values of the OEF are calculated from the corresponding images that are taken when the optical microscope lens moves at equal steps starting from beneath the focal plane, through the focal plane, then stopped above the focal plane. The ideal "focusing curve" versus "lens position" should have single peak with two mathematically monotonic sides; the steeper the side is, the higher the focusing resolution is and so the sharper the image contrast [15].

Since the DCT evaluation function was found to be the most capable focusing evaluation function among the others, it is taken as the example to explain the problem of autofocusing by using a single optical vision sensor based on the OEF. A series of images were taken at 5 μm intervals by the microscope lens with an approximate 100 μm DOF. The focusing values of the DCT evaluation function responding to the different images were calculated at each position and are plotted in Fig. 2. The starting vertical positions in Fig. 2 are different for the elliptic cylinder with holes and the flat workpiece with a hardness indentation because the two workpieces are not at the same height. Therefore, Fig. 2 was drawn such that the vertical position of an image whose DCT value is the maximum is considered to be approximately the true focal plane and is chosen as the zero microscope lens position. Consequently, the other vertical positions of the images either higher or lower than this zero are presented as negative or positive positions respectively. The DCT curve for the hardness indentation on the flat workpiece appears much sharper than holes on the elliptical cylinder.

3. Dual-sensor-autofocusing

In consideration of the problems associated with OEF-based focusing, this paper proposes an active and fix-focusing method