Zhang, Tao, Gao, Feng and Jiang, Xiang

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Tao Zhang[1, a], Feng Gao[2,b,#] and Xiangqian Jiang[3,c]

[1]EPSRC Center, University of Huddersfield, Huddersfield, HD1 3DH, UK

[2]EPSRC Center, University of Huddersfield, Huddersfield, HD1 3DH, UK

[3]EPSRC Center, University of Huddersfield, Huddersfield, HD1 3DH, UK

[a]Tao.Zhang@hud.ac.uk, [b] F.Gao@hud.ac.uk, [c]x.jiang@hud.ac.uk

[#]F.Gao@hud.ac.uk

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Abstract. Double-sided high-sloped structured surfaces such as V-groove surfaces and Fresnel lenses are widely used in optical fibre positioning, retro-reflection, grating, light guiding and light concentration for solar power installation. Both the surface finish as well as the dimensions of the structured surfaces play important roles in the quality of the final products. Numerous efforts have been put into the study of characterisation of these types of surfaces. However, only part of the parameters can be acquired and analyzed. It is still impossible to measure and generate the whole topography of these types of structured surfaces. This results in the manufacturing process suffering from high scrap rates. In this paper, an orthogonally placed dual probing system based on Wavelength Scanning Interferometry (WSI) aiming to measure the whole topography of the double-sided high-sloped structured surfaces simultaneously is presented. Each of the probes form an interferometer, and measures the facets of the double-sided high-sloped surfaces in one direction and acquires part of the topography. The whole topography is then stitched together using the two datasets based on the relationship between the coordinate systems of the two probes. The relationship between the two probes is acquired through the calibration of a specially designed 3D artefact. The artefact contains geometric features on each of the facets and is calibrated by a combination of several measurement methods to establish the space coordinates of the features. By matching the corresponding features on the measurement results acquired with each of the probes of the new setup to the reference topography using a 3D registration algorithm such as ICP (Iterative Closest Points) and its variants, the relationship between the coordinate system of each probe and the coordinate system of the reference topography can be calculated. Then the relationship between the coordinate systems of 2 probes can be determined, which can then be used to stitch the whole topography. The setup and the math model has been built and some initial results have been acquired.

1. Introduction

The micro-fabricated structured surfaces with multi-side high sloped facets, such as micropyramidal arrays, V-grooves or lenslet arrays have found wide applications in optical industries such as optical communication, retro-reflection and light guiding applications [1-6]. The manufactured items are reported to suffer from high scrap rates as high as 50-70% since the fabrication depends heavily on the experience of processing engineers adopting an expensive trial-and-error approach currently [7] meaning conquering this issue becomes increasingly meaningful.

Currently, it is a big challenge to measure the structured surfaces with multi-side high sloped facets to get a high-precision topography, no matter contact or non-contact method. The stylus profilometry, for instance, can provide nanometer-scale resolution profile, but regarding areal measurement, the resolution decreases because of the jump between different profiles. Furthermore, the stylus might cause damage to the sample being inspected. Optical scanning techniques such as confocal microscopes and interferometers, are also restricted in this area, either the maximum measurement angle is too limited [8], or the resolution too low when measuring structured surfaces with multi-side high sloped facets. A Scanning Electron Microscope (SEM) is capable of observing a variety of structures with high lateral resolution. However, SEMs are not able to acquire the height information [9]. Even with the powerful Scanning Probe Microscope (SPM) family instrument, including Atomic Force Microscope (AFM) and Scanning Tunnel Microscope (STM), the axial range (normally just several microns) is still a bottleneck to restrict its application in this area [10]. Li et al developed a compact and fast Autostereoscopy-based Three-Dimensional On-machine Measuring (ATDOM) system to achieve efficient on-machine measurement [2, 3]. However, the result shows that the system can only measure the dimensions of the microstructures such as the depth, width and length instead of acquiring the topography.

Wavelength Scanning Interferometry (WSI) has many distinct features [11]. Firstly, compared to Vertical Scanning Interferometry (VSI), WSI requires no mechanical scanning, which means the probe is fixed during measurement and the scanning process could be very fast, with the potential of on-line measurement. Also the resolution is very high, which has been proved to reach nanometer axial accuracy in the previous research. Consequently, WSI is adopted in this research to acquire the topography of double-sided near-right-angle structured surfaces.

2. Methodology

Setup. The Dual Probe Wavelength Scanning Interferometer (DPWSI) system, as illustrated in Fig. 1, mainly consists of a halogen lamp, an acousto- optical tunable filter (AOTF) and 2 WSI probes or interference objectives based on Michelson which are orthogonally placed for micro and nano-scale areal surface measurement. The AOTF filters the white light from the halogen lamp into single-wavelength which is fed into the interferometers for illumination, by changing the frequency of the driving RF signal, the wavelength scanning is achieved [11]. The 2 probes are identical and with a large working distance of 30 mm, enables the measurement of large objects. Each of the probes forms an interferometer, which simultaneously measures the structured surface in two orthogonal directions. During the wavelength scanning process, 256 interferogram frames from each of the probes are captured by the corresponding cameras, which are then analyzed to acquire the measurement volume information of each probe respectively. In order to build up the whole topography information of the measured sample the two measurement data sets should be combined together based on the space coordinate calibration using a specially designed calibration sample and 3D registration algorithm.

Calibration principle. The interference microscope objectives we used adopts a Michelson interferometer setup. The light beam reflected from the reference mirror interferes with the light beam reflected from the sample being measured, as illustrated in Fig. 2. The light reflected from the reference mirror REF1 and REF2 interfere with the light beam reflected from the sample respectively. The measurement result acquired from each interferometer is the optical path difference between the sample surfaces to the corresponding virtual image of the reference plane, in other words, the measurement results have a fixed relationship with respect to the locations of the two virtual images of the reference mirrors, namely VREF1 and VREF2. Since there is no mechanical movement during the measurement process, the reference mirrors REF1, REF2 and the beam-splitters BS1, BS2 are fixed to each other all the time. Thus the relationship between the two probes can be established through the space coordinate calibration, then the whole topography of the sample can be obtained.

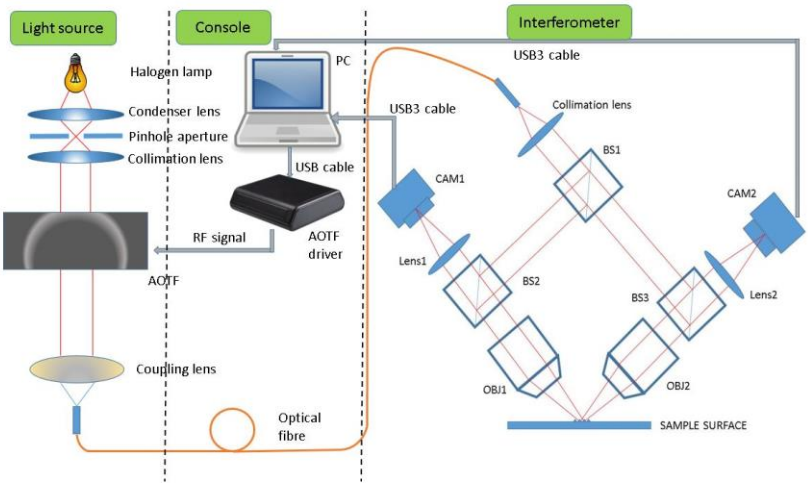
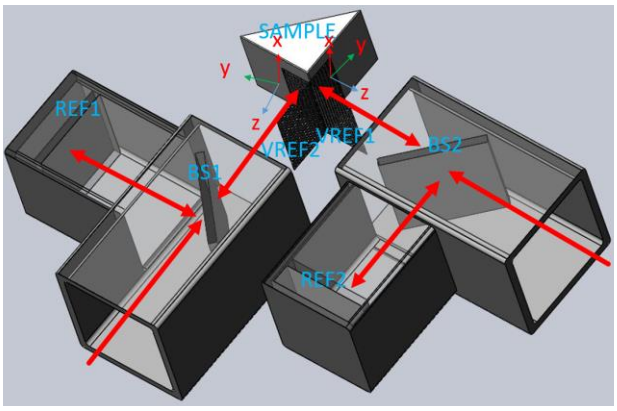


Fig. 1. Block diagram of the setup.



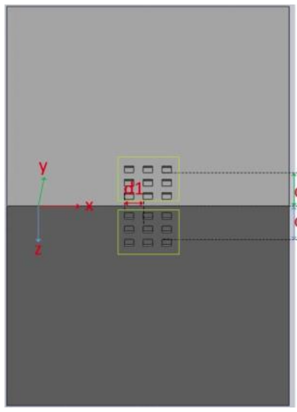


Fig. 2 Fig. 3

Fig. 2. The coordinate system of the probes.

Fig. 3. The relative location of the 2 faces of the artefact.

Since there is almost no overlapping measurement area between the 2 probes. The calibration is based on a specially designed calibration artefact with some features which are an array of 3 by 3 50 µm squares with 100 um distance between each columns and rows as shown in Fig. 3. The idea is by matching the measurement results by the 2 probes of DPWSI of the areas including the features as shown in the 2 rectangles in Fig. 3 to the reference whole topography of the artefact respectively to establish the relationship between the coordinate systems of the 2 probes and the coordinate system of the reference topography with 3D registration algorithm. Then the relative location of the coordinate systems of the 2 probes can be determined by calculation. The 3D registration algorithm requires the features in order to achieve reasonable resolution of the matching.

If P_n, $P_n^{'}$ represent the quaternions of the feature points such as corners or centers of the features in the reference topography, and Q_n, $Q_n^{'}$ represent the quaternions of the corresponding feature points in the measurement results by the 2 probes respectively. The following equations must be satisfied:

$$\begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix} Q_n^{'} = P_n^{'} . \tag{1}$$

$$\begin{pmatrix} R_2 & t_2 \\ 0 & 1 \end{pmatrix} Q_n = P_n . \tag{2}$$

$$R_n = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_n & \sin\alpha_n & 0 \\ 0 & -\sin\alpha_n & \cos\alpha_n & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} * \begin{pmatrix} \cos\beta_n & 0 & -\sin\beta_n & 0 \\ 0 & 1 & 0 & 0 \\ \sin\beta_n & 0 & \cos\beta_n & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} * \begin{pmatrix} \cos\gamma_n & \sin\gamma_n & 0 & 0 \\ -\sin\gamma_n & \cos\gamma_n & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

$$t_n = \begin{pmatrix} t_{nx} & t_{ny} & t_{nz} \end{pmatrix}. \tag{4}$$

Where R_1, R_2 refer to the rotation matrices from the coordinate systems of the 2 probes to the reference topography, while t_1, t_2 represent the translation matrices from the coordinate systems of the 2 probes to the reference topography, α_n, β_n, γ_n represent the rotation angles between the coordinate systems around the x, y, z axes, t_{nx}, t_{ny}, t_{nz} refer to translation components along the x, y, z axes. So there are 12 unknown variables in total. Theoretically if there are enough pairs of feature points, i.e. more than 4 pairs (since 3 equations can be acquired with each pair of feature points), the matrices will be able to be determined. The feature points can be extracted with image processing algorithm from the CCI and SEM results combination and the DPWSI results respectively with an edge extraction method such as Sobel operator and Watershed [12,13]. The spike errors such as batwing effect might be a problem so a cluster filter is used to remove the outliers before the extraction. These equations can be theoretically solved with Procrustes analysis. However, since the feature points have errors when extracted, a 3D registration algorithm such as Iterative Closest Points (ICP) needs to be used to improve the matching accuracy. By solving these equations, the coordinate system of the two interference probes is established. After that, the two data sets acquired from the 2 probes can be bound together to form the whole topography of the structured surface as:

$$\begin{pmatrix} \begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix} X \\ \begin{pmatrix} R_2 & t_2 \\ 0 & 1 \end{pmatrix} Y \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix} X \\ \begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} R_2 & t_2 \\ 0 & 1 \end{pmatrix} Y \end{pmatrix} = \begin{pmatrix} X \\ \begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} R_2 & t_2 \\ 0 & 1 \end{pmatrix} Y \end{pmatrix} \tag{5}$$

Where X refers to the result measured with probe 1, while Y represents the result acquired with probe 2. To reduce the computational time, the result can be rotated and translated in the same coordinate system as shown above without changing the result.

The artefact is a certified calibration standard cube, with 2 adjoining faces perpendicular to each other within 2 seconds of arc (the real deviation is 1.2 arc-seconds measured with autocollimator). The roughness and flatness of the 2 faces are both very high (S_a better than 30nm, flatness better than 50nm) and the edge between the 2 faces is very sharp. The features were milled with a Focused Ion Beam (FIB) with the depth of the features between 200-300nm. To our knowledge from both the literature and experiment, none of the existing instruments is able to acquire the topography of the structured surface of the artefact with sufficient resolution to detect the whole features. The reference topography is reconstructed by combining the results acquired with Taylor Hobson CCI 3000 and FEI Quanta 200 3D FIB/SEM workstation as illustrated in Fig. 3. The areas including the features on both facets (illustrated as the 2 rectangles in Fig. 3) can be measured with Taylor Hobson CCI with nanometer scale vertical resolution. The relative location between the 2 faces can be measured with SEM with submicron resolution, acquiring the distances d_1, d_2 and d_3 in 3 different directions as shown in Fig. 3. With the angle between the 2 planes, the topography can be reconstructed by stitching the data together based on the coordinate system shown in Fig. 3 with the following restrictions:

$$\begin{cases} distance\left(f_{1,p1},\ f_{1,p2} \right) = d_1 \\ distance\left(f_{2,p1},\ p_2 \right) = d_2 \\ distance\left(f_{2,p2},\ p_1 \right) = d_3 \end{cases} \tag{6}$$

Where P_n refers to the fitted plane of face n=1 or 2, $f_{m,pn}$ represents the selected feature on plane P_n, m=1 or 2. The stitching can be accomplished by keeping the data of 1 face still, rotate and translate the other face to satisfy these restrictions with only rigid transformations.

3. Experimental results and discussion

Both probes of DPWSI have been calibrated with the step-height standard specimens with depths of 178 nm, 500 nm, 1.2 µm and 2.1 µm. The result shows each probe has achieved nanometer scale vertical resolution. Fig. 4 is the measurement result of a 178 nm step height sample, the deviation is only 5 nm.

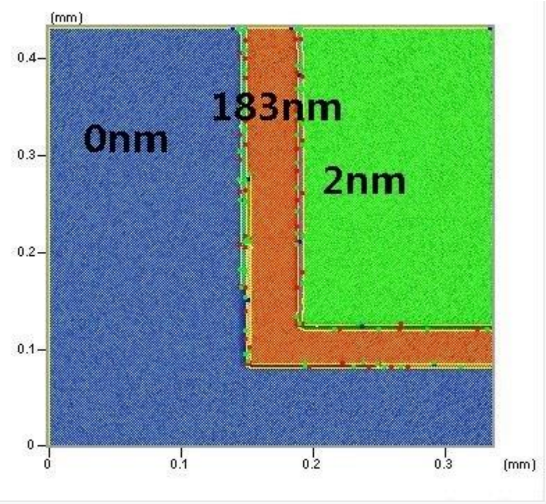
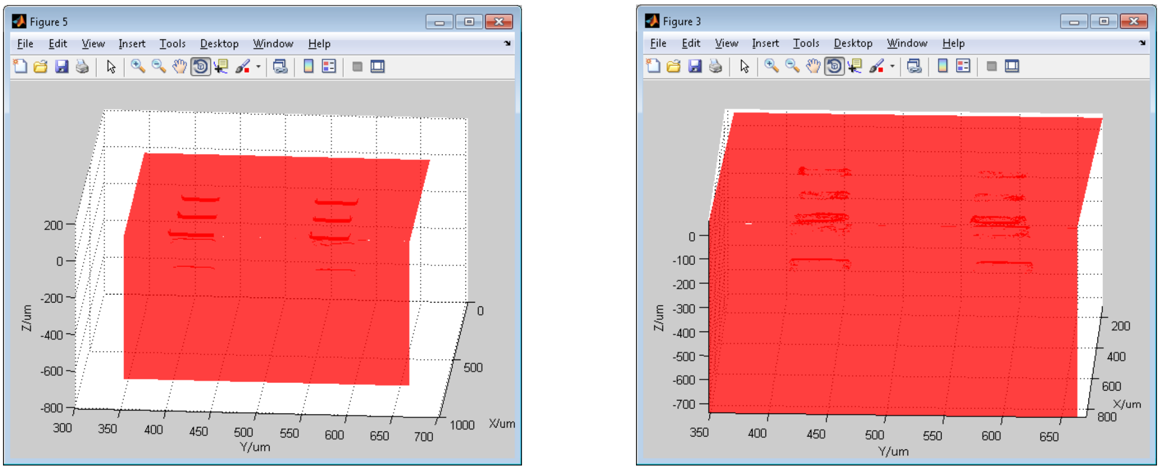


Fig. 4. The areal step height measured by one of the DPWSI probes.



(a) (b)

Fig. 5. (a) The reference topography measured with Taylor Hobson CCI 3000 and FEI Quanta 200 3D FIB/SEM workstation. (b) The same sample measured with DPWSI.

The reference topography has been stitched as shown in Fig. 5 (a). The system has been calibrated. The stitched result with DPWSI is shown in Fig. 5 (b). The experiment shows it is very difficult to align the datasets directly with ICP algorithm. The best way to make the alignment is to extract the features in the datasets first, and then make alignment with the corresponding features. The 3D registration result between CCI and both DPWSI probes shows the average deviation between the matched areas is micrometer scale in lateral direction and submicron level in axial direction. There are many reasons for the deviation. The spike errors like batwing are an important error source, but can be eliminated by the cluster filter and outlier removal algorithm. The imperfect surface finish of the bottom of the features is another error source, which causes difference between the instruments because the numerical aperture (NA) of the objectives are different. However, the error can be reduced if more features are manufactured and adopted. Despite all of these error sources, the average deviation of the registration is micrometer level. It is similar to the lateral resolution of the setup (about 4 μm). Since only rigid transformations are adopted in the registration, the shape of the 2 faces are not changed, thus the vertical resolution of the 2 faces remains the same in nanometer scale after the stitching.

The experimental result shows the proposed measurement system has demonstrated a novel approach to measure structured surfaces with double high-sloped facets and output the topography with nanometer scale vertical resolution on each face and micrometer scale lateral resolution between the 2 faces.

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