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Surface roughness mapping of large area curved aerospace components through spectral correlation of speckle images

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Abstract: Measurement of surface roughness over a large area is a very challenging task due to the limitations with the existing techniques. Surface roughness measurement techniques including stylus and microscopy are limited by its point-by-point data acquisition and a small Field of View (FOV). In effect, any solution that would subdue these limitations would be characterized by its full-field nature, large FOV and the ability to acquire and process data at high speeds. To meet these requirements, large area speckle imaging has been used to obtain areal surface roughness parameters through the processing of spectrally correlated speckle images. An automated optical system is developed for surface roughness evaluation of components with large and curved surface areas. In order to extract areal surface roughness parameters from the captured set of images, processing algorithms are developed. The methodology is first validated using a comparator plate containing areas having an average surface roughness (R_a) ranging between 0.2 μm to 0.6 μm . Further, statistical significance tests are conducted to determine the main factors affecting system performance. The measurement results are compared and validated using a 3D optical microscope. The results obtained from the blind tests performed on aerospace component surfaces as large as 450 mm x 210 mm are also presented.

1. Introduction

The past few decades have seen exponential growth in the manufacturing and inspection requirements of specialized aerospace components. The dominant characteristics of futuristic aerospace components would have large surface areas ($\geq$ few meters) while their feature sizes can be highly resolved (in micrometers) [1]. However, surface topography measurements for certifying these components are not on par with the rising demands of the manufacturing sector. Far-fetched requirements on measurement speed, resolution, and accuracy have rendered traditional techniques such as contact stylus ineffective in surface topography measurements. Therefore, to fill these gaps up, there is an inevitable need for developing systems capable of evaluating the surface topography with high accuracies over a large area.

As per the ISO 25178 part 6 (2010), all the currently available conventional and non-conventional techniques for surface topography measurements can be classified into line profiling, areal profiling, and areal integrating techniques [2, 3]. The conventional contact-based stylus instruments [4], White Light Interferometry (WLI) [5], and statistical speckle analysis [6] are some examples of these techniques. They have been widely used by aerospace manufacturers to certify adherence to the respective manufacturing standards. However, these

techniques are either limited by sample contamination [7], measurement speed, or the FOV [1, 8]. In order to overcome these shortcomings for the measurement of futuristic aerospace components, there is a definite need to investigate technologies including non-contact laser-based optical metrology.

Since the invention of lasers in the early 1960s, there has been much interest in developing speckle techniques for surface metrology [9, 10]. Initially regarded as a noise that can significantly affect the image quality, speckle patterns were later understood to be an explicit sensor to obtain surface topographic information [11, 12]. Since then, laser speckles have been widely used for multiple applications that demand surface quality checks [13, 14]. Out of all the speckle based techniques, speckle correlation techniques for surface topography measurements have been widely investigated in great detail [6, 15-18]. In particular, Spectral Speckle Correlation (SSC) for surface topography measurements provides accurate measurements of surfaces having an average roughness (Ra) that ranges from 0.1 to 5 μm . Multiple researchers have demonstrated the capability of SSC in surface roughness measurements. *Giglio et al.*, experimentally studied the dependence of SSC with the average roughness parameter by assuming a linear relationship between the average and the Root Mean Square (RMS) of the surface roughness which remains valid for surface roughness profiles that have a Gaussian spread [19]. *Persson*, demonstrated theoretically and experimentally that the measurement range of SSC using a visible illumination source is confined between 0.5 μm and 5 μm (Average surface roughness, Ra). He also reported the sensitivity of the method towards misalignments and vibrations [15]. Three different surfaces machined in different ways were used in the experiment: annealed pickled, ground, and spark eroded. For the anisotropic surfaces, the measurement sensitivity was found to be dependent on the choice of the illumination wavelengths. The differences from the theoretical curve were found to be dependent on the surface roughness fluctuation (anisotropy) and the imperfections in the measurement system. To further improve the measurement range, *Ruffing and Fleischer* theoretically and experimentally estimated the dependence of spectral speckle correlation on partially developed speckle patterns. The feasibility of surface roughness measurements on surfaces with wavelengths smaller than the illumination wavelength was established under the assumption of a large number of scattering cells [20]. Recently, *Spagnolo* extended the measurement range of SSC by incorporating a wavelength tunable laser with fine-tuning capabilities [21] and *Goch et al.* studied the requirements of speckle correlation techniques for on-line inspection of surface roughness [22]. Alternatively, comparing the autocorrelation function of the observed speckle images, *Yoshimura et al.* and *Lehmann* presented a theoretical approach to evaluate the surface roughness parameters depending on the intensity modulation [23, 24]. *Pino et al.* and *Dhanasekar et al.* demonstrated the use of the autocorrelation function to determine the surface quality of manufactured papers sheets and ground (and milled) surfaces, respectively [25]. For the in situ measurements of large measurement areas, *Andreas and Dirk* developed a speckle-based measurement approach to measure the surface quality (on a nanometer scale) of working rolls' with measurement speeds $>0.5 \text{ m}^2/\text{min}$ [26]. Further, the measurement uncertainty of this technique was estimated by *Stefan et al.* to determine the feasibility of the measurement techniques for real-time, in-process measurements [27]. Even though speckle autocorrelation techniques have been investigated to measure surface roughness parameters of shiny surfaces (in the order of $\sim 100 \text{ nm}$) which have large surface areas, they are not fully capable of catering to the measurement requirements posed by the aerospace industry. In this context, we develop, demonstrate and investigate the capability of SSC to cater to the measurement requirements of aerospace components having large surface areas with microscale surface features.

In this paper, the capability of SSC for fast and accurate measurement of surface topography over a large FOV is proposed and illustrated. The developed system is validated by measuring the surface roughness of a comparator plate (FOV $\sim 10 \text{ mm} \times 10 \text{ mm}$) with a Ra ranging between 0.2 μm and 0.6 μm . Additionally, validation tests are performed using a 3D optical

microscope. Further, standard algorithms are employed for image analysis to determine the Key Performance Variables (KPV's). Details on system automation and measurements made on an aerospace component surface over a 450 mm x 210 mm area are presented.

2. Theoretical Analysis

When a spatially coherent light illuminates a rough surface, the reflected light scatters and interferes to produce random light and dark patterns, termed as speckles. Two speckle patterns recorded one after the other are partially correlated if the speckle statistics are slightly modified by changing the orientation of the illumination or varying the illumination wavelength. Necessary conditions for correlating two consecutive speckle patterns include, a) The RMS of the surface roughness is greater than the wavelength of the coherent illumination source, b) it forms fully developed speckles (speckle contrast equals 1) and the surface height probability distribution is Gaussian and c) it is formed by isotropic and homogenous material whereby shadowing, multiple reflections and volume scattering are neglected [6]. SSC exploits the relationship between the size of an individual speckle and the wavelength of the illumination source. Let $I_1(i, j)$ and $I_2(i, j)$ be the pixel intensities of two different speckle patterns imaged using two different illumination wavelengths, λ_1 and λ_2 , respectively. Before calculating the pixel-wise correlation coefficient, an area-of-interest (AOI) is chosen (window size: $l \times b$). The pixel intensities of the speckle patterns after the $l \times b$ window is applied can be written as, $I_1(i_l, j_b)$ and $I_2(i_l, j_b)$. The pixel-wise Spectral Speckle Correlation of the defined window, $SSC(i_l, j_b)$ can be deduced from these images by using equation (1) [15, 18, 21, 28].

$$SSC(i_l, j_b) = \frac{\left[\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} I_1(m, n) \times I_2(m, n) \right] - \left[\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} I_1(m, n) \times \sum_{i_l=1}^{i_l} \sum_{j_b=1}^{j_b} I_2(m, n) \right]}{\sqrt{\left[\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} (I_1(m, n))^2 - \left(\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} I_1(m, n) \right)^2 \right] \times \left[\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} (I_2(m, n))^2 - \left(\sum_{m=1}^{i_l} \sum_{n=1}^{j_b} I_2(m, n) \right)^2 \right]}} \quad (1)$$

Here, m and n denote an individual picture element of the AOI defined by an $l \times b$ window. In addition, the theoretical equation governing the relationship between the degree of correlation, $SSC(i_l, j_b)$ and the RMS surface roughness, $R_q(i_l, j_b)$ can be written as [15, 18, 28],

$$R_q(i_l, j_b) = \frac{\sqrt{-\log[SSC(i_l, j_b)]}}{2 \cos \theta_{inc} \Delta k} \quad (2)$$

Here, θ_{inc} is the angle of illumination, which is equal to the angle of observation, as shown in Figure 1 (a). Additionally, Δk can be described as,

$$\Delta k = \frac{2\pi \Delta \lambda}{\lambda_1 \lambda_2} \quad (3)$$

Here, λ_1 and λ_2 , are the chosen illumination wavelengths. $\Delta \lambda$ is the difference between λ_1 and λ_2 . Additionally, assuming the surface under test has a Gaussian distribution, R_q can be related to Ra using equation (4) [29].

$$R_a(i_l, j_b) = \sqrt{\frac{2}{\pi}} R_q(i_l, j_b) \quad (4)$$

In order to determine the SSC values for a preferred range of Ra (0.2 μm and 0.6 μm), a feasibility study was conducted to determine the optimal values of θ , λ_1 and λ_2 (using equations (1), (2), (3) and (4)). The configuration used for the feasibility study is shown in figure 1 (a). The results of the feasibility study are shown in figures 1 (b) and 1 (c). For example, a $\Delta\lambda$ value of 26 nm can be used to accurately measure the surface roughness varying between 0.1 μm and 1.6 μm .

Fig. 1 (a) Depicts the experimental arrangement for the SSC experiments. Results from the feasibility study performed to determine the dependence of SSC on Ra (fixed $\Delta\lambda$) and θ (fixed Ra) are shown in (b) and (c), respectively.

3. Materials and Methods

3.1 Sample Details

A stainless-steel plate (300 mm x 150 mm x 2 mm) was manufactured with a fixed degree of twist. The degree of twist was estimated to replicate the designs of critical rotating aircraft engine components, as shown in Figure 2 (a), details of which was obtained from the aircraft engine manufacturers. The sample was divided into 5 sections having different Ra values using

different grades of sandpaper to finish the surface. From each of these sections, a representative $\sim 10 \text{ mm} \times 10 \text{ mm}$ area is chosen for our study. These areas are indicated in Figure 2 (b).

Fig. 2 (a) Shows the manufactured sample ($300 \text{ mm} \times 150 \text{ mm} \times 2 \text{ mm}$) with a fixed degree of twist. Areas for surface roughness measurements ($10 \text{ mm} \times 10 \text{ mm}$ squares) are indicated in (b).

Additionally, in order to confirm the Gaussian surface distribution (as necessitated for SSC measurements), the histogram of the surface profile was measured using a 3D optical microscope with a long working distance objective lens (20X; 0.4 Numerical Aperture (NA), working distance $\sim 19 \text{ mm}$). The histogram calculated for location 3 is shown in Figure 3 (a). The histogram suggests that the surface profile is almost Gaussian. The skew observed in the histogram can be related to the contact ratio of the surface profile. Since the skew is observed to be small, its effects are neglected. In addition, we also observe that the sample twist restricts the 3D surface topography measurements on locations 1, 2, 4 and 5 because of the constraints posed by the working distance of the objective lens used. The experimental arrangement for 3D surface topography measurements using a long working distance objective lens is shown in Figure 3 (b).

Fig. 3 The histogram of the surface distribution at location 3 is plotted in (a). The measurement arrangement using a 3D optical microscope with a long working distance objective lens (20X; 0.4 NA, working distance 19 mm) is shown in (b).

3.2 Parametric Study on Factors Affecting the SSC Value

The results from the parametric study conducted in our previous work are used as the benchmark to prepare the experimental configuration [30]. The SSC factor is calculated for surfaces having Ra between $0.1 \text{ }\mu\text{m}$ and $3.2 \text{ }\mu\text{m}$. The angle of illumination and the specimen tilt were varied for every SSC factor calculated, to study the effect of specimen twist [30]. The angle of illumination was varied between $\theta=0^\circ$ and $\theta=45^\circ$ while the specimen tilt angle was varied between $d\theta=-4^\circ$ and $d\theta=4^\circ$. The calculated SSC factor was observed to have a strong

dependency on the angle of illumination and the specimen tilt (deviation angle) for surfaces having $Ra < 0.8 \mu\text{m}$. Exponential variation of SSC with Ra for an illumination angle of 45° was observed to be able to optimally differentiate samples having a Ra ranging between $0.1 \mu\text{m}$ and $2 \mu\text{m}$. Stringent alignment requirements and adequate aperture settings are mandated for higher measurement accuracy and precision. It was observed that the correlation properties of the speckle patterns are lost beyond the aperture size of $f/11$. The speckle size for each of the tests was estimated using equation (5) [31, 32]. From the equation, the speckle size, d_m , can be related to the illumination wavelength, λ , the aperture size, $f/\#$, and the magnification of the imaging system, M .

$$d_m = 1.22\lambda [f/\#][1 + M] \quad (5)$$

3.3 Imaging System Design

As a result of the parametric study, the imaging system parameters are chosen based on the sensitivity of the system for surface roughness measurements [30]. Parameters include geometrical coordinates (x , y and z) for positioning the camera and also the camera parameters (such as the aperture size, $f/\#$, and the magnification of the imaging system, M). In addition, to facilitate the need for a large FOV, a robust system having 5 Degrees of Freedom (DOF) is configured. The schematic diagram of the system is shown in Figure 4 (a).

Fig. 4 The schematic diagram of the imaging system designed is shown in (a). (b) and (c) shows the imaging camera and the 3-axes translational stage assembly of the developed system, respectively.

The coordinate system is defined with respect to the position of the specimen (mount). Figures 4 (b) and 4 (c), show the laboratory setup of the imaging system envisaged for the large area surface topography measurement. Three translation stages (THORLABS, LTS200/M) having inbuilt stepper motors were mounted for X-Y-Z translation. The stages used had a maximum traverse distance of 300 mm. A high-resolution CCD camera (THORLABS DCC3260M) having a zoom lens (Nikon AF Nikkor 50 mm lens with F/1.8D) was mounted onto a rotational stage enabling pitch and yaw movements. Using this system, at a Working Distance (WD) of 160 mm, a FOV of 60 mm x 45 mm can be targeted. By increasing the WD to 80 mm, a FOV of 280 mm x 220 mm is obtained.

3.4 Illumination System Design

According to the parametric study, the illumination system design is far more critical. The angle of illumination and the deviation angle (specimen tilt) were identified as two of the most critical parameters introducing uncertainties in the SSC measurements. A wavelength tunable Argon

laser (MODU-LASER[®], Stellar-Pro select 150) with wavelengths 457.9 nm, 488 nm, 514.5 nm, and a Multi-Line output is chosen for the tests. According to the theoretical calculations performed in the parametric study, λ_1 and λ_2 are chosen to be 488 nm and 514.5 nm, respectively such that $\Delta\lambda$ is ~ 26 nm. The chosen wavelength range caters to the surface roughness requirements (measurement range and resolution) specified by aircraft engine manufacturers [30]. A motorized filter wheel with a controller (THORLABS FW103H/M) is employed to switch between 488 nm and 514.5 nm with high speeds. Therefore, we ensure that surface roughness measurement sensitivity of the system ranges from 0.1 to 1.6 μm (From figure 1 (b)). In order to facilitate a uniform illumination over the surface of the specimen with reasonable control over the incidence angle, an optical fiber-based illumination configuration is proposed. The schematic diagram of the optical fiber-based illumination system is shown in Figure 5 (a). The laboratory prototype of the optical fiber-based illumination system is shown in Figures 5 (b) and 5 (c). As per the parametric study conducted, the measured SSC factor was observed to have a strong dependency on the angle of illumination [30]. Therefore, the optical fiber was coupled together with the imaging camera to form a single unit. This configuration ensures that the angle of incidence is fixed.

Fig. 5 The schematic of an optical fiber-based illumination system is shown in (a). The laboratory prototype showing the proximal and distal end of the illumination optical fiber is depicted in (b) and (c), respectively.

3.5 System Automation

The developed SSC system is automated to inspect large areas. The graphic user interface (GUI) developed takes in the following user inputs, a) wavelength control parameters, b) camera parameters, c) linear stage parameters and d) data saving parameters. By controlling the motorized filter wheel, the illumination wavelengths are switched between 488 nm and 514.5 nm. The camera parameters are controlled to ensure that the captured intensity is within the dynamic range. The linear actuation stage enables x-y-z axes movements for large surface area measurements. Data saving parameters ensure the output files are organized for post-processing.

3.6 Image Processing Algorithm for Large Area Roughness Map Display

From the pixel-wise SSC (i_i, j_b) values calculated, the pixel-wise surface roughness map is calculated using equation (2) [33]. Two speckle images captured at λ_1 (488 nm) and λ_2 (514.5 nm) are shown in Figure 6 (a) and Figure 6 (b), respectively.

Fig. 6 Examples of speckle images captured (chosen AOI) at two different wavelengths, $\lambda_1 = 488$ nm and $\lambda_2 = 514.5$ nm is shown in (a) and (b), respectively. The correlation map calculated using subroutine 1 is shown in (c). The roughness map and the sub-sampled roughness map calculated via the algorithm described in subroutine 2 is shown in (d) and (e), respectively ($[x, x] = [4, 4]$; Color bars indicate the calculated sub-sampled average surface roughness).

These images are correlated using the developed algorithm which estimates the pixel-by-pixel correlation values of the two speckle patterns and generates the correlation plot, shown in Figure 6 (c). The algorithm for generating the correlation map is described in subroutine 1 (Appendix A1). This algorithm allows the user to select the AOI. The AOI is selected such that the black (dark) regions which do not contain any information are eliminated. The dependence of the cropping parameters on the measured correlation coefficients was previously determined and is employed for this study [30].

Further, the correlation plot is converted into a surface roughness map using equation (2) and (3), shown in Figure 6 (d) [33]. In addition, the surface roughness map is sub-sampled using the camera calibration parameters. Each pixel in the camera corresponds to a specific area on the sample. By setting these calibration parameters, a sampling area (in pixels) is chosen based on the ISO 25178 part 6 standards [2]. This way, the measured values provide a more realistic indication of the surface roughness parameters for industrial applications. Also, the measured values can be compared with conventional surface roughness technologies (whose accuracy and repeatability are determined by these standards). For example, figure 6 (e) shows an example of a sub-sampled roughness map generated from a cropped area containing 220-pixels x 220-pixels. The specimen area per unit pixel was estimated to be 1 mm x 1 mm by performing the camera calibration. Therefore, in order to address the requirement for a 4 mm sampling area, we sub-sample the roughness map shown in figure 6 (d) using a sampling area, $[x, x] = [4, 4]$ (in pixels) as per the ISO standards. The algorithm developed for roughness map display is detailed in subroutine 2 (Appendix A2).

Multiple images are captured to measure the surface roughness from a large surface area. Therefore, an image stitching algorithm was developed [34]. The algorithm takes into account

the overlap between the captured images. The flow chart for the stitching algorithm is shown in Figure 7 (a). Figure 7 (b) shows examples of correlation maps obtained from multiple areas on the sample surface. The left and right images are merged, followed by the top and bottom images using the stitching algorithm. Further, the central parts of the images are merged from four correlation maps, with a 50% overlap. In Figure 7 (b), while each correlation map images correspond to 15 cm x 11 cm on the sample, the merged image covers 22.5 cm x 16.5 cm. Here, unlike the example mentioned in figure 6 (e), the area per unit pixel was estimated to be 0.117 mm x 0.117 mm. Therefore, as per the ISO standards, in order to address the requirement for a 4 mm sampling area, we sub-sample the roughness map shown in figure 7 (b) using a sampling area, $[x, x] = [36, 36]$ using the algorithm described in subroutine 2.

Fig. 7 (a) Algorithm used for stitching the roughness map with a defined overlap. An example of calculating the merged image from four correlation maps with a 50% overlap is shown in (b). while each individual correlation map images correspond to 15 cm x 11 cm on the sample, the merged image covers 22.5 cm x 16.5 cm ($[x, x] = [36, 36]$; Color bar in (b) indicate the calculated sub-sampled average surface roughness).

To calculate the surface roughness from the speckle images, the user is asked to calibrate the system by choosing an origin ($x=0$; $y=0$; $z=0$). A coordinate system similar to the one shown in Figure 4 is used as a reference. Secondly, the user defines the scan length ($x=L_1$; $y=L_2$; $z=L_3$) and the image overlap. Thirdly, two speckle images are captured at illumination wavelengths, λ_1 , and λ_2 (automated filter wheel switches between λ_1 and λ_2). The roughness map and the correlation map are calculated (using sub-routine 1 and 2) and displayed. Further, the sub-sampled roughness map based on the spatial calibration scheme is displayed. This process is repeated multiple times until the user-defined scanning area is covered ($x=0$; $y=0$; $z=0$ to $x=L_1$; $y=L_2$; $z=L_3$). Further, as per the image overlap parameters, the stitching algorithm displays the roughness map corresponding to the AOI.

4. Results and Discussions

4.1 Measurement Results on the Twisted Plate

Five locations (1-5) on the twisted plate (300 mm x 150 mm x 2 mm) as described in section 3.1 (Figure 2) are scanned using the SSC system. For each of the locations, the measurement

FOV is $\sim 10 \text{ mm} \times 10 \text{ mm}$. Correlation plots and sub-sampled average roughness plots are calculated using $[x, x] = [4, 4]$. The sub-sampled surface roughness map for the positions 1-5 is shown in Figures 8 (a), (b), (c), (d) and (e), respectively.

Fig. 8 Sub-sampled surface roughness map for positions 1-5 is shown in (a), (b), (c), (d) and (e), respectively ($[x, x] = [4, 4]$; Color bars indicate the calculated sub-sampled average surface roughness).

Areal surface roughness parameters are measured using a high-resolution 3D optical microscope to validate the results obtained from the proposed system. Since speckle-based techniques are suitable for large area measurements, we measure the entire $10 \text{ mm} \times 10 \text{ mm}$ area in one shot. Therefore, to test the repeatability of the system, we constrain our measurements onto the same area, and the standard deviations result from repetitive measurements obtained from the same area under investigation. The total measurement time taken for $10 \text{ mm} \times 10 \text{ mm}$ using the proposed technique is ~ 1 second. In contrast for the high-resolution 3D optical microscope, since high NA objective lenses are used for 3D surface topography evaluation, the field of view restrictions impose additional constraints on the captured 3D topography that includes scanning speed and scanning time. An objective lens with a high NA (low WD) cannot be used to capture the areal surface topography due to the sample twist which therefore restricts the resolution of the 3D surface topography (from Figure 3(b)). Further, in order to cover a $10 \text{ mm} \times 10 \text{ mm}$ area, 48 measurements with 20 % overlap are made to obtain the surface topography and areal roughness parameters. A Gaussian Regression Filter is used for the measurements with the Short Wavelength Cut-off (S-filter) set at 0.8 mm . Even though the measurement accuracies are improved, the measurement time drastically increases. Here, the standard deviations are calculated from multiple measurements on the same area (which requires 48 images to be collected with a 20 % overlap).

Table 1 compares the results obtained using both these systems. Measurement errors are calculated to determine the system uncertainty. Knowing the stringent requirements on the illumination angle on measuring the SSC parameter, the percentage error in the SSC parameter was calculated to evaluate the overall system uncertainty. From the calculated measurement errors, it can be observed that the percentage errors increase for areas having areal surface roughness values below the illumination wavelength. This resonates with the observations made by *Ruffing and Fleischer* on the effect of partially developed speckles on SSC [20]. In addition, the errors due to optical alignment and the surface height distribution not being purely Gaussian must be considered.

Table 1 Comparison of measurements obtained using the proposed SSC system and the Bruker Contour GT 3D.

Measurement Location	Number of Samples	SSC Measurement S_a (μm)	3D Microscope S_a (μm)	Measurement Error (%)
1	20	0.55 ± 0.001	0.49 ± 0.001	12
2	20	0.52 ± 0.001	0.45 ± 0.001	16
3	20	0.48 ± 0.001	0.42 ± 0.001	14
4	20	0.41 ± 0.002	0.35 ± 0.001	17
5	20	0.38 ± 0.001	0.30 ± 0.001	27

4.2 Measurement Results on an Aircraft Engine Component

A large and shiny aircraft engine component is used for the test, to determine the validity of the technique for large area surface topography evaluation. The FOV under investigation is 450 mm x 210 mm. A sequence of scanning steps has been implemented to obtain the roughness map of the sample under test. The optical fiber-based illumination system, along with the imaging camera acts as a probe head, which can be scanned across the large area to obtain the speckle images. Each frame of capture corresponds to an area of 60 mm x 45 mm at a working distance of 160 mm. Here, in order to address the requirement for a 4 mm sampling area, we sub-sample the roughness map using a sampling area, $[x, x] = [38, 38]$ using the algorithm described in subroutine 2. An overlap of 50% is applied at each frame of image capture. The automated system captures the images using a predefined trajectory, and the speckle images are saved for processing. The image stitching algorithm has been used to obtain the roughness map of the component surface under test. The measurement procedure for this test is similar to the ones used for determining surface roughness parameters from the twisted sample (see section 3). Figures 9 shows the illuminated area of the sample and roughness map obtained from a 450 mm x 210 mm area. The measured average areal surface roughness, S_a using the proposed technique was found to be within 10% of the actual value measured using conventional systems.

Fig. 9 Illuminated area of an aerospace engine component and the sub-sampled roughness map calculated ($[(x, x)] = [38, 38]$; Color bars indicate the calculated sub-sampled average surface roughness).

4.3 Measurement Uncertainty Analysis

The measurement system developed has multiple factors that influence the measurement uncertainty directly or indirectly. In order to determine the influential uncertainties in surface topography parameter measurements, Haitjema, provides practical solutions to various aspects of uncertainties as per the ISO 25178 standards [35]. The influential factors affecting the measurement uncertainties can be classified into three categories. The first category (or primary aspects) of factors that affect the measurement uncertainty are geometric deviation of the instrument which directly affects the measured parameter value. Parameters including, amplification, noise and linearity are primary aspects especially for surface topography parameters defined in the z-direction (Detailed by ISO 25178-600 & 25178-601). The second category of factors indirectly affect the surface topography parameters measured. Parameters such as, filter cut of length, digitizing steps and mechanical surface effects (such as coatings) are defined within this category. In contrast to the first two categories, the third category undermines the importance of sample surface inhomogeneity in accurate measurement of surface topography parameters. Measurement uncertainties arising from the choice of filters due to local surface variations fall within this category. In this study, we have focused on evaluating the parameters resulting from the influential uncertainties in surface topography parameter measurements. Further, in order to determine the degree of influence of each of these factors, a screening experiment is performed. Among all the factors that affect the experiments, ten factors are chosen based on experience. In general, the factors affecting the SSC measurements can be classified into, spatial parameters, camera parameters, laser parameters

and environmental noise. All the chosen factors along with their “high” and “low” settings are listed in Table 2. In addition, the performance of the proposed technique in case of sample surfaces having surface roughness lesser than the illumination wavelength and for sample surface height distributions not purely Gaussian need to be considered. However, this study is beyond the scope of this study and therefore will be considered as future work.

Spatial parameters are associated with the sample positioning. ΔY and ΔZ parameters in Table 2 are examples of this category. These factors arise from sample misalignments along the Y and Z axes (shown in Figure 4(c)) during the measurements. In addition, it must be noted that the misalignments along the X-axis are equivalent to changes in the focal plane of the camera. This, along with parameters such as camera tilt, camera pan, lens aperture, exposure settings, and FOV, belong to the second category, namely, camera parameters. Finally, laser parameters such as the laser power, and environmental noise parameters such as the ambient light settings are also listed for the trial.

A 2-level factorial experiment was designed, given the list of factors and their range. The measurement response is calculated as the deviation of the measured average surface roughness from the ideal value.

Table 2 Factors considered for the 2-level factorial design and their range.

Number	Parameter	Range	
		Low	High
1	Camera Pan	0°	10°
2	Camera Tilt	0°	10°
3	ΔY	0	10 mm
4	ΔZ	0	10 mm
5	Camera Focus	In-focus	Out of focus
6	Lens Aperture	f/11	f/22
7	Exposure Settings	Underexposed	Overexposed
8	Field of View	Small	Large
9	Laser Power	Low	High
10	Ambient Light	Off	On

By compiling and analyzing the experimental outcomes, a Pareto chart is drawn. The chart shown in Figure 10 calculates the effect of each of the factors on the measurement uncertainty. Factors that strongly affect the response is determined by the value of its effect beyond the statistical significance marked by the dotted red line in Figure 10 (at 95% Confidence Interval). According to the definition, the exposure settings, camera tilt, and the ΔY are the three factors that affect the measurement uncertainty. It could be inferred from these results that image capture settings play an essential role in the measured output parameter. Also, the camera tilt and ΔY are both parameters along a direction where the curvature of the sample is more prominent. Hence, adjusting for curvature is also important to control variation in the measured output parameter.

Fig. 11 The Pareto chart of effects calculated using a 95% confidence interval.

5. Conclusions

An automated optical system is developed for the surface roughness evaluation of large area curved aerospace components. The proposed system contains optimized imaging and illumination sub-systems to ensure robustness and compactness. The system has been automated for image capture and saving, image stitching, and displaying the roughness map. The metrology system has been validated using a 3D optical microscope. Measurements are made on a comparator plate containing areas with a R_a varying from 0.2 to 0.6 μm . A 10 mm x 10 mm surface area was chosen from each of the sections, and the surface roughness parameters were measured. Further, the measurements on an aerospace component surface over a 450 mm x 210 mm area is also presented. Parametric study on measurement uncertainty was also conducted to determine the factors affecting the performance of the system. The camera parameters and sample curvature were determined to be the dominating factors affecting the surface roughness measurement accuracy. The proposed system is envisaged for applications that necessitate a non-destructive, non-contact, and time-efficient surface topography inspection of critical aerospace components.

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Disclosures

The authors declare no competing financial interests.

Appendix A: Algorithms Developed to Generate the Correlation Map and Roughness Map

A.1 Calculating the Correlation Coefficients

Subroutine 1: Pre-processing the Obtained Speckle Images and Calculate the Correlation Coefficient

Check: Confirm the availability of the necessary image processing toolbox

Input: $A(i, j)$ and $B(i, j)$ [images captured with λ_1 and λ_2]

1. $A(i, j)$ and $B(i, j)$ are converted to *double*;
 2. the size of the image in pixels is calculated, size $[A(i, j)/B(i, j)]$ as *length in pixels* and *width in pixels*;
 3. User Prompt $p = \text{Choose image cropping parameters to select area of interest from } A(i, j) \text{ to be correlated with } B(i, j)$;
 4. **if** $p = 1$
 5. | Select the cropping rectangle parameters, R_i and R_j (in pixels);
 6. | **if** $R_i > \text{length in pixels}$ or $R_j > \text{width in pixels}$
 7. | | *print: you have exceeded the image dimension; else continue*
 8. | **End**
 9. | **else continue**
 10. **end**
 11. $\text{sub_}A(i_b, j_b) = \text{image crop}(A) \text{ using } R_i \text{ and } R_j$;
 12. $\text{sub_}B(i_b, j_b) = \text{image crop}(B) \text{ using } R_i \text{ and } R_j$;
 13. $A'(i_b, j_b) = \text{sub_}A(i_b, j_b) \times \text{sub_}A(i_b, j_b)$;
 14. $B'(i_b, j_b) = \text{sub_}B(i_b, j_b) \times \text{sub_}B(i_b, j_b)$;
 15. $AB'(i_b, j_b) = \text{sub_}A(i_b, j_b) \times \text{sub_}B(i_b, j_b)$;
 16. $I_{\text{sub_}A}(i_b, j_b) = \sum_1^l \sum_1^b \text{sub_}A(i_b, j_b)$;
 17. $I_{\text{sub_}B}(i_b, j_b) = \sum_1^l \sum_1^b \text{sub_}B(i_b, j_b)$;
 18. $I_{AB'}(i_b, j_b) = \sum_1^l \sum_1^b AB'(i_b, j_b)$;
 19. $I_{A'}(i_b, j_b) = \sum_1^l \sum_1^b A'(i_b, j_b)$;
 20. $I_{B'}(i_b, j_b) = \sum_1^l \sum_1^b B'(i_b, j_b)$;
 21. $SSC(i_b, j_b) = [I_{AB'}(i_b, j_b) - (I_{\text{sub_}A}(i_b, j_b) \times I_{\text{sub_}B}(i_b, j_b))] / \text{sqrt} [(I_{A'}(i_b, j_b) - I_{\text{sub_}A}(i_b, j_b)^2) \times ((I_{B'}(i_b, j_b) - I_{\text{sub_}B}(i_b, j_b)^2))]$; Calculates the pixel-pixel correlation map in the defined window (i_b, j_b) within (i, j) ;
 22. *Plot* $SSC(i_b, j_b)$;
- Output:** $SSC(i_b, j_b)$;
-

A.2 Plotting the Roughness Map

Subroutine 2: Plotting the Roughness map using the Correlation Map

Input: $\lambda_1, \lambda_2, SSC(i_b, j_b)$;

1. calculate $\Delta k = [2\pi (\lambda_1 - \lambda_2)] / (\lambda_1 \lambda_2)$;
 2. $\theta_{inc} = \pi/4$, is the illumination angle (equal to observation angle);
 3. initialize $R_q(i_b, j_b)$ and $R_a(i_b, j_b)$ with all zero image;
 4. $D_{eno} = 2 \times \cos\theta_{inc} \times \Delta k$;
 5. $R_q(i_b, j_b) = [\text{sqrt}(-\log(SSC(i_b, j_b)))] / D_{eno}$, calculates the roughness map.
 6. $R_a(i_b, j_b) = \text{sqrt}(2/\pi) \times R_q(i_b, j_b)$;
 7. Plot $R_a(i_b, j_b)$;
 8. Estimate x from camera calibration, *Pixels to Length*;
 9. Calculate i_l' and j_b' from $\text{mod}(i_b, x)$ and $\text{mod}(j_b, x)$, respectively;
 10. Initialize $R_{anew}(i_l', j_b')$ and $\text{Temp}_n(i_l', j_b')$ with all zero image;
 11. for $in_x: x: i_l'$
 12. | for $in_y: y: j_b'$
 13. | Initialize $\text{Temp}_{sum}(x, x)$ with all one's image;
 14. | $\text{Temp}_n(x, x) = R_{anew}(in_x: in_x + x - 1, in_y: in_y + y - 1)$;
 15. | $\mathbf{p}(x, x) = \sum_1^x \sum_1^x \text{Temp}_n(x, x) / x^2$;
 16. | $\text{Temp}_{sum}(x, x) = \text{Temp}_{sum}(x, x) \times \mathbf{p}(x, x)$;
 17. | $R_{anew}(in_x: in_x + x - 1, in_y: in_y + y - 1) = \text{Temp}_{sum}(x, x)$;
 18. | end
 19. end
 20. plot $R_{anew}(i_l', j_b')$;
- Output:** $R_{anew}(i_l', j_b')$;
-

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