euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Optical roughness measurements with robot-assisted part inclination compensation

Dirk Stöbener[1, 2], Andreas Fischer[1, 2]

[1]University of Bremen, Bremen Institute for Metrology, Automation and Quality Science (BIMAQ), Linzer Str. 13, 28359 Bremen, Germany
[2]University of Bremen, Center for Materials and Processes (MAPEX), P.O. box 33 04 40, 28334 Bremen, Germany

d.stoebener@bimaq.de

Abstract
The production of metallic sheet metal parts (e.g. for the automotive industry or for microscopic components in medical technology) represents a significant branch of the European industry. One of the main production difficulties lies in maintaining the specified surface roughness in the highly formed areas of the sheet metal. Due to the high production cycle rates, only optical methods can be used to continuously inspect the surface quality of all manufactured components. One promising roughness measurement method is based on polychromatic laser speckles, which is able to measure roughness values Sa of up to several micrometers. However, if the surface is tilted compared to the calibration situation of the measurement system, significant measurement deviations occur or no measurement is possible.
Therefore, a robot-assisted speckle roughness measurement procedure is presented, which consists of two steps. In the first step, the inclination of the surface is estimated from the acquired speckle image by evaluating the longitudinal speckle elongation directions. Then the sensor head, which is mounted on a 6-axis robot, is iteratively reoriented according to the estimated inclination. In the second step, the remaining inclination of less than ±1.25° is compensated with a model-based speckle evaluation of a newly acquired speckle image. As a result of our validation experiments, the roughness measurement is enabled with a remaining uncertainty of < 0.1 µm for surface inclinations up to 15°.

Measurement, roughness, optical, robot, inclination compensation

1. Introduction

Formed sheet metal parts are subject to increasing demands in terms of surface quality. This leads to a growing need for fast, reliable and in-process or near-process surface inspection systems that can identify and quantify potential manufacturing problems at the earliest possible stage. They must be insensitive to the adverse environmental conditions and thus, for example, tolerate an inclination of the local surface normals of moulded components regarding the observation direction.

One of the most commonly used parameters for surface quality assessment is the surface roughness Sa, which is measured post-process mainly with tactile sensors. Tactile measurements offer a high precision and a sufficiently large measurement range, but the measurement velocity for large areas is too slow for process-internal measurements due to the pointwise scanning operation [1] .

Optical methods measure contactless and much faster, but are often sensitive to vibrations like, e.g., the imaging methods confocal microscopy, chromatic confocal microscopy or white-light interferometry, and the measurements can also be influenced by a surface inclination. As an example, an additional measurement uncertainty of 0.2 µm per degree of inclination could be observed for a process-internal roughness measurement with white-light interferometry [2].

An alternative to imaging methods are instantaneous profile and areal roughness measurements with scattered light approaches. The method total integrated scattering measures the intensity ratio between an incoherent, incident beam and the scattered light [3]. However, its application in production chains is obstructed because of the complex measurement setup. Other, commercially available measuring devices, using incoherent illumination, are based on angle resolved scattering analysis. They can determine the roughness and additionally the shape of parts in production environments using a measuring distance of 5 mm and a spot size of 0.9 mm. They achieve a roughness measuring range of $0.01\ \mu m < Sa < 2\ \mu m$ at measurement frequencies of 2 kHz and accept inclination angles within ± 5.7° [4]. Since they acquire the roughness information only along a measurement line, the direction of interest on the surface must be known and thoroughly aligned to the device.

Further scattered light approaches are based on coherent illumination, which results in a speckle pattern in the image of the measured surface. This pattern contains surface roughness information [5], which can be extracted by means of speckle correlation techniques. For monochromatic speckles, the autocorrelation function is evaluated [6]. The usable measurement range of $10\ nm < Sa < \lambda/8$ [7] impedes its application on sheet metal parts as their surfaces are mostly rougher. Angular speckle correlation uses the correlation of speckle patterns obtained from two different angles of illumination [8]. This technique requires a knowledge of the illumination angles and thus also the surface inclination [9].

Polychromatic speckle correlation is based on a polychromatic surface illumination with closely spaced wavelengths and identical illumination angles, resulting in an image with speckles elongated radially with respect to the optical centre of the image [10]. It has been shown that the elongation effect depends on the surface roughness [11,12] and that it can be evaluated via the autocorrelation function of different image parts. The method enables roughness measurements with a measuring spot size of 1 mm in a range of $0.05\ \mu m < Sa < 5\ \mu m$, which is suitable for sheet metal formed parts [13]. But, theoretical studies show that the method is also susceptible to surface inclinations [14]. The resulting roughness measurement deviations can, however, be compensated for by an enhanced speckle image evaluation for small inclination angles in the ± 1.25° range [15]. An approach that enables reliable roughness measurements at higher arbitrary surface inclinations of up to ± 15° is pending.

Therefore, the aim of the presented research is to enhance the existing polychromatic speckle correlation approach to compensate large surface inclination angles by an automated, robot-based sensor reoriention. For this purpose, it is investigated whether the compensation algorithm used in [15] is able to also extrapolate large inclination angles with sufficient accuracy from the captured speckle images for the reorientation of the sensor by a 6-axis-robot.

Section 2 explains the polychromatic speckle correlation measurement principle. The used experimental sensor setup and the robot are described in section 3 and the achieved angle determinations and roughness measurement results are presented in section 4. Finally, section 5 concludes the findings and gives an outlook on further research questions.

2. Measurement principle

The measurement principle of polychromatic speckle correlation makes use of the effect of polychromatic speckle elongation. The effect and its use for roughness measurements is explained in section 2.1. It is followed by a description of the algorithm for the determination of the optical centre of the speckle image in section 2.2, which is the base for the mechanical and the algorithmic inclination compensation procedures presented in section 2.3.

2.1. Roughness measurement with polychromatic speckle elongation

By illuminating the measuring zone with polychromatic light, the speckle images from each wavelength overlap on the monochrome camera chip. The used polychromatic light illumination usually consists of two or more light wavelengths separated by a few nanometres each. The slightly varied wavelength results in a similar but not identical speckle pattern that is stretched in radial direction from the optical centre of the speckle image. Hence, for polychromatic illumination with close wavelengths but identical angles of illumination, the overlapping speckles form radially symmetrical, linear structures, i.e. so-called elongated speckles, with respect to the optical centre [10], see Figure 1. The local speckle elongation is evaluated by calculating the autocorrelation function of local evaluation windows.

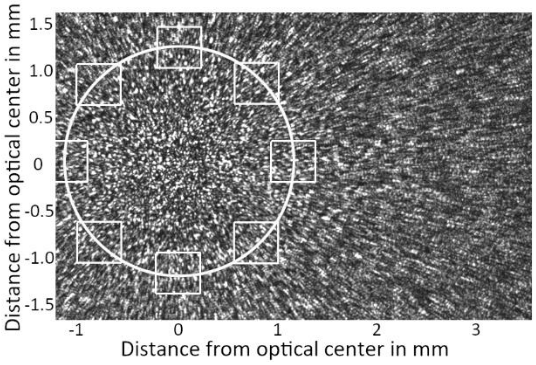

Figure 1. Trichromatic speckle pattern captured with a monochrome camera showing the elongation effect in each of eight evaluation windows located on a circle around the optical centre. The optical centre of the speckle pattern is shifted to the left of the geometrical centre of the captured image due to an inclination of the measured surface of 0.7°.

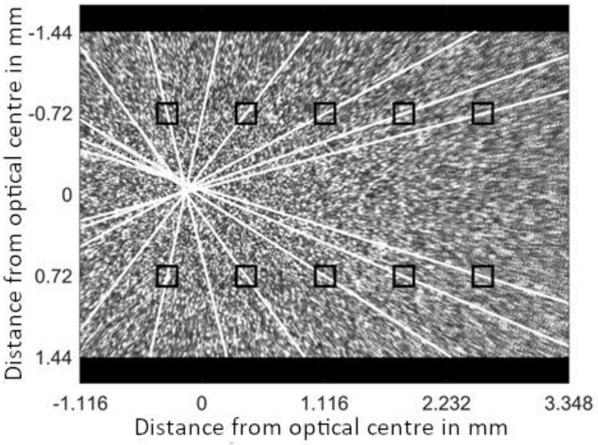

Figure 2. Determination of the optical axis position in the speckle image by the longitudinal speckle elongation orientation intersection method for a small inclination angle of 0.75° (depicted exemplarily for 10 evaluation windows).

To reduce the influence of photon shot noise and speckle noise on the autocorrelation result [16], an average over 4 to 16 evaluation windows (depending on the situation) is calculated, which all have the same distance to the optical centre of the speckle image, see Figure 1 . For each window, the widths of the autocorrelation function parallel and perpendicular to the radial direction are determined at the function’s 1/e-decrease. The ratio between both widths is a measure for the local speckle elongation and its relation to the roughness value Sa is obtained via a calibration function determined in advance with the help of surface standards [15].

2.2. Optical centre determination

A surface inclination causes a displacement of the optical centre from the geometrical image centre. If using fixed evaluation window positions with respect to the geometrical image centre, the speckle elongations for the individual evaluation windows are calculated at different radial distances from the optical centre. This leads to a corruption of the calculated average speckle elongation and the surface roughness derived from it. In order to be able to position the evaluation windows at a constant distance from the optical centre, the displacement of the optical centre caused by the surface inclination must be determined.

For this purpose, 48 evaluation windows (50 x 50 pixels) are distributed equally over the entire image and the orientation of the longitudinal axis of the elongated speckles is calculated via a two-dimensional Gaussian approximation of the upper part of the autocorrelation function [15]. Since the elongated speckles result from the radial elongation of the speckle images of the individual wavelengths, the optical centre lies at the intersection of all calculated longitudinal axes, see Figure 2. The intersection point is calculated using the least square method for the perpendicular distances between the optimal position of the optical centre and the individual longitudinal axes. From the displacement of the optical centre with respect to the centre of the speckle image, the surface inclination angle can be determined via the parameters of the optical components.

2.3. Algorithmic and robot-assisted inclination compensation

If the position of the optical centre in the speckle image is known, the positions of the evaluation windows for the autocorrelation functions can be adjusted so that they all have the same radial distance to the optical centre (*algorithmic* *compensation*), see Figure 1. With this method, the deviations of surface roughness measurements could be reduced from up to 20 % to less than 5 % [15]. However, algorithmic compensation only works as long as the optical centre or at least a quarter of the positioning circle of the evaluation windows is still in the speckle image. For the used setup (see section 3), this is the case for surface inclinations up to approximately ± 1.25°.

With larger surface inclinations, the optical centre lies far outside the speckle image so that a positioning of evaluation windows is no longer possible. Therefore, the new approach presented here iteratively adapts the sensor orientation to the surface inclination until the optical centre is in the speckle image (*mechanical compensation*). For the adjustment of the sensor orientation, the sensor is mounted to a 6-axis robot. With the optical centre position algorithm, the optical centre's approximate distance to the image centre is extrapolated via the intersection of the longitudinal axes of the elongated speckles (similar to the position determination in section 2.2) and converted into a rotation angle for the robot using the optical parameters of the measurement setup. In this case, the evaluation windows for the position determination of the optical centre are all far away on one side of the centre, leading to an inaccurate determination of the centre position. The robot therefore rotates the sensor by only 70% of the determined angle in order to avoid overshooting and oscillation around the zero inclination point. When the optical centre reached the speckle image, a final rotation (< 1.25°) is carried out to align the sensor observation direction as parallel as possible to the surface normal. This is finally followed by the algorithmic compensation of the remaining inclination.

3. Experimental setup

The used setup of a trichromatic speckle elongation roughness sensor ist depicted in Figure 3. It consists of three single-mode pigtailed laser diodes with the wavelengths $\lambda_1 = 633$ nm, $\lambda_2 = 637$ nm, $\lambda_3 = 642$ nm and output powers $P_1 = 50$ mW, $P_2 = 50$ mW, $P_3 = 20$ mW, which are used to illuminate the surface to be measured. A combination of the wavelengths with nearly equal intensities is achieved with beam combiners with a coupling ratio of 25:25:50. The resulting trichromatic laser beam is directed through a polarizing beam splitter onto the measuring surface, resulting in a measuring spot size of 1 mm in diameter after passing through a retardation plate. The light scattered from the surface of the measurement object passes back through the retardation plate and the beam splitter and is afterwards focused with a $f = 60$ mm biconvex lens onto a monochrome CCD camera (The Imaging Source, DMM 22BUC03-ML) with 744×480 pixel and a pixel size of 6 µm. The biconvex lens has a distance of $d = 100$ mm from the measured surface. The polarizer and the retardation plate are inserted into the setup to maximize the light intensity on the camera chip.

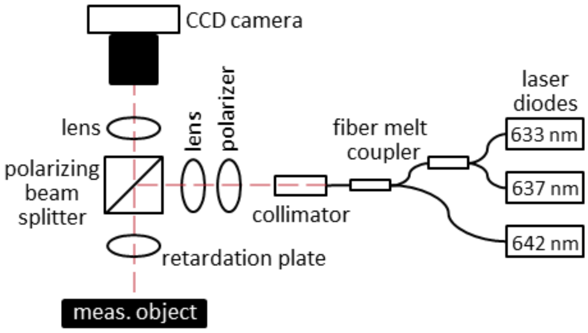

Figure 3. Principle arrangement for roughness measurements using speckle patterns resulting from trichromatic illumination.

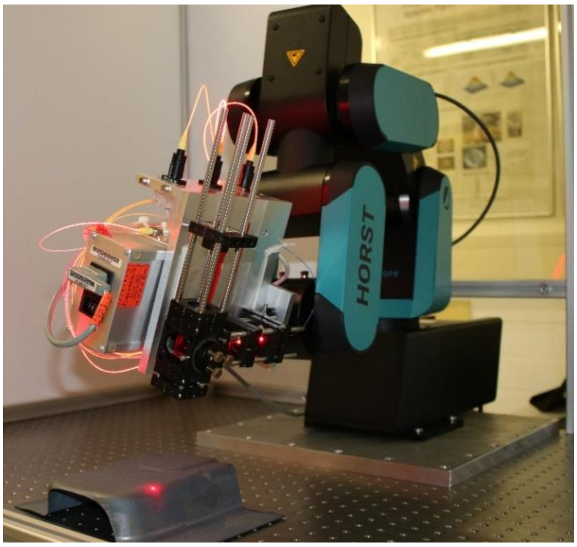

Figure 4. Optical roughness sensor positioned with the 6-axis-robot above a workpiece region with inclined surface. The red dot on the workpiece marks the measurement zone of the sensor.

A roughness standard Microsurf 331 with surface roughnesses of $Sa = 0.8$ µm, 1.6 µm and 3.2 µm produced by spark erosion is used as the measurement object. Its inclination to the observation direction is adjusted with two goniometer stages.

To automatically orient the sensor's observation direction parallel to the surface normal of the measurement object (mechanical compensation), the sensor setup is mounted to the tool adapter of a small industrial 6-axis-robot (fruitcore robotics GmbH, HORST 600), see Figure 4. The tool-centre-point of the robot is defined in advance equal to the measuring spot of the sensor by means of calibration measurements. With this preparation, the transfer of the inclination angle determined by the sensor is sufficient to reorient the sensor without altering the position of the measuring point.

The complete measurement process is controlled by a Python script, which toggles the image capture, evaluates the optical centre position, calculates the roughness value and controls the sensor orientation by communication via XML-RPC with the robot.

4. Results

To verify the new mechanical compensation approach for inclination angles above 1.25°, a test series was carried out with varying surface inclination angles > 1.25° around both axial directions of the camera chip with only the mechanical compensation activated. In the angle range between 1.25° and approx. 15°, the mechanical compensation is able to align the sensor in every tested case, so that the optical centre is finally located in the speckle image. Thus, it is ensured that the algorithmic compensation is applicable in the second compensation step. The uncertainty of the determined external position of the optical centre increases with increasing radial distance between the optical centre and the image centre. For larger distances, the relative uncertainty reaches expected values of up to 30 %. Note that this value prohibits the use of more than the chosen 70 % of the calculated rotation angle in the mechanical compensation method, since one of the method's goals is the prevention of overshooting of the sensor's rotational position.

With inclination angles > 15°, cases occur where the compensation algorithm determines a movement opposite to the actually required compensation direction. This leads to alternating movement directions in the following positioning steps without the average sensor position approaching the centre of the speckle image. The compensation therefore fails in these cases. This effect is due to the longitudinal axes of the elongated speckles in the different evaluation windows becoming more and more parallel to each other as the distance between the optical centre and the centre of the image increases. This leads to large position uncertainties of the optical centre, see Figure 5. In this case, additional sources of uncertainty, such as shot noise and speckle noise, can cause the directions of the longitudinal axis to be tilted to such an extent that the algorithm positions the optical centre on the wrong side of the speckle image. As a consequence, the safe use of the mechanical compensation is restricted to an inclination range of ± 15°.

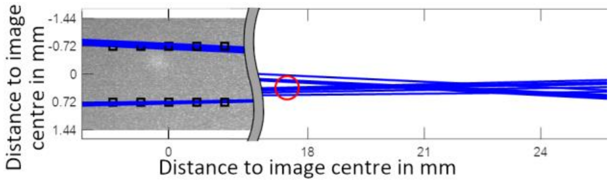

Figure 5. Determination of the optical axis position from a speckle image by the longitudinal speckle elongation orientation intersection method for an inclination angle of ~12°. The red circle marks the theoretical intersection position of the longitudinal speckle elongation directions, which are represented by the blue lines.

To ensure that the mechanical compensation does not influence the algorithmic compensation, a test series with ten measurements each on three surfaces of the surface standard was carried out. The surface inclinations were changed to an arbitrary value < 15° for each measurement. In this test series, too, the system was able to position the optical centre in the speckle image in every case, so that the algorithmic compensation could be performed. Figure 6 shows the average roughness measurement results and the standard deviations at the end of the iterative compensation cycle (mechanical and algorithmic). Since the achieved surface roughness values are in good agreement with the reference values of the standard and show only small uncertainties up to 0.1 µm, no deviating influence of the mechanical compensation procedure can be observed. This result validates the enhanced compensation approach for a surface inclination range of ± 15°.

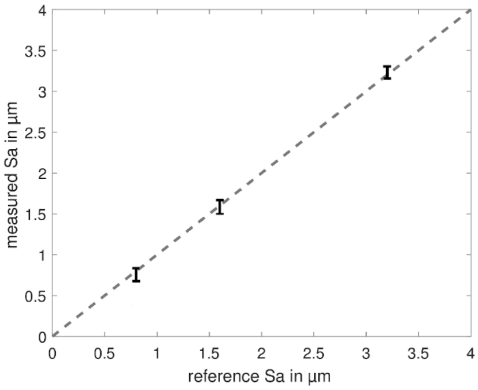

Figure 6. Roughness measurement results for 3 different surface roughnesses with 10 arbitrarily chosen surface inclinations between 2° and 15° each. The dashed line represents equity between measured and reference roughness values.

5. Conclusions

To overcome the surface inclination restriction of the polychromatic speckle correlation roughness measurement method, the evaluation algorithm is enhanced regarding the extrapolation of the optical centre position and the measurement system is extended by a 6-axis-robot to enable an inclination-compensating reorientation of the sensor.

Test measurements show that although the uncertainty of the optical centre position determination increases with larger inclination angles, the new iterative mechanical compensation approach is always able to compensate for the inclination by an iterative repositioning of the sensor with the robot. In conjunction with the already existing algorithmic compensation approach for small inclination angles, roughness measurement results for surfaces with any inclination of up to 15° are achieved, which are in good agreement with reference measurements. Higher inclination angles, which are approximately known, can also be taken into account by a pre-positioning of the sensor before the measurement within a tolerance of ± 15°. As a result of our work, the application range of the polychromatic speckle sensor regarding tolerable unknown surface inclinations has been increased by more than one order of magnitude to an industrially suitable range of ± 15°.

Future work will focus on investigating improved algorithms for determining the optical centre position and for the mechanical compensation to shorten the reorientation cycles and to possibly widen the acceptable range of surface inclinations further by reducing the positioning uncertainty.

References

[1] Vorburger T V, Rhee H-G, Renegar T B, Song J-F and Zheng A 2007 Comparison of optical and stylus methods for measurement of surface texture *Int. J. Adv. Manuf. Tech.* **33** 110-8

[2] Biro I and Kinnell P 2020 Performance evaluation of a robot-mounted interferometer for an industrial environment *Ah. S. Sens.* **20** 257

[3] Mazule L, Liukaityte S, Eckardt R, Melninkaitis A, Balachninaite O and Sirutkaitis V 2011 A system for measuring surface roughness by total integrated scattering *J. Phys. D: Appl. Phys.* **44** 505103

[4] Brodmann R and Allgauer M 1989 Comparison of light scattering from rough surfaces with optical and mechanical profilometry *Surface Measurement and Characterization* pp 111-8.

[5] Goodman J W 1976 Some fundamental properties of speckle *J. Opt. Soc. Am.* **66** 1145-50

[6] Patzelt S, Stöbener D and Fischer A 2019 Laser light source limited uncertainty of speckle-based roughness measurements *Appl. Optics* **58** 6436-45

[7] Fischer A and Stöbener D 2019 In-process roughness quality inspection for metal sheet rolling *CIRP Ann. – Manuf. Technol.* **68** 523-6

[8] Persson U 2006 Surface roughness measurement on machined surfaces using angular speckle correlation *J. Mater. Process. Tech.* **180** 233-8

[9] Salazar F, Belenguer T, Garcia J and Ramos G 2012 On roughness measurement by angular speckle correlation *Metrol. Meas. Syst.* **19** 373-80

[10] Tomita Y, Nakagawa K and Asakura T 1980 Fibrous radial structure of speckle patterns in polychromatic light *Appl. Optics* **19** 3211-8

[11] Parry G 1974 Some effects of surface roughness on the appearance of speckle in polychromatic light *Opt. Commun.* **12** 75-8

[12] Stansberg C 1979 Surface roughness measurements by means of polychromatic speckle patterns *Appl. Optics* **18** 4051-60

[13] Lehmann P, Patzelt S and Schöne A 1997 Surface roughness measurement by means of polychromatic speckle elongation *Appl. Optics* **36** 2188-97

[14] Lehmann P 2003 *In-process laser measurement methods based on Fourier analysis (in German)* (Renningen: expert verlag)

[15] Stempin J, Tausendfreund A, Stöbener D and Fischer A 2021 Roughness measurements with polychromatic speckles on tilted surfaces *Nanomanuf. Metrol.* **4** 237-46

[16] Alexe G, Tausendfreund A, Stöbener D, Langstädtler L, Herrmann M, Schenck C and Fischer A 2020 Uncertainty and resolution of speckle photography on micro samples *Nanomanuf. Metrol.* **3** 91-104