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Lateral scanning white-light interferometry with integrated displacement measurements using laser speckles

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Abstract
Lateral scanning white-light interferometry (LSWLI) is a method for topography measurements on moving surfaces. What sets it apart from the more commonly used vertical scanning approach is that the scanning motion is a tilted or even curved movement consisting of a lateral and a vertical component. This scanning is beneficial for in-process measurements in processes, which cannot be easily interrupted, e.g., live quality assessment of sheet metal rolling. For the evaluation of LSWLI recordings, it is essential to know the surface displacements between the captured image frames. In in-process environments, however, the process-internal motion sensors are often inaccessible for third party devices. Therefore, an in-process LSWLI system needs its own displacement measurement sub-system that is applicable in particular not only on rough but also on high-quality, smooth surfaces.
The integrated displacement measurement needs to be similar in timing and location to the WLI recording. Splitting up the setup's field of view into two regions of interest (ROI) using optical filters – a larger WLI-ROI for topography measurement and a smaller Speckle-ROI for the displacement measurement – assures that both measurements are performed simultaneously and with almost no spatial separation. The displacement measurement is accomplished with digital speckle correlation using laser speckles. In contrast to an incoherent illumination and digital image correlation, laser speckles enable displacement measurements even on smooth surfaces with a high contrast-to-noise ratio.
In order to achieve topography results in the quality typically associated with white-light interferometry, the displacement has to be determined with sub-pixel-uncertainty. The presented approach has been experimentally validated to fulfil this uncertainty requirement with a Speckle-ROI of only 5 % of the total sensor area. In conclusion, the presented combination of LSWLI measurements with integrated speckle measurements enables a compact solution for the precise in-process inspection of rough and smooth surfaces.

white-light interferometry, digital speckle correlation, displacement measurement, topography

1. Introduction

To satisfy the rising quality demands of smooth surfaces on consumer goods and industrial intermediate products, there needs to be metrology capable of measuring these surfaces quickly and accurately. The closer the measurement is to manufacturing the better - since early detection of defects reduces production costs.

Several manufacturing processes for smoothly finished, delicate functional and decorative surfaces involve continuously rotating materials and/or tools. Therefore, there is demand for a precise and contactless topography measurement system on curved surfaces of continuously rotating objects.

One widespread topography measurement techniques is white-light interferometry (WLI), which is capable of areal measurements with height uncertainties of < 1 nm. WLI has been defined in DIN EN ISO 25178 [1] and further insights on the typical vertical scanning WLI (VSWLI) approach can be found in these comprehensive review papers [2,3].

In measurement tasks, where the objects' rotation cannot reasonable be stopped for vertical scanning, lateral scanning white-light interferometry (LSWLI) as introduced by Olszak[4] is favourable. Here, the correlograms for topography determination are recorded during a scan over a tilted straight or curved scan path of the object through the field of view (FOV) of the WLI optics. Setting up the LSWLI so that the scan path coincides with the given motion of the object, allows for measurements on continuously moving objects.

Originally LSWLI was designed with translatory scan motions in mind, but it also works with with rotatory scan motions with non-negligible curvature [5]. The height h_{12} between two surface points $i = 1{,}2$, which were recorded moving through the FOV on a rotatory scan path, is given by

$$h_{12} = \frac{(\mathrm{X}_1 - \mathrm{X}_2)\tan\left(\frac{\Theta_1+\Theta_2}{2}\right)}{\cos(\Theta_1) - \cos(\Theta_2)} \cdot \left(\cos(\Theta_1)\sqrt{\frac{\sin^2(\Theta_2)}{\cos^2(\Theta_1)} + 1} - 1\right). \qquad (1)$$

All quantities needed for the height calculation, the positions of interference maxima X_i and the local surface tilt angles Θ_i, can be extracted from the recorded correlograms. However, the correlograms must be reconstructed from the raw recordings first, which is more complicated in LSWLI than in VSWLI, as the surface points move through the FOV during recording. Therefore, accurate tracking of the surface displacement during the measurement process is necessary.

The primary design consideration for a displacement measurement system for LSWLI is the final achievable topographical height uncertainty, which ultimately depends on the correlogram quality. In order to maximize correlogram quality, the displacement measurement needs to be carried out as close - temporally and spatially - to the WLI recording as possible. Other design considerations concern the topics of practical sensor combination and integration as well as the flexibility of the complete system for different measurement applications.

The issue of the surface displacement measurement has been addressed in various works since the inception of LSWLI [4-7]. However, all of them rely on external displacement measurement systems or assume that the movement of the object is correctly and steadily following its preset value. These approaches have the inherent disadvantage of not being synchronous to the WLI measurement and not being able to recognize local changes in speed, e.g., due to strong deviations from the assumed concentric rotation.

The aim of this article is to introduce a displacement measurement system that fulfils the aforementioned design challenges, using the approach of integrating a digital speckle correlation (DSC) displacement measurement system into the optical path of the LSWLI. With this approach, the correlogram and displacement measurements are carried out synchronously with one single camera on only slightly different regions, which minimizes respective synchronization deviations.

The measurement principle of the combined LSWLI and DSC approach is introduced in section 2. An evaluation of the DSC-based displacement measurements and results of a topography measurement using the combined LSWLI-DSC-measurement approach are presented and discussed in section 3. Finally, the findings are summarized and the conclusions are drawn in section 4.

2. Materials and Methods

2.1 Measurement principle

The measurement approach is based on the integration of a DSC displacement measurement system into the optics of a WLI. Recording the raw signals for both DSC and WLI with the same camera has several practical advantages. Firstly, due to the global shutter of the camera, both signals are recorded synchronously. Secondly, both measurement sub-systems are perfectly aligned to each other, as they share the same pixel grid. Thirdly, the displacement is measured on the same pixel-scale as the topography, which eliminates the uncertainty due to unit conversions and allows for flexible use on translatory and rotatory scanned objects alike. The two raw signals are recorded in dedicated regions of interest on the camera chip. The regions of interest are set up physically by using optical filters.

In the region of interest for the displacement measurement with DSC, the white-light for the WLI measurements is filtered out with a short-pass optical filter, which covers about 5 % of the total area of the camera sensor. DSC is a variant of the digital image correlation method. Here, a coherent light source is used instead of an incoherent illumination and the occuring laser speckles are used as trackable objects. Assuming a rigid surface, the observed displacement of a surface between two images can be determined by finding the maximum of the cross-correlation function. The digital image correlation algorithm in this article was published by Guizar-Sicairos et al. [8]. Using laser speckles allows displacement measurement even on smooth surfaces, which do not possess any dominant, trackable features, such as scratches or dust particles.

The topography measurement with LSWLI is recorded in the remaining camera sensor area, where the laser light is filtered out with a long-pass optical filter. A basic schematic for LSWLI on a rotating measurement object is depicted in Figure 1. When a surface point passes through the coherence region on the scan path indicated by the blue arrow, its observed intensity is modulated due to white-light interference effects as shown in the graph at the bottom. The maximal signal is located where the surface point intersects the plane with zero optical path difference in both arms of the interferometer (zero OPD-plane). Note that because the scan path is curved, the frequency of the correlogram's fringes decreases approaching the scan path's apex.

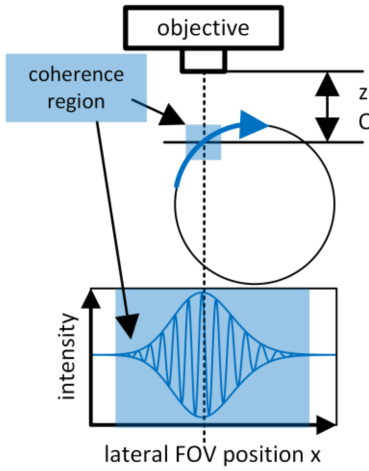

Figure 1. Schematic of the LSWLI principle. Blue arrow: rotatory scan path. Zero OPD: distance to the interferometric objective, where reference arm and measurement arm of the interferometer have a zero optical pathlength difference. The graph shows a correlogram observed by the LSWLI.

The correlograms are recorded in an image series. Within this image series, the surface points to which the correlograms belong to are moving laterally through the image. Using the integrated DSC or an external displacement measurement system, the correlograms can be reconstructed. Afterwards the topographical heights of the surface points are calculated from the reconstructed correlograms. As shown in Eq. 1, two maximum locations and the corresponding local surface tangent angles are needed for the height calculation. The maximum locations are obtained by fitting a Gaussian curve over the envelope of the correlogram to find its maximum. The local surface tangent angles are determined with Munteanu's method [6], which makes use of the frequencies of the correlogram's fringes. The local frequencies are obtained through wavelet transformation.

2.2 Experimental Setup

The experimental setup is depicted in Figure 2. The WLI is equipped with a 10x/0.3 Mirau objective, a CMOS camera with 2.3 MP and a LED with a central wavelength of 520 nm as white-light source. The speckles are produced with a 850 nm laser diode. The optical filters for the regions of interest are mounted in a closed filter box. The WLI region is filtered with a 750 nm short-pass filter and the DSC region is filtered with a 650 nm long-pass filter. The measurement object for the experimental validation is a section of a linear-encoder-strip fastened on a cylinder section with a curvature radius of 65.3 mm. The cylinder is mounted on a rotation stage with a rotation encoder and is scanned with a continuous rotation with a circumferential speed of 0.17 mm/min and a frame rate of 5 fps, which results in an apparent surface speed of approx. 1 pixel per frame.

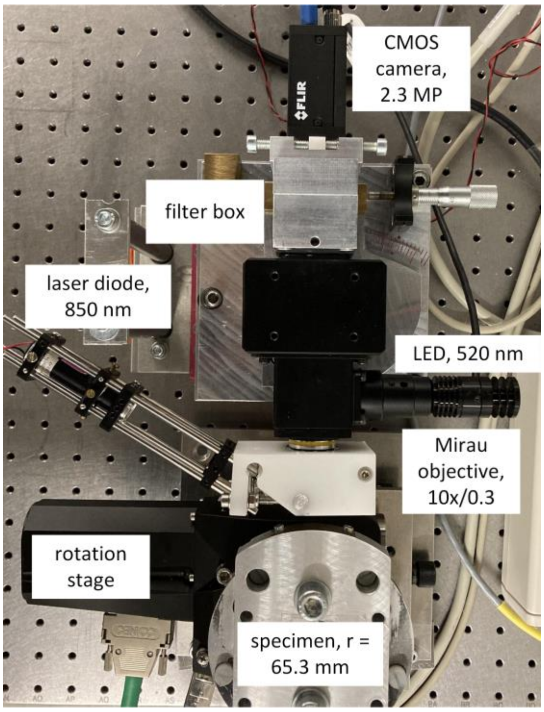

Figure 2. Experimental setup for rotatory LSWLI with integrated DSC.

3. Experimental results

3.1 Displacement measurement

To examine the quality of the displacement measurement results obtained from the integrated DSC system, the results are compared to the angular displacement data retrieved from the rotation encoder of the rotation stage. To allow a comparison, the obtained angular displacements from the rotation encoder are converted to surface displacements in pixels using the radius of the scan path and the image magnification. Figure 3 shows the differences between the cumulative displacements of DSC and the displacements calculated from the encoder angle data.

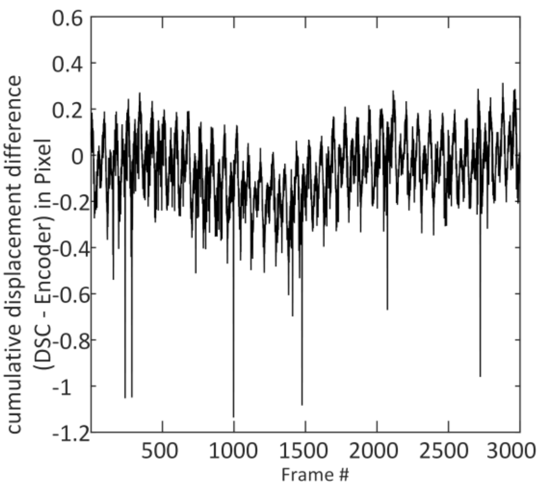

Figure 3. Difference of DSC-sourced cumulative displacements and encoder-sourced displacements converted from degrees to pixels.

The graph contains prominent periodic saw-shaped deviations, which are explainable by timing jitter between the trigger for the camera recordings and the serial COM-communication with the encoder to query the encoder position. The other, low frequency and low amplitude fluctuation of the deviations can be attributed to occurring velocity instabilities of the rotation stage or changes in the observed surface motion, e.g., due to eccentricity or surface waviness. The standard deviation of the position difference between cumulative DSC displacements and rotation encoder positions amounts to $s = 0.14\,\text{pixel}$. This means that a reconstruction of the correlograms using DSC is possible with at least the same sub-pixel accuracy as with the rotation encoder, keeping in mind that the true displacement is unknown and the encoder is merely representing the state-of-the-art for rotatory LSWLI. The integrated DSC, however, has the distinct advantage, that it works without any extra synchronisation efforts or unit conversion issues.

3.2 Topography

To investigate the influence of the displacement measurement on the resulting topography of the specimen, the LSWLI recording is evaluated with the DSC values and the encoder values. The resulting LSWLI-sourced topographies are depicted in Figure 4, complemented with a VSWLI measurement of the same surface as a reference.

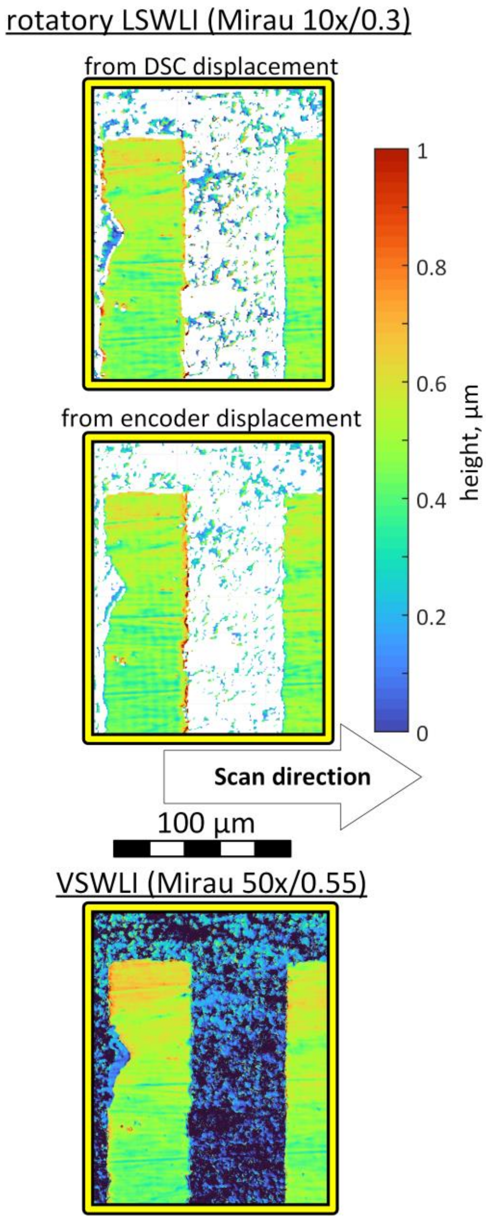

Figure 4. Results of topography measurements. Top: topography detail calculated using DSC displacements. Center: topography detail calculated using rotation encoder displacements. Bottom: topography detail obtained from VWLI reference measurement.

The characteristic stripes of the specimen are visible in both topographies measured with LSWLI. While the VSWLI was able to capture both the smooth and the rough regions of the specimen, the LSWLI is restricted to the smooth stripes of the specimen. The reason for this is the limited height measurement range of the LSWLI. The VSWLI has a measurement range of 400 µm, while the LSWLI only has a range of about 15 µm. The limited height range is the price of the ability to measure on continuously moving objects. Comparing the chipped edge of the left smooth stripe in the two LSWLI topographies, there are less evaluated surface points in the encoder-based topography than in the DSC-based topography. This can be attributed to a worse correlogram reconstruction from using the encoder displacements. In the rough areas and especially near the edges of the stripes the receivable interference signal intensity is lower, which requires good displacement data to enable evaluation of these weaker signals. The standard deviations of the heights of the smooth stripes are used as a figure of merit for the estimation of the surface roughness parameter Sq. The surface roughness was calculated for nine smooth stripes. The resulting mean Sq-values and their respective standard deviations for each measurement method are listed in Table 1. Each of the three results lies in the confidence intervals of the others. This is an indication, that the LSWLI system is a valid measurement system to be used on this kind of surface, although it is still in an developmental status compared to the commercial VSWLI.

Table 1. Comparison of the standard deviations of the differently measured surface topography as a figure of merit for the measured surface roughness.

measurement approach	Mean surface roughness Sq in nm	Standard deviation of Sq in nm
LSWLI with DSC	54.10	3.69
LSWLI with encoder	52.16	4.55
VSWLI as reference	57.34	6.39

4. Conclusion

The aim of this article was to introduce an *integrated* DSC displacement measurement system for LSWLI. The proposed measurement system is capable of providing displacement data with the necessary low measurement uncertainty that is required for rotatory LSWLI measurements. With the integrated DSC system the LSWLI is able to measure as a closed system without needing further external sensors. Compared to the external encoder approach, which is the state of the art, the DSC system can be used without calibrations, synchronisations or unit conversions, not only for rotatory LSWLI but for translatory LSWLI as well.

Experiments showed that the displacement measurement can be carried out with sub-pixel resolution, allowing for accurate topography measurements. As an example, only single-nanometer deviations occurred for the measured surface roughness using VSWLI as a reference.

Future work will be oriented towards in-process capabilities of the LSWLI approach. Steps are to be taken to allow for measurements on quickly rotating objects and the robustness of the evaluation algorithm needs to be increased for the use in harsh industrial environments.

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