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Reducing the Speckle-induced Measurement Uncertainty in Laser Triangulation Sensors

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***Abstract*—Laser triangulation sensors are one of the most commonly used optical sensors in dimensional metrology and quality control. This paper presents a method for simulating the laser speckle-induced measurement uncertainty, representing a major performance limitation of these sensors, as well as the effects of speckle reduction mechanisms based on spatio-temporal averaging. To investigate the relation between triangulation angle and the resulting speckle-induced uncertainty, simulations are performed for three sensor geometries, revealing that a larger angle results not only in a smaller measurement range but also in a reduced influence of laser speckle and a smaller uncertainty. A parameter study on a speckle-reducing moving diffuser mechanism, integrated into the optical sensor path, investigates the achievable improvement for various combinations of motion frequency and amplitude. The accuracy of the simulation results is validated by measurements conducted with an experimental setup, demonstrating good agreement between the measured and simulated uncertainty values with and without the speckle reduction mechanism. It is shown that the diffuser is capable reducing the resulting speckle-induced measurement uncertainty by up to 63%.**

***Index Terms*—laser speckle, triangulation sensor, measurement uncertainty, simulation tool, speckle reduction**

I. Introduction

Quality requirements in the manufacturing industry are ever increasing, such that robust high precision measurement systems are more and more required [1]. To enable real-time control of manufacturing process and continuous quality control, measurements should be performed directly in the production line to detect errors at an early stage [2], without decreasing the throughput [3]. State of the art sensor systems for these applications are mostly based on optical principles, like laser triangulation, the confocal chromatic principle or white light interferometry [4]. Compared to tactile sensors they provide shorter measurement times, higher throughput and they are based on non-contacting measurement principles, minimizing the physical interaction with the sample [5].

Among available optical measurement systems, laser triangulation sensors are one of the most commonly used ones in quality control and dimensional metrology, due to their high resolution of down to 30 nm and their large measurement range of up to 1 m [6]. The measurement principle is robust in handling varying reflection properties of the sample and illumination conditions, since intensity is typically adjusted according to the sample surface property and optical filters are used to reduce influence of external illumination. The principle enables measurements on specular and diffuse reflective surfaces and is based on a rather simple design [6].

The achievable accuracy and uncertainty of a laser triangulation sensor is to a major extend restrained by laser speckle noise on the detector [7], [8]. With an optically rough surface being illuminated by coherent light, each illuminated spot on the micro-structured surface represents an individual scatterer, scattering the incoming light randomly in direction, amplitude and phase [9]. A superposition of the scattered waves on the detector results in a grainy pattern of bright and dark spots, affecting the calculation of the center of gravity of the measurement spot in a stochastic manner and adding uncertainty to the measurement. This influence of speckle on the resulting uncertainty has been experimentally studied and mathematically modeled for microscopic measurements on various technical surfaces [10] in the past. Further also a framework for uncertainty propagation in laser line sensors [11] and a sensor-realistic simulation approach for the evaluation of optical measurement systems, both relying on rather complex mathematical models, have been developed [12].

In terms of reducing speckle effects on the resulting measurement uncertainty, an approach with a dual-view triangulation sensor has been proposed, which is, however, limited to certain surface profiles [13]. For reducing the effects of speckle in various laser-based systems, there are several general approaches available [14], upon which the spatio-temporal averaging with a moving diffuser plate is one of the most common ones [14]. However, up to this point it remains unclear, how speckle-induced effects on the resulting measurement uncertainty as well as means for their reduction can be systematically considered and assessed in the design phase of laser-based sensors.

The contribution of this paper is an accurate method for simulating (i) the effects of speckle on the uncertainty of a laser triangulation sensor as well as (ii) the effects of a speckle reduction mechanism based on spatio-temporal averaging, and (iii) its experimental validation. This article is an extension of our previous work, which focused solely of the simulation and analysis of the speckle-induced measurement uncertainty [15]. The integrated simulation method, presented in Section II, enables the consideration of various optical elements, a fast modification for various sensor geometries, the efficient consideration of geometric uncertainty sources as well as various parameter combinations of a diffuser mechanism and provides several simulation outputs, such as sensor characteristic or uncertainty. In Section III a parametric study on the relation of triangulation angle and uncertainty as well as on the

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relation of motion parameters of the diffuser and the resulting uncertainty reduction is conducted and the experimental setup with integrated speckle reduction mechanism is designed. Section V compares the experimental and simulation results and Section VI concludes the paper.

II. Simulation Methods

A. Laser Speckle Simulation

The simulation method integrates the stochastic nature of laser speckle with the deterministic properties of the ray tracing method in order to make it applicable for the design of optical sensors [16]. Starting with the definition of the system geometry, the location, orientation and size of the laser source, the target surface, the detector (with number and size of pixels) and the imaging as well as the focusing lens are defined. The laser spot on the target is approximated by N_1 point sources, which are laterally distributed within the spot diameter and randomly distributed within the expected surface roughness R_{z1} of the target material in z-direction. The related intensities of the point sources are normally distributed to resemble a Gaussian beam intensity profile (see Fig. 1).

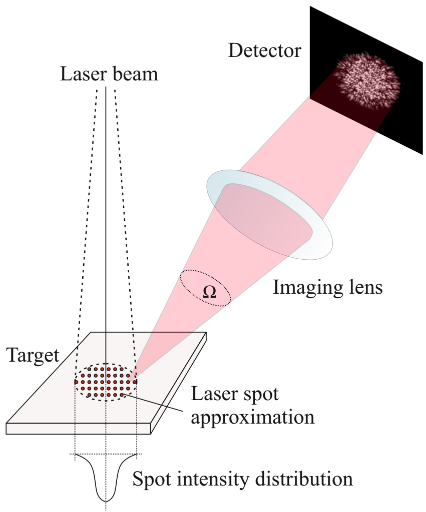

Fig. 1. Simulation environment. The laser spot on the target is approximated by N_1 point sources with normally distributed intensity profile and height distribution according to the roughness of the surface. Ray tracing of N_2 rays beaming out under solid angle Ω is performed for each point for calculation of the phase image on the detector.

To determine the intensity profile of the N_1 point sources on the detector, N_2 rays are used, which beam out equally distributed over a pre-set solid angle Ω, which is matched to the size of the imaging lens. Using the ray tracing, each of the emerging rays is propagated through the imaging lens towards the detector. All rays not intersecting with the pre-defined detector area, are discarded for the further considerations. With the known laser wavelength and the individual optical path lengths, the phase of each ray at the intersection point with the detector can be calculated. To calculate possibly missing phase values, grid data interpolation with a mesh grid according to the pixel size is employed. This sequence is repeated for all N_1 point sources. The spot image on the detector including the resulting laser speckle is then calculated by complex superposition of the intensity and phase image matrices of the individual point sources.

An out-of-plane target displacement is simulated via manipulating the absolute laser point source positions and the solid angle Ω according to the defined geometry. The illuminated spot area is varied according to the parameters of the focusing lens, such that point sources leaving the spot area are set invalid. After adapting the point source positions and the illuminated area on the surface, which keeps its Gaussian intensity distribution, a new detector image including speckle is generated according to the previous procedure. Based on the respective spot image on the detector, the center of gravity (CoG) is calculated as measure for the distance to the target, which is affected by the uncertainty introduced by the laser speckle. The formation of a representative speckle pattern requires a minimum number of point sources N_1 for approximating the laser spot on the target, which should, however, be kept as small as possible for the sake of computational efficiency. Setting the number of point sources to $N_1 = 100$ leads to a good approximation of a fully developed speckle pattern for the given case. The basic implementation of the simulation method is done in *MATLAB* (MathWorks Inc., MA, USA) using the *Optometrika* library [17], which provides basic ray tracing functionality together with a number of optical elements. Further details on the simulation procedure can be found in [16], [18].

B. Simulation of speckle reduction mechanism

In order to reduce the influence of laser speckle on the resulting measurement uncertainty, several approaches are available, upon which the spatio-temporal averaging with a moving diffuser plate is most widely used [14]. For this purpose an expanded laser beam is directed towards a moving, highly scattering diffuser, e.g. a sandblasted ground glass. Each point on the diffuser surface scatters the laser light, and by means of a moving diffuser, the scattered fields from several positions add up on intensity basis on the detector area, which reduces the speckle contrast.

For enabling the consideration of such a speckle reduction mechanism with its related components in the design phase, the diffuser is modeled by an additional phase matrix, as schematically illustrated in Fig. 2. The range of randomly distributed phase values of the diffuser phase matrix is obtained via the surface roughness R_{z2}, determined by its grit polish, and the known laser wavelength. Locating the diffuser in the optical path, results in modified initial phase values Φ_n of the individual N_1 point sources approximating the laser spot on the target. These initial values are added to the phase values of each ray of a respective point source obtained from beam propagation to the detector, altering the resulting phase image matrix (see Section II-A).

For simulating the temporal modification of the resulting speckle pattern due to linear spatial displacement of the diffuser, the continuous intensity variation is approximated by

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the superposition of a discrete number of different speckle patterns. The effective range of motion of the physical diffuser within a sampling interval of the detector is determined by the diffuser motion frequency f_D and amplitude A_D as well as the detector sampling rate f_s. Considering a constant diffuser velocity for reasons of simplicity, the effective unidirectional displacement $A_{D,eff} = A_D \cdot 2 \cdot f_D/f_s$ is obtained.

Using an average spot diameter d_{spot}, which is set to half the maximum spot size at the end of the measurement range, the physical diffuser displacement can be divided into

$$n = \frac{1}{d_{spot}} \cdot A_D \cdot 2 \cdot \frac{f_D}{f_s}. \quad (1)$$

non-overlapping segments, resulting in the same number of fully uncorrelated speckle patterns. The simulation mimics the diffuser motion by n times shifting the phase matrix laterally by the average spot diameter, which also determins the required matrix size. The resulting detector image is then obtained by superimposing and normalizing the resulting n speckle patterns on the detector.

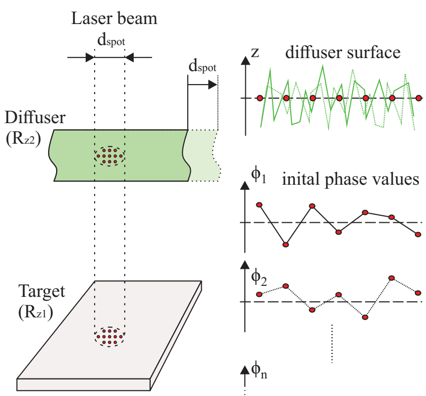

Fig. 2. Simulation of speckle reduction mechanism. A continuous intensity variation is approximated by the superposition of n different speckle patterns. For this purpose the diffuser phase matrix (green) is n times displaced by d_{spot} to obtain n uncorrelated speckle patterns on the detector due to varying initial phase values Φ of the laser spot approximating point sources.

III. Analysis of Speckle-Induced Uncertainty

A. Triangulation Sensor Geometry

Triangulation sensors typically consist out of a laser diode, emitting the laser beam which is focused onto the sample via the focusing lens. Light hitting the sample is diffusely scattered at the point where the beam irradiates the surface. As shown in Fig. 3, the imaging lens projects this scattered light spot onto the detector. The lateral position of the projected spot on the detector provides an accurate measure for the distance between sensor and sample. To precisely obtain this distance, an equally sharp projection of the light spot onto the detector is required over the entire measurement range [5]. In order to meet this requirement, the components of the triangulation sensor are aligned according to the Scheimpflug condition, which is a generalized form of the thin-lens equation for non-parallel planes [19]. This Scheimpflug condition is satisfied, if the object, (imaging) lens and image plane intersect in a single line (see intersection line in Fig. 3) [20].

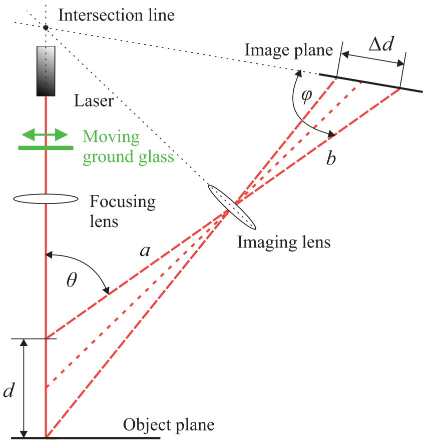

Fig. 3. Measurement principle of triangulation sensor. The sensor is composed of a laser source, a focusing lens, an imaging lens and detector, which are aligned according to the Scheimpflug condition. The sensitivity of the sensor is mainly determined via the triangulation angle θ. A moving ground glass is added to reduce the formation of speckle on the detector.

The relation between the position of the laser spot, or more precisely its CoG, on the detector Δd and the distance between sensor and sample d, which is shown in Fig. 3, is given by [19]

$$\Delta d = d \cdot \sqrt{1+\left(m_L+\frac{u_0}{f}\right)^2} \cdot \frac{m_L f}{d(m_L-\frac{u_0}{f})+\sqrt{1+m_L^2}(2u_0-m_L f-\frac{u_0^2}{m_L f})} \quad (2)$$

with θ the triangulation angle between object plane and optical axis of the imaging lens and the resulting constant $m_L = \tan(\theta)$, f the focal length of the imaging lens and u_0 the distance between center point of the lens and intersection line. From this relation it is apparent that the resulting sensitivity $k(d)$ of the triangulation sensor is non-uniform and decreases with increasing values of d.

The setup schematic (see Fig. 3) also includes a moving ground glass as diffuser mechanism, which is used to reduce the formation of speckle on the detector and will be revised in Section IV.

B. Speckle-induced Uncertainty Simulation

In order to investigate the capabilities of the simulation method to assess arbitrary triangulation sensor designs, the sensor characteristic, the speckle-induced uncertainty of the resulting CoG displacement Δd on the detector are simulated for three sensor assemblies. Additionally the uncertainty of the actual distance measurement, obtained via CoG displacement and the local sensitivity (see (2)) is calculated. All three assemblies are composed of the same optical elements including a focusing lens (bi-convex, focal length 50 mm, aperture 25.4 mm), imaging lens (focal length f = 16 mm, aperture

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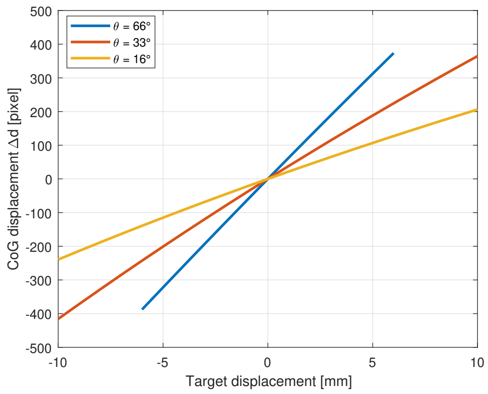
6.4 mm) and a detector (640 x 480 pixels with a size of 1.85 μm). All assemblies are designed for the same distance u_0 = 95 mm and triangulation angles of $\theta = \{16°, 33°, 66°\}$. The surface roughness of a typical aluminium target is set to R_{z1} = 6 μm and the used spot diameter varies between 37 μm and 80 μm in the center and at end of the measurement range, respectively. The diffuser mechanism (see Section III-C) is not considered in this simulation. The remaining geometric dimensions of each setup can according to Fig. 3 be calculated via [5]:

$$a = tan(\theta) \cdot u_0 \tag{3}$$

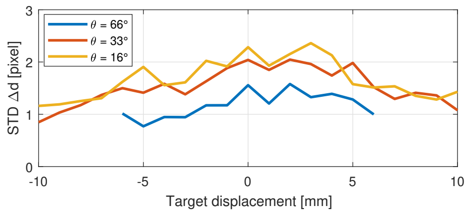
$$b = a \cdot f/(a - f) \tag{4}$$

$$\phi = tan^{-1}(u_0/b) \tag{5}$$

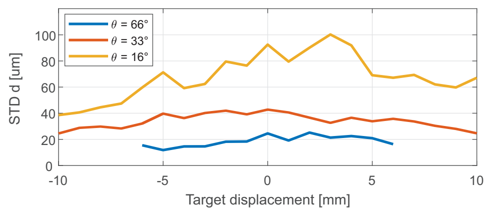
In Fig. 4 the simulation results are depicted for all three sensor assemblies. The resulting sensitivities are shown in Fig. 4



(a) Sensor characteristic



(b) CoG standard deviation on the detector.



(c) Standard deviation of the measured distance.

Fig. 4. Simulated sensor characteristic and speckle-induced uncertainty. (a) shows the simulated sensor characteristic for all three geometric configurations. (b) depicts the CoG standard deviation on the detector of 50 simulations at each target displacement and (c) the resulting standard deviation of the measured distance, derived via the sensor characteristic.

and amount around the center of the measurement range to 22.15 pixel/mm (41 μm/mm), 38.87 pixel/mm (71.9 μm/mm) and 63.42 pixel/mm (117.3 μm/mm) for the three angles, respectively, scaling approximately with the ratio of the tangent values. Given the higher sensitivity of the larger triangulation angles and the fixed detector size for all setups, the measurement range decreases accordingly for larger values of θ.

To obtain a measure for the speckle-induced uncertainty of the CoG displacement Δd as a function of the triangulation angle and the distance d, 50 simulations with randomly varying point source locations, approximating the spot on the target (see Section II-A), are performed at distance steps of 1 mm for each of the three assemblies and the standard deviation (STD) of Δd is calculated. The results depicted in Fig. 4(b) show an almost symmetric STD CoG value distribution for the two smaller triangulation angles, with the smallest angle giving the slightly higher uncertainty values. The largest angle shows an almost constant uncertainty distribution over the target distance with a significantly smaller average uncertainty value. Using the calculated STD values of Δd and the local sensitivity of the sensor $k(d)$ (see Fig. 4(a)), the STD of the actually measured distance can be calculated as measure of the resulting measurement uncertainty. Figure 4(c) shows the resulting uncertainty values with mean values of 0.0187 mm, 0.0392 mm and 0.068 mm for the angles of 66°, 33° and 16°, respectively. Considering the increased measurement range with smaller angle θ, the increase in measurement uncertainty is not surprising with the ratios of speckle-induced uncertainty to range staying almost constant between 0.2% and 0.26%. However, the assembly with θ = 66°, shows with 0.2% the smallest ratio, suggesting a reduced influence of speckle on the resulting uncertainty with larger triangulation angles.

C. *Diffuser-induced uncertainty reduction*

In order to investigate the capabilities of the extended simulation method to also consider the speckle- and thus uncertainty-reducing effect of a moving diffuser mechanism, the speckle-induced uncertainty of the resulting displacement measurement d is simulated and compared for the nominal 33° configuration with an without diffuser. The consideration of the speckle-reducing effect enables the determination of required motion amplitude and frequency of a ground glass with defined roughness in advance, such that the necessary components for the diffuser mechanism can be selected in the design phase.

Figure 5 depicts the simulated STD (50 simulations) of the distance measurement with and without diffuser over the measurement range. Without the diffuser the standard deviation increases towards the center of the measurement range to about 40 μm, which is caused by the varying spot diameter on the sample and the subsequently changing intensity distribution. The laser spot is focused on the center of the measurement range, such that the smallest spot diameter and highest intensity is obtained. The simulation with speckle reducing mechanism is done for a diffuser with R_{z2} = 10 μm, a motion amplitude A_D = 0.25 mm and a motion frequency of f_D = 40 Hz. With a sampling rate of the detector f_s = 50 Hz and an average spot diameter of d_{spot} = 40 μm, the simulation

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calculates and superimposes n = 10 speckle patterns according to (1). The standard deviation stays almost constant at around 11 μm in this case, such that the uncertainty can be reduced by up to 72%.

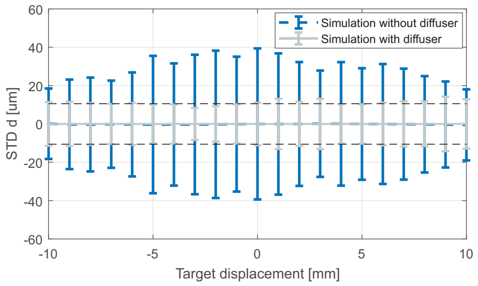

Fig. 5. Simulated standard deviation of the measured distance with and without a diffuser (50 simulations at each displacement). The diffuser is considered to move in a sinusoidal pattern with an amplitude of 0.25 mm and a frequency of 40 Hz. Without diffuser the STD increases to 40 μm in the center of the measurement range, while remaining nearly constant at 11 μm with diffuser mechanism.

To investigate the influence of the motion amplitude and frequency on the resulting uncertainty reduction for a fixed sampling rate f_s = 50 Hz, a simulation study is conducted by varying a single parameter around the nominal case of 0.25 mm motion amplitude and 40 Hz frequency and obtaining the STDs at single millimeter steps over the entire measurement range (compare Fig. 5). From the results of each parameter combination, the average STD over the entire measurement range is calculated. The results are depicted in Fig. 6 and show that the average STD decreases for increasing values of both parameters. Without any motion, the average standard deviation over the measurement range is about 22 μm, which can for example be reduced by almost 50%, if the chosen diffuser is moved with an amplitude of 0.25 mm and a frequency of 40 Hz. The smaller the oscillation frequency (or amplitude) is with respect to the fixed sampling frequency (or spot diameter), the less spatio-temporal averaging is possible, as less modification of the speckle pattern is obtained, and the less the speckle-induced uncertainty is reduced. For larger values of oscillation frequency and amplitude the effect of uncertainty reduction levels off at around 10 μm for the chosen configuration, as a further increase in averaging can no longer be obtained. In general, a small amplitude and high frequency is favored over the opposite case, since a smaller ground glass can be used, resulting in a more compact speckle reducer with low power consumption.

IV. Experimental Setup

The experimental setup of the triangulation sensor is depicted in Fig. 7 and is composed of a CMOS sensor (DMM 37UX266-ML, Imaging Source GmbH, Germany; 640 x 480 pixel with a size of 1.85 μm) as detector and a laser source (LDM635/1LJ, Roithner Lasertechnik GmbH, Austria), which is focused on the target via a bi-convex lens (N-BK7 LB1471, Thorlabs Inc.) with a focal length of 50 mm. The setup is designed for a measurement range of

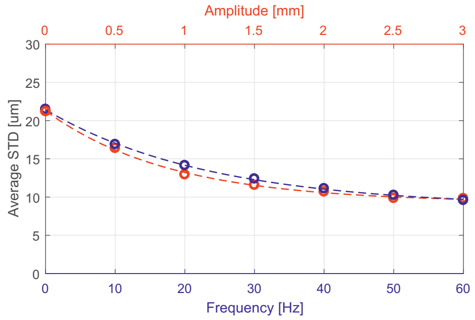

Fig. 6. Simulated dependence of resulting measurement uncertainty on diffuser motion amplitude and frequency for a fixed sampling frequency f_s = 50 Hz. The nominal configuration is an amplitude of 0.25 mm and an oscillation frequency of 40 Hz. Both curves are obtained by varying only the respective parameter. For both cases the standard deviation decreases towards higher values.

$\pm$ 10 mm with the minimum spot diameter placed in the center of the measuring range a triangulation angle of θ = 33° and a distance u_0 = 95 mm. The imaging lens (V-4316-2.5, Marshall Electronics Inc.; f = 16 mm) is used to obtain the image of the measurement spot on the CMOS detector and is placed in a distance of a = 141 mm from the center of the measurement range. The CMOS sensor is mounted in a distance of b = 14.4 mm from the imaging lens and is rotated by φ = 81°.

The diffuser mechanism is implemented via a ground glass (DG05-120, Thorlabs Inc.), which is actuated by a Lorentz actuator (AVM12-6.4, Akribis Systems GmbH) and suspended by a 3D-printed flexure. The diffuser is installed between the bi-convex lens and the laser source. This locates the diffuser in the part of the optical path in which the laser beam is still collimated, avoiding a potential additional uncertainty of the measurement spot location due to a lateral displacement of the focus point on the sample caused by the diffuser motion. The Lorentz actuator is current controlled and the motion amplitude of the ground glass is monitored via a laser triangulation sensor (ILD2200-40, Micro-Epsilon Messtechnik GmbH & Co; not mounted in Fig. 7). The aperture is inserted to reduce the influence of stray light from the diffuser.

In order to enable out-of-plane as well as in-plane displacement of the target, which is a machined aluminum part, it is placed on two stacked linear stages. For accurate displacement of the target in the measurement direction (out-of-plane) a position-controlled linear stage (VT-80 62309120, Physik Instrumente GmbH, Germany) with a resolution of 500 nm and a range of 80 mm is used, covering the entire measuring range of the sensor assembly. For in-plane displacement a piezoelectrically actuated and position controlled linear translation stage (ELL17 / M, Thorlabs Inc.) with a range of 28 mm is used, in order to enable experiments with varying speckle distributions in the same target distance.

V. Results and Discussion

To validate the performance of the simulation method considering the influence of speckle and the effect of the

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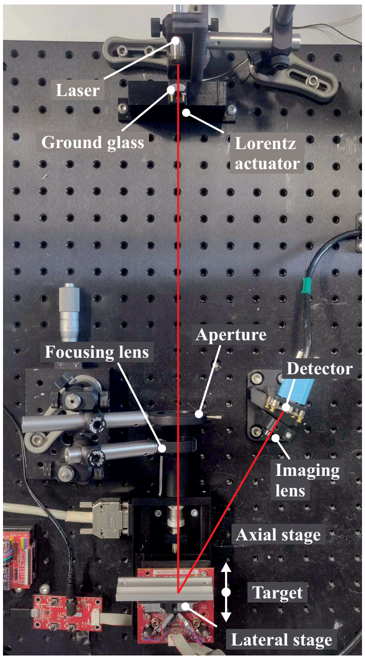

Fig. 7. Experimental setup. The laser of the source passes through the ground glass, which is displaced by a Lorentz actuator, an aperture and the focusing lens before hitting the target. The spot on the target is via the imaging lens imaged on the detector. Linear stages are used to displace the target in- and out-of-plane.

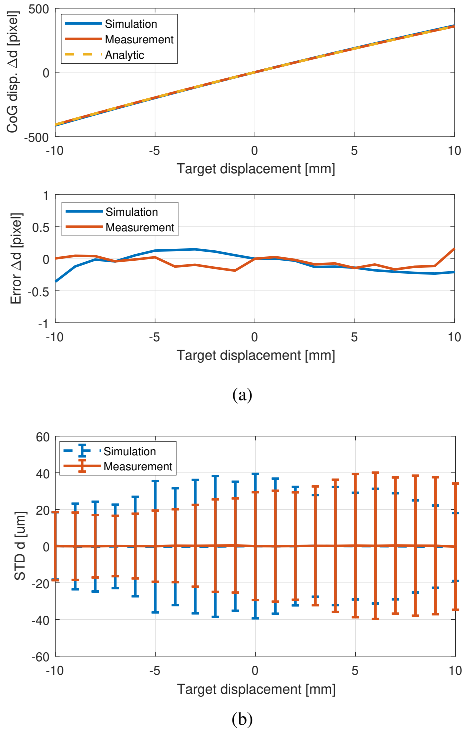

Fig. 8. Comparison of simulated and measured sensor characteristic and measurement uncertainty. (a) shows the simulated, measured and analytically calculated characteristic as well as the mean error in terms of CoG location on the detector with respect to the analytic value. (b) is a graph for the standard deviation of 50 simulation and measurement results at each displacement. The uncertainty increases by about a factor of two from start (z = -10 mm) till end (z = 10 mm) of the measurement range.

diffuser mechanism, the resulting measurement uncertainty for the designed experimental setup with and without diffuser is evaluated for 1 mm steps over the entire measurement range of $\pm$10 mm. To obtain STDs at each displacement, 50 measurements are obtained at each distance with the target being laterally displaced before each measurement in order to obtain uncorrelated and sufficiently varying speckle patterns on the detector.

In Fig. 8(a) the simulated and measured sensor characteristic are shown, as well as the error of both characteristics with respect to the analytic solution based on the nominal geometric dimensions of the assembly. The simulated characteristic is obtained by taking the mean value of 50 simulations at each target displacement in order to minimize the influence of speckle-induced uncertainty. It can be seen that both errors stay within half a pixel of the detector throughout the entire measurement range, indicating the good agreement of all three sensor characteristics and minimal mounting tolerances of the experimental setup.

To compare the simulation result in terms of speckle-induced uncertainty, the graph in Fig. 8(b), shows the STD of 50 simulations (blue) and 50 measurements (red) at each target displacement. It can be seen that the results match well, showing only small deviations over the majority of the measurement range. The simulation shows a rather equal uncertainty distribution over the measurement range, while the measured uncertainty gradually increases towards larger displacements, and doubles from about 20 μm to about 40 μm. At smaller distances the simulation thus tends to overestimate the resulting uncertainty as compared to the measurement, while it tends to underestimate it towards larger displacements. The increasing uncertainty of the measurement towards larger displacements can be explained by the decreasing sensitivity of the sensor assembly, resulting in smaller and more focused spot images on the detector, with speckle of higher relative intensity and thus higher influence on the CoG uncertainty.

To illustrate the effects of the diffuser mechanism on the shape of the measurement spot image on the detector, which is decisive for the calculation of the CoG and therewith the measurement uncertainty, Fig. 9 shows the measured detector output in the region of the spot location. In Fig. 9(a) and (b) the detector output without diffuser is shown with the intensity on the vertical axis in (a) and a top view on the x-y-plane in (b). It can be seen that the intensity is highly unevenly distributed over the illuminated pixels and clearly deviates from an ideal Gaussian intensity profile. The related speckle pattern can be observed with high intensity pixels determining the resulting CoG location of the spot in a disproportional way. When integrating the diffuser mechanism (f_D = 40 Hz, A_D = 0.25 mm) the detector outputs in Fig. 9(c) and (d) are obtained. The spot image shows an almost normal intensity distribution, with only

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a single pixel with higher intensity. The maximum intensity is a factor two smaller than without diffuser and the intensity is more evenly distributed over a larger number of pixels, which enables a more reliable calculation of the CoG location and a decrease of the measurement uncertainty. On the other hand a larger spot diameter is obtained, which may decrease the lateral resolution to a certain extent, representing a potential drawback together with an increased system complexity due to the diffuser mechanism.

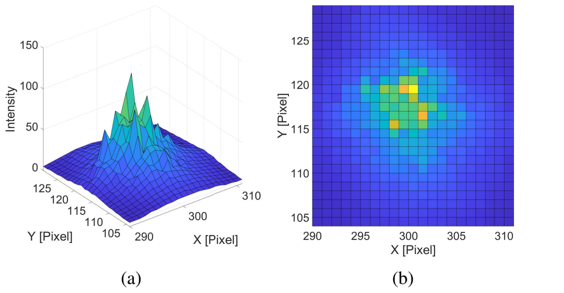


Fig. 9. Imaged measurement spots on the detector. (a) and (b) show the part of the detector with the imaged measurement spot, which significantly deviates from a Gaussian intensity profile due to speckle effects. (c) and (d) show the smoothed measurement spot with diffuser and more normally distributed intensity values.

Assessing the uncertainty reduction in the actual measurement due to the integration of the diffuser mechanism, Fig. 10 compares the graphs of the standard deviation of 50 measurements at each target displacement for the setup with and without diffuser. It can clearly be seen that while the uncertainty of the measurement without diffuser increases gradually towards larger displacements, as discussed previously, the uncertainty of the measurement with diffuser stays almost constant around 15 μm over the entire measurement range. This equals a significant reduction of the resulting speckle-induced measurement uncertainty of up to 63%, as compared to the setup without diffuser.

To validate the simulation results of the parameter variation study from Section III-C, the according measurements are performed for each parameter combination. The results of the measurement as well as the ones from the simulation are depicted in Fig. 11. As can be observed, the simulation results are in good agreement with the measurement results in terms of the overall tendency, showing the average STD decreasing towards higher motion amplitudes and frequencies of the

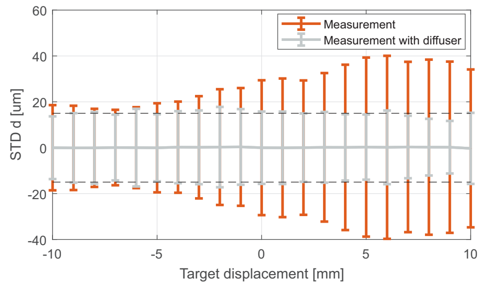


Fig. 10. Measurement uncertainty with and without diffuser. The standard deviations of respectively 50 measurement results at each displacement are shown. While the uncertainty without diffuser increases by a factor of two over the measurement range, it stays almost constant around 15 μm with diffuser.

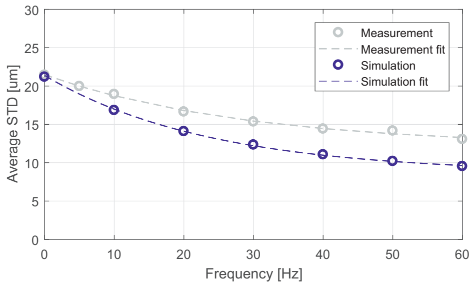
diffuser. At the largest values, saturation of the uncertainty reducing effect can be observed, as the motion frequency reaches and eventually exceeds the detector sampling frequency. The simulation continuously results in smaller uncertainty values as compared to the measurement, with the deviation increasing with the increasing level of speckle reduction. This is explained by the fact that the simulation does not consider other major sources of uncertainty of the experimental triangulation sensor assembly, such as the detector noise [21]. As the overall uncertainty results from the quadratic sum of the individual STDs when considering uncorrelated noise sources, a larger divergence is obtained when the influence of speckle noise is reduced, as compared to the constant noise of other sources in the setup of about 9 μm. In both cases, i.e. increasing frequency or amplitude, the STD of the measurement results can be decreased from about 22 μm, without diffuser motion, a 13 μm, for the fastest diffuser movement, which corresponds to an average reduction of the uncertainty over the entire measurement range by 40%.

In summary it is shown that the simulation method can be used to accurately estimate the resulting speckle-induced uncertainty of designed laser-triangulation sensor assemblies with additional speckle reduction mechanism, which enables a reduction of the average measurement uncertainty by up to 63%.

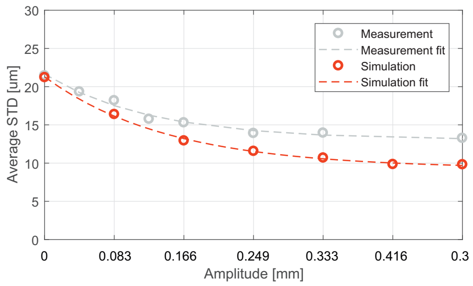
VI. Conclusion

This paper presents a method for the accurate simulation of the laser speckle-induced measurement uncertainty as well as the effects of diffuser-based speckle reduction mechanisms for the design of laser-triangulation sensor assemblies. For this purpose the simulation method integrates the stochastic nature of laser speckle with the deterministic properties of ray tracing simulations, enabling it to capture also stochastic in addition to deterministic sensor properties. To demonstrate the methods flexibility and investigate the influence of the triangulation angle on the resulting speckle-induced uncertainty, three sensor geometries with triangulation angles of $16°, 33°$ and $66°$ are designed and simulated. The simulations show that the speckle-induced uncertainty varies over the entire measurement range, particularly for smaller angles,

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2022.3230481



(a)



(b)

Fig. 11. Comparison of simulated and measured reduction of measurement uncertainty. (a) in dependence of frequency at 0.25 mm amplitude. (b) in dependence of the amplitude at 40 Hz frequency.

with the average uncertainty decreasing from 0.26% to 0.2% of the measurement range, if the triangulation angle is increased from 16° to 66°. A parametric study on the speckle reduction mechanism shows that the uncertainty decreases with increasing motion amplitude or frequency of the diffuser glass until the effect saturates when sufficient spatio-temporal averaging of the resulting speckle field is achieved for the given detector sampling rate. To validate the accuracy of the simulation method and its results, an experimental setup with a triangulation angle of 33° and an integrated diffuser mechanism in the optical path is constructed and evaluated. The uncertainty measurements show good agreement with the simulated values, both resulting in an average standard deviation of the CoG of about 30 μm. Experiments also validate the parametric simulation study on the speckle reduction mechanism, reducing the speckle-induced measurement uncertainty by up to 63%.

ACKNOWLEDGMENT

The financial support by the Christian Doppler Research Association, the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology and Development, Micro-Epsilon Messtechnik GmbH & Co. KG and Atensor Engineering and Technology Systems GmbH is gratefully acknowledged.

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Pre-print version of the article: Ernst Csencsics, Johannes Schlarp, Tobias Glaser, Tobias Wolf, and Georg Schitter, "Reducing the Speckle-induced Measurement Uncertainty in Laser Triangulation Sensors," *IEEE Transactions on Instrumentation and Measurement*, in press, 2022. DOI: 10.1109/TIM.2022.3230481

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