Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system

Johannes Schlarp[a], Ernst Csencsics[a], and Georg Schitter[a]

[a]TU Wien, Automation and Control Institute (ACIN), Gusshausstrasse 27-29, 1040 Vienna, Austria

ABSTRACT

Designing fast and high-resolution 3D measurement systems, which are key enabler for the production of the future, is a challenging task, since optical, electrical and mechatronic components with respective specifications need to be integrated. Particularly the resulting measurement uncertainty is of highest interest but can currently only be roughly determined in advance. This paper proposes an uncertainty framework for an optical scanning 3D triangulation sensor system to calculate the influence of the alignment and component specifications on the achievable system performance. This enables to calculate the required uncertainty of each component for given overall uncertainties in the lateral and axial direction. The default and best achievable specification for the manufacturing tolerances of each component, sensor noise and resolution of the detector, and angular resolution of the fast steering mirror used to manipulate the illumination path, are specified in advance. To keep the overall system cost low, the simulation of the optical path is initially performed with the default specifications. By comparing this simulation result with the ideal case, the overall uncertainties and contribution of each component can be determined. If the calculated uncertainties do not meet the requirements, the specification for the component, which contributes most to the uncertainty, can be gradually improved within the maximum specification. The procedure is repeated until the required levels of uncertainty are obtained or until it cannot be further improved since the maximum specifications have been exceeded. This ensures that only the specifications required to achieve the specified uncertainty are tuned.

Keywords: Measurement uncertainty in optical systems, Error modelling in optical systems, Modelling of optical metrology systems, Optical metrology, 3D sensor

1. INTRODUCTION

Inline measurement systems, capable of measuring the 3D surface of the sample, are a key technology for the production of the future, since they enable to detect errors at an early stage and also ensure a consistent quality of the produced goods.[1,2] To achieve the high throughput required for inline measurements, optical scanning systems are commonly applied, due to the low moving mass and subsequent high scan speed.[3] Optical scanning triangulation and confocal chromatic scanning systems are reported in [4,5] and [6], respectively. The achievable accuracy of these measurement systems is, however, only validated on the real system, such that the error contribution of the various components and their specification can currently not be precisely differentiated from each other.

The fundamental uncertainty limit of a laser triangulation sensor, caused by speckle effects, is discussed and experimentally obtained in [7]. However, the influence of the alignment and the specifications of the various components is not considered. A mathematical framework for statistical modelling and propagation of the uncertainties in a 3D inspection using a laser scanner is presented in [8]. However, the mathematical model is only applicable for a laser scanner with a constant illumination path. Furthermore, the specifications of the various components are not taken into account. Monte Carlo simulations are commonly employed to estimate the uncertainty of a measurement system.[9] The simulation is based on repeated sampling of the input random variables to obtain the output probability density function, such that it is useful for estimating complex output

Further author information: (Send correspondence to Johannes Schlarp)
Johannes Schlarp: E-mail: schlarp@acin.tuwien.ac.at, Telephone: +43 (0)1 588 01-376 516

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

functions. However, the sampling space grows exponentially with the input dimension and should be performed for each measurement point, such that it is not feasible for an optical scanning system.

The contribution of this paper is an uncertainty framework for an optical scanning 3D triangulation sensor system, which can tune the specifications of the individual components to reach a specified in-plane and out-of-plane uncertainty. In Section 2 the setup of the optical scanning triangulation sensor system and the simulation procedure is discussed. Section 3 and 4 deal with the error sources in the in-plane and out-of-plane direction, respectively. The tuning algorithm which adapts the component specification is described in Section 5. Finally, Section 6 concludes the paper.

2. SIMULATION PROCEDURE

The simulations to determine the measurement uncertainty are performed in Matlab (type: Matlab 2021a, MathWorks Inc., USA). Initially, the position and orientation of all the individual components and also their properties, e.g. focal length, angular position, number of pixels, are defined. Subsequently, the propagation of the beam is calculated. If the beam hits a mirror surface the direction of the reflected beam is calculated with the Housholder matrix.[10]

The optical scanning triangulation sensor system reported in [11] forms the base for the uncertainty analyze. The optical path of the scanning system can be split up in an illumination and reflection path, which is also depicted in Fig. 1. The illumination path consists of a point laser source, a fast steering mirror (FSM) and a static mirror which are used to illuminate the sample, change the in-plane position of the laser spot on the sample and fold the optical path, respectively. In the reflection path a lens is used to focus the diffusely scattered laser spot on the the sample onto the detector.

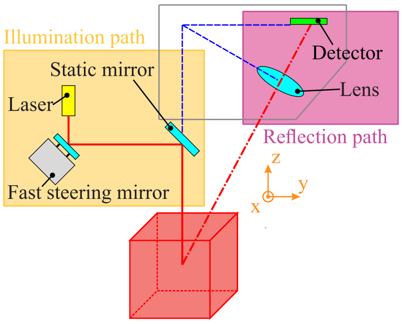


Figure 1. Schematic of the optical scanning triangulation sensor system. A fast steering mirror is used to manipulate the in-plane position of the laser spot on the sample. A static mirror folds the optical path and a lens is used to focus the diffusely scattered spot onto the detector.

By changing the angular position of the FSM within the actuation range, the in-plane scan area as well as the reference scan pattern can be determined. The measurement distance in the out-of-plane direction can be specified by obtaining the image on the detector, while changing the distance between sensor and sample. If the scattered spot is still obtainable on the detector, the selected distance is within the measurement distance.

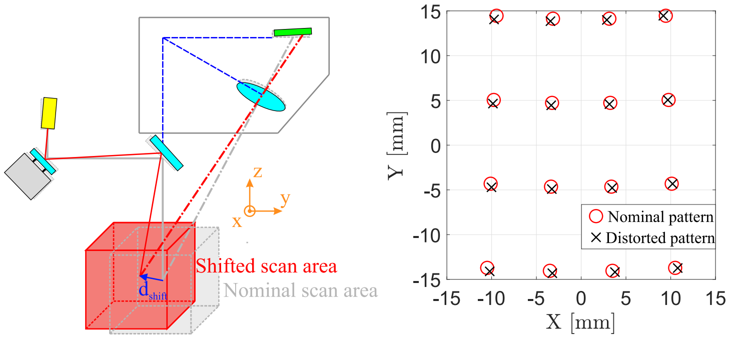
While the illumination path influences the in-plane performance, e.g. in the x and y-direction, the reflection path affects the performance in the out-plane direction, e.g. z-direction. To calculate the uncertainty caused by a deviation of one specification, multiple simulations for various parameters within the probability density function are performed. By subtracting the obtained scan area from the reference scan area and by taking the probability density function into account, the uncertainty distribution for this specification can be calculated. This simulations are performed in sequence for each specification. If the individual distortions are normally distributed and uncorrelated the overall uncertainty can be calculated in the following form[12]

$$\sigma_{total} = \sqrt{\sum_{i=1}^{n} \sigma_i^2} \tag{1}$$

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

with n the number of varied parameters and σ_i the standard deviation for the parameter i in the respective direction.

A misalignment of an optical component can lead to a shift of the entire scan area, as well as a distortion of the scan pattern, which is depicted in Fig. 2(a) and Fig. 2(b). The shift of the entire scan area does not influence the achievable performance of the scanning system. However, this shift can be important for a commercial optical scanning system, as a replacement of a defective scanning system could result in a shift in the absolute readings.



(a) Shifted scan area (b) Distorted scan pattern

Figure 2. A misalignment of the components leads to a shift (a) and distortion (b) of the scan area. The shift of the scan area does not influence the measurement uncertainty.

3. IN-PLANE ERROR PROPAGATION

Alignment

For each component a deviation from the nominal position is simulated in all three translational and rotational directions, to determine the influence of the component placement on the overall performance. Since the illumination path of the scanning system consists out of three components, 18 parameters are required to analyze the influence of a misalignment. As already described earlier, for each parameter the scan pattern over the entire scan area is simulated, subsequently the resulting standard deviation for the shift and distortion are calculated.

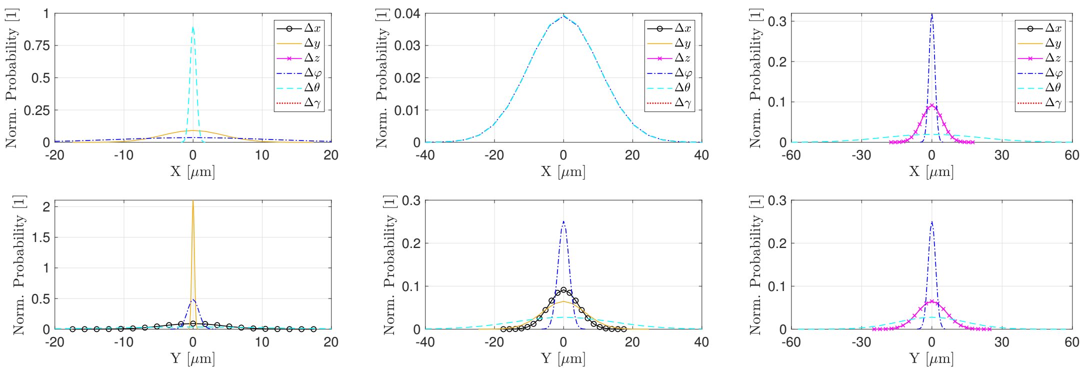
For a standard deviation σ of 0.1 mm for the translational and 1.7 mrad for the rotational directions, the resulting distortions are depicted in Fig. 3. As can be observed, not all parameters contribute to the uncertainty, due to symmetries. However, the distribution of the parameters which contribute to the measurement uncertainty are normally distributed and uncorrelated, such that the standard deviation can be calculated.

In Table 1 the resulting standard deviations for each parameter are shown. Rotational deviations, e.g. θ_{Stat}, result in a larger distortion compared to the translational deviations, which are caused by the long optical path between the components and the measurement range, i.e. large optical lever. The overall standard deviations, due to a misalignment, can be calculated with Eq. 1 to $\sigma_{x,mis}$=28.2 µm and $\sigma_{y,mis}$=26.2 µm.

Table 1. Distortion caused by a misalignment in x and y-direction

Translation	x_L	y_L	z_L	x_{FSM}	y_{FSM}	z_{FSM}	x_{Stat}	y_{Stat}	z_{Stat}
Dis. σ_x [µm]	0	4.4	0	0	0	0	0	4.4	4.4
Dis. σ_y [µm]	4.4	0.19	0	4.4	6.2	0	0	6.2	6.2
Rotation	φ_L	θ_L	γ_L	φ_{FSM}	θ_{FSM}	γ_{FSM}	φ_{Stat}	θ_{Stat}	γ_{Stat}
Dis. σ_x [µm]	11	0.44	0	10.2	10.1	0	1.2	20.3	0
Dis. σ_y [µm]	0.8	11	0	1.6	14.3	0	1.6	14.3	0

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

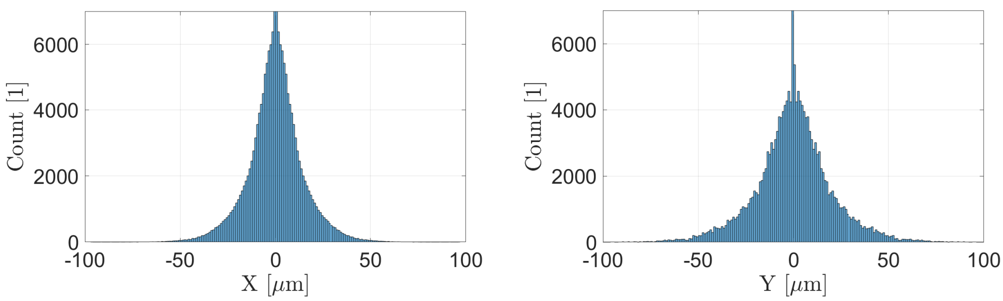


(a) Laser (b) FSM (c) Static mirror

Figure 3. Uncertainty distribution in the x- and y-direction, due to a misalignment of the components in the illumination path. The uncertainty caused by a misalignment is either normally distributed or zero. Especially, rotational deviations lead to a large uncertainty, due to the large optical lever.

Position uncertainty of the FSM

The sensor noise of the FSM leads to a position uncertainty in the x and y-direction. This sensor noise can be modelled by a white Gaussian noise. Figure 4 depicts the position uncertainty in the x- and y-direction for a sensor noise of 2 µrad rms. The resulting deviation of the scan pattern from the reference position is approximately normally distributed, such that the standard deviation can be calculated to $\sigma_{x,FSM}$=13.1 µm and $\sigma_{y,FSM}$=18.5 µm. The standard deviation is not equal in the x and y-direction since the lateral scan area is also non-uniform (see [11]).



(a) (b)

Figure 4. Simulated position uncertainty caused by a sensor noise of the FSM of 2 µrad in (a) x-direction and (b) y-direction. The uncertainty is approximately normally distributed.

4. OUT-OF-PLANE ERROR PROPAGATION

Alignment

The reflection path of the system defines the uncertainty in the out-of-plane direction. Since the reflection path consists only out of a lens and detector, 12 parameters are required to analyze the influence of a misalignment. Like in the in-plane-error propagation (see Sec. 3) the uncertainty caused by a misalignment is either normally distributed or zero. In Table 2 the standard deviations are shown for a misalignment with standard deviation

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

σ of 0.1 mm for the translational and 1.7 mrad for the rotational directions. Since the detector size (4.75 mm) is small compared to the measurement range (25 mm), a small translational misalignment already leads to a significant measurement uncertainty in the out-of-plane direction. The overall standard deviations, due to a misalignment, can be calculated with Eq. 1 to $\sigma_{z,mis}$=145.5 µm.

Table 2. Distortion caused by a misalignment in z-direction

	x_{Lens}	y_{Lens}	z_{Lens}	φ_{Lens}	θ_{Lens}	γ_{Lens}	x_{Det}	y_{Det}	z_{Det}	φ_{Det}	θ_{Det}	γ_{Det}
Dis. σ_z [µm]	0	106.7	25.7	0	0	0	0	91.6	25.7	7.6	0	0

Detector noise and pixel size

The detector represents a large source of uncertainty in the out-of-plane-direction. Generally the signal to noise (SNR) ratio and number of bits of the ADC of the CMOS sensor used as detector are known, such that the uncertainty due to the quantization and sensor noise can be calculated.

For an image sensor with a 10-bit ADC, which is commonly used for triangulation sensors, the influence due to the quantization was analyzed. Therefore, the relationship between the distance between sensor and sample and the detector position was derived. The resulting uncertainty over the entire measurement range has a normal distribution, such that the standard deviation $\sigma_{z,ADC}$ can be calculated to 3.6 nm.

To analyze the influence of the sensor noise, a simulation is performed with a signal to noise ration of 43 dB. Based on this ratio a white Gaussian noise is generated for each pixel of the the detector. This noise is added to the signal generated by the reflected laser beam from the sample and the simulation is performed over the entire measurement range. The resulting uncertainty has a normal distribution, with a standard deviation $\sigma_{z,Noise}$ of 207 µm. This simulation was performed without a threshold, such that the noise over the entire detector affects the uncertainty. By adding a threshold, which was set to 10% of the maximum intensity, the influence of the noise can be significantly reduced to a standard deviation of 1.18 µm. This threshold is commonly applied in laser triangulation sensors to improve the accuracy.[13]

5. TUNING ALGORITHM

In the previous chapters the in-plane and out-of-plane uncertainty for a typical optical scanning triangulation sensor system were described. By combining the various standard deviations according to Eq. 1 the overall uncertainty can be calculated to $\sigma_{x,total}$=31.1 µm $\sigma_{y,total}$=32 µm and $\sigma_{z,total}$=145.5 µm. However, generally the required uncertainty for the in-plane and out-of-plane direction are known in advance and should be fulfilled by the measurement system. To tune the specifications required to achieve the specified uncertainty, an automatic tuning algorithm is developed, which is depicted in Fig. 5. Initially, the default and best achievable specification for the manufacturing tolerances of each component, sensor noise and resolution of the detector, and angular resolution of the fast steering mirror used to manipulate the illumination path are defined. Subsequently, the algorithm calculates the overall uncertainties and contribution of each component. If the calculated uncertainties do not meet the requirements, the specification for the component, which contributes most to the uncertainty,

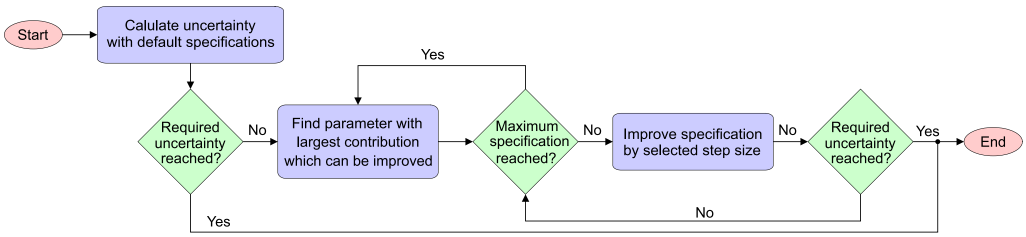


Figure 5. Flowchart for tuning the parameters of the scanning system to achieve the required uncertainty level. The tuning algorithm is performed consecutively for each direction. The parameter with the largest uncertainty contribution is tuned until the maximum specification or the required uncertainty is reached.

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

is gradually improved until either the required uncertainties are achieved or the best achievable specification is obtained. In case the required uncertainty is not achieved despite the selection of the best achievable specification, the specification with the next highest contribution is tuned, which can also be seen in Fig. 5. This procedure is consecutively performed for each in-plane and out-of-plane direction, however the selected specifications can only be improved in each step.

To validate the tuning algorithm an overall in-plane uncertainty of 22 µm and an out-of-plane uncertainty of 30 µm was selected. The default manufacturing tolerances were chosen to a σ of 0.1 mm for the translational and 1.7 mrad for the rotational directions, while the maximum specification were selected to σ of 20 µm and 350 µrad. For the FSM a sensor noise of 2 µrad rms was selected as the default and 1 µrad rms as the maximum specification. The SNR of the detector can be varied between 43 dB and 60 dB, while the number of bits of the ADC can be selected between 10 and 12-bit.

The selected default specifications match with the results presented in the previous chapters, such that for the optical scanning system with a measurement range of 15x23x25 mm an uncertainty of $\sigma_{x,total}$=31.1 µm, $\sigma_{y,total}$=32 µm and $\sigma_{z,total}$=145.5 µm is achieved without the tuning algorithm. The algorithm initially tunes the specification of the static mirror θ_{Stat} to 350 µrad, which reduces the uncertainty in the x-direction to 24 µm. Since the maximum specification of θ_{Stat} is reached, while the required uncertainty is still not achieved, the sensor noise of the FSM is tuned to 1.3 µrad rms. With this specifications the uncertainty in the x-direction can be reduced to 21.8 µm. Furthermore, the uncertainty in the y-direction is also already reduced to 25.19 µm. The algorithm only tunes the specification of the FSM θ_{FSM} to 700 µrad, to achieve a $\sigma_{y,total}$ of 21.49 µm. To reach the required uncertainty level in the z-direction, the tuning algorithm subsequently tunes the position of the lens and the detector in the following order y_{Lens}, y_{Det}, z_{Lens} and z_{Det} to the maximum specifications of 0.02 mm. As a result, the overall uncertainty in the z-direction $\sigma_{z,total}$ is reduced from 145.5 µm to 29 µm by the tuning algorithm for a measurement range of 25 mm.

In summary, the measurement uncertainty of an optical scanning triangulation sensor system is analyzed and tuned to meet the required uncertainty level of 22 µm for the in-plane and 30 µm for the out-of-plane direction.

6. CONCLUSION

In this paper the simulation procedure, the error propagation in the in-plane and out-of-plane direction and the tuning algorithm, which adapts the component specifications to meet the required uncertainty level, are shown. The optical path of an optical scanning laser triangulation sensor system is simulated, such that the shift and distortion of the scan area can be determined. The alignment of the laser, FSM and static mirror and the position uncertainty of the FSM lead to an error in the in-plane direction, while the alignment of lens and detector, and the specification of the detector, i.e. noise and pixel size, lead to an error in the out-of-plane direction. The tuning algorithm automatically adapts the specification of the components until the required uncertainty level is reached. The algorithm was successfully validated for an optical scanning system with a measurement range of 15x23x25 mm, reducing the uncertainty to 22 µm and 29 µm for the in-plane and out-of-plane direction, respectively. Ongoing work addresses the integration of a data-driven calibration of the scan pattern into the uncertainty framework and the extension towards other optical scanning systems.

ACKNOWLEDGMENT

The financial support by the Christian Doppler Research Association, the Austrian Federal Ministry for Digital and Economic Affairs, and the National Foundation for Research, Technology and Development, as well as MICRO-EPSILON MESSTECHNIK GmbH & Co. KG and ATENSOR Engineering and Technology Systems is gratefully acknowledged.

REFERENCES

[1] Schmitt, R. and Moenning, F., “Ensure success with inline-metrology,” *XVIII IMEKO world congress Metrology for a Sustainable Development* (2006).

[2] Gao, W., Haitjema, H., Fang, F., Leach, R., Cheung, C., Savio, E., and Linares, J.-M., “On-machine and in-process surface metrology for precision manufacturing,” *CIRP Annals* **68**(2), 843–866 (2019).

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, “Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system,” *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155

[3] Yu, C., Chen, X., and Xi, J., "Modeling and calibration of a novel one-mirror galvanometric laser scanner," *Sensors* **17**(1), 164 (2017).

[4] Schlarp, J., Csencsics, E., and Schitter, G., "Optical scanning of a laser triangulation sensor for 3-d imaging," *IEEE Transactions on Instrumentation and Measurement* **69**(6), 3606–3613 (2020).

[5] Rioux, M., "Laser range finder based on synchronized scanners," *Applied optics* **23**(21), 3837–3844 (1984).

[6] Wertjanz, D., Kern, T., Csencsics, E., Stadler, G., and Schitter, G., "Compact scanning confocal chromatic sensor enabling precision 3-d measurements," *Applied Optics* **60**(25), 7511 (2021).

[7] Dorsch, R. G., Häusler, G., and Herrmann, J. M., "Laser triangulation: fundamental uncertainty in distance measurement," *Applied optics* **33**(7), 1306–1314 (1994).

[8] Mohammadikaji, M., Bergmann, S., Irgenfried, S., Beyerer, J., Dachsbacher, C., and Wörn, H., "A framework for uncertainty propagation in 3d shape measurement using laser triangulation," in [*2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings*], 1–6, IEEE (2016).

[9] Papadopoulos, C. E. and Yeung, H., "Uncertainty estimation and monte carlo simulation method," *Flow Measurement and Instrumentation* **12**(4), 291–298 (2001).

[10] Householder, A. S., [*The theory of matrices in numerical analysis*], Courier Corporation (2013).

[11] Schlarp, J., Csencsics, E., and Schitter, G., "Design and evaluation of an integrated scanning laser triangulation sensor," *Mechatronics* **72**, 102453 (2020).

[12] Willink, R., [*Measurement uncertainty and probability*], Cambridge University Press (2013).

[13] Keferstein, C. P. and Dutschke, W., [*Fertigungsmesstechnik*], Springer Vieweg, Wiesbaden (2010).

Pre-print version of the article: Johannes Schlarp, Ernst Csencsics, and Georg Schitter, "Analyzing error sources and error propagation in an optical scanning 3D triangulation sensor system," *Proc. SPIE 12222, Optical System Alignment, Tolerancing, and Verification XIV* 122220I, 2022. DOI: 10.1117/12.2632155