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Influence of Scheimpflug condition on measurements of a scanning laser line sensor for 3D imaging

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Abstract. Satisfying the Scheimpflug condition in a rotational scanning 3D triangulation sensor system can be challenging. By violating this condition an reproducible measurement error is generated, which is caused by the out of focus projected laser point on the detector. In this work a ray-tracing simulation of the scanning system is performed, in order to determine potential aberrations. With the reference measurement of a flat surface the error due to violation of the Scheimpflug condition is obtained. The error is systematic and reproducible and can be compensated by a correction polynomial, with coefficients determined by using the least squares method. Experimental results reveal, that the measurement error can be significantly reduced by the correction polynomial.

1. Introduction

Optical 3D measurement systems have become increasingly important for the quality assurance within production processes [1, 2]. Most often point or line sensors are combined with external actuators, such as linear stages, coordinate measurement machines or industrial robots in order to obtain the surface profile of a sample [3]. The most commonly used optical sensors for these dimensional metrology and quality control tasks are laser triangulation sensors [3]. They determine the distance between sensor and sample, by projecting the diffuse reflection of the laser point from the sample surface onto a detector. With the position of the projected point on the detector and the known geometric relations of the sensor, the distance between sensor and sample can be determined [4]. In order to obtain a sharp image of the diffusely reflected laser point over the entire measurement range, the Scheimpflug condition has to be fulfilled [5], which is an extension of the thin-lens equation for non parallel object and image planes [4]. In Fig. 1 a schematic illustration of the Scheimpflug condition is shown. If the object, lens and image plane intersect in one line (intersection line), all

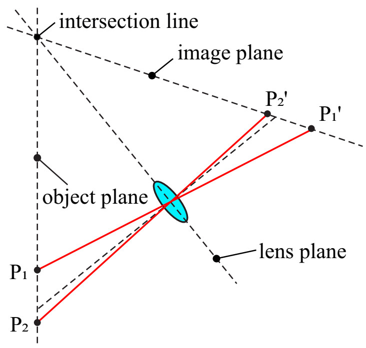

Figure 1. Schematic illustration of the Scheimpflug condition. All points P_i in the object plane are focused on the points P_i' in the image plane, if the three planes intersect in one line.

points in the object plane are projected sharply in the image plane [6]. However, for rotational scanning 3D triangulation systems, in which only the optical path of the sensor is manipulated, by e.g. a fast steering mirror, the Scheimpflug condition can hardly be fulfilled [4]. Recently, two scanning 3D laser line sensor geometries have been proposed, in which only one system satisfies the Scheimpflug condition [7]. The measurement results of the system not satisfying the Scheimpflug condition show systematic errors which are not present for the other system and could thus be caused by the violation of the imaging condition.

The contribution of this paper is the determination and correction of the measurement error when violating the Scheimpflug condition. In Section 2 a ray-tracing simulation of the scanning laser line sensor, proposed in [7], is evaluated. The error caused by the violation of the Scheimpflug condition is identified and corrected in Section 3. The correction method is validated in Section 4, and Section 5 concludes the paper.

2. Simulation of the measurement system

To determine potential aberrations of optical systems in advance, ray-tracing simulations can be performed [8]. Therefore, the positions and properties of the individual optical components are assigned initially. Then the optical path is calculated and indicated by the simulation program.

In Fig. 2 the ray-tracing simulation of the scanning system geometry not fulfilling the Scheimpflug condition, proposed in [7], is depicted. The illumination path of the laser line sensor is manipulated by a static mirror and a tip-tilt mirror. By rotating the tip-tilt mirror around the x axis, the lateral position of the laser line on the sample is varied, such that the surface profile can be obtained by the 2D sensor. Since the illumination path is manipulated close to sensor, a tip-tilt mirror with a small aperture size can be used enabling higher scan speeds. Measurement points which are located in the z-plane fulfil the Scheimpflug condition and are therefore the only points sharply projected onto the detector. This fact is illustrated in the zoomed image in Fig. 2 and may cause a systematic measurement error (see also [7]). To minimize the error due to violating the Scheimpflug condition the optical components are arranged in a manner, that in the zero position of the tip-tilt mirror, the laser line hits the z-plane in the center of the measurement range of the laser line sensor. The ray-tracing simulation was also performed for the second scanning system geometry, proposed in [7], which does fulfil the Scheimpflug condition. In this measurement system all measurement points are sharply projected onto the detector.

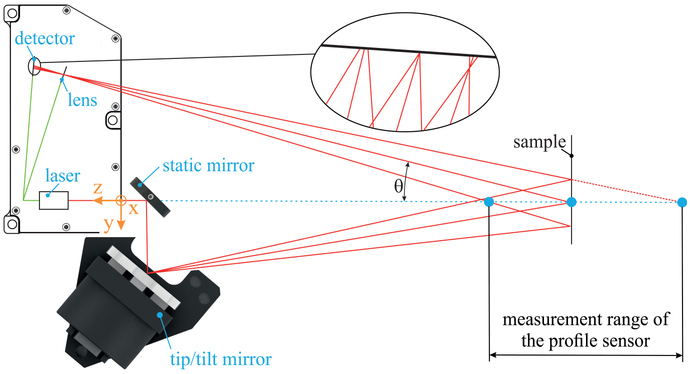

Figure 2. Ray-tracing simulation of the scanning laser line sensor. The position of the laser line on the surface can be scanned in one axis by the tip-tilt mirror. The lens projects the diffusely reflected laser line onto the detector. Only measurement points that are in the z-plane are then sharply imaged on the detector.

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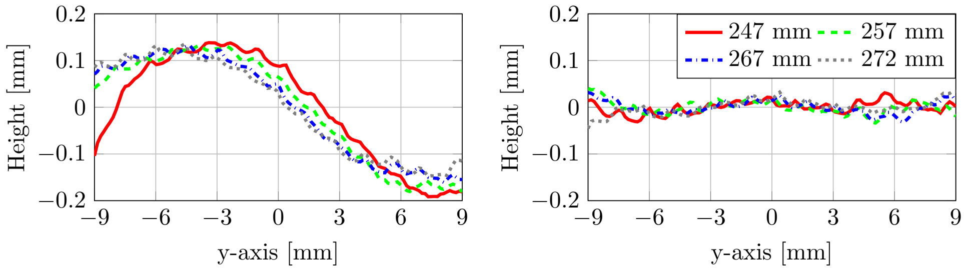
3. Identification of systematic measurement error

To accurately determine the error caused by the violation of the Scheimpflug condition, a sample with a flat surface is measured. In Fig. 3(a) the measurement results of the scanning laser line sensor are shown for different distances between sample and sensor. For a better comparison of the measurement results, the distance between sensor and sample, previously determined by a reference measurement and essentially representing an offset, is subtracted. The resulting curves are all S-shaped and slightly change their shape with the distance. This error cannot be caused by inaccurate alignment, since this would only lead to a linear error. However, the error



(a) (b)

Figure 3. Shown are the (a) uncorrected and (b) corrected measurement result of a flat surface, for different nominal distances between sensor and sample. With the correction polynomial the error can be reduced significantly.

is reproducible, i.e. it is possible to correct it by means of a correction polynomial. In order to correct the S-shape in y-direction a third order polynomial is required. In the z-direction (i.e. height) the curve changes linear (shift in negative y- direction), therefore a first order polynomial is sufficient. The correction polynomial is therefore proposed as follows

$$z_{corr} = a_{0,0} + a_{1,1}y_l + a_{1,2}y_l^2 + a_{1,3}y_l^3 + a_{2,1}z_l + a_{3,1}y_l z_l + a_{3,2}y_l^2 z_l, \quad (1)$$

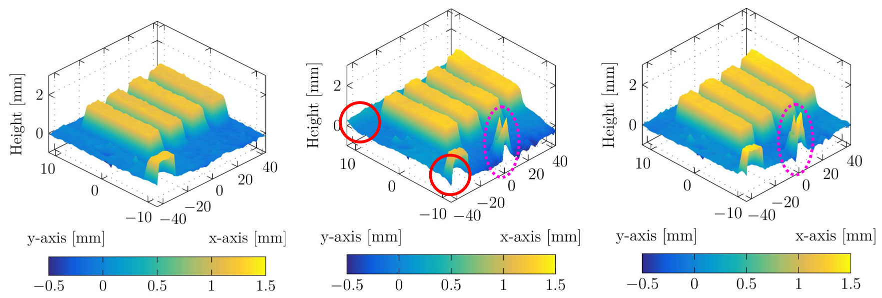
with z_l the measured distance between sensor and sample, y_l the calculated position of the laser line on the sample in y-direction and the last two terms representing coupling terms for improved matching. The parameters $a_{i,j}$ of the correction polynomial, shown in Tab. 1, are estimated with the least squares method [9]. In Fig 3(b) the corrected profile of the measured flat surface is shown. The rms error can be reduced from 101.4 μm to 13.3 μm, which denotes a reduction by a factor of 7.6.

Table 1. Coefficients of the correction polynomial.

Parameter	$a_{0,0}$	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{2,1}$	$a_{3,1}$	$a_{3,2}$
Value	6.38e-1	-1.46e-2	-2.32e-2	2.82e-4	2.3e-3	6.85e-5	-8.39e-5

4. Validation of the correction method

To validate the correction method various samples, e.g. memory chips on a graphic card, are measured. Furthermore, reference measurements are performed with a position controlled linear stage (see [7]). As shown in Fig. 4, an artefact around x = 0 mm and y = −10 mm is observable for the uncorrected and corrected scan (magenta dashed circle), which is caused by a multiple reflection at a solder joint. By slightly tilting the sample this multiple reflection can be avoided. The surface of the uncorrected rotational scan in (b) seems to be slightly bent (red circle). This error can be corrected by the polynomial from Eq. (1). In the surface profile of the corrected rotational scan in (c) no bending effects are observable and it shows good agreement with the reference measurement, shown in (a).



(a) (b) (c)

Figure 4. Comparison between (a) reference measurement, (b) uncorrected rotational scan and (c) corrected rotational scan. The artefacts in the rotational scans are caused by multiple reflections. With the correction polynomial the systematic error (bending) in the result can be removed.

In summary, the error caused by the violation of the Scheimpflug condition in the investigated geometry of a rotational scanning triangulation system, can be reduced by a factor of 7.6 when applying the proposed correction polynomial.

5. Conclusion

In this paper a correction method for the error caused by a violation of the Scheimpflug condition in a scanning triangulation sensor system is presented. The reflected laser line cannot be projected sharply onto the detector over the entire measurement range. The resulting optical path is calculated using ray-tracing simulations. A reference measurement of a flat surface allows to determine the error and coefficients of the correctional polynomial. With the for the sensor geometry fixed polynomial, the error caused by violating the Scheimpflug condition can be reduced by a factor of 7.6.

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