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Error compensation for laser line scanners

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Abstract

This paper presents an algorithm to compensate the systematic error of lasers line scanned data based on the measurement error model of the measurement system. The iterative process of the algorithm is used to determine geometrical features accurately, solely making use of an optical measurement device. The systematic error on the task-specific measurement is reduced by the algorithm. The validation of the algorithm consists of the evaluation of multiple compensated measurements on calibrated ring gauges with different diameters and similar surface properties as the acquisition artefact of the measurement error model. Furthermore, a validation is performed on a gauge block. Experimental research shows the reduction of the systematic error as a function of the scan strategy due to the compensation by the algorithm.

Keywords: Metrology, Laser line scanner, Coordinate Measurement Machine (CMM), Systematic error

1. Introduction

The ongoing trend in the manufacturing industry to produce lot-size-one products pushes the manufacturing metrology forward to deliver high quality assurance and traceability [1]. Due to this trend the quality inspection becomes a bottleneck in the manufacturing process, hence the time a measurement takes needs to be minimized [2]. Optical probes, such as laser line scanners (LLSs), replace the time-consuming conventional measurement systems, such as tactile probing devices. LLSs offer a high measuring speed and a dense point cloud generation [3]. Therefore LLSs have the potential to overcome the bottleneck in the manufacturing process. However LLSs lack accuracy compared to tactile probing systems [4-6]. In order to form an appealing alternative, the task-specific measurement error of optical probes needs to have the same order of magnitude as those performed with tactile probing.

A method to obtain the measurement error model of an LLS as a function of the position and orientation of the LLS with respect to the measurand has recently been developed [7]. The role of this model is twofold. Firstly the accuracy of the LLS is improved by compensating the bias on a measurement according to the systematic error model. Secondly virtual measurements based on the random error model allow to determine the task-specific measurement uncertainty according to the GUM [8]. Still this proposed method to obtain the measurement error model requires a tactile reference measurement for the correction of the data generated with the LLS.

Therefore this paper proposes an algorithm to exclude the need for tactile measurement in the compensation of the optical obtained data. The presented algorithm improves the accuracy of the task-specific measurement of geometrical features, such as cylinders and planes. The algorithm is experimentally validated on a set of ring gauges with different diameters and by measuring the distance between to opposite surfaces of a gauge block.

2. Laser line scanner

An LLS projects one or more planes of laser light onto the workpiece surface and tracks the intersection thereof with a sensor. This allows the determination of surface coordinates by triangulation (Figure 1). As a result of their non-contact character, LLSs have a high measuring speed and a high density sampling point generation compared with conventional tactile probing systems [3,9]. Over the last decades the accuracy of the LLS has improved considerably [3]. The accuracy of the results of optical scanners is not only dependent on the positioning and orientation with respect to the workpiece surface [5,10], but the accuracy is also dependent on the characteristics of the surface such as: colour, roughness [11] and reflection [12], and external factors such as: vibrations, temperature and ambient light. The influence of external factors is minimized by measuring in a stable environment, such as a laboratory environment. The quality of the point clouds can be characterized by four parameters: density, completeness, noise and accuracy [13,14]. The inspection of CMMs with optical distance sensors is regulated by ISO 10360-8. The objective of this standard is to test the error indication of a calibrated test length and to test the errors of the optical sensor [15]. As a result measurements according to this standard have direct traceability. Furthermore the standard provides task-specific information of the performance of the CMM under similar conditions. However ISO 10360-8 doesn't provide information for each measured point with an optical scanner. This means that Monte Carlo simulations cannot be performed based on ISO 10360-8 in order to evaluate the measurement uncertainty. The sensor characteristics, as a function of the relative position of the measurand compared to the measurement device and the surface properties of the measurand, are required when evaluating a measurement on different artefacts by means of a virtual

measurement system. Methods to quantify [16] and model [7] the measurement errors of laser-based scanners in function of the uncertainty contributors have been developed over the recent years.

Figure 1: Triangulation principle of an LLS.

The measurement error of sampled points can be decomposed in two directions, namely the axial and radial direction. The axial direction is on the line from the sampled point towards the sensor of the LLS. The radial direction is perpendicular to the axial direction. In a typical LLS the radial error is an order of magnitude smaller than the axial error. Furthermore the high-density point cloud is generated over a surface, i.e. mostly the radial direction of the sampled points, therefore the radial error is considered negligible compared to the axial error.

Figure 2: Scan depth, in-plane angle and out-of-plane angle of an LLS [7].

A method to obtain the measurement error model for an LLS is proposed in [7]. The measurement error model models both the systematic error and the random error in the axial direction as a function of the track settings: the distance between the inspected surface and the CCD sensor, also referred to as scan depth, the in-plane angle and out-of-plane angle between the laser line scanner and the surface (Figure 2). Other measurement uncertainty contributors, i.e. the characteristics of the surface and the external factors, are not included in the measurement error model. Therefore a ring gauge is proposed as an artefact for acquiring the error model. Data points on the ring gauge are obtained with an LLS over multiple different scan paths by manipulating the position of the LLS relative to the artefact. Based on the position of the artefact, the orientation and scan path of the LLS, the track settings along with the measurement error can be calculated for the obtained data points. The full mathematical description for this calculation can be found in [7] and a graphical interpretation for the following mathematical calculation is given in Figure 3. The position of the laser source, X_0 , of a scanned point, X_s , on the scan path with start point, S , and end point, E , can be found by equation 1.

$$\begin{Bmatrix} X_{0,x} \\ X_{0,y} \\ X_{0,z} \end{Bmatrix} = \frac{\begin{pmatrix} X_{s,x} \\ X_{s,y} \\ X_{s,z} \end{pmatrix} - \begin{Bmatrix} S_x \\ S_y \\ S_z \end{Bmatrix}}{\overline{SE}^2} \cdot \overline{SE} + \begin{Bmatrix} S_x \\ S_y \\ S_z \end{Bmatrix}. \quad (1)$$

Figure 3: Graphical interpretation for the calculation of the measurement error and the corresponding track settings [7].

Based on the position of the laser source and the scanned point, the direction of the laser beam can be determined. On the intersection of the laser beam and the reference cylinder the calibrated point, X_c , can be found. The normal, $\vec{n}$, in the calibrated point on the cylinder with orientation, $\vec{a}$, and centre point, C , can be found by equation 2.

$$\vec{n} = \frac{\vec{a} \cdot \begin{pmatrix} X_{c,x} \\ X_{c,y} \\ X_{c,z} \end{pmatrix} - \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix}}{\vec{a}^2} \vec{a} + \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix} - \begin{pmatrix} X_{c,x} \\ X_{c,y} \\ X_{c,z} \end{pmatrix}. \quad (2)$$

The track settings can be calculated with the following equations: the scan depth, d , with equation 3, the in-plane angle, α_{in} , and out-of-plane angle, α_{out} , can be found with respectively equation 4 and 5. In the calculation of both angles, $\vec{v}$ is the view direction of the LLS, which is manipulated with the articulating probe head of the CMM.

$$d = |X_0 X_c| = \sqrt{(X_{0,x} - X_{c,x})^2 + (X_{0,y} - X_{c,y})^2 + (X_{0,z} - X_{c,z})^2}. \quad (3)$$

$$\alpha_{in} = \begin{cases} \text{if } \arccos \left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right) \cdot \overline{SE}}{\left\| \vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right\| \|\overline{SE}\|} \right) \geq 90^\circ: -\arccos \left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right) \cdot \overline{ES}}{\left\| \vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right\| \|\overline{ES}\|} \right) \\ \text{if } \arccos \left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right) \cdot (\overline{SE} \times \vec{v})}{\left\| \vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right\| \|\overline{SE}\|} \right) < 90^\circ: \arccos \left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right) \cdot \overline{ES}}{\left\| \vec{n} - \frac{\vec{n} \cdot (\overline{SE} \times \vec{v})}{\|\vec{n}\|^2} (\overline{SE} \times \vec{v}) \right\| \|\overline{ES}\|} \right) \end{cases}. \quad (4)$$

$$\alpha_{out} = \begin{cases} \text{if } \arccos\left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right) \cdot (\vec{SE} \times \vec{v})}{\left\|\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right\| \|\vec{SE} \times \vec{v}\|}\right) \geq 90^\circ: -\arccos\left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right) \cdot \vec{ES}}{\left\|\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right\| \|\vec{ES}\|}\right) \\ \text{if } \arccos\left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right) \cdot (\vec{SE} \times \vec{v})}{\left\|\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right\| \|\vec{SE} \times \vec{v}\|}\right) < 90^\circ: \arccos\left(\frac{\left(\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right) \cdot \vec{ES}}{\left\|\vec{n} - \frac{\vec{n} \cdot \vec{SE}}{\|\vec{n}\|^2} \vec{SE}\right\| \|\vec{ES}\|}\right) \end{cases} \quad (5)$$

The measurement error, ε , for the scanned point is the difference of the distance between the laser source and the scanned point and the distance between the laser source and the calibrated point.

$$\varepsilon = |X_0 X_s| - |X_0 X_c|. \quad (6)$$

Based on the measurement errors, a second degree polynomial function is determined as a function of the three parameters of the measurement strategy, i.e. d , A_{in} and A_{out} . The coefficients of the polynomial function, $c_{s1} \dots c_{s10}$, are determined by a least squares fit. The systematic error, E_{sys} , can be expressed by equation 7.

$$E_{sys}(d, A_{in}, A_{out}) = [c_{s1} \quad c_{s2} \quad \dots \quad c_{s10}] \begin{bmatrix} d^2 \\ dA_{in} \\ dA_{out} \\ d \\ A_{in}^2 \\ A_{in}A_{out} \\ A_{in} \\ A_{out}^2 \\ A_{out} \\ 1 \end{bmatrix}. \quad (7)$$

The data, used for the polynomial fitting, is acquired on one reference ring with a calibrated diameter of 125.001 ± 0.001 mm. The lowest order polynomial that provides a good fit is used in order to obtain a robust fitting. The correctness of the polynomial function can be evaluated by considering the distribution of the residual errors, i.e. the difference between the polynomial function and the data. Deviations from the normal distribution indicate that the least squares fitting of the polynomial function differs from the measured data, which show a normally distributed measurement noise. When deviations come forward out of the comparison, a higher order polynomial should be used. Figure 4 shows the cumulative distribution function (CDF) of the residuals and a standard normal distribution fitted through the residuals. The irrelevant measured data, due to saturation, are omitted. It can be concluded from the comparison that the polynomial function well represents the systematic error, since the CDF of the residuals closely resembles a standard normal distribution. Deviations from the standard normal distribution are below $1.5 \mu\text{m}$. It can also be concluded from the CDF that the random error has a standard deviation of $21 \mu\text{m}$.

Figure 4: Comparison between the CDF of the residuals of the polynomial fit (blue) and the fitted standard normal distribution (red).

Further proof of the validity of the measurement error model can be given by comparing the model with the state-of-the-art performance evaluation tests. Figure 5 depicts the systematic error obtained by the measurement error model. The variables of the model are: a constant in-plane angle of 30° , a scan depth varying from 90 mm to 150 mm, an out-of-plane angle of respectively 0° , 5° , 10° and 15° . The range of the scan depth is chosen to be in the field of view of the LLS, used for the acquisition of the data, i.e. Nikon Metrology LC60Dx. This means that the depicted values are relevant for the experiments performed in this paper. Similarly Figure 6 depicts the standard deviation of the random error. The depicted diagram is obtained by using the measurement error model with the same variables as Figure 5. The modelled characteristics on the errors in function of the track settings show resemblance with the performance evaluation by Van Gestel [5], indicating the validity of the measurement error model. As conclusion derived both from the CDF of the residuals, depicted in Figure 4, and a comparison with other literature, Figure 5 and 6, it can be accepted that the measurement error model corresponds with the physical characteristics of the measurement device.

Figure 5: The systematic error based on the polynomial function with an in-plane angle of 30° .

Figure 6: The random error based on the polynomial function with an in-plane angle of 30°.

3. Cylinder determination algorithm

3.1. Working principle

The measurement error model offers the possibility to compensate systematic errors and calculate the measurement uncertainty [7]. However this method still relies on the fact that the calibrated diameter, orientation and centre point of the cylinder are known. When performing quality inspections in an industrial environment these parameters need to be determined, so these are unknown at the time. Performing the correction based on the least-squares cylinder will result in an incorrect systematic error compensation, since the used parameters for the compensation differ from the parameters of the actual cylinder. As a result the systematic error on each data point is overcompensated or undercompensated. Therefore it would be better to have an algorithm to determine the parameters of the cylinder with solely the use of an LLS and more advanced than the compensation based on the least-squares cylinder. The procedure of the introduced algorithm includes: a parameter selection, a correction procedure for multiple simulated cylinders, a least-squares cylinder fitting for the corrected data and a selection of the outcome with the smallest error. This means that corrections are performed until the least squares cylinder of the corrected data corresponds with the parameters, which determine the correction of the measured points. A schematic flowchart of the algorithm is shown in Figure 7. Each step in the algorithm is explicitly explained below.

Figure 7: Structure of cylinder determination algorithm.

Step 1: Input. The input of the algorithm is a point cloud obtained with the LLS and the scan strategy. The point cloud Ω is a set of points with xyz-coordinates. The scan strategy consists of the scan trajectory and view direction, $\vec{v}$.

Step 2: Estimation. The next step is to define an estimation of the four parameters of the cylinder: the central axis, $\vec{a}$, the radius, R , the x and y coordinate of the centre point, CM . For the centre point only the x and y coordinate are considered since an upward orientated cylinder with an infinite height is created, preferably these coordinates are the intersection of $\vec{a}$ and the xy-plane. As a first estimation the least squares cylinder of the measured data can be used. Furthermore the range over which the parameters are searched needs to be defined. Each parameter has five uniformly distributed values over this range. For each combination of these four parameters a cylinder is created, i.e. there are 625 (5^4) different cylinders.

Step 3: Error compensation. For each measured point P the systematic error is compensated. Therefore the projection, I , of P along $\vec{v}$ on the generated cylinder in step 2 needs to be found. Since I can be found along the line through P with direction, $\vec{v}$, and scalar t :

$$\begin{Bmatrix} I_x \\ I_y \\ I_z \end{Bmatrix} = t\vec{v} + \begin{Bmatrix} P_x \\ P_y \\ P_z \end{Bmatrix} \mid P \in \Omega(1)$$

The point on the central axis of the cylinder closest to I is point C , therefore $\vec{CI}$ is perpendicular to the central axis:

$$\vec{a} \cdot \vec{CI} = 0, \quad (2)$$

Which can be written as:

$$\vec{a} \cdot \left(\begin{Bmatrix} I_x \\ I_y \\ I_z \end{Bmatrix} - \begin{Bmatrix} C_x \\ C_y \\ C_z \end{Bmatrix} \right) = 0. \quad (3)$$

Since C lies on $\vec{a}$ through CM (Figure 7), the following equation, with scalar s , applies:

$$\begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix} = s\vec{a} + \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \quad (4)$$

Substitution of (4) in (3) gives:

$$\begin{aligned} \vec{a} \cdot \left(s\vec{a} + \begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix} - \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right) &= 0 \\ \vec{a} \cdot \left(\begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix} - \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right) \\ \Leftrightarrow s &= \frac{\vec{a} \cdot \left(\begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix} - \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right)}{\vec{a}^2}. \end{aligned} \quad (5)$$

Point C can be found by substituting (5) and (1) in (4):

$$\begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix} = \vec{a} \frac{\vec{a} \cdot \left(t\vec{v} + \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} - \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right)}{\vec{a}^2} + \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix}. \quad (6)$$

The distance d between points C and I can be given as a function of scalar t :

$$d(t) = \sqrt{(I - C)^2}. \quad (7)$$

The substitution of (1) and (6) in (7) results in:

$$d(t) = \sqrt{\left(t\vec{v} + \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} - \vec{a} \frac{\vec{a} \cdot \left(t\vec{v} + \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} - \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right)}{\vec{a}^2} + \begin{pmatrix} CM_x \\ CM_y \\ CM_z \end{pmatrix} \right)^2}. \quad (8)$$

Since I is the projection of P on the generated cylinder the distance, d , should be equal to the radius, R . This results in three possible situations, which are illustrated in Figure 8:

Case 1: $\forall t \in \mathbb{R}, d(t) \neq R$. In this situation the sampled point should be deleted, since it is apparently not sampled from the surface of the cylinder.

Case 2: $\exists! t \in \mathbb{R}, d(t) = R$. The projection I can be found by equalizing equation (8) to R .

Case 3: $\exists t_1, t_2 \in \mathbb{R}, d(t_1, t_2) = R$. The projection I is not unique, therefore an additional condition is required in order to avoid two theoretical solutions. Since the projection direction is the view direction, the largest positive scalar gives projection I . Due to the fact that equation 8 considers a cylinder infinite in height, while in reality the cylinder is finite, two scalars can be found for the intersection of the line from equation 1 and the cylinder.

When all the projections for the generated point cloud are found, the scan depth, in-plane angle and out-of-plane angle can be calculated, similar as presented in [7]. Based on these track settings the point cloud is compensated. This step is performed on each generated cylinder, as a result each cylinder is represented by a unique compensated point cloud.

Figure 8: The projection I (red cross) of a measured point on the scannable area of the inner cylinder of the ring gauge (green check pattern).

Step 4: LSQ fitting cylinder. The least squares cylinder is fitted to each compensated point cloud. The difference between the parameters of the original cylinders and the least squares fitted cylinders are calculated. The difference on the orientation of the central axis, ϵ_{axis} , of the LSQ fitted cylinder, $\vec{a}_{LSQ}$, and the generated cylinder, $\vec{a}_{gen}$, is given by the angle between the vectors:

$$\epsilon_{axis} = \tan^{-1} \frac{\|\vec{a}_{LSQ} \times \vec{a}_{gen}\|}{\|\vec{a}_{LSQ}\| \cdot \|\vec{a}_{gen}\|} \quad (9)$$

The error on the radii of the cylinders, ϵ_{radius} , is:

$$\epsilon_{radius} = \sqrt{(R_{LSQ} - R_{gen})^2}. \quad (10)$$

Since the generated cylinder, in Step 3, is infinite in height and the least squares cylinder of the compensated data is finite, the error on the centre point, ϵ_{pos} , should be calculated with points on the same plane, i.e. the xy -plane. Therefore the centre point of the least squares cylinder, CM_{LSQ} , is projected along its central axis, $\vec{a}_{LSQ}$, on the xy -plane in order to have the same z -coordinate as the middle point of the generated cylinder, CM_{gen} . This results in CM_{proj} , with scalar k :

$$\begin{Bmatrix} CM_{LSQ,x} \\ CM_{LSQ,y} \\ CM_{LSQ,z} \end{Bmatrix} + k \begin{Bmatrix} a_{LSQ,x} \\ a_{LSQ,y} \\ a_{LSQ,z} \end{Bmatrix} = \begin{Bmatrix} CM_{proj,x} \\ CM_{proj,y} \\ CM_{proj,z} \end{Bmatrix} . \quad (11)$$

Since CM_{proj} and CM_{gen} are both on the xy -plane, they have a same z -coordinate:

$$\begin{aligned} CM_{proj,z} &= CM_{LSQ,z} = CM_{gen,z} + ka_{gen,z} \\ \Leftrightarrow k &= \frac{CM_{LSQ,z} - CM_{gen,z}}{a_{gen,z}} . \end{aligned} \quad (12)$$

Therefore:

$$CM_{proj,x} = CM_{gen,x} + \frac{CM_{LSQ,z} - CM_{gen,z}}{a_{gen,z}} a_{gen,x} , \quad (13)$$

$$CM_{proj,y} = CM_{gen,y} + \frac{CM_{LSQ,z} - CM_{gen,z}}{a_{gen,z}} a_{gen,y} . \quad (14)$$

The error on the position is calculated as follows:

$$\epsilon_{pos} = \sqrt{(CM_{LSQ,x} - CM_{proj,x})^2 + (CM_{LSQ,y} - CM_{proj,y})^2} . \quad (15)$$

The cylinder's parameters resulting in the lowest weighted combination of errors on the parameters become the new best parameter estimation.

Step 5a: Reduce range. The range on the parameters, in order to generate cylinders, is larger than the specified limit. In this case the range is divided by two and the process is repeated from step 2.

Step 5b: Finalisation. The range is smaller or equal to the specified limit. The parameters of the outcome of step 4 are the parameters of the cylinder determined by the algorithm.

3.2. Validation: cylinders

The proposed algorithm is validated by a comparison with the uncompensated data and the data compensated based on a tactile measurement. The error on the least squares fitting diameter of the cylinder of the three data sets is compared. The validation needs to be performed on objects with uniform surface properties, similar as used for the determination of the measurement error model, and in an environment which minimizes, or eliminates, the external uncertainty contributors. Therefore the comparison is made for fifty measurements on four ring gauges with a diameter of 50 mm, 70 mm, 100 mm and 125 mm. A measurement comprises an arc segment measured with 2500 data points. The measurements are performed with a Nikon Metrology LC60Dx LLS mounted on an LK Altera 15.7.6 CMM in a metrology laboratory with a controlled temperature of $20^\circ\text{C} \pm 1^\circ\text{C}$. Figure 9 depicts the measurement system, the ring gauges and the used coordinate frame. All measurements of one ring gauge are performed on constant scan track. Details of the scan track relative to the centre of the cylinder and the vector of the view direction are given in Table 1. The information in Table 1 includes the vector of the constant view direction, which is used to measure all the ring gauges. The start and end coordinate of the scan trajectory relative to the centre of the cylinder, with respect for the general coordinates axis are included (Figure 9). Furthermore the orientations of the central axis of the ring gauge are listed in Table 1. The scan trajectory determines the scan depth, in-plane angle and out-of-plane angle, i.e. the parameters

which determine the systematic error. Therefore the scan trajectory has a direct influence on the task-specific systematic error. Based on this information the scan depth, in plane angle and out of plane angle can be calculated. Furthermore this scan information can be used to replicate the experiments. The outcome of the comparison is shown in Figure 10. As can be seen in the figure, the bias of the compensation methods varies between the different ring gauges and is well reduced by the compensation method. The compensation method reduces the systematic error from approximately 100 μm , without compensation, to 20 μm after compensation. The origin of the remaining systematic error is twofold. On the one hand, the standard deviation inherent to each systematic error has to be taken into account. On the other hand, a difference between the model, i.e. a second degree polynomial, and the reality has to be considered. When comparing the four ring gauges, it cannot be concluded that the compensation of the systematic error based on the algorithm is less accurate than the tactile based compensation. The comparison shows that the uncertainty interval of the three methods is comparable. From this comparative study it can be concluded that the algorithm can replace the tactile measurement for the compensation of the systematic error. As can be seen in Figure 10, the uncertainty on the diameter is too large to prove conformance to a tolerance in any industrial application, since it is an order of magnitude larger than the conventional tactile measurement systems. The standard deviation varies from 15 μm to 50 μm , dependent on the diameter of the ring gauge and the scan trajectory. The uncertainty is not influenced by the compensation method. The magnitude of the uncertainty interval can be explained by the varying systematic error as a function of the in-plane angle and the out-of-plane angle, causing extra curvature on a surface and the measurement strategy of the cylinder, i.e. the cylinder is measured over one arc segment. Therefore it is recommended to measure cylinders over multiple arc segments distributed over the cylinder's surface. In this way the effect of the added curvature of one arc segment is reduced.

Figure 9: The measurement system, Nikon Metrology LC60Dx LLS mounted on an LK Altera 15.7.6 CMM, scanning the ring gauge with a diameter of 125 mm and centre C. The measurement is performed over the scan trajectory from point A to point B with view direction, $\vec{v}$.

Figure 10: Comparison between the compensation methods based on the error relative to the calibrated value.

Table 1: The scan trajectory of the centre of the field of view relative to the centre of the cylinders in order to obtain Figure 10.

		X / mm	Y / mm	Z / mm
	Vector of the view direction:	0.000	0.866	-0.500
Cylinder diameter 50 mm	Start scan track:	28.295	28.231	-8.421
	End scan track:	-22.974	28.231	-8.421
	Orientation cylinder:	$5.129 \cdot 10^{-5}$	$4.467 \cdot 10^{-4}$	1.000
Cylinder diameter 70 mm	Start scan track:	39.218	33.171	-9.505
	End scan track:	-35.297	33.171	-9.505
	Orientation cylinder:	$4.161 \cdot 10^{-4}$	$1.300 \cdot 10^{-3}$	1.000
Cylinder diameter 90 mm	Start scan track:	44.918	50.938	-8.860
	End scan track:	-48.330	50.938	-8.860

	Orientation cylinder:	$4.127 \cdot 10^{-4}$	$1.497 \cdot 10^{-4}$	1.000
Cylinder diameter 125 mm	Start scan track:	69.057	63.528	-11.916
	End scan track:	-60.202	63.528	-11.916
	Orientation cylinder:	$3.305 \cdot 10^{-5}$	$-4.443 \cdot 10^{-5}$	1.000

3.3. Validation: planes

The proposed algorithm can be altered in order to find the compensated measurement for flat surfaces instead of cylinders. The parameters used in the algorithm for planes are the normal on the surface and the middle point of the surface. The validation of the algorithm is performed on a gauge block with a length of $100.000 \pm 0,001$ mm. ISO 10360-8 section B.2 addresses the bidirectional measurements for verifying bidirectional length measuring performance with an optical sensor and is followed when performing the validation [15]. The measurements are performed with a Nikon Metrology LC60Dx LLS mounted on an LK Altera 15.7.6 CMM. The CMM has a volumetric accuracy of $2 \mu\text{m} + 2.5 \mu\text{m} / \text{travelled metre}$. The articulating probe head, Renishaw PH10M PLUS, has a repeatability characterized by a standard deviation of 0.83". Since the measured sides of gauge block are at opposite directions the articulating probe head has to reposition and rotate the LLS in order to scan both surfaces. Therefore the measurement error introduced by the CMM and the articulating probe head becomes significant, especially in comparison with the compensation of the cylinders where it was negligible. As a consequence the orientation changes of the probe head are minimised. By varying the scan depth, rather than the in-plane angle or the out-of-plane angle, only one reorientation of the probe head is required. The outcome of the compensation after multiple reorientations will be influenced by a random error introduced by the probe head. The validity of the compensation of measurements under different orientations is proven with the compensation on cylinders.

The validation is as follows: firstly one plane of the gauge block, referred to as the datum plane, is scanned at different scan depths. There is a constant interval between the different scan depths. Scan depth 7 corresponds with the centre of the field of view at the datum plane. At lower scan levels, the LLS is positioned closer to the inspected surface. Due to the reflective surface character of the steel gauge block, scan depth 8 is the furthest possible scan level from the inspected surface to obtain sufficient data for a comparison between the different scan depths. The in-plane angle during the scan process is 30° , this corresponds with the angle at which the measurement error model is obtained. The out-of-plane angle is 15° in order to avoid saturation due to the direct reflection of the laser beam into the detector of the LLS. At each scan depth five repeated measurements are taken. The coordinates of the scan tracks at the different scan levels are listed in Table 2. Afterwards the LLS is rotated with the articulating probe head and the second plane is measured similarly as the datum plane. The information of the scan trajectories can be found in Table 3. Both tables include the start and end coordinates of the scan trajectory with respect to the coordinate frame of the CMM, the same frame as depicted in Figure 9. The data in Table 2 and 3 show that the different scan depths are equidistant to each other.

Table 2: The CMM coordinates of the scan trajectories for the measurement of the datum plane.

	Start scan track			End scan track		
	X/mm	Y/mm	Z/mm	X/mm	Y/mm	Z/mm
Scan depth 1:	695.589	359	-416	695.589	429	-416
Scan depth 2:	692.990	357.5	-414.5	692.990	427.5	-414.5
Scan depth 3:	690.392	356	-413	690.392	426	-413
Scan depth 4:	687.794	354.5	-411.5	687.794	424.5	-411.5
Scan depth 5:	685.196	353	-410	685.196	423	-410
Scan depth 6:	682.598	351.5	-408.5	682.598	421.5	-408.5
Scan depth 7:	680	350	-407	680	420	-407
Scan depth 8:	677.402	348.5	-405.5	677.402	418.5	-405.5

Table 3: The CMM coordinates of the scan trajectories for the measurement of the second plane.

	Start scan track			End scan track		
	X/mm	Y/mm	Z/mm	X/mm	Y/mm	Z/mm
Scan depth 1:	764.412	341	-416	764.412	411	-416
Scan depth 2:	767.010	342.5	-414.5	767.010	412.5	-414.5
Scan depth 3:	769.608	344	-413	769.608	414	-413
Scan depth 4:	772.206	345.5	-411.5	772.206	415.5	-411.5
Scan depth 5:	774.804	347	-410	774.804	417	-410
Scan depth 6:	777.402	348.5	-408.5	777.402	418.5	-408.5
Scan depth 7:	780	350	-407	780	420	-407
Scan depth 8:	782.598	351.5	-405.5	782.598	421.5	-405.5

Based on the measured data of the surfaces and the scan trajectories the systematic error of the measurements are compensated by the proposed algorithm. The distance between two surfaces at the same scan depth is determined according to ISO 14405-2:2018 [17]. This standard implies a that datum plane is established, which aligns the workpiece in space. The datum is determined by the least squares plane. The distance to the second plane is from the centre of the datum along its normal to the least squares plane of the second surface. Figure 11 shows the error on the length for the uncompensated surfaces as a function of the scan depth and for compensated surfaces. The regression line through the data shows the influence of the scan depth on the length based on uncompensated point clouds. The systematic error of the length measurement, based on the uncompensated data, varies between $-5\text{ }\mu\text{m}$ and $-30\text{ }\mu\text{m}$. The compensation by the proposed algorithm makes the systematic error on the measured length of the gauge block independent of the scan strategy and results in a constant systematic error of the length measurement of $7.5\text{ }\mu\text{m}$. The systematic error that remains in this example after the compensation can be partially linked to the standard deviation on the systematic error on each measurement and to the difference between the model and the real characteristics of the scanner. Furthermore, due to the orientation change, in order to scan the opposite surfaces, the measurement error of the CMM and the error of the articulating probe head have to be taken into account.

Figure 11: Comparison between the error on the measured length of a gauge block and error obtained with the compensation algorithm.

4. Conclusions

This paper summarizes a method to obtain the measurement error model for an optical measurement device as a function of the scan strategy. The correctness of the model is proven on multiple artefacts. Furthermore an algorithm is presented to determine geometrical features with increased accuracy. The algorithm reduces the systematic error as a function of the position and orientation of the measurement device relative to the measurand. The effectiveness of the algorithm is shown on two different geometrical features, i.e. cylinders with different diameters and a gauge block. The algorithm reduces the systematic error of the diameter from approximately 100 μm to 20 μm . After compensation, the systematic error of the gauge block approximately 7.5 μm instead of a variable systematic error between -5 μm and -30 μm . Regarding future work, firstly it should scrutinize the influence of form errors of the geometrical features on the effectiveness of the compensation algorithm. Secondly, the measurement error model can be integrated in a virtual measurement device, both the CMM and the LLS should be included in this digital twin.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights:

- Measurement error model for laser line scanner to simulate the systematic error.
- Algorithm to compensate the systematic error on a measurement of geometrical features.
- Experimental validation of the algorithm on ring gauges and a gauge block.