On Performance Verification of Simultanous 4-axis 3D geometric Optical Instrument

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Abstract

A 4-axis system configuration of an optical instrument has a significant advantage in improving accessibility to measure a part geometry, such as micro-tools and micro-moulds. Performance verification of measurement involving simultaneous 4-axis movement is a new challenge, since in the ISO10360 standard, it is separately considered as linear and rotational movement. An innovative artefact along with its procedure for performance verification of simultaneous 4-axis 3D optical metrology is proposed. The proposed artefact will have minimal manufacturing and calibration costs. The artefact is useful for both manufacturer and customer in guaranteeing the instrument traceability path to the definition of the meter.

1 Introduction

Technological advancement in manufacturing enables the scaling down of critical geometrical dimension with increasing complexity of feature geometry. Optical metrology is a prominent solution for inspection of this type of micro features due to its flexibility of accessing the part surface, fast data acquisition, and eliminating the risk to damage the part surface.

Traceability is the main concern in metrology to create unbroken chain of calibration from the optical instrument to the definition of metre. ISO 10360-8 [1] addresses this issue for optical distance-sensor based performance verification. In this standard, there are three errors to be verified: length measurement error, probing error (size and form) and flatness measurement error. A reference artefact is needed to carry out the performance verification. Claverley and Leach [2] has recently reported a review paper regarding reference artefact development for the performance verification, including Computed Tomography (CT) system.

Recently, many manufacturers of optical metrology instruments provide an additional rotation axis (the 4^{th}-axis) to increase part accessibility, e.g. for cutting tool measurement. Performance verification for rotational axes of an instrument is described in ISO 10360-3 [3] this is based on a tactile coordinate measuring machine (CMM). The problems of spatial length measurement and rotational movement verification are addressed separately by the standard. Due to the availability of the rotational axis, there are situatiuons where measurement involving all axes simultaneously occur (3-axes and the 4^{th}-axis).

In this study, a new concept for performance verification for simultaneous 4-axis 3D geometric measurement by focus-variation based microscope is introduced this includes a developed reference artefact along its procedure. The advantage of using a reference artefact is that we can realize a measurement by combination of linear and rotational axis simultaneously. The instrument has the additional rotational axis to increase the accessibility of part surface and to acquire more complete measurement points, e.g. undercut measurement. This is a significant advantage for micro dimensional and geometrical metrology purposes.

Focus-variation microscopy (FVM) vertically scans a part surface within a defined z-range within which the surface lies [4]. Maximum focus variation value is calculated to detect the part surface within the scan range. The measured focus variation at each z-position $F_z(x,y)$ is formulated as:

$$F_z(x,y) = FM(reg_w(I_z(x,y))) \qquad (1)$$

Where $reg_w(I_z(x,y))$ is the local region of the image $I_z(x,y)$ at position z and centered at (x,y) coordinate. The calculation method of FM is:

$$FM = \frac{1}{n^2} \sum_{reg_w(I_z,x,y)} (GV_i - \overline{GV})^2 \qquad (2)$$

Where GV_i is the grey-value of the *i-th* pixel and $\overline{GV}$ is the average grey value of $reg_w(I_z(x,y))$. After that, $F_z(x,y)$ is calculated, a function will be fitted to determine the maximum value within the z-range to detect the part surface z-location at (x,y). Figure 1 depicts the Illustration of focus variation working principle.

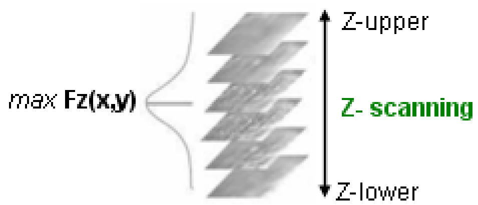

Figure 1: Focus-variation working principle.

The measuring volume of the system is dependent on the type of configuration and measurement. These types of measuring volume are briefly discussed as follows.

1.1 Measuring volume for 3-axis and 4-axis configurations

The 3-axis configuration is able to utilize the whole measurement volume of the instrument, which is 100 x 100 x 100 mm^3. This is possible since there is no rotational unit occupying the measuring space. Instead, for 4-axis configuration, the rotational unit is put on the measuring table and reduces the measuring volume to 40 x 40 x 40 mm^3. The measuring volume for 3- and 4-axis configurations is shown in figure 2. Hiersemenzel et al [5] proposed a cylindrical artifact for length error evaluation for the 3-axis configuration. Another proposal for an artifact along its verification procedure for 3-axis configuration has been reported in [6]. Meanwhile, the proposal for artifacts and their procedure for performance verification for 4-axis configuration can be found in [7]. In Moroni et al [6][7], a standard steel sphere of G10 [8] mounted on a plate was used to determine the distance to the center as a measure of length. The use of a steel sphere is feasible as also has been reported in [9]. The artifact and procedure in [6][7] follows ISO 10360-8 and provides the parameter for length measurement error, probing error, and flatness measurement error. Additionally in [7], the rotational axis error following ISO 10360-3 can be obtained.

In the case of performance verification for 4-axis configuration, it seperates the linear movement (3-axis) and rotational movement (4th-axis) as coherent within the ISO 10360 series. ISO 10360-8 address linear measurement and ISO 10360-3 adresses the rotational movement. In reality, it is possible to measure a part involving simultaneous movement both for the three linear and one rotational axis. For example, if one wants to measure a distance between features on cylindrical part in which 3D linear movement and rotational movement should be used simultaneously. This type of measurement is still not considered in the ISO 10360 standard series.

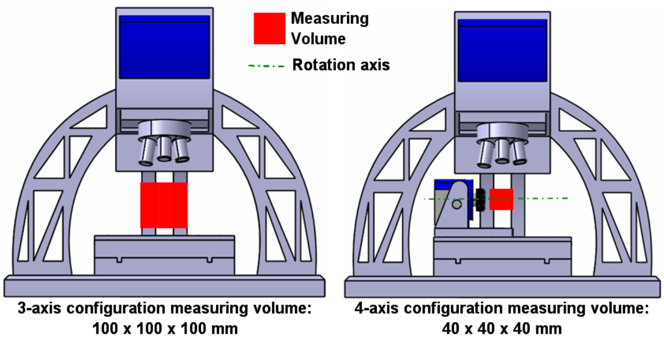

Figure 2: Measuring volume for 3-axis and 4-axis configuration.

1.2 Measuring volume for simultaneous 4-axis measurement.

For simultaneous 4-axis movement, the measuring volume is different from those for 3-axis and 4-axis configurations. The idea of this simultanoues movement is to bring all the features to be measured up above the rotational axis (figure 3 green dashed-line) in order to avoid objective lens collision and to allow easy access to the part features. In this 4-axis simultaneous measurement, the measuring volume becomes 100 x 100 x 60 mm^3 (x,y,z) and is illustrated in figure 3. It is clear from this figure that, the red box, indicating the measuring volume, is above the rotational axis line. If one compares with 4-axis measuring volume, it can be observed that the rotational axis is in the middle of the measuring volume (figure 2 right).

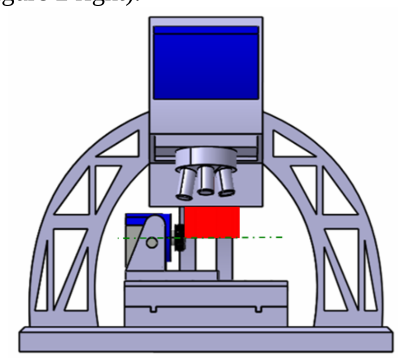

Figure 3: Measuring volume for simultaneous 4-axis geometric measurement.

2 Artifact of simultaneous 4-axis geometric measurement

2.1 Mathematical background for length in 4D

In 4D simultaneous movement, the measuring volume is still a parallelpiped and defined by a x,y, and z coordinates. Inspite of this, it can be represented as four tuples (x,y,z,θ). The x,y,z coordinates represent the 3D linear movement, meanwhile the additional angle of θ represents the rotational movement. As such, it becomes 4D movement. Hence, the eight corners of the parallelpiped measuring volume are defined as:

$$\{\, (0,0,0,\theta), (0,0,z,\theta), (0,y,0,\theta), (0,y,z,\theta), (x,0,0,\theta), (x,0,z,\theta), (x,y,0,\theta), (x,y,z,\theta) \,\} \quad \text{where } \mathbf{x} \in \{0,x\}, \mathbf{y} \in \{0,y\}, \mathbf{z} \in \{0,z\} \tag{3}$$

Due to this reason, 4D diagonal movement requires a definition of the rotational axis. The rotational axis can be defined as a point on the axis $\mathbf{x} = [x_0, y_0, z_0]^T$ and a direction normal vector (direction cosine) $\mathbf{a} = [a, b, c]^T$. Then, a point $\mathbf{p}$ in 4D (x,y,z,θ) has to be transformed to a point $\mathbf{p}'$ at 3D (x', y', z') diagonal position for a certain angle of rotation θ.

To do this transformation, one can consider $\mathbf{p}$ in a Cartesian coordinate system having the z-axis unit coincide with the rotational axis **a** and its point on origin as **x.** Hence, a possible solution for the transformation matrix from $\mathbf{p}$ to $\mathbf{p}'$ is:

$$\mathbf{i}' = \frac{\mathbf{j} \times \mathbf{a}}{\|\mathbf{j} \times \mathbf{a}\|} \qquad \mathbf{j}' = \mathbf{a} \times \mathbf{i}' \qquad \mathbf{T} = \begin{bmatrix} \mathbf{i}' & \mathbf{j}' & \mathbf{a} & \mathbf{x} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Hence, the point transformation becomes:

$$\mathbf{p}' = \mathbf{T}\mathbf{p} \Leftrightarrow \mathbf{p}' = \begin{bmatrix} \mathbf{i}' & \mathbf{j}' & \mathbf{a} & \mathbf{x} \\ 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{p} \tag{5}$$

Figure 4 illustrates the mapping from 4D diagonal to 3D diagonal.

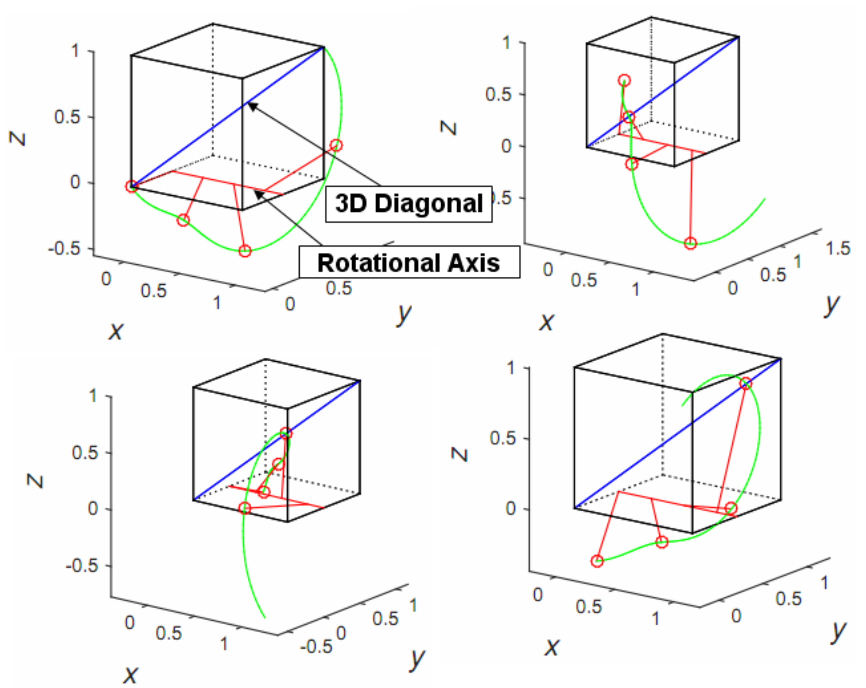

Figure 4: Illustration of 4D movement to 3D diagonal mapping.

2.2 Artifact: proof-of-concept

The proposed artifact to evaluate 4D simultaneous movement should follow the mathematical basis explaned in the previous section. The main structure of the artifact is a milled-cylindrical part made of aluminium. To obtain the distance between two points, steel spheres based on [8] with grade G10 are used. There are four spheres configuration on the artifact: 4D diagonal 1, 4D diagonal 2, x-axis, and y-axis. In each configuration, there are four spheres having different distances to each other. With this configuration, five different lengths can be measured along a direction with a minimum number of spheres such that it is easier to manufacture and calibrate. The artifact is shown in figure 5. The design of the artifact is due to the fact that the initial part is from a solid aluminum cylinder having a diameter of 80 mm. General dimension of the artifact is 90 x 80 x 80 mm^3. It is worth noting that the artifacet shape is not as important as the position and the configuration of the steel spheres. As such, it is possible to have a different shaped artifact with similar spheres configuration and position.

Figure 6 shows the artifact mounted on the instrument rotational axis along with the measuring volume. One can observe that the size of the artifact is relatively large. The weight of the artifact is around 60% of the maximum 3.5 kg allowable mass for the rotational unit. In this condition, the performance verification also take into account of weight of the part, since rotational performance depends on the weight of the part. Figure 7a shows the corresponding sphere number and position in the 3D diagonal of the measuring volume box.

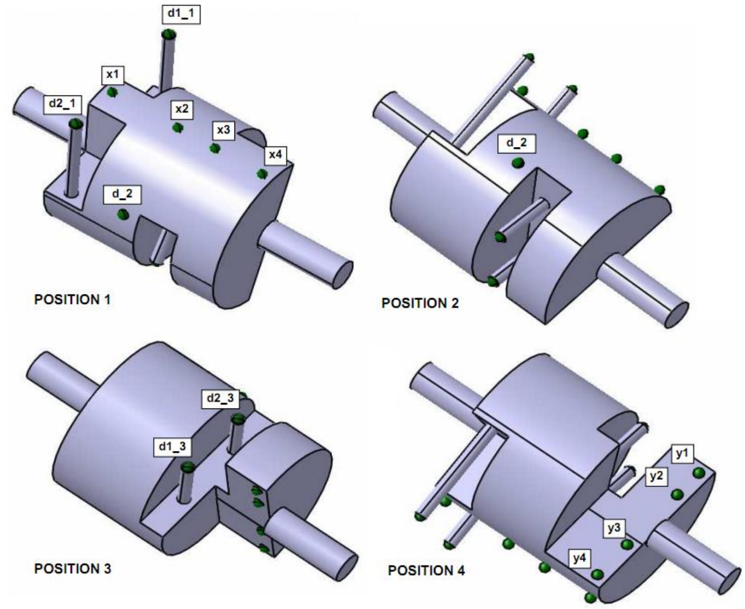

Figure 5: The proposed artifact for 4D simultanous measurement.

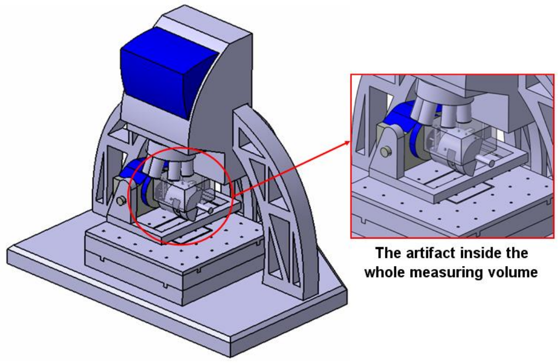

Figure 6: The proposed artefact inside the measuring volume.

2.3 Calibration

A traceable tactile CMM was used in the calibration procedure. It has maximum permissible error of $E_{0,MPE}$=2+L/300 µm, where L is in mm. Calibration procedure is carried out to determine the length between center of two spheres. The method used for the length calibration is a multi position strategy (Figure 7b). In figure 7b, the artifact is placed vertically such that all the stylus (star-configuration) can reach the spheres. With this strategy, the measurement of the artifact is taken with four differents positions to take into account the volumetric error of the CMM in the calibration uncertainty. Expanded calibration uncertainties are around 0.3-0.4 µm. There is no calibrated artifact needed for this calibration method. Results of length calibration (along with their calibration uncertainties, stated according to GUM [10]) are detailed in table 1.

Table 1: Calibration results and their uncertainties

Confguration	**Sphere number (fig.5)**	**Length (mm)**
Diagonal 1	d1_1, d_2, d1_3, y4	87.8687(2), 65.2852(2), 76.8955(3), 72.2985(2), 86.7703(2)
Diagonal 2	d2_1, d_2, d2_3, y1	52.1173(2), 36.9054(2), 41.0268(2), 72.0085(3), 120.4139(3)
X-direction	X1,x2,x3,x4	34.0044(1), 20.0244(2), 26.0139(2), 46.0381(2), 80.0420(2)
Y-direction	Y1,y2,y3,y4	11.9895(2), 43.0304(2), 14.9954(2), 58.0212(2), 70.0106(2)

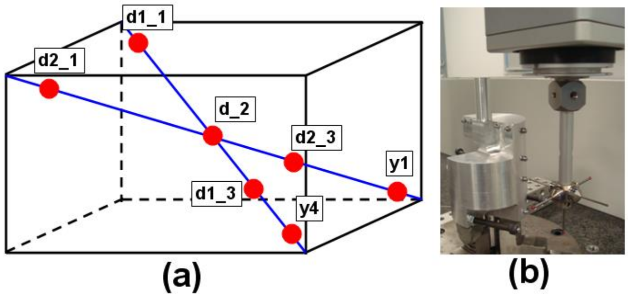

Figure 7: (a) The corresponding sphere number and position in the 3D diagonal of the measuring volume box and (b) artifact calibration process.

3 Performance verification

Procedure for performance verification of this type of 4D simultanous measurement is different than with the usual 3-axis linear measurement protocol. The main difference is that this performance verification requires rotational axis of the measurement to determine the transformation matrix for the obtained points. Hence, the first step in the performance verification is measurement of a precision cylinder made of steel to determine the rotational axis. The cylinder used is the cylinder supplied by the instrument manufacturer. From the point cloud obtained from the cylinder surface, a cylinder is fitted. From the fitted cylinder, the rotational axis (a 3D line) is derived by a point on the axis (line) and its normal direction vector. Figure 8a shows the measurement of a precision cylinder to determine the rotational axis of the measurement.

After the rotational axis is determined, the artifact is mounted on the rotational unit (replacing the precision cylinder). After the artifact is mounted, the measurement then is carried out. For linear error verification, the procedure is similar to that one found in [6] and [7], which is by measuring the four spheres reciprocally (left-to-right-to-left, for X-direction and down-to-up_to_down).

A different procedure is needed for the diagonal measurement. There are two types of diagonal: diagonal 1 and 2 (see table 1 for the involved spheres in each diagonal). Diagonal 1 is obtained by measuring spheres d1_1 to y4. Meanwhile, for diagonal 2, it is obtained by measuring spheres d2_1 to y1. The measurment of these diagonals required movement of all 4-axes. To complete the diagonal measurement, four artifact positions are required (see figure 5). To obtain all the required positions (to form 3D diagonal inside the measuring volume), three rotations are required. To measure sphere d_2, around 70^0 rotation is required. From position 2, around 80^0 rotation is required to measure sphere d1_3 and d2_3. Finally, from position 3, around 110^0 rotation is carried out to measure sphere y1 and y4. Total rotation required to measure the four diagonal spheres is around 260^0. Figure 8b presents the artifact mounted on the rotational axis.

Each rotation angle, read by the instrument rotation encoder, to obtain points on the spheres. The recorded rotation angle will be used to transform the points. The fitted sphere, used to derive its center, is applied to the transformed points. Finally, the length calculation between two spheres are carried out to verify the measurement error. The verification procedure needs around one hour for each diagonal configuration. The objecive lens used is 5X magnification lens.

Reciprocal measurmenet is carried out to take into account the hysterisis of the instrument’s moving stage and rotational unit. For each configuration, measurments are carried out three times. In the performance verification process, the error is defined as the difference between the calibrated length (used as conventional true value) and the measured length. The length is the distance between two spheres.

Results for two volume diagonals performance verification is presented in figure 9. The calculated error is obtained from the combination of 3-axis linear error and rotational error since a simultanous 4-axis movement is involved to position the spheres along the 3D volume diagonal (see figure 7a). Minimum error obtained is around 21 µm. Meanwhile, a considerably large maximum error around 500 µm is obtained. One of possible main contributor for the large error is the weight of the artifact which effects the performance of rotational axis. In addition, error due to changing the piece from the precision cylinder to the artifact in the verification procedure is also contribute to the obtained large error.

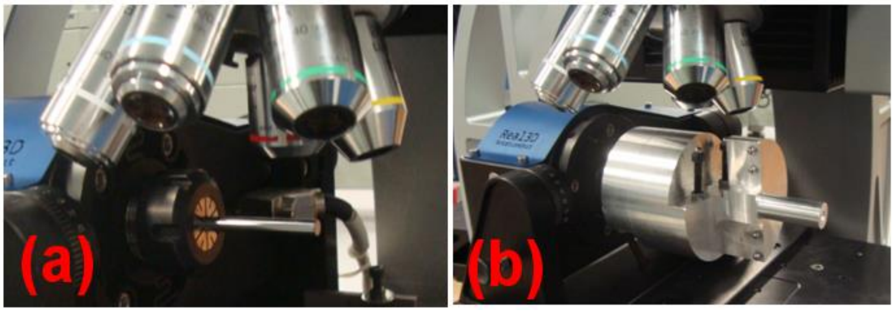

Figure 8: (a) Measurement of precision cylinder to determine the rotational axis and (b) Procedure of performance verification.

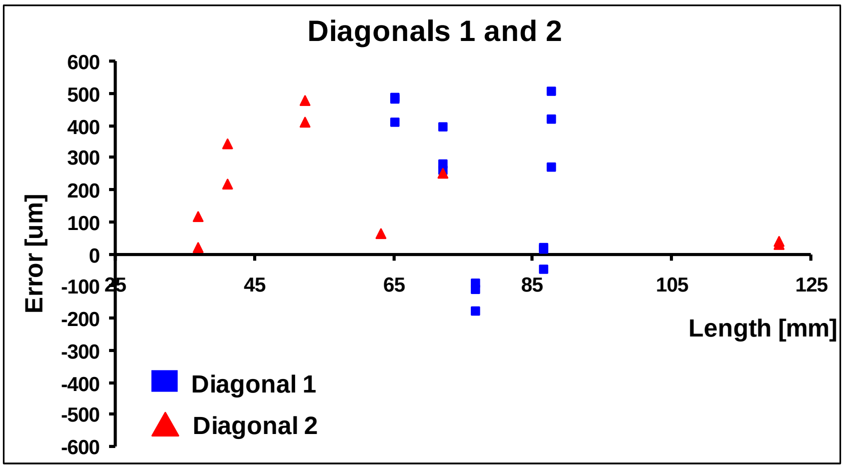

Figure 9: Length measurement error for diagonal 1 and 2.

4 Conclusions and future works

In this paper, a proof-of-concept artifact along with its verification procedure is proposed. The current standard of ISO 10360 series address the performance verification for 3-axis linear and rotational axis separately. As such, the main goal of this performance verification is to determine the maximum permissible error of 4-axis simultanously length measurement. This type of measurement involving all the 4-axis is common in application since naturally, one would bring the feature to be measure up above the rotational axis line to have better accessibility and to avoid collision between objective lens and the part. Mathematical background to represent 4D movement into 3D diagonal of measuring volume is presented as a guide for the design of the artifact. From the first performance verification result, a maximum large error around 500 µm was obtained. The error is combined contribution of 3-axis linear and rotational error. A large weight of the artifact is a possible as one of main contributor to the increase of rotational error. The future works will be development of a lighter artifact, with reduced number of spheres and reduce risk of collision between the artifact and objective lens, which can captured length measurement error inside the measuring volume.

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