Calibration of 2D and 3D Optical Measuring Instruments in Industrial Environments at Submillimeter Range

A. Mínguez-Martínez, J. de Vicente

***Abstract*—**Modern manufacturing processes have led to the miniaturization of systems and, as a result, parts at the micro and nanoscale are produced. This trend seems to become increasingly important in the near future. Besides, as a requirement of Industry 4.0, the digitalization of the models of production and processes makes it very important to ensure that the dimensions of newly manufactured parts meet the specifications of the models. Therefore, it is possible to reduce the scrap and the cost of non-conformities, ensuring the stability of the production at the same time. To ensure the quality of manufactured parts, it becomes necessary to carry out traceable measurements at scales lower than one millimeter. Providing adequate traceability to the SI unit of length (the meter) to 2D and 3D measurements at this scale is a problem that does not have a unique solution in industrial environments. Researchers in the field of dimensional metrology all around the world are working on this issue. A solution for industrial environments, even if it is not complete, will enable working with some traceability. At this point, we believe that the study of the surfaces could provide us with a first approximation to a solution. In this paper, we propose a calibration procedure for the scales of optical measuring instruments, particularizing for a confocal microscope, using material standards easy to find and calibrate in metrology and quality laboratories in industrial environments. Confocal microscopes are measuring instruments capable of filtering the out-of-focus reflected light so that when it reaches the detector, it is possible to take pictures of the part of the surface that is focused. Varying and taking pictures at different Z levels of the focus, a specialized software interpolates between the different planes, and it could reconstruct the surface geometry into a 3D model. As it is easy to deduce, it is necessary to give traceability to each axis. As a complementary result, the roughness Ra parameter will be traced to the reference. Although the solution is designed for a confocal microscope, it may be used for the calibration of other optical measuring instruments, by applying minor changes.

***Keywords*—**Industrial environment, confocal microscope, optical measuring instrument, traceability.

I. Introduction

TRADITIONAL manufacturing processes do not always allow to carry out process monitoring and control automatically nor do they allow obtaining small batches of products with a high degree of customization efficiently and profitably [1]. In order to be competitive in today's highly changing market, manufacturers have been forced to make changes to the way they work in order to meet customer needs. In 2011, the government of Germany developed the term Industry 4.0, which is understood as the application and integration of cyber physical systems within industrial production [2]. One of its objectives, from a manufacturing point of view, is to develop products with a high degree of customization and short life cycles in the market in a cost-effective way [1].

One of the main pillars of Industry 4.0 is Additive Manufacturing (AM) [2]. In these manufacturing processes, the model information of the part is taken from a CAD (computer-aided design) file, it is divided into layers that have all the necessary information and each layer is printed on top of each other until the final part is obtained [3]. Thanks to these technologies, parts with almost any geometry, that could not be obtained through traditional manufacturing processes, can be manufactured. In the 1980's, AM technologies were used to create models and prototypes, in a fast and efficient way, which allowed to get an idea of what engineers had in mind. This practice is known as "Rapid Prototyping" (RP) [2], [3] and allows to manufacture and analyze the parts in a fast and economical way. RP looks like it could allow mass customization of products at a reduced cost [3], [4], which is aligned with the principles of Industry 4.0. One of the most frequent analyses performed by manufacturers is a dimensional check. What is sought is to determine if the parts are in accordance with the design specifications. Because of this, manufacturers have had to deal with concepts as uncertainty, calibration, and metrological traceability [5]. In the field of Metrology, these concepts are defined as [6]:

- *Measurement uncertainty* (Section 2.25 of [6]): "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used".
- *Calibration* (Section 2.39 of [6]): "operation that, under specified conditions, establishes a relation between the quantity values with measurement uncertainties, provided by measurement standards, and corresponding indications with associated measurement uncertainties and uses this information to establish a relation for obtaining a measurement result from an indication".
- *Traceability* (Section 2.41 of [6]): "property of a

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measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty".

Besides, one of the industry trends is the miniaturization of systems [7]. In the field of Dimensional Metrology, one of the main lines of work today is to standardize the activities and concepts of micro and nanotechnologies. (MNT) [8]. Providing adequate traceability to 2D and 3D measurements at these scales is a problem that is currently being studied. ISO Technical Committee (TC) 229, with its different Joint Working Groups (JWGs) [8], and the research project 20IND07 TracOptic "*Traceable Industrial 3D roughness and dimensional measurement using optical 3D microscopy and optical distance sensors*" of the European Metrology Research Programme EMPIR [9] are examples of both academic and industrial interest in the standardization of MNT activities.

In this article we present a procedure to provide metrological traceability to the scales of a confocal microscope in industrial environments, as described in [10]. It is sought that the point-to-point measurements made with this measuring instrument have an adequate traceability to the unit of length of the SI, the meter. Standard materials that are easy to find and calibrate will be used in accredited metrology laboratories and industrial environments. Although the calibration procedure is designed for a confocal microscope, it can be adapted to other measuring instruments with a similar operating principle with minor changes.

Below, we detail some concepts that are handled and that we consider it may be important to comment on.

A. Coordinate Measurements

Coordinate Measurement (CM) is the measurement of spatial coordinates performed by a Coordinate Measuring Machine (CMM). A CMM is a measurement instrument capable of determining the spatial coordinates of the surface of a part using a probing system [11].

Performance verification and calibration of CMMs are terms commonly confused [8], [12]. Performance verification is a series of tests that try to prove that a given CMM meets the manufacturer's design specifications. The ISO 10360 series of specification standards shows how to perform performance verification of CMMs. Besides, calibration could be performed if we can measure, with their corresponding uncertainties, the 21 error components of the CMM. Working in this way the error map of the CMM could be compensated. But, again, the uncertainty of this error map must be estimated too [8].

The traceability of CMMs is difficult to demonstrate [8]. Normally, 10360-type tests are carried out to allow us to determine the correct operation of the machine. The uncertainties associated with the measurements made with the CMM are then determined by comparison with a standard reference material [13] or by simulating different conditions of the measurement process [14].

At the micro- and nano-level, a new kind of CMMs have been developed that are called micro-CMMs [15]. The verification and calibration of micro-CMMs is of special interest due to the need to obtain 3D measurements with great precision and low uncertainties [16]. However, when samples are analyzed with micro-CMM they can be damaged by the contact probing systems used. Therefore, 3D optical measuring instruments are gaining weight in the field of CM [17]. From the point of view of Industry 4.0, manufacturers are expected to increasingly introduce these measuring instruments to improve the control of manufacturing processes, reduce costs and improve the quality of their services and products. [18].

B. 3D Microscopy

In general, 3D microscopy can be understood as obtaining 3D images using an optical measuring instrument. Typically, these measuring instruments can provide us with the coordinates (x, y, z) of the points on the surface in two ways [19]: as $z(x, y)$ or as $z(x)$ for each y coordinate. Among the different optical measuring instruments that exist, we want to highlight four (Fig. 1):

- *Machine vision systems (MVS)*: macro-scale 3D optical measuring instruments that allow the calculation of 3D coordinates of points in the sample using a statistical adjustment of convergent light beam. Then, the data are extracted, and a 3D reconstruction of the sample is generated [18], [20].
- *Point autofocus instruments (PA)*: measuring instruments that focus on a point on the surface automatically and measure the height of the focused point. By moving the sample, the height of the points on the surface can obtained [8].
- *Confocal Microscopy (CM)*: "surface topography measurement method whereby a pinhole object illuminated by the light source is imaged by a lens onto the surface being studied and the light is reflected back through the lens to a second pinhole placed in front of a detector and acting as a spatial filter" [19]. This kind of microscopes work looking for a maximum intensity.
- *Focus Variation Microscopy*: "surface topography measurement method whereby the sharpness of the surface image (or another property of the reflected light at optimum focus) in an optical microscope is used to determine the surface height at each position along the surface" [19]. This kind of microscopes work looking for a maximum contrast.

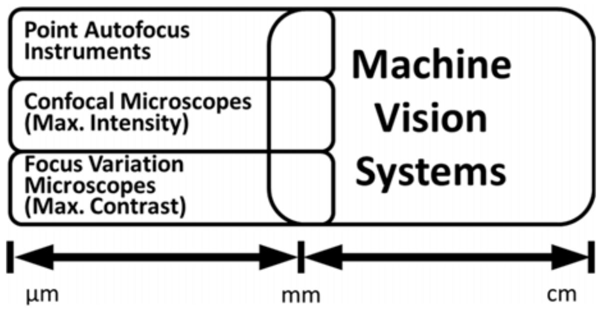

Fig. 1 Range of use of 3D Microscopes

In this article we will focus on the confocal microscope. Confocal microscopes are measuring instruments that have two pinholes that allow filtering light that is out of focus (Fig. 2)

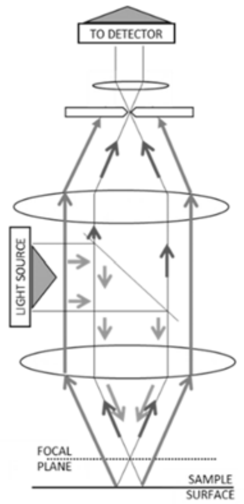

Fig. 2 Operating principle of confocal microscopes [10]

C. Confocal Microscopy

Fig. 3 shows the parts of a confocal microscope [10].

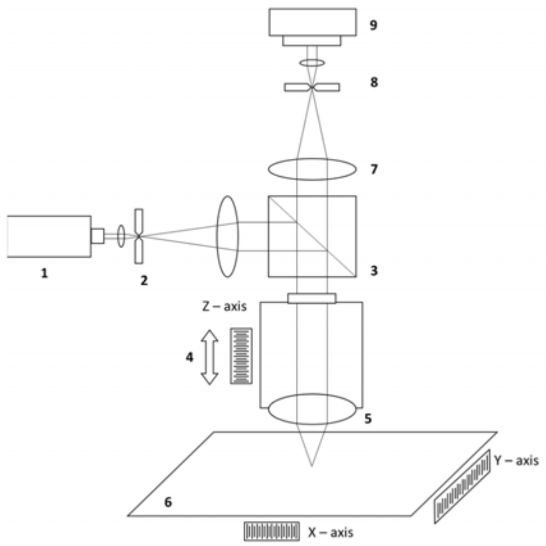

Fig. 3 Parts of confocal microscope: (1) Light source, (2) Source Pinhole, (3) Beam splitter, (4) Electronic controller and actuator on the Z axis, (5) Objective, (6) Sample surface, (7) Beam condenser, (8) Detector pinhole, (9) Detector [10]

When an image is taken with the confocal microscope, a photograph of everything in focus is acquired. Focusing on successive planes along the Z axis, surface data can be acquired. This allows the generation of a 3D model using specialized software. This process is called voxelization [10]. To provide traceability to the measurements made with these optical measuring instruments, it is necessary to carry out a calibration of the scales along the axes.

II. Materials and Methods

This section presents the measuring instruments to be used, the matrix model for the correction of the measurements made with the confocal microscope and the steps to follow in the calibration procedure of the scales of the confocal microscope. Only measurements are contemplated in which the samples do not move in the XY plane.

A. Measuring Instruments

The proposed calibration procedure is designed for [10]:

- *Leica DCM3D confocal microscope* (Wetzlar, Germany) with a 10× objective (EPI-L, NA = 0,30). Field of view 1270 µm × 952 µm (768 × 576 pixels); 1.65 µm nominal voxel width. The overall range of the z-axis is 944 µm using 2 µm axial steps (voxel height).
- *SensoSCAN—LeicaSCAN DCM3D 3.41.0 software* developed by Sensofar Tech Ltd. (Terrassa).

All standard materials described below were calibrated in an Accredited Laboratory. Although the complete range on the Z axis is de 944 µm, it will only be calibrated for a displacement of 150 µm since it is the distance normally used to measure the samples.

B. Matrix Model for the Correction of Measurements

We propose the following matrix model of linear calibration that corrects the point-to-point measurements carried out with the confocal microscope. It should be noted that it is designed for measurements in which the sample does not move in the XY plane.

$$\vec{X} = \begin{bmatrix} 1 + c_{xy} + a & \theta/2 & 0 \\ \theta/2 & 1 + c_{xy} - a & 0 \\ 0 & 0 & 1 + c_z \end{bmatrix} \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (1)$$

where $c_{xy,}$ is the deviation from the actual width of the voxel ω_{xy} of the nominal width of the pixel $\omega_{xy,nom}$; c_z is the parameter that corrects the deviation of the width from the nominal value; a is the difference between pixel widths along the X-axis (ω_x) and the Y-axis (ω_y); θ is the perpendicularity error between the X-axis and the Y-axis; (p, q, r) is the vector of the raw measurements obtained with the confocal microscope.

All uncertainties will be calculated according to [21] and [22]. This model allows to correct the deviations in the dimensions of the voxel.

C. Flatness Verification

An optical flat placed in two positions is used (Fig. 4) and the root mean square (RMS) is determined [10] as it is more statistically stable than other parameters.

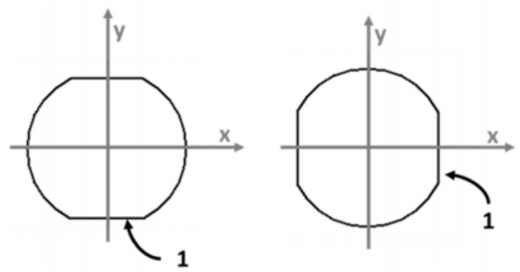

Fig. 4 Positions of the optical flat in flatness verification

D. XY Plane Calibration

A stage micrometer placed in four positions is used (Fig. 5).

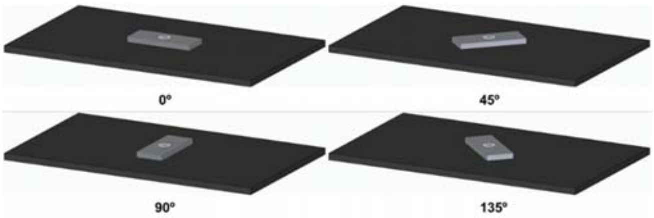

Fig. 5 Positions of the stage micrometer in XY plane calibration

Using a specialized software that pursues the stroke recognition, which looks for the lighting change and calculating the midline of the grooves, the distance between all the strokes is determined. The 45º and 135º positions seek to correct the possible paths of perpendicularity between the X and Y axes.

E. Z-Axis Calibration

A steel precision sphere with 4 mm diameter is used and measures the spherical cap (Fig. 6) in three different positions and with two types of lighting.

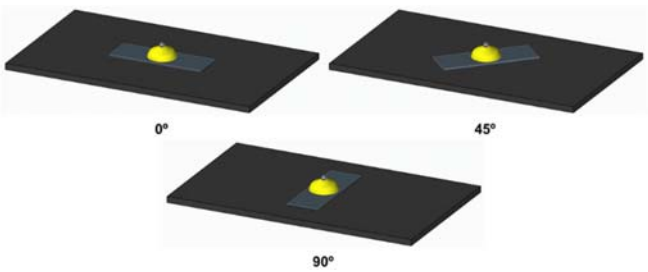

Fig. 6 Positions of the precision sphere in Z-axis calibration

The point cloud obtained is adjusted to an ellipsoid by software described in [10]. In case the diameter measured along the Z axis is different from that of the XY plane, it is corrected. Therefore, this step must be performed once the XY plane has been calibrated.

F. Roughness Calibration

Since the control software allows it, the calibration of the Ra roughness parameter will be carried out. For this, regular periodic glass patterns and irregular periodic patterns measured in the two directions of the XY plane in 5 different zones (Fig. 7) are used.

In this case it was necessary to introduce a correction due to the noise introduced by the instrument.

III. Results

Fig. 8 shows the measurement results for flatness verification (Fig. 8 (a)), for XY plane calibration (Fig. 8 (b)), for Z-axis calibration (Fig. 8 (c)) and for roughness calibration (Fig. 8 (d)).

With the data obtained, the parameters were estimated obtaining the following correction matrix:

$$\vec{X} = \begin{bmatrix} 1.008\,790 & -0.000\,399 & 0 \\ -0.000\,399 & 1.008\,870 & 0 \\ 0 & 0 & 1.010\,100 \end{bmatrix} \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (2)$$

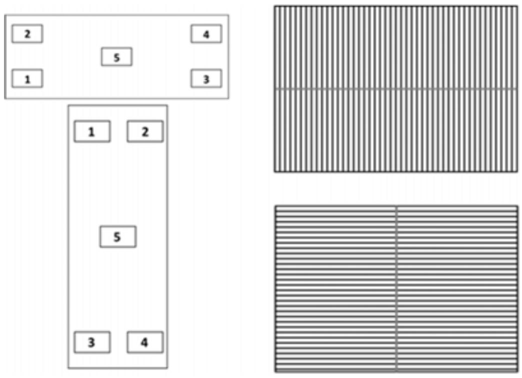

Fig. 7 Positions of the roughness reference standards in roughness calibration

Propagating the uncertainties according to [21] and [22], the following equations were obtained for the calculation of the output uncertainties of the measuring instrument:

- Uncertainty for point-to-point measurements in the XY plane:

$$U(L_{xy}) \leq 1.9\ \mu\text{m} + L_{xy}/1600 \quad (3)$$

- Uncertainty for point-to-point measurements in the Z-axis:

$$U(h) \leq 2.2\ \mu m + h/120 \quad (4)$$

- Uncertainty for roughness measurements:

$$U(R_a) < 0.25\ \mu\text{m} \quad (5)$$

IV. Conclusion

A complete calibration method has been presented that provides adequate traceability to the scales for length measurements and roughness measurements made with the optical system of a confocal microscope.

- The calibration procedure is reasonably simple.
- Reference standards are selected that are easy to find and calibrate.

The procedure makes it possible to estimate:

- For dimensional measurements: coef. of amplification, linearity and flatness defects, perpendicularity errors, repeatability and the relative difference between pixel dimensions on the X and Y axes.
- For roughness measurements: the bias that appears, the repeatability, and the noise of the instrument that affects the roughness measurement.R_a
- Obtained formula that gives a solution to the problem of estimating uncertainties for a finite number of metrological tasks.

The proposed methodology could be used to:

- Provide traceability to other similar measuring instruments, that is, that work with images represented by voxels (i.e. focus variation microscopes and vision machines systems).

- Provide traceability to measurements made with 3D optical instruments in industrial environments.
- Offer calibration services to the industry.
- Accredit dimensional measurements with 3D optical instrumentation in calibration laboratories.

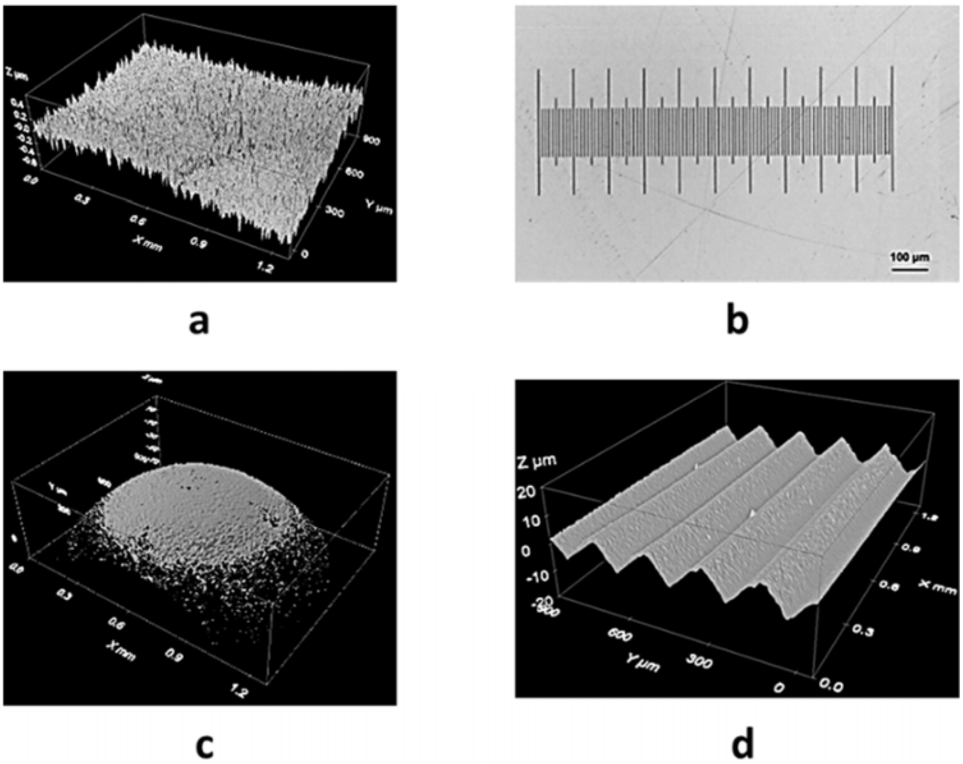

Fig. 8 Examples of measurement obtained with the confocal microscope in: (a) Flatness verification, (b) XY Plane calibration, (c) Z-axis calibration, (d) Roughness calibration

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