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The importance of optical metrology at the micro- and nano- scale in Industry 4.0

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Abstract

Manufacturing processes are currently required to produce parts with dimensions lower to 1 mm. For some specific applications, traditional manufacturing methods are not capable of satisfying the requirements of the designs. Additive Manufacturing (AM) technologies, one of the pillars of Industry 4.0, play an important role to produce detailed parts with these dimensions. AM technologies makes possible to obtain prototypes and perform proofs of concept in a faster non-expensive way, therefore speeding up the development and manufacture of new products. To ensure the quality of the products, manufacturers should ensure, among others, that the dimensions of the parts meet the requirements of the design. Given the current trend towards miniaturization of the systems, coordinate measurement systems (CMMs) commonly used in dimensional metrology cannot always be used as contact probing systems may damage the parts. 3D optical measuring instruments can be a good solution as they provide results quickly and without the samples being affected by the measurement process. In this article, we review the main 3D optical measuring instruments that can be used in quality control at the micro- and nano- scales.

Keywords: "Type your keywords (at least 3) here, separated by semicolons ;"

1. Introduction

Traditional manufacturing methods do not always allow small batches of products to be obtained efficiently and cost-effectively. Manufacturing processes are often independent, and the integration of production systems is weak (Shi et al.,, 2020; Park, 2016). Besides, safety also plays a very important role when developing new products and implementing production machinery. The increasingly widespread use of digital technologies has led to a digital transformation in the industry (Alonso et al., 2019). This is known as Industry 4.0.

The concept of Industry 4.0, or Smart-factory, was first introduced at the Hanover Fair in 2011 by the Government of Germany and consists of the application of cyber-physical systems (CPS) in industrial production systems, that is, in the digitalization and robotization of production and logistics processes (Ghobakhloo, 2018; Andonov and Cundeva-Blajer, 2018).

From the manufacturing point of view, its main objective is to obtain a productive system capable of creating small batches of products, with short life cycles and extreme mass customization in a cost-effective way (Shi, 2020). The main technological trends are (Alonso et al., 2019; Ghobakhloo, 2018):

- Internet of Things (IoT): among which we have Internet of Services (IoS), Internet of People (IoP) and Intenet of Data (IoD).
- Cloud computing.
- Big Data technologies.
- Blockchain.
- Augmented reality (AR).
- Cybersecurity.
- Automation and industrial robotics.
- Simulation and modeling techniques
- Additive manufacturing (AM)

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All pillars of Industry 4.0 are aimed at achieving increased product quality and maximizing process performance while reducing costs (Alonso et al., 2019).

It is important to highlight the concept of AM. In these manufacturing processes, part model information is taken from a CAD (computer-aided design) file and divided into layers along the Z axis. Each layer contains all the geometric and structural information of each Z level. With this information, each layer is printed on the previous one until the complete geometry is obtained (Wong, 2012). Thanks to these technologies, parts with complex geometries that, using traditional manufacturing methods, would be very difficult and expensive to obtain can be manufactured. Since the 1980s, AM technologies have been used to manufacture models and prototypes of what engineers had in mind. This is what is known as Rapid Prototyping (RP) (Ghobakhloo, 2018; Wong, 2012) and allows to analyze these parts in a fast, efficient way and with a reduced cost. In this way, thanks to RP, the objective of "mass customization" of Industry 4.0 can be met (Townsend, 2016).

One of the most widespread trends at the industrial level since the electronic revolution of the mid-1960s is the miniaturization of systems (Madou, 2002; Frazier, 1995). Manufacturing processes have had to be adapted to enable the manufacturing of products at scales below the millimeter with enough quality level. However, before they can be used, all products must go through quality control to determine the conformity of parts and prototypes with the engineers' design specifications.

The goal of this document we to rise the importance of the main 3D optical measuring instruments to perform the measurement of micro- and nanoscale parts in a fast, agile, and economical way, how they are integrated within the framework of Industry 4.0 and the problem of calibrating these devices.

2. Optical metrology in Industry 4.0

Among the different quality control tests, dimensional verification is often one of the most carried out. Therefore, manufacturers have had to deal with concepts such as uncertainty, calibration, and metrological traceability (Sladek, 2016). These concepts are defined in (Joint Commitee for Guides in Metrology, 2012) as:

- Measurement uncertainty (Section 2.25): “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”.
- Calibration (Section 2.39): “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): “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty”.

As it can be seen, Metrology, and particularly Dimensional Metrology (DM), is a tool that manufacturers use to meet the challenge of ensuring product quality (Alonso et al., 2019).

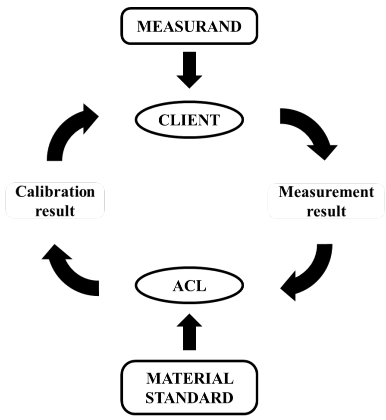

Fig. 1. Calibration process.

With a traced measuring instrument, one of the most used methods to give traceability to manufactured parts is to compare the measured value on the part with the known value of a standard material reference and determine the difference between both measures (Raghavendra and Krishnamuthy, 2020).

As shown in Fig. 1, customer reference instruments under calibration are traditionally sent to an Accreditation and Certification Laboratory (ACL) to perform its calibration. Once calibrated, the ACL sends it to the customer. This practice, although it is effective and provides good results, the time consumption, costs, and risk of being damaged during transport makes it inefficient (Alonso et al, 2019; Andonov and Cundeva-Blajer, 2018). Another common practice that is widespread is that of the "mobile laboratory", that is, the ACL goes with its technicians and its standards to the customer's installations. Then, they calibrate al the reference instruments that should be calibrated for as long as necessary, without the client having to send any equipment.

The technologies that support Industry 4.0 offer us a solution that consists of connecting calibration laboratories and customer laboratories by sending the measurement and calibration data. To do this, instead of sending the measuring instruments to the ACL for calibration, this is carried out on-line. The customer should have a calibrated standard in their installations, and, with an operator, the ACL guide the data collection process. Once the results of the measurements have been taken, they are sent to the ACL and, after carrying out the data processing, the ACL sends the calibration results to the client (Alonso et al., 2019; Andonov and Cundeva-Blajer, 2018). This philosophy makes it possible to save both time and money and does not jeopardize the integrity of the reference instruments or the material standards during the displacements. However, it also presents several challenges that need to be addressed (Alonso et al., 2019; D'Emilia and Gaspari, 2018):

- As measurements are carried out outside the ACLs, the temperature and humidity conditions that affect the measurement cannot be controlled.
- Measurement systems must be adapted so that they can be used by non-specialist personnel.
- Each measuring instrument should be connected to the network to allow both remote operation and data transmission.
- Data integration.

At macro scale-, the comparison method is widely used for the calibration of gauge blocks, as specified in Section 8.4 of (ISO, 1998), and for measurements carried out with Coordinate Measurement Machines (CMM), following the principles of (ISO, 2005). Another method, collected in (ISO, 2008), consists of the simulation of different conditions de measure. At scales below the mm, the solution is more complicated since contact stockings can damage samples. Optical measuring instruments, whether the different types in Fig. 2, seem to be a good solution to obtain measurements at these scales with great precision (Claverley and Leach. 2015).

We believe that optical measuring instruments (see Fig.2) will play a very important role soon. Their wide field of work, the possibility of performing many metrological tasks, and the possibility of connecting them to the network makes them a good option within the framework of Industry 4.0. Among them we find:

- Machine Vision Systems (MVSs) MVSs are macro-scale, 3D optical devices capable of obtaining a series of data from an image using a statistical adjustment of convergent light beam. Then, it is possible to analyze them creating a 3D reconstruction of the sample and allow decisions to be made based on it (Alonso et al., 2019; Woodhouse et al., 1999).

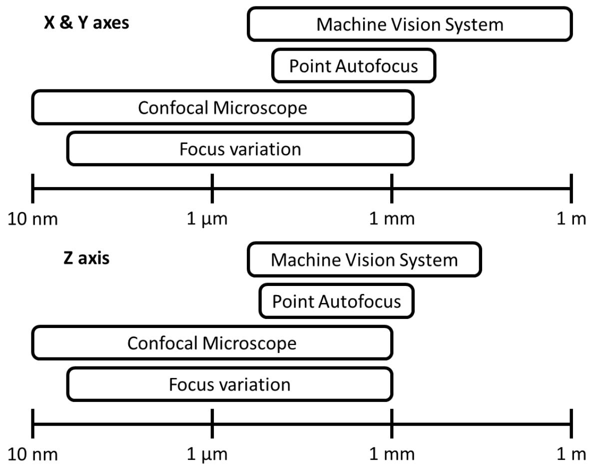

Fig. 2. Working scales of Optical Measuring Instruments.

- Point autofocus instruments (PA): are measuring instruments that determine the z-coordinate of a focused point on the surface automatically. By moving the sample, the height of all the points on the surface can obtained (Leach, 2010). Basically, these are traditional measuring microscopes (in principle 2D) to which, by means of an automatic type autofocus, it has been possible to add a probing system on the Z axis and, therefore, are also able to measure the third coordinate.
- 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" (ISO, 2010). 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" (ISO, 2010). This kind of microscopes work looking for a maximum contrast.

It is important to highlight that Focus Variation and Confocal Microscopes reach resolutions of up to 10 nm on the Z axis. On the X and Y axes their resolutions can be greater than 0.3 μm Considering the current trend in industry to miniaturization and the difficulty of carrying out measurements in these ranges commented above, these measuring instruments would represent a good option to carry out 3D dimensional measurements.

These types of measuring instruments are used in a very wide range of fields. Among them we can find the identification and classification of materials (Penumuru et al. 2020), the measurement of distances, angles and other geometries, the determination of 2D and 3D surface roughness parameters (Mínguez-Martínez, 2019), the analysis of biological samples, etc. As can be seen in Fig. 2, these measuring instruments cover a range of dimensions ranging from 0.01 μm to 4-5 mm.

The advantages of optical measuring instruments are:

- By adding the z-coordinate to a measuring microscope, the 3D geometry of surfaces can be analyzed, and quantitative and qualitative data can be obtained from them.
- One single measurement image permits to obtain a lot of measurements and it could be used later to obtain other dimensions and non-measured dimensional characteristics.
- In the environment of Industry 4.0, these measuring instruments would enable to characterize AM manufactured parts, that usually have very small dimensions and, therefore, reduced manufacturing tolerances.
- The measurement is carried out without contacting the surface of the part. This way, the AM produced parts are not subject to the risk of being damaged during the measurement process. In addition, the accessibility of optical measuring instruments is higher than that of contact probing systems.
- With an adequate calibration together with the integration within the quality system of the factories, these measuring instruments are expected to allow the obtention of results with great precision in a fast, agile, adaptable to different needs, economical and without jeopardizing the integrity of the standards. This makes optical measuring instruments very important tools soon.

However, the calibration of these devices still needs to be standardized. The material standards that can be found, both included in the ISO standards and commercially, use to be very complete and cover many metrological tasks. However, they are usually expensive to obtain and calibrate, they need specialized, technical staff to use them and many of them do not always allow traceability to point-to-point measurements. Providing adequate traceability to 2D and 3D measurements at these scales is one of the biggest challenges facing the field of DM. ISO Technical Committee (TC) 229, with its different Joint Working Groups (JWGs) (Leach, 2010), 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 (ENMPIR, 2021) are examples of both academic and industrial interest in the standardization of this issues.

In literature it is possible to find some approaches to calibration methods to these measuring instruments. For example, in (Mínguez-Martínez and Oliva, 2019), we propose a procedure to accomplish the calibration of a confocal microscope using material standards easy to find and calibrate in industrial environments. This procedure is designed to give traceability to point-to-point measurements performed with this kind of 3D optical microscope. It is important to say that could be adapted to be used with the other 3D optical measuring instruments.

3. Conclusions

Industry 4.0 is a revolution at all levels of the production process. In an environment in which accurate measurements need to be obtained in a fast, agile, and economical way, the technologies offered by Industry 4.0 allow us to connect a client with the ACLs to provide traceability to the measuring instruments of the different manufacturers. This document presents the most widely used optical measuring instruments and highlights the importance they are expected to have in the coming years.

In addition, the importance of the concept of traceability of optical measuring instruments to make 2D and 3D measurements at scales below mm is highlighted. However, the task of giving adequate traceability, with enough precision for each application, to 3D optical measuring instruments is one of the challenges that dimensional metrology is facing.

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