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Measurement and correction of the slope angle of flat surfaces digitized by a conoscopic holography system

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ABSTRACT

Conoscopic Holography (CH) is a non-contact interferometric technique used in surface digitizing. Similarly to other laser techniques it is influenced by the optical behaviour of the part surface and the conditions during scanning (geometry, strategy, etc.). In this work, a CH system and a touch probe (TP) integrated in a CMM were used to analyse the CH behaviour for measuring the slope angle of flat surfaces in inspection tasks. For this purpose, several digitizing tests were performed with both sensors on a square specimen under different slope angles. The tests were performed for two different orientations of the laser spot as well as at three different positions within the sensor depth of field (DOF). The specimen angles determined by each sensor were compared to each other and the difference (*slope deviation*) was used as an indicator of the CH behaviour. Considering the results, some recommendations were provided for digitizing sloped flat surfaces with the CH sensor and it was also developed a model to predict and compensate the measurement deviations of this sensor with regard to the TP.

1. Introduction

Industrial use of commercial scanners like non-contact digitizing systems has grown significantly in recent years with a wide range of applications that go from dimensional metrology to reverse engineering [1–3]. Apart from avoiding contact with the object to be measured, the main advantages over contact systems are the ability to capture small geometries and complex shapes as well as the high rate for points acquisition. Additionally, the portability of non-contact systems offers the possibility to be installed on different equipment such as coordinate measuring machines (CMM), articulated arm coordinate measuring machines, machine tools or production systems, which certainly favours its industrial application.

Despite the above advantages, commercial non-contact scanners are usually less accurate than the traditional contact-type methods, since their accuracy depends strongly on the relative position and orientation of the sensor with regard to the digitized part, the configuration parameters of the sensor, the part geometry, the optical properties of material, the surface roughness, etc.

Currently, there exist numerous non-contact techniques for surface digitizing, such as those based on triangulation laser which are more deeply analysed and disseminated every day [4–11]. Some of them [4–6] examined the effect of scan distance and beam incident angle on the random and systematic errors of the scanner. In the case of Feng et al. [4] and Isheil et al. [6] also provided models for compensating the measurement errors.

Using a triangulation laser scanner installed in a CNC platform Vukašinović et al. [8] found that the intensity of the light reflected by a digitized surface decreased as the surface slope increased. The best measurement results were obtained for surfaces with a good diffuse reflection and nearest to the sensor. Considering these influence factors the authors provided a mathematical model to predict the measurement uncertainty for a laser-scanning process [9].

The study presented by Bin et al. [10] used a laser sensor mounted on a 5-axes machining centre to analyse the effects of the position and orientation on the laser measurement of free-form surfaces. To improve the measurement accuracy, a measurement strategy that considered the position and orientation of the sensor and a semi-quantitative error-compensation model based on geometrical optics was proposed. Manorathna et al. [11] presented a set of performance evaluation tests for a 3D laser scanner attached to a 6-axes robot. The scanner was evaluated under operating conditions such as different surface reflectivity, view angle, surface roughness and stand-off distance. The best working range was

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established and the regions of noise and missing data were identified and quantified.

Apart from these works related to laser triangulation sensors, the performance of other scanning technologies has not been fully described yet. This is the case of Conoscopic Holography (CH), an interferometric technique based on the double refractive property of birefringent crystals. It was first described by Sirat and Psaltis [12] and patented by Optimet Optical Metrology LTD. The underlying physical principle of measurement of this type of sensor is included in the guideline VDI/VDE 2617-6.2 [13]. Malet and Sirat [14] stated that the performance of a conoscopic system can be described by the quartet of precision, depth of field, speed and transverse resolution. Furthermore, many advantages of CH in front of laser triangulation were reported by Sirat et al. [15]: better accuracy and repeatability, good behaviour for a wide variety of materials, ability to digitize steep slope surfaces and feasibility to combine the sensor with different lenses to adapt to various depths of field. Finally, being a collinear system allows for accessing to complex geometries such as holes or narrow cavities, by using simple devices for light redirection.

All these characteristics demonstrate the feasibility of CH systems for being applied to different fields of industry, including quality assessment, reverse engineering or in-process inspection [16].

Nevertheless, CH digitizing quality may be affected by a lot of factors similarly to other optical techniques. In the work by Paviotti et al. [17] a preliminary study on the assessment of angle-dependent errors for a conoscopic holography laser sensor was presented. They used a calibrated sphere to analyse the influence of the incident angle by means of a free of angle-dependent error indicator based on the difference between the measured Z coordinate and its expected value. They obtained some results on the systematic error and the uncertainty of this indicator. Lathrop et al. [18] applied CH technology for surface digitizing of biological tissues. Signal-to-Noise Ratio (SNR) was used to adjust the sensor in order to obtain reliable measurements. They concluded that the nature of surface material (colour, texture) and the sensor setting parameters had notable influence on digitizing quality.

Following recommendations by the manufacturer, different authors [19–21] used SNR as a quality indicator to adjust the CH sensors. Nevertheless, Fernández et al. [22] stated that the use of this indicator is not sufficient to guarantee good accuracy in the measurements carried out by the CH sensor. In those cases with high precision requirements, a geometrical type indicator should be used to ensure minimum errors in measurement.

The standard ISO 10360-8 specifies the acceptance tests for performance verification and reverification of CMMs with optical distance sensors [23]. The tests evaluate different types of errors (probing form error, probing size error, length measurement error, etc.) that may be affected by the surface slope at each digitized point. However, this standard does not provide any specific test to determine the slope angle error. Thus, in the present work, a commercial-type CH system integrated in a CMM was used to analyse the ability of this type of sensor for measuring the slope angle of flat surfaces in inspection tasks. Two EDM manufactured specimens were used to define different angles. They were scanned under each angle by means of the CH sensor as well as with a TP. Furthermore, the scanning procedures were repeated for two different orientations of the laser spot as well as at three different positions of the specimens within the CH sensor DOF. Since the precision of the TP is independent of the specimen slope and its location within the DOF, the angles determined by the CH sensor were compared to those obtained by the TP. Considering the results, some recommendations for digitizing sloped flat surfaces with the CH sensor are provided. Finally, a model to predict and compensate the measurement deviations of this sensor with regard to the TP is developed and validated.

Table 1
Characteristics of the conoscopic holography sensor Mark 10.

Property (Lens 100 mm)	Value
Dimensions ($L \times W \times H$) (mm)	167 × 79 × 57
Weight (g)	720
Measuring frequency, F (Hz)	up to 9000
Power level, P[a]	0–63
Depth of field, DOF (mm)	35
Stand-off (mm)	95
Min Stand-off (mm)	92
Max Stand-off (mm)	98
Laser spot size X[b] (μm)	43
Static resolution (μm)	0.1
Precision (μm)	15
Reproducibility 1σ (μm)	4
Angular coverage (°)	170

[a] Maximum power level (63) is equivalent to 1 mW.

[b] Spot size is the effective width for measurement that contains 50% of the energy delivered, as measured at the centre of the working range.

2. Description of the measuring system

The work described in this study was performed by means of the Conoscopic Holography (CH) sensor Conoprobe Mark 10 by Optimet, equipped with a lens of 100 mm focal length and 35 mm of working range (depth of field). The visible light source is a Class II laser diode which wavelength of 655 nm. This is a point-type sensor, thus each reading provides the value of the distance from the transmitter to the projection of the laser beam on the material surface (spot). The spot shape is not completely round but it is elliptical indeed (Fig. 1). The minor axis of the ellipse is aligned with the X direction of the CH sensor (X_{CH}) whereas the major axis coincides with the Y direction of the sensor (Y_{CH}). Table 1 shows the main characteristics of the CH sensor [24].

In order to perform accurate sweeps of a surface, the CH sensor was integrated in a DEA Swift Coordinate Measuring Machine (CMM). The maximum permissible error of length measurement ($E_{L,\ MPE}$) and maximum permissible single stylus form error ($P_{FTU,MPE}$) of this CMM were certified as (ISO 10360-2 and ISO 10360-5):

$$E_{L,MPE} = \left(4 + 4 \cdot 10^{-3} \cdot L\right)\ \mu\text{m, being } L \text{ in mm} \tag{1}$$

$$P_{FTU,MPE} = 4 \mu\text{m} \tag{2}$$

This CMM is operated by means of the measurement and control software PC-DMIS. Volumetric reasons led to install the sensor on the Y axis of the CMM. This implies that the sensor can be displaced on a plane parallel to the $X - Y$ reference system, but not in Z direction (Fig. 2).

Once the CH sensor is attached to the CMM, it is necessary to perform a calibration procedure in order to know the coordinates of any digitized point with respect to the machine origin. This calibration was carried out using a calibrated sphere. The procedure was described by Fernández et al. [25] and inspired on the work by Smith and Zheng [26] was used in this work.

Besides, in order to perform the scanning tests in a continuous mode, it is necessary to synchronize X and Y movements of the CMM with the instant in which the CH sensor captures and records the measurement of a point. The Conoprobe Mark 10 is able to read the pulses of the CMM encoders and uses them as triggering signals for taking the measurements. In the CMM used in this work, it was determined that the distance traversed along an axis corresponding to one encoder pulse is 0.004 mm. In the tests the distance between points captured was set to 0.040 mm, thus the triggering signal was activated each 10 pulses (see Section 3.3).