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Surface roughness influence on chromatic confocal dimensional measurements

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Abstract
Over the last decades, optical metrology has gained increasing relevance in the industrial scenario, due to the growing demand for high-speed, high-precision, and non-invasive measurements. In this context, chromatic confocal sensors (CCSs) have emerged as a valuable solution offering nanometric resolution and sub-micrometric accuracy, making them suitable for use in metrological applications. On the other hand, their performance can be significantly affected when dealing with non-cooperative surfaces, i.e., surfaces that pose challenges to optical systems due to their inherent characteristics (e.g., complex geometry, reflectivity-related effects, etc.), such as rough surfaces. This contribution focuses on the systematic offset observed on rough surfaces when CCS-based dimensional measurements are compared with tactile ones. An extensive experimental campaign was conducted on stainless-steel specimens produced by different processes and surface roughness *Ra* in the range 0.01-50 µm. Results reveal that for fine finishes, the deviation between the CCS and tactile probe remains within the probing-size error limits, whereas on rougher surfaces, CCS measurements exhibit systematic deviations exceeding the optical distance probe specifications. Based on the experimental results, a simple and straightforward correction model based on surface roughness parameters is proposed.

Dimensional metrology; Chromatic confocal distance sensor; Surface roughness; Optical-tactile deviation; Error compensation.

1. Introduction

The increasing demand for high-throughput and high-precision inspection in advanced manufacturing has favoured the adoption of optical sensors in dimensional metrology [1]. Compared with contact probing systems, optical technologies offer higher acquisition rates and avoid surface deformation, making them attractive for inspecting fragile or complex components [2]. Among optical distance sensors, chromatic confocal sensors (CCSs) have emerged as they provide nanometric resolution and sub-micrometric accuracy [3]. Despite these advantages, the interaction between optical sensors and industrial surfaces remains a critical issue. Unlike calibrated artefacts, manufactured components often exhibit non-cooperative surface conditions, such as high roughness, which can significantly affect optical measurements [4]. In practice, this may lead to discrepancies when optical and tactile measurements are compared. Previous studies have investigated the influence of surface properties on CCS performance, often focusing on a limited range of roughness values. However, a quantitative understanding of how roughness affects CCS-based dimensional measurements across a wide, industrially relevant range of surface roughness values remains incomplete.

This contribution focuses on the effect of surface roughness on CCS-based dimensional measurements, with two main objectives: (i) identifying the surface roughness regime in which CCS measurements remain consistent with tactile probing, and (ii) proposing a simple and straightforward compensation strategy to reduce systematic optical-tactile deviations on rough surfaces.

2. Materials and methods

The experimental campaign was designed to assess the influence of surface roughness on dimensional measurements using a CCS (also referred to as optical distance sensor) mounted on a multisensor CMM. The analysis was carried out assuming that the optical probe axis is normal to the test surface selected in this study. The measured distance d provided by the CCS can be expressed as:

$$d = d_m + \Delta d \tag{1}$$

where d_m is the distance measured and Δd is the systematic optical-tactile deviation, defined as the difference between CCS and tactile measurements acquired in the same measuring volume. The aim of this study is to characterise Δd as a function of surface roughness and to identify conditions under which a correction is required. The analysis focuses on the high-roughness range, where CCS deviations are expected to be most significant.

2.1. Experimental setup

Measurements were carried out in a temperature-controlled laboratory (20 ± 0.5 °C) using a multisensor CMM ZEISS O-Inspect 322 equipped with a 2 mm stylus tip. The maximum permissible error of length measurement is $E_{0,MPE}$ = (1.6 + L / 200) µm (L in mm), and the repeatability limit is $R_{0,MPL}$ = 1.2 µm. The CCS features a micrometric optical spot and a maximum permissible probing size error (PS-MPE) of 5 µm.

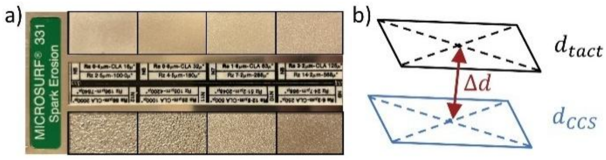

Figure 1. a) spark erosion roughness specimen; b) schematic definition of the optical-tactile deviation Δd.

Four stainless-steel roughness specimens, produced by polishing, grinding, end milling and spark erosion were selected to span typical industrial surface textures (*Ra* ≈ 0.01 - 50 µm), for a total of 29 test surfaces. Figure 1a) shows an example roughness specimen. For each surface, a 5 × 5 mm region was acquired using both probes along 10 parallel scan lines, resulting in approximately 1000 measured points per dataset. A least-squares plane was fitted to each point cloud. The optical-tactile deviation Δd, defined in Equation (1), was evaluated as the difference along the z-direction between d_{CCS} and d_{tact}, corresponding to the coordinates of the centres of the planes fitted to the optical and tactile datasets, respectively. A schematic representation of the definition of the optical-tactile deviation Δd is shown in Figure 1b).

Surface texture characterisation was carried out using an optical profiler (Sensofar S Neox) operating in confocal microscopy mode with a 20× objective. Roughness parameters were evaluated in accordance with the ISO 21920 series.

3. Results and discussion

In Figure 2, the mean of the optical-tactile deviation Δd and the standard deviation of ten repetitions are summarized as a function of the surface roughness parameter *Ra* for all 29 test surfaces. For fine surfaces, corresponding to *Ra* values below approximately 3 µm, the deviation remains within the probing size limits specified for the CCS. In this roughness regime, CCS-based dimensional measurements can therefore be considered consistent with tactile probing, and no systematic correction is required.

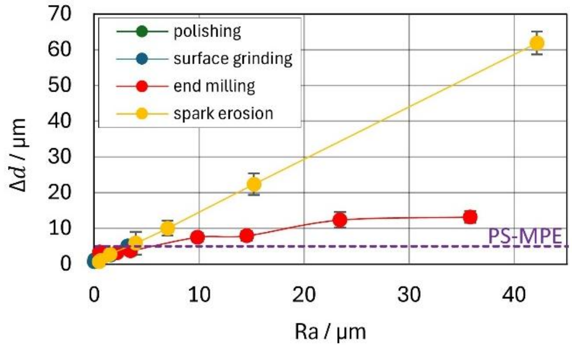

Figure 2. Optical-tactile deviation Δd as a function of *Ra*

As surface roughness increases, a clear systematic deviation emerges. For rougher surfaces, particularly those produced by end milling and spark erosion, Δd exceeds the nominal probing-size error of the optical sensor.

Although *Ra* provides a first indication of this trend, it does not fully describe the observed deviations across different manufacturing processes. A stronger correlation was found with the mean peak height parameter *Rp*. When Δd is plotted against *Rp*, as reported in Figure 3, the data tends to stabilise onto a constant value, regardless of the machining process.

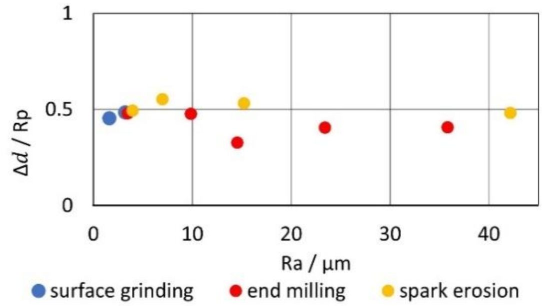

Figure 3. Ratio $\Delta d/Rp$ in relation to *Ra*

Based on the experimental evidence, a simple empirical compensation model was formulated by expressing the optical-tactile deviation as a proportional function of *Rp*:

$$\Delta d \approx k \cdot R_p \tag{2}$$

where k is an experimentally determined coefficient. For the investigated conditions, k was found to be approximately 0.5. This behaviour can be explained by the fundamentally different interaction mechanisms of optical and tactile probes. The CCS, characterised by a micrometric optical spot, samples both peaks and valleys of the surface, whereas the tactile probe predominantly interacts with surface asperities due to its finite tip size. As the height of the surface peaks increases, this difference in interaction leads to an increasing offset between the two measurement principles.

By compensating for the roughness-induced bias, CCSs can be reliably employed beyond their typical operating domain, enabling their application to rough, non-cooperative surfaces.

5. Conclusions and outlook

This paper investigated the influence of surface roughness on dimensional measurements obtained using a CCS mounted on a multisensor CMM, with tactile probing from the same measuring volume used as reference. An extensive experimental campaign was conducted on stainless-steel surfaces produced by different manufacturing processes and spanning a wide surface roughness range (*Ra* ≈ 0.01 - 50 µm).

The results demonstrate that for fine surfaces (*Ra* < 3 µm), CCS-based measurements are consistent with tactile probing within the sensor specifications. For rougher surfaces, however, a systematic optical-tactile deviation emerges and increases with surface roughness, exceeding the nominal probing-size limits of the optical sensor.

A correlation between the deviation and the mean peak height parameter *Rp* was identified. This enabled the formulation of a simple roughness-based compensation model that reduces the mismatch between optical and tactile measurements on rough surfaces. The proposed approach extends the reliable applicability of CCSs in dimensional metrology under non-ideal surface conditions. Future work will address the influence of probe size, surface tilting, and complex geometries on the proposed compensation strategy. , as well as It will also investigate the use of areal parameters to further refine the model, and integratethe integration of roughness-based correction models into uncertainty evaluation frameworks for multisensor dimensional measurements.

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