Development of a traceable performance verification route for optical micro-CMMs

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Abstract

There is growing industrial interest in improved measurements of small-scale objects, with demands for co-ordinate geometry data with higher resolution and accuracy than existing tactile CMMs can provide, and for instruments to have better data acquisition capabilities. Whilst traditionally contacting stylus-based co-ordinate measuring machines (CMMs) have been used for 3D measurement of small-scale objects, there is now significant interest in optical instruments. The introduction of optical techniques has already caused innovative advances in dimensional metrology. However, in a similar manner to contact CMMs, demonstrating confidence in the measurement data requires a robust performance verification route, traceable to the definition of the metre.

The focus variation (FV) technique has the potential to be used for co-ordinate metrology on the micro- to millimetre scale, however, before a machine using such a technique is brought to the market, a suitable verification procedure should ideally exist. The ISO 10360 suite of specification standards for CMM verification is designed for tactile instruments and some optical instruments, but does not specifically reference the FV technique. Progress in the development of a verification artefact that specifically addresses the needs of a CMM based on FV is presented. The potential for using spheres as part of a performance verification artefact is investigated.

1 Introduction

Focus variation (FV) is a technique that has been implemented in surface metrology instruments in the past decade. The technique has developed from ‘depth of field’ [1] to ‘depth from focus’ [2] to ‘shape from focus’ [3], until it finally developed into ‘focus variation’ [4] with highly sophisticated hardware and software.

The hardware of FV instruments is closely related to that of a microscope; both focus white light onto a surface and the reflected light forms an image of the object on a detector. The important difference is the variable focal plane, which allows images to be taken at different positions along the vertical axis.

During a measurement, a stack of images (figure 1) is acquired with different areas of the object’s surface in focus. Subsequently, the images are processed to evaluate the degree of focus for each pixel in each image by contrast analysis using a robust sum-modified-Laplacian algorithm [4]. The next step in the image processing is to use a Gaussian distribution to interpolate the focus measured and thus to create a three-dimensional (3D) representation of the surface.

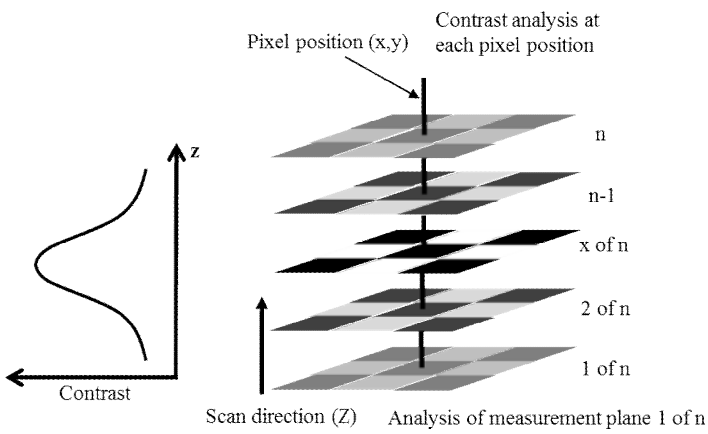

Figure 1: FV method - (left) evaluation of the focus measure, (right) maximum focus measure using Gaussian distribution

The ISO 10360 [5] suite of standards provides a framework for co-ordinate measuring machine (CMM) verification and health checking, identifying artefacts and methods. ISO/DIS 10360-8.2 [6] is specifically concerned with verification of CMMs that use optical distance sensors and presents an opportunity for traceable artefact development in the context of novel optical micro-CMMs. The FV technique lends itself to being considered for use as a non-contact micro-CMM as well as carrying out its more traditional role as a surface topography measuring technique. A key element of the current research is to develop suitable verification procedures in parallel with instrument development, to allow geometric verification of the instrument and short term

instrument health checking. However, an important issue with FV is that any reference artefact must have a certain level of surface roughness [4] for the sensor system to work effectively.
The work reported here describes the research associated with the development of a novel reference artefact based on precision spheres and compliant with ISO/DIS 10360-8.2, which allows a non-traditional optically-based CMM to be assessed for probing form and size error.

2 Experimental procedure

Spheres of size and form error suitable for use in the development of a novel reference artefact are produced in various materials. The spheres tested as part of this work were 1 mm nominal diameter precision spheres manufactured from aluminium oxide (ruby), zirconia, silicon nitride and stainless steel. The tested spheres had the following diameter tolerances: ruby (1.3 µm); zirconia (0.8 µm); silicon nitride (1.3 µm); stainless steel (38 µm) [7, 8].
The measurement procedure for each of the spheres was as follows:

- place the sphere into a holder in the measuring volume and adjust the scan length (*z*-axis travel) and settings, using a 50× magnification lens;
- measure each sphere three times (retrieve 3D model of the surface) using only one field of view;
- sphere fitting (robust method) in software to the surface data repeated five times; and
- record radius of fitted sphere.

It should be noted that the data for the ruby sphere were collected with a 10× magnification lens rather than a 50× magnification lens because of the sphere's highly reflective surface. Measurements taken with a low magnification objective have a lower lateral resolution and, therefore, higher contrast on smooth surfaces than those taken with a high magnification objective.
It was necessary to prepare the ruby spheres to provide a higher degree of surface roughness than an unprepared sphere. Ruby and zirconia spheres were etched in order to roughen their surfaces. The etchants and etching times are shown in table 1. The results of the etching process are discussed in section 4.

Table 1: etchants and etching times of the ruby and zirconia spheres

Material	Ruby	Zirconia
Etchant	1 % HF acid	6 % HF acid
Etch times	5 minutes to 100 minutes	5 minutes to 40 minutes

3 Results for non-etched spheres

Figure 2 shows the results of the measurements of four non-etched spheres using the four different materials, as captured by a FV instrument. From a purely

qualitative perspective, the ruby sphere is imaged with many spikes and data holes. Zirconia can be measured without many data holes and any spikes. It can be seen that data are missing at the edges of the images, where the surface curvature increases. It can also be noted that there are patches of smooth and featureless data (shown in the grey scale image as small dark patches). Both features indicate that the sphere's roughness is almost too smooth for satisfactory FV instruments.
From figure 2, it can be seen that (in qualitative terms) silicon nitride spheres give better measurement results than zirconia spheres. The silicon nitride sphere features a highly contrasted surface, not caused by applied micro-scale roughness as much as the chemical composition of the material. The surface representation is continuous, without any data loss or spikes. Finally, surface representation of the stainless steel sphere compares well to that of silicon nitride. The surface is continuous, which indicates a sufficient micro-scale roughness present on the sphere.

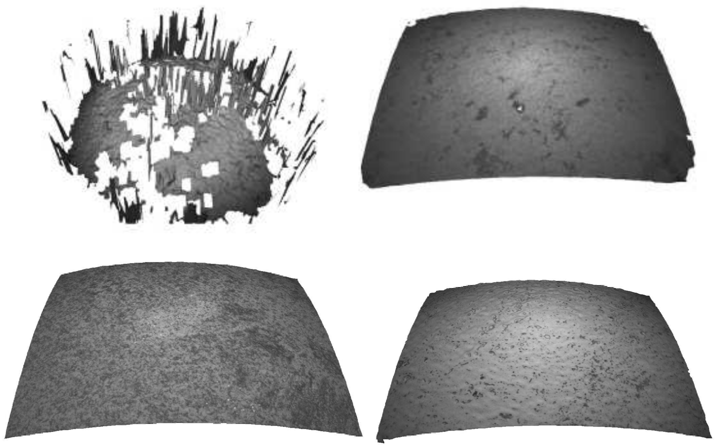

Figure 2: Surface representation of all four materials: ruby (10×) zirconia (50×), silicon nitride (50×) and stainless steel (50×)

The next stage of this work is to quantitatively characterise the surface with the instrument's software. The spheres' radii have been measured by using a function that allows fitting of a virtual geometric sphere to the data set. The results are presented graphically in figure 3. The large error bars (the standard deviation of the repeated measurements of each sphere) attached to the data points for the ruby spheres confirm the unsuitability of ruby for the FV technique. The sphere fitted to the measured ruby surface has a large deviation (20.40 μm) from the nominal due to the influence of spikes on the sphere fitting calculations. It should also be noted that the 10× lens will also contribute to a larger uncertainty of measurement. In contrast, zirconia spheres were measured well and the spread of measurements was very small (0.84 μm). However, the deviation from the average nominal value is as large as the measurement deviation of the ruby spheres. The average measured radius of the silicon nitride sphere has a deviation smaller than 1 % (2.25 µm) of the nominal radius. The results with the least amount of deviation are obtained with stainless steel spheres, which have only 1 µm deviation from the nominal radius. However, the spread of measurements (3.25 µm) is larger than for silicon nitride and zirconia spheres.

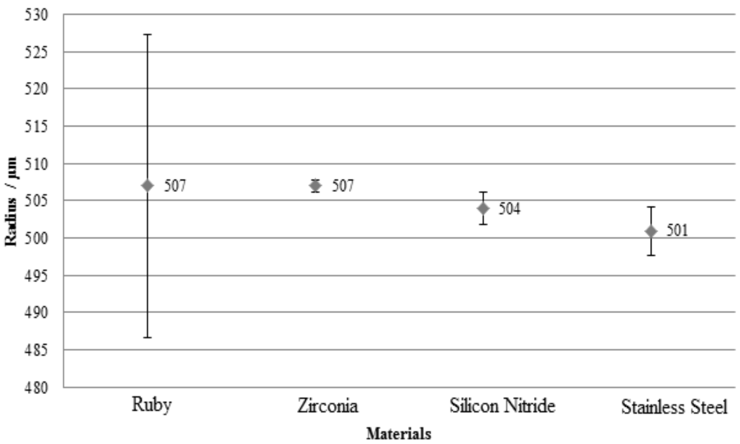

Figure 3: Comparing the ability of a FV instrument to measure the radius of spheres made of different materials.

4 Results for etched spheres

The results of the previous set of experiments show that ruby (as manufactured for CMM styli) is not suitable for FV instruments and that zirconia is almost too smooth. Therefore, ruby and zirconia spheres underwent an etching process, as described in Section 2, in order to produce two series of etched spheres. However, etching ruby spheres improved measurability, but did not significantly improve the overall results, because the etching process did not occur homogeneously on the whole surface but instead concentrated on particular areas, possibly where the crystal structure featured defects.

The etching process was more successful for the zirconia spheres. For each etched sphere, the radius was measured using the sphere fitting technique. Figure 4 shows that the sphere that underwent an etch duration of twenty minutes produced a measurement deviation of 0.54 µm from the nominal radius.

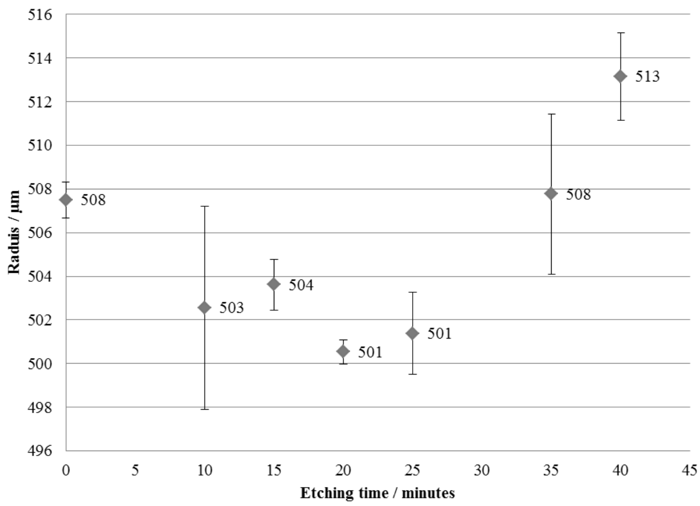

Figure 4: The effect of etching: zirconium spheres (500 µm radius)

It should be pointed out that the results reported here are based on single spheres only. Repeated measurements are currently being completed in order to provide further confidence with these data. It is also necessary to determine why the apparent sphere diameter increases at extended etch times, which may be a function of material deposit in the etchant, or a statistical spread in the sphere manufacturing specification. The error bars in figure 4 are the standard deviation of the repeated measurements of each sphere.

5 Discussion

It is noticeable that the measured radii (figure 3) of the ruby, zirconia and silicon nitride spheres are larger than the nominal value of 500 µm. This raises the question as to whether or not the spheres are coincidentally slightly larger than indicated by each independent manufacturer or whether it is due to the measurement and the robust sphere fitting function of the FV instrument [9]. As noted before, each of the spheres has a diameter tolerance. Except for the stainless steel spheres, each of the spheres has a measured diameter outside the manufactured tolerance, so the error is more likely to be due to the measuring instrument. The spheres now require independent verification using a contact micro-CMM.

Considering the cost of each sphere (with their respective qualities), the materials can be listed, starting with the most expensive: silicon nitride, ruby, zirconia and stainless steel. Experimental results show no correlation between the cost of a sphere and the quality of performance for this particular application.

Etching has a positive effect on the measurability of ruby and the zirconia spheres. However, despite the etching, ruby spheres should not be considered for

a verification artefact used for FV micro-CMMs, because they consistently show the largest deviation (when using a 10× lens) and they are still too smooth.
The performance of the measured spheres could potentially be improved if a larger area of the sphere's surface was measured (by using an image stitching technique). This is part of current research and will be reported at a later point in time.

6 Conclusions

The conclusions of the comparison of different materials for spheres measured with the FV technique are as follows:

- Silicon nitride may be the most appropriate material to use for a verification artefact because it results in good data quality.
- Stainless steel is inexpensive and performs well (as shown in initial tests); however, data loss and spikes could occur if the measurement settings are not finely tuned, because of localized smoothness
- Zirconia should only be considered if the etching procedure (twenty minutes etching time) can reproduce a number of spheres with the same nano-scale surface roughness. However, etching is an additional manufacturing process that has control issues and is therefore undesirable.
- Ruby should not be considered for a verification artefact for an optical instrument of this nature.

Current work is now concentrated on using silicon nitride and steel spheres using the image stitching function to gather more geometrical information.

7 Acknowledgements

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