An optical CMM system for nominally flat surfaces with sub-micron precision

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A solution to the sub-micron dimensional measurement of nominal flat high precision components is presented. The system comprises a calibrated X,Y motion system with vertical confocal point sensing. The measurement data is a standard 2.5D format. The system developed is tested for repeatability and accuracy on a calibration artifact developed for the purpose. The system described addresses the measurement of components better than the current accuracy and precision of conventional coordinate measurement machines (CMM's). Results are presented for the system in a normal office environment. The results show a precision in dimensional characterisation of better than 50 nm. The results demonstrate a solution for high precision (nanometre repeatability) dimensional component metrology.

Key Words: Optical CMM, dimensional metrology, nano-metrology

Introduction

Surface metrology is dominated by a range of technologies where the area measured is limited by the numerical aperture (NA) of the optic used. For areas larger than the visible area the individual viewed areas must be stitched together into a composite surface measurement. This requires that the motion system must be high precision to minimise error sources. The use of areal measurements for dimensional metrology outside of the limits of the optical system (NA) is limited by the precision of the motion system and associated data processing.

Optical scanning of a surface using a confocal single point sensor (confocal scanning or CFS), when linked to a high precision motion system allows surface dimensional metrology within the envelope of the motion system, and not limited by the NA. In this work a CFS system is optimised as a dimensional metrology, coordinate measurement system, [1]. By the nature of the X,Y motion the system is limited to nominally flat surfaces within a measurement envelope/volume. The X,Y limits depend on the motion system but are typically > 50 mm x 50 mm and with a vertically motion (Z) of 25 mm. This allows the investigation of accuracy and precision of dimensions within the X,Y plane. Commercial CMM systems are generally limited in precision to typically 1 µm, with only some specialised systems developed by national metrology laboratories or research centres offering precision below 0.1 µm (100 nm), [2].

Metrology System

The measurement system used in this study is a XYRIS Ultra 2020 L. The key specifications of the system are absolute vertical accuracy (Z) better than +/- 100 nm with resolution of 3 nm. Absolute lateral accuracy (XY) is better than +/- 500 nm over the full XY motion system range (50 mm x 50 mm) with positional repeatability +/- 40 nm or better. These values are calibrated by RLU-10 Interferometric laser encoder (Renishaw, UK) and UKAS/NIST traceable calibrated standards (Edmund Industrial Optics, NJ, USA) and (Taylor Hobson, UK). Illustrative measurement time is 40 s for 101 x 101 data (10k points) and 8 minutes for 1001 x 1001 (1M points) measurement points. The system is housed in a non-hermetically sealed enclosure in a normal office environment without temperature control.

The flatness of a motions system is essential for the precision metrology of surfaces. Fig.1 shows a comparison of the flatness of a standard motion system of Standard Deviation in Z (unfiltered Sq parameter) of 171 nm, compared to the Ultra system with a corresponding value of 49 nm.

This improved flatness is vital for areal measurement over large areas and for any measurement involving low level volumetric evaluation of surfaces e.g. wear and erosion, [3].

Methodology

To define the performance of the XYRIS system, three test samples are investigated and shown in Fig. 2. (A) is calibrated optical graticule with defined length (1.000 +/- 0.002 mm) and 100 graduations (0.010 +/- 0.001 mm); (B) a calibrated gauge pin (⌀ = 0.500 +/- 0.001 mm), and (C) a metal web artefact suspended between two gaps, nominally 0.218 mm in width.

The three samples are referenced against a calibrated microscope (Olympus Corporation, Shinjuku, Japan). To undertake the dimensional studies the measurement data grid spacing is varied from a normal surface areal measurement where both the X, and Y axis have the same grid spacing. For example, the grid spacing used in Fig 1. Is 201 x 201 data with points measured evenly in X and Y every generating a grid spacing (δ) of 125 µm. For dimensional metrology applications the scanning axis is the prime source of data, with high spatial resolution in the X axis (i.e. fine grid spacing) and low spatial

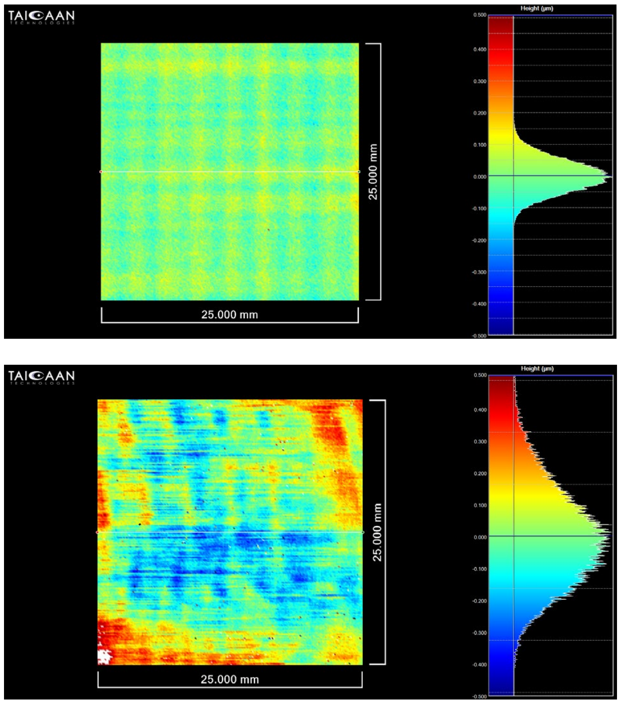


Fig. 1. Flatness of a 25 mm (X) x 25 mm (Y) region of motion system, with colour scale showing height (+/- 500 nm). (top) Ultra, (bottom) standard

resolution in the Y axis (i.e. coarse grid spacing). Example measurement data formats are 6001 x 11. The 6001 data in X is then processed for the dimensional information. The scanning described introduces a source of error linked to the time duration of the measurement and associated environment changes, such as small changes in temperature over the duration of the measurement. These factors are reduced by high-speed scanning with the full data field in Fig. 2 captured in 240 s, with temperature variation less than +/- 0.1 °C. With the dimensional scanning the measurement time is typically < 60 s. It is also ideal that the rectangular features measured are perpendicular to the scanning (X) axis. To achieve this prior placement of the sample is required to ensure the parallelism of the measurement and reduce cosine errors. In the data presented the alignment is better than <1° from orthogonal i.e. the absolute value is better than 99.98%.

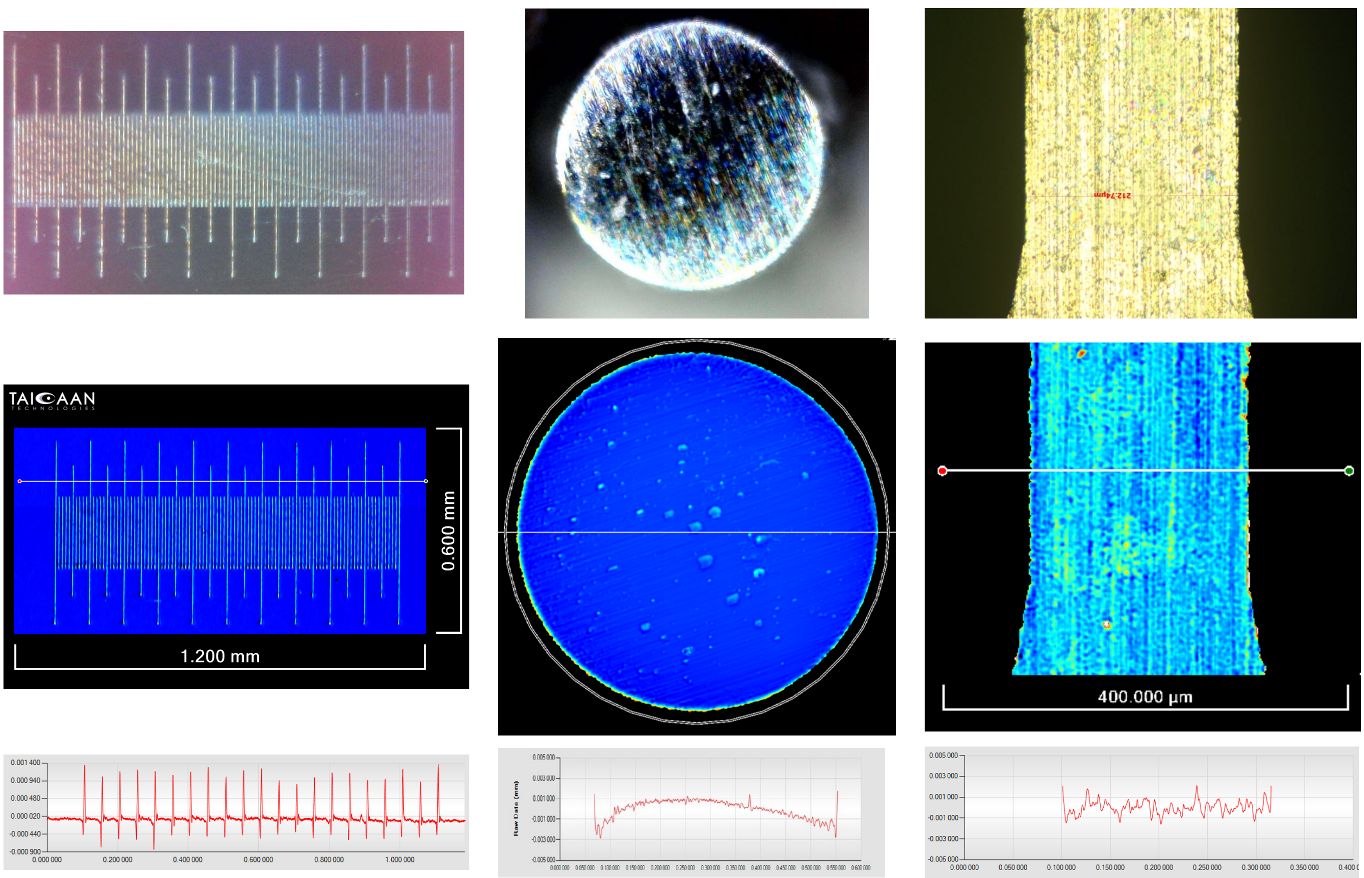
Edge Detection. A critical aspect of the dimensional analysis is the definition of the edge of the sample. Optical sensors are known to exhibit artefacts at the edge features [4]. To solve this, a light level is defined below which the sensor signal is rejected. This approach delivers high level precision of the edge detection, from which the mean value of the dimensions can be calibrated from a known artefact.

Web Sample. To measure the web sample, the absolute width of the sample is determined by evaluating the sample width variation over a 0.2 mm section. This is because the web edges are not entirely regular such that the web width varies slightly. Further, to obtain the precision of the measurement axis the grid spacing in the scanning axis is reduced to 0.2 and 0.050 µm and the web width is measured repeatedly at a single location. The data processing of the X measurement is fully automated within TaiCaan Technologies metrology software BEX®.

Results

Calibrated Graticule Sample (A). In Fig.2 (A), the sample is measured at 21 evenly separated cross sections over 1.2 mm with δ = 0.200 and 0.05 µm in X. The width is defined from the peak of the first etched graduation to the peak of the final graduation. The results in Table 1, show the mean length as 1.00167 mm, 1.67 µm above the nominal value, within the calibrated tolerance, and with a standard deviation (SD) of 0.38 µm. The sample demonstrates a difficulty in providing an ultra-precision measurement where the form of the calibrated artefact is not regular and presents uncertainty at the required level of precision, as shown in Fig 3. Fig.3 shows the graduations are neither uniform in shape or separation and that the micro roughness at the nanometre scale can influences the precise position of the peak. This is apparent in the SD of the 21 cross section measurements. Table 1 shows 90 repeats at the same location to have a precision (SD) of 0.146 µm.

Calibrated Gauge Pin Sample (B). The solution to the problem of an ill-defined edge/datum is to use a calibrated gauge pin as shown in Fig.2 (B), where the end of the pin has



(A). 1.2 mm (X) by 0.6 mm (Y) (B). 0.6 mm (X) by 0.6 mm (Y) (C). 0.4 mm (X) x 0.4 mm (Y)

Fig. 2 Microscopy (top), XYRIS Ultra 2020L measurement height map, colour scale +10 to -1 µm in height (middle) and 2D cross section along the white line (bottom).

been finely polished to provide a distinct edge with a calibrated dimension. The pin is measured over 0.6 mm x 0.6 mm with grid spacing δ = 0.2 µm in X and Y. The centre coordinate of the measurement is found using a circle of best fit, and cross section taken through the centre along the X axis, as shown. Table 2 shows the diameter to be 500.0 µm, in agreement with both the calibrated tolerance and calibrated vernier callipers.

Metal Web Sample (C). The metal web artefact is shown in Fig.2 (C). Three measurements are taken, as shown in Table 3, XYRIS grid spacing δ = 0.2 and 0.05 µm. There is good agreement in the web width between the microscopy measurements and the XYRIS with 215.8 and 215.7µm respectively. The precision of the web width, shown in Fig. 4 and Table 3, from 1,000 repeats with δ = 0.05µm (50 nm) shows a mean value 214.666 µm with a standard deviation of 0.044 µm (44 nm).

Table 1. Calibrated Graticule (A)

Graticule Sample	(X) Grid Resolution (µm)	Length (µm)	Standard Deviation (µm)
Calibrated Length	-	1,000 +/- 2	-
Mean of 21 Measurements (location varied)	0.200	1,001.67	**0.383**
Mean of 90 Measurements (location consistent)	0.050	1,001.64	**0.146**

Table 2. Calibrated Gauge Pin (B)

Gauge Pin Sample	Grid Resolution (µm)	Diameter (µm)
Calibrated Diameter	-	500 +/- 2
Vernier Measurement	1	**500**
XYRIS Measurement	0.2	**500.0**

Table 3. Web sample (C)

Web Sample	(X) Grid Resolution (µm)	Length (µm)	Standard Deviation (µm)
Optical Microscopy (200 µm section)	-	215.7	**3.309**
XYRIS Measurement (200 µm section)	0.2	215.8	**0.383**
XYRIS Measurement (1000 repeats)	0.05	214.66	**0.044**

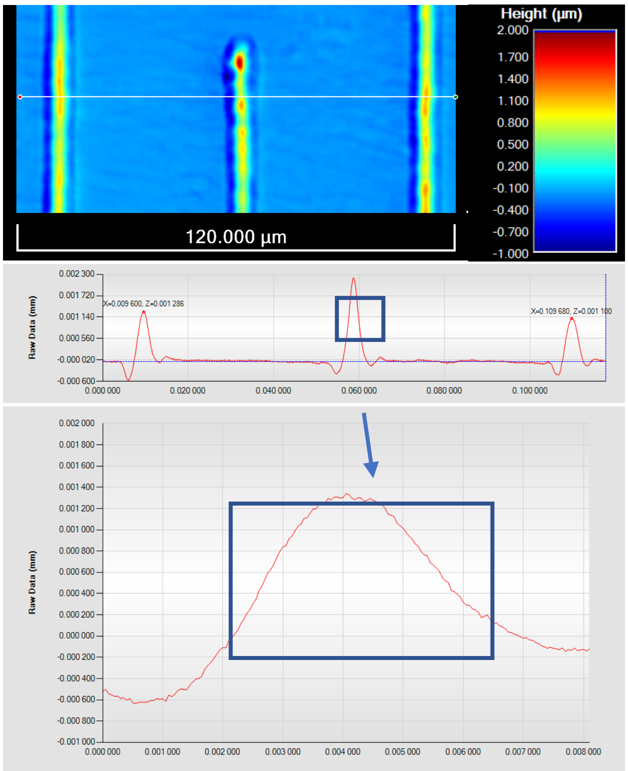


Fig. 3. Colour height map (top) (+2 to -1 µm) and 2D cross section along white line (bottom) showing the variation in form and spacing of graduations nominally separated by 50 µm on a calibrated graticule.

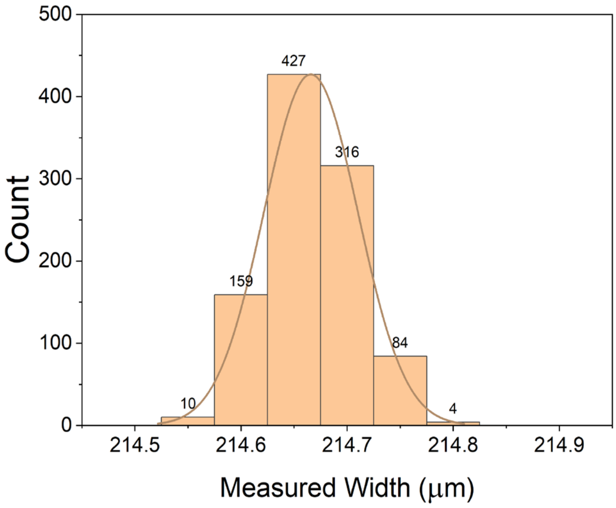


Fig. 4. Histogram of 1,000 repeat web measurements taken with a grid spacing of 0.05 µm. Mean width is 214.66 µm, standard deviation of 0.044 µm and a total range (min to max) of 0.250 µm

Conclusions

A standard single point confocal scanning system is used with an ultra-precision motion system to measure calibrated and nominal artefacts. The results on repeatability of measurement at a single location shows a precision (SD) of 44 nm under normal laboratory conditions.

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