euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Development of an all-optical dimensional measuring system

Richard Leach[1,2], Waiel Elmadih[1], Samanta Piano[1], Mohammed A. Isa[1], Danny Sims-Waterhouse[1,2], Nicholas Southon[1], Wahyudin P. Syam[1]

[1]*Manufacturing Metrology Team, University of Nottingham, UK*
[2]*Taraz Metrology, Nottingham, UK*

richard.leach@nottingham.ac.uk

Abstract
We present the novel design of an all-optical dimensional measuring system (AODMS) for measuring the geometry and surface texture of small-scale components. The system is designed to operate in a cube of 100 mm sides, with micrometre or sub-micrometre measurement uncertainties. The AODMS includes a four-axis motion system for mounting and moving the sample to be measured, a photogrammetric system for coordinate measurement and motion system tracking, a combination of coherence scanning interferometry and focus variation microscopy for texture measurement and a metrology frame fabricated using additive manufactured lattice structures with internal resonating bandgaps for vibration isolation. The paper will discuss the development of the AODMS, the experimental realisation of the instrument and the first steps in its validation.

Coordinate metrology, surface topography, information-rich metrology

1. Introduction

To address the need for three-dimensional (3D) measurement of the geometry of complex milli- to micro-scale components, there have been a number of developments of tactile micro-coordinate measuring machines (CMMs) – see [1] for a recent review. However, the commercial success of such CMMs has been limited due to their delicate mechanics, complexity of use, contact nature and slow measurement speeds. To address these limitations, several optical surface topography measuring instruments have been equipped with multi-axis motion systems to allow them to act as CMMs (e.g. [2]), but for geometry measurement they require multiple stitching operations and can be slow. Optical probes have also been integrated with tactile CMM platforms (e.g. [3]) or robot arms (e.g. [4]), but these are usually for geometry measurement only and often have limitations in terms of object accessibility.

In this paper, we present the novel design of an all-optical dimensional measuring system (AODMS) for measuring the geometry and surface texture of micro-scale components. The system is designed to operate in a cube of 100 mm sides, with micrometre or sub-micrometre measurement uncertainties. This new system is designed to be fast and produce dense point clouds; characteristics that are not shared with tactile instruments [1]. It is important to state up front that the AODMS is not designed to be a state-of-the-art coordinate measuring system and/or surface texture measuring instrument – rather it is a platform to demonstrate the concepts of "information-rich metrology" (IRM) [5]. When manufacturing a product, we have information about the product before we start manufacture. We usually have computer models, information about the materials, and we often know what to look out for in terms of defects. This "a priori" information can be used to enhance the measurement process by focusing on what exactly needs to be measured, so decreasing the time to do it. Most of the above information becomes available at product development and at manufacturing process planning, and we are asserting that such information may also bring benefit to metrology.

Several examples of IRM will be investigated using the AODMS, but first, we need a highly stable platform with multi-scale sensing capabilities. This paper concerns the design and development of such a platform.

2. System design

The core design principle of the AODMS is to combine two scales of optical measurement to create a system for measurements of the geometry and surface texture of small-scale components. Additively manufactured lattice structures are incorporated into the design to aid in vibration isolation, with the aim of improving the performance of the optical measurements.

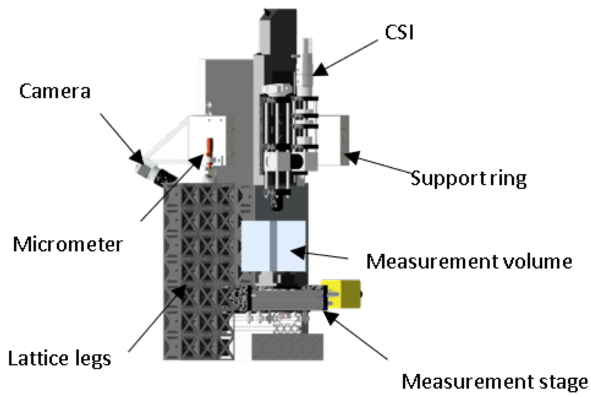

Figure 1 Computer render section view of the AODMS, with the central cube being the measurement volume possible with both texture and form sensors.

The optical texture sensor (see Section 2.2) is mounted on an aluminium ring, which places the thermal centre close to the optical axis of the surface texture measurement. The ring also places all three photogrammetry cameras (see Section 2.1) equidistant from the centre of the measurement volume. The ring is kinematically coupled with the lattice legs (see Section 2.5), using micrometers and three ball and vee-groove kinematic couplings [6]. A computer rendered cut-away depiction of the system is shown in Figure 1 and Figure 2 is a photograph of the assembled system.

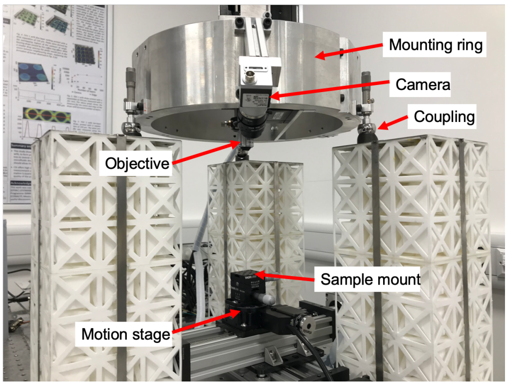

Figure 2 Photograph of the AODMS.

The position of the measurement stage is tracked with the photogrammetry system (see Section 2.4). This allows us to use low accuracy, low cost (but high repeatability) motion stages, and anchors the measurement stage co-ordinate system to the optical co-ordinate system.

2.1. Form measurement

The AODMS is capable of performing geometry (form) measurement using the multi-camera system. The form of a sample is reconstructed with photogrammetry; a passive triangulation-based technique in which the 3D location of corresponding image features between two or more images can be triangulated [7]. Typically, SIFT features are used as they are considered the most effective feature detection method due to their robustness to changes in perspective [8]. The multi-camera setup, along with the rotation stage, allows the system to capture many images of a sample to be measured from a wide range of positions. Smooth objects can be measured by taking advantage of illumination with a stationary laser speckle pattern (not shown) [9].

The photogrammetry system is based on an open-source photogrammetry pipeline called OpenMVG (Open multi-view geometry). However, OpenMVG is based on self-calibration and, therefore, only produces point clouds with an arbitrary scale factor. In order to apply a scale factor to the form measurements, a pre-calibration procedure is used in order to determine the true metric location of the three cameras with respect to each other. The pre-calibration procedure consists of imaging of a calibrated checkerboard artefact as described by Zhang [10]. The pre-calibration procedure provides both a characterisation of the camera intrinsic and extrinsic parameters as well the relative distances between the cameras. The calibrated camera-to-camera distances allow the photogrammetry point cloud to be appropriately scaled and metric information about the sample form to be evaluated. Further scaling and uncertainty estimation for the photogrammetry system are described elsewhere [11]. Figure 3 shows a point cloud measured with the photogrammetry system, where the measured ball diameter is 12.096 mm with a standard deviation of 0.060 mm. Of course, traceability for these measurements is still part of the work in progress, although we have recently published on the how to establish uncertainty for the photogrammetry measurements [11].

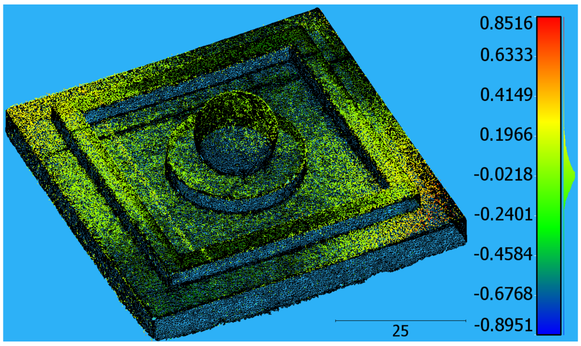

Figure 3 Initial photogrammetry measurement.

2.2. Texture measurement

The optical setup for the surface texture measurement is a coherence scanning interferometer (CSI) sensor [15]. The optical setup consists of a Kohler axial illumination system and a microscope equipped with a 10× Mirau objective. Figure 4 shows the optical design and setup. The optical sensor is mounted on a precision linear stage with an axial resolution of 20 nm.

From the CSI sensor, two types of raw data can be obtained: CSI data as the primary raw data type and focus variation (FV) data [13] as the secondary raw data type. The purpose of using two types of data is to combine the benefit of CSI for measuring smooth and highly reflective surfaces and the benefit of FV for measuring rough surfaces with high-slope angles. These two types of raw data can be extracted from a single measurement with the optical system.

2.3. Data fusion

As well as using checkerboard targets to provide high-accuracy localisation of the motion stage, the SIFT features described in Section 2.1 can be used to track the location and orientation of the sample. The feature information captured during the photogrammetry measurement process can be used to locate the photogrammetry point cloud within the surface texture measurement coordinate system. By locating the photogrammetry point cloud in the same coordinate system as the surface texture measurement, the two data sets can be combined and fused in order to generate a single data set covering both sample form and surface texture information.

In order to ensure that the coordinate systems of both the form and surface texture measurement systems are accurately aligned, some common features visible in both measurement systems are required. The optical targets shown in Figure 5 provide an good solution to this, as the intersections between the squares of the checkerboard can be seen in the surface texture measurements and can be triangulated to sub-pixel accuracy by the photogrammetry system. By measuring at least three checkerboard intersections with both systems, the relative rotation and translation between the two coordinate systems can be determined.

The outcome of this fusion of form and texture information allows for the generation of sample measurements with improved dynamic range of spatial frequencies. Additionally, the methodology allows for the sample to be removed and replaced in any orientation and still allow the two measurements to be registered. This ability to manually move the sample to any orientation and still be able to register texture measurements negates the need for any highly complex and high-cost precision lateral motion stages (see Section 2.4).

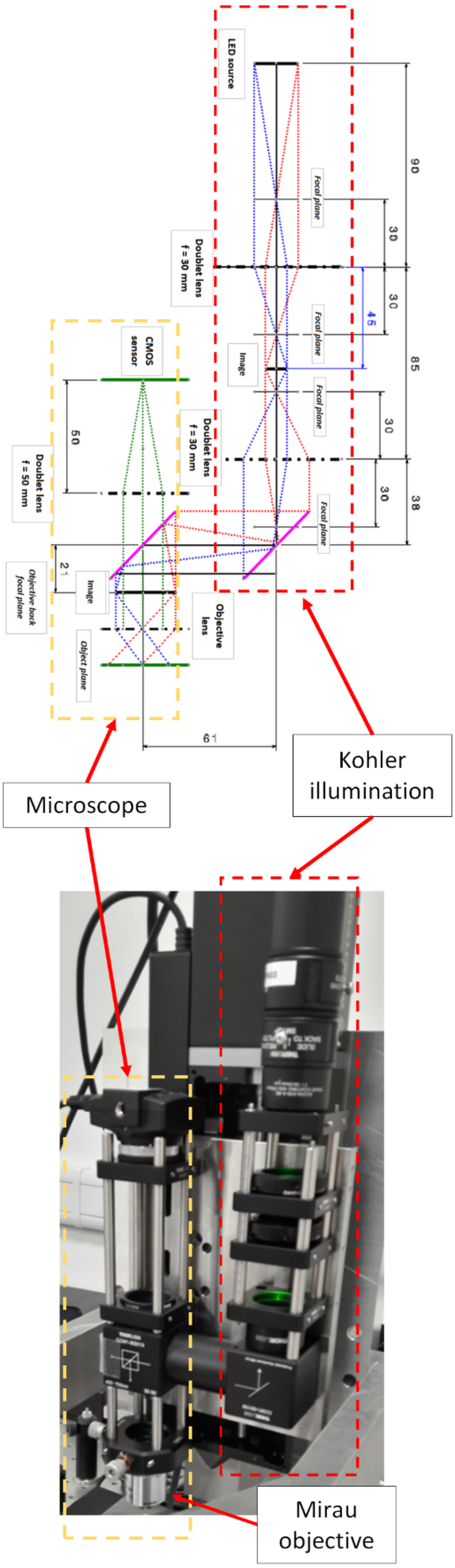

Figure 4 The optical design and setup of the CSI sensor.

2.4. Motion system

The AODMS has positioning capacity in the lateral x and y directions up to 100 mm. In addition, motion of the texture sensor measurement head in the z-direction allows positioning of the measurement range in a desired region. The fourth degree of motion is for the multi-view imaging at various rotational positions θ as illustrated in Figure 5. Machine vision cameras are used for the purpose of photogrammetric 3D measurement, positional tracking for registration and geometric characterisation of the rotation axis.

There are three machine vision cameras (see Section 2.1) in the setup of the AODMS for multi-view monitoring of the position of a measured sample. The use of multiple cameras improves the tracking accuracy and the visibility of optical targets that can be occluded by the measured sample. Four checkerboard-patterned optical targets are placed at the corners of the measurement plate shown in Figure 5. The tracked positions are used for stitching and fusing surface texture measurements at different xy positions.

The position and orientation of the rotation axis, about which images are acquired for photogrammetry, is evaluated through a geometric characterisation process. This is necessary in order to accurately relate the image-based photogrammetric coordinate measurements to the actual dimensions and position of the measured sample. The details of the stage characterisation process using the camera data are given elsewhere [14].

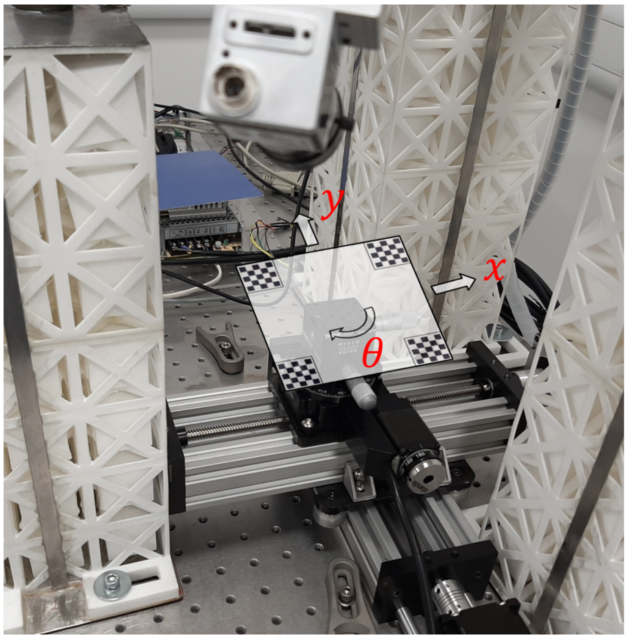

Figure 5 Measurement stage showing optical targets and motion directions. Note that the workpiece metrology frame shown in Figure 2 had not been assembled at the time of this photograph.

2.5. Vibration isolation

Design of the support frame and workpiece metrology frame of the AODMS used additive manufactured (AM) lattice structures to mimic the vibration isolation behaviour of elastic bandgap structures [15]. Bandgap structures provide enhanced vibration isolation, in comparison to solid structures, with vibration transmissibility of up to -66 dB as reported elsewhere [16]. We targeted the low-frequency vibration range from 50 Hz to 150 Hz, which corresponds to the vibration of a typical laboratory environment (below 50 Hz we rely on the use of a massive concrete structure on which the instrument is mounted). However, it is challenging to use existing bandgap structures to isolate this low-frequency range. This is because the resulting unit cells size would be larger than the envelope of the AODMS and the geometrical features of the lattices would be impossible to manufacture with current AM machines. The support and workpiece metrology frames of the AODMS share a novel lattice structure design for low-frequency vibration isolation. This design incorporates an energy absorption mechanism in the form of a cubic solid structure with stiffeners, as shown in Figure 6.

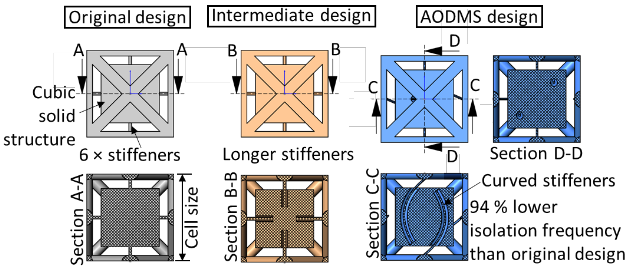

Figure 6 Design of lattice unit cells for low-frequency vibration isolation.

The support frame and workpiece metrology frame are shown in Figure 7. For an illustration of the ability of the structures to isolate vibration, a vibration test was set up, integrating a mechanical shaker, a piezoelectric accelerometer and a laser vibrometer. The transmissibility of vibration through the support frame was measured, referencing acceleration data from the accelerometer and vibrometer, as shown in Figure 8.

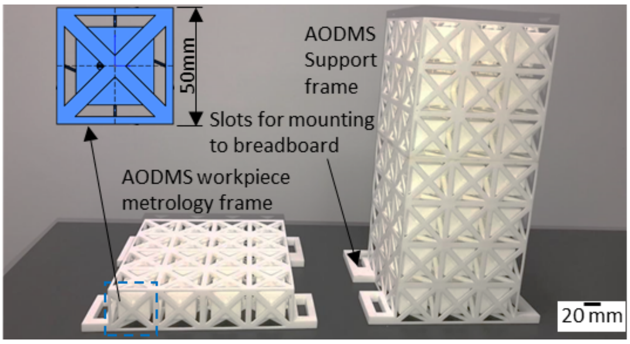

Figure 7 Support frame and workpiece metrology frame as manufactured from Nylon 12.

Below the targeted isolation region, the response is slightly below 0 dB. The first resonance of the structure is designed at the start of the isolation frequency range, at 50 Hz. Above 50 Hz, the energy absorption mechanism is in action and results in wide bandgap behaviour from 50 Hz to 1000 Hz. The transmissibility reaches as low of -62 dB. Note that whilst this is the lowest bandgap frequency reported in the literature to date [16], the use of bandgaps usually has the detrimental effect of amplifying low-frequency vibration (as can be seen in Figure 8). For now, we rely on the high-mass passive isolation of the large concrete support table (and isolated laboratory floor) to reduce this effect and we continue research to push the lower end of the bandgap frequency to 0 Hz.

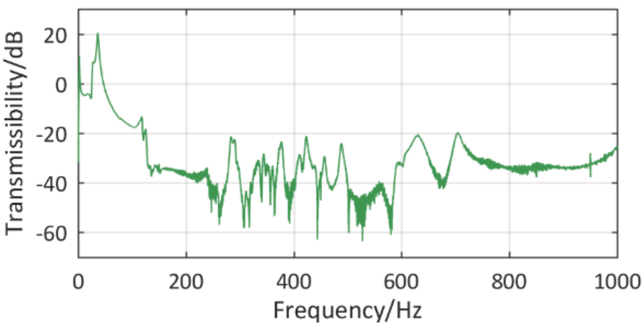

Figure 8 Experimental testing results for the support frame.

To avoid the thermal expansion of the Nylon-12 having a significant effect on the metrology loop, the lattice structures are sandwiched between low-expansion Invar sheets which are rigidly connected to each other with Invar strips (shown in Figure 2 and Figure 5).

3. Current status of AODMS

At the time of writing, the full system had only just been assembled and initial tests are still underway. Some early data from the registration and fusion process are described elsewhere [17] and a paper on the enhanced stage tracking is in press [18]. Further results will be presented at the 20th euspen Annual Conference and Exhibition.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/M008983/1]. Thanks also to Dr Rong Su, Dr Ian Maskery and Ahmed Mohammed (University of Nottingham), Dr Wu Jianwei and Dr Bo Zhao (Harbin Institute of Technology), Fabrizio Medeossi (University of Padua), and Phil Krause (now Cranfield University).

References

[1] Thalmann R, Meli F, Küng A 2016 State of the art of tactile micro coordinate metrology *Appl. Sci.* **6** 150
[2] Zangl K, Danzl R, Helmli F, Prantl M 2018.Highly accurate optical µCMM for measurement of micro holes *Proc. CIRP* **75** 397-402
[3] Xiong H, Pan M, Zhang X 2010 The development of optical fringe measurement system integrated with a CMM for products inspection *Proc. SPIE* **7855** 78551W
[4] Du H, Chen X, Xi J, Yu C, Zhao B 2017 Development and verification of a novel robot-integrated fringe projection 3D scanning system for large-scale metrology Sensors **17** 2886
[5] Senin N, Leach R K 2018 Information-rich surface metrology *Proc. CIRP* **75** 19-26
[6] Leach R K, Smith S T 2018 *Basics of Precision Engineering* (CRC Press)
[7] Luhmann T, Robson S 2011 *Close Range Photogrammetry: Principles, Techniques and Applications* (Whittles Publishing)
[8] Lowe D G 2004 Distinctive image features from scale-invariant keypoints *Int. J. Comp. Vis.* **60** 91–110
[9] Sims-Waterhouse D, Piano S, Leach R K 2017 Verification of micro-scale photogrammetry for smooth three-dimensional object measurement *Meas. Sci. Technol.* **28** 055010
[10] Zhang Z 1999 Flexible camera calibration by viewing a plane from unknown orientations *Proc. 7th IEEE Int. Conf. Comp. Vis.* **1** 666–673
[11] Sims-Waterhouse D, Isa M A, Piano S, Leach R K 2020 Uncertainty model for a traceable stereo-photogrammetry system *Prec. Eng.* in press
[12] de Groot P 2011 Coherence scanning interferometry. In: Leach R K *Optical Measurement of Surface Topography* (Springer: Berlin)
[13] Helmli F 2011 Focus variation instruments. In: Leach R K *Optical Measurement of Surface Topography* (Springer: Berlin)
[14] Isa M A, Sims-Waterhouse D, Piano S, Leach R K 2019 Kinematic error analysis of stage tracking using stereo vision *Proc. ASPE, Pittsburgh, USA, Oct.* 151-156
[15] Syam W P, Jianwei W, Zhao B, Maskery I, Elmadih W, Leach R K 2018 Design and analysis of strut-based lattice structures for vibration isolation *Prec. Eng.* **52** 494-505
[16] Elmadih W, Chronopoulos D, Syam W P, Maskery I, Meng,H, Leach R K 2019 Three-dimensional resonating metamaterials for low-frequency vibration attenuation *Sci. Rep.* **9** 11503
[17] Leach R K, Sims-Waterhouse D, Medossi F, Savio E, Carmignato S, Su R 2018 Fusion of photogrammetry and coherence scanning interferometry data for all-optical coordinate measurement *Ann. CIRP* **67** 599-602
[18] Isa M A, Sims-Waterhouse D, Piano S, Leach R K 2020 Volumetric error modelling of a stereo vision system for error correction in photogrammetric three-dimensional coordinate metrology *Prec. Eng.* in press