3D Optical Scanner Dimensional Verification Facility at the NPL's "National FreeForm Centre"

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Abstract

Fringe projectors and other high precision 3D optical surface-form scanners are rapidly being adopted by industry in favour of Cartesian CMMs because of their advanced metrology benefits, which include point-cloud data capture, portability and speed. However, certain surfaces and geometries are challenging for such scanners to measure accurately, resulting in unreliable dimensional data. NPL (National Physical Laboratory) has developed an environmentally controlled 3D optical scanner dimensional verification facility to simulate typical usage conditions where temperature and lighting may vary. In addition, a range of test artefacts have been specifically developed to identify scanners' sensitivity to colour, resolution, roughness, and laser scanning articulating arm scan velocity.
This paper describes NPL's verification facility that is to be launched within the year and has been developed with the aim of providing a 3D optical scanner verification service to global industry ensuring greater confidence in their measurement capability.

1 Introduction

3D optical scanners, such as fringe projectors and laser scanning articulating arms, are quickly taking the place of fixed tactile based CMMs as their portability and rapid production of results make them particularly attractive away from the metrology laboratory and local to the production line, as well as outside at excavation sites and crime scenes. Having been developed in the 1950s [1], the performance of tactile CMMs is well understood [2], trusted and established [3]. In contrast, 3D optical scanners are a relatively new and fast developing technology, whose development has accelerated with increasing access to low cost, powerful computers and cheaper optics. While 3D optical scanners offer the potential of great positives, such as massively increased measurement speeds, equipment portability and relative ease when measuring freeform surfaces, their limitations are still to be fully understood and international standards that describe suitable tests and procedures for their acceptance and use are yet to be developed, for example, VDI/VDE 2634 [4], the German guideline for optical 3D measuring systems addresses neither freeform surfaces nor surface finish.

The National FreeForm Centre, established in 2009, has developed a purpose-built dimensional verification laboratory to assess 3D optical scanner performance and environmental sensitivities with the aim of providing global industry with greater confidence in their measurements. This paper reports the development of NPL's 3D optical scanner verification facility.

2 The 3D optical scanner verification facility

NPL's 3D optical scanner verification facility comprises a purpose-built environmentally-controlled laboratory (approximate dimensions: 3 m by 5 m by 2.5 m), test artefacts, tests and test equipment that have been developed to examine the performance of 3D optical scanners. With adjustable lighting conditions and a temperature range from 16 °C to 24 °C, the facility is designed to simulate the typical environments where 3D optical scanners are increasingly being used. Fringe projectors commonly have ~(400×400×300) mm measurement volumes with manufacturers claiming measurement accuracies < 10 µm, while laser scanning articulating arms frequently work in ~33 m^3 spherical volumes with claimed accuracies < 100 µm. To characterise such instruments, NPL's National FreeForm Centre have designed artefacts and test procedures to obtain data quality (how representative the measured data is of the object being measured) and data quantity (the amount of measured data) information with regards to instrument environmental sensitivities, such as temperature and lighting, instrument properties, such as resolution, measurement volume and the effects of scanner orientation, and artefact properties such as angle, colour, reflectance, roughness and material. Specific laser scanning articulating arms tests also identify sensitivities to scan velocity, height and joint encoder angle. The facility's tests are described in more detail below:

2.1.1 Temperature effects

Temperature is of critical importance when performing accurate dimensional measurements, not only affecting the object being measured but also the performance of 3D optical scanners [5]. Instrument manufacturers use different methods to overcome temperature effects: some 3D optical scanners are manufactured using carbon fibre, which is known for its low thermal expansion coefficient [6], but may also exhibit hysteresis making its behaviour difficult to predict [7]. Other manufacturers use aluminium as it has well-known thermal properties and is therefore easier to predict than other materials. Thermocouples embedded within an aluminium frame can be used to correct for expansion or contraction due to temperature change and provide a warning when the instrument's calibration is likely to be affected.

3D optical scanner temperature tests at NPL are designed to measure dimensional sensitivities to changing temperature. The tests comprise setting the facility to a particular set point temperature, either 16 °C or 24 °C, and placing the scanner inside it to stabilise. Once the scanner is at a stable temperature, it is calibrated and set to continuously measure the ~300 mm separation between two 50 mm diameter spheres attached to a 340 mm long Zerodur bar, shown in figure 1. As dimensional measurements are taken, the temperature of the facility is changed until it reaches the opposite set point (24 °C or 16 °C). To close the measurement loop, the scanner is recalibrated and the measurements are repeated while the facility's temperature is returned to its original setting. The dimensional data from the series of measurements is subsequently analysed to identify changes in the measured separation distance between the sphere centres.

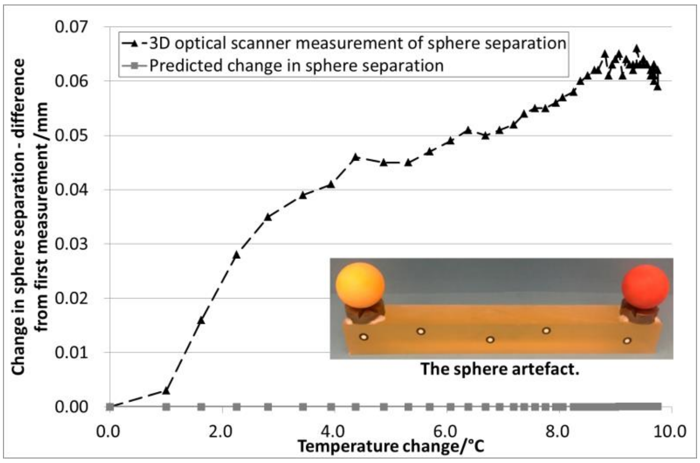

Figure 1: Preliminary measurements showing the sphere artefact and the effect of temperature on dimensional measurements from a fringe projector.

Figure 1 presents preliminary results from measurements on a fringe projector which demonstrate the importance of understanding 3D optical scanner temperature effects. The results, which will be reported in a future paper [8], show a 6 µm per °C change in the separation between the two spheres.

2.1.2 Multi-faceted test artefact for normal and 45° measurements

The optical properties of the measurement object's surface are known to affect 3D optical scanners [9]. Lambertian surfaces that diffusely reflect projected light are ideal for 3D optical scanner measurements, while they may record little useful data from specular surfaces that reflect projected light away like a mirror. Surface colour may also affect the data that a 3D optical scanner is able to record [10]. The data quantity may be affected as some 3D optical scanning systems may have difficulty distinguishing a red laser line on a red surface or dark fringes projected onto a dark surface. NPL has observed an embossing effect between regions of high colour contrast when scanning flat surfaces that have a multi-coloured pattern, suggesting that data quality is affected.

The National FreeForm Centre has developed multi-faceted test artefacts to quantify 3D optical scanners' ability to measure surfaces with different reflectances, roughnesses and colours. In addition, surfaces of specific interest to industries that include aerospace, automotive, manufacturing, medical and heritage are addressed.

Figure 2: The NPL 2D material coupon plate.

Figure 2 presents one of the multi-faceted test artefacts, the NPL 2D material coupon plate. This comprises eight artefact coupons surrounding a central, highly Lambertian, sintered PTFE (Spectralon®) reference coupon. The 60 mm by 60 mm square coupons include materials such as aluminium, carbon fibre and titanium. The coupons are selected depending on the measurand, i.e. a scanner's ability to measure roughened surfaces, and are measured with the calibrated scanner using optimal measurement parameters, at normal and ± 45° orientations relative to the scanner's projector. The point clouds from the measurements are then analysed using software to identify a 30 mm by 30 mm region within the centre of each coupon. The number of points within this region is normalised against an identical region within the "white" central Spectralon reference coupon to obtain a data quantity measurement and therefore determine a scanner's ability to measure a particular surface reflectance, roughness, colour or material.

2.1.3 Multi-faceted test artefact for multiple angle measurements

Figure 3 presents NPL’s 3D material coupon plate that, like the NPL 2D material coupon plate, is designed to assess a scanner’s ability to measure different surfaces finishes, but at a greater number of angles with respect to the scanner’s projector.

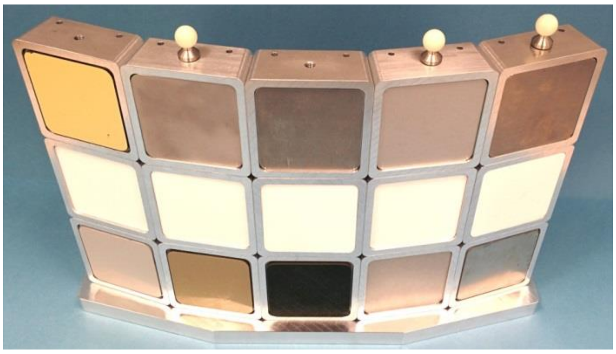

Figure 3: The NPL 3D material coupon plate.

NPL’s 3D material coupon plate comprises three rows and five columns of coupons; a 150° angle separates each column rather than forming a plane. Five Spectralon reference coupons are placed along the NPL 3D material coupon plate’s central row, while the artefact coupons are placed in the rows above and below. The NPL 3D material coupon plate is mounted on a rotation stage and measured by the calibrated scanner with optimal measurement parameters, through the range of angles of interest, with each column normal to the scanner during one of the scans. As in the case of the NPL 2D material coupon plate measurements, the point clouds from the NPL 3D material coupon plate measurements are then analysed and the 30 mm by 30 mm regions within the coupons and the Spectralon references are compared.

2.1.4 Illumination effects

3D optical scanners have been shown to be affected by the ambient lighting [11, 12]. Changes in ambient lighting, flashes from welding processes and projected shadows may all affect the measurements performed by 3D optical scanners.

Figure 4: A fringe pattern projected onto the NPL 150 mm Freeform artefact.

NPL's 3D optical scanner verification facility incorporates tests to quantify the effects on measured dimensions (data quality) and data quantity of 3D optical scanners in environments with different and changing illumination. In this illumination test the scanner is initially calibrated under the conditions recommended by the manufacturer and used to measure artefacts such as the NPL 150 mm Freeform artefact [13] (shown in figure 4), the NPL 2D material coupon plate and sphere artefacts without any ambient lighting. The artefacts are then measured while a programmed set of different illuminations (lighting levels, colours and patterns) are projected onto them. Each measurement point cloud is then analysed to identify changes in artefact dimensions and data quantity with changes in the illumination conditions.

2.1.5 3D Optical Scanner Measurement Resolution

As the take up of 3D optical scanners becomes more widespread in industry, greater demands will be placed on them to measure ever finer detail. To help 3D optical scanner manufacturers verify their instruments, NPL have developed the NPL Bessel plate artefact to provide a means of resolution measurement. The Bessel plate artefact is a (170×170×45) mm aluminium plate with a circular pattern cut into its top surface that is based upon the zero-order Bessel function of the first kind, to provide a series of ripples with an exponential decay in amplitude and also frequency with increasing distance from the plate's centre.

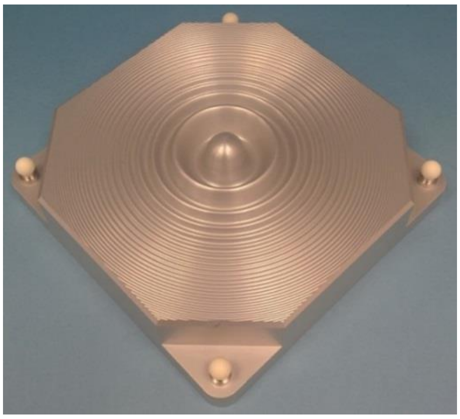

Figure 5: The NPL Bessel plate artefact.

3D optical scanner resolution is assessed by comparing scanner measurements of the NPL Bessel plate with its CAD model, with particular attention paid to the fine ripples on the outer regions of the plate. The artefact's surface has been measured using a profilometer to verify that is in agreement with the CAD model, within machining tolerances. The test is not for absolute measurement but to identify when the measuring instrument smooths the ripples to an extent that it is no longer a representation of that surface.

2.1.6 Scanner Orientation

3D optical scanners are now being attached to robotic arms to create automated measurement systems, particularly for the automotive industry [14-16]. The scanners on these systems will be subject to a wide range of orientations and slight movement of their optical components would change measurement dimensions.

NPL's National FreeForm Centre have developed a system to quantify orientation effects on 3D optical scanners that uses a frame to ensure that a sphere artefact retains its position relative to a calibrated scanner while the scanner is oriented through a range of pitch and roll angles. The point clouds from the measurements are analysed to identify changes in artefact dimensions (sphere centre separation distances) with respect to scanner orientation.

2.1.7 Measurement Volume

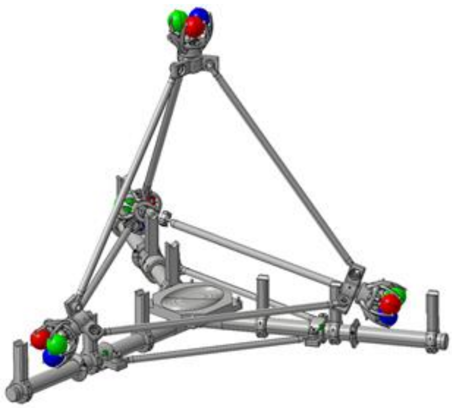

Figure 6: The NPL tetrahedral and Bessel plate artefacts.

Lower cost 3D optical scanners are becoming increasingly available on the market that, to be more affordable, may not incorporate the costly low aberration optics of more expensive scanners. While the lower cost scanners might be very capable of measuring artefacts placed at their measurement volume's centre, artefacts placed at its extremities may be more prone to dimensional error. The National FreeForm Centre has developed a tetrahedral artefact, shown in figure 6, to test for 3D optical scanner sensitivities to artefact position within the measurement volume. The NPL tetrahedral is modular and comprises coloured alignment spheres separated by changeable fixed-length rods that provide sphere separations of 300 m, 600 m and 1000 m allowing it to fit within a range of volumes; the coloured balls aid detection of colour sensitivity effects possibly caused by chromatic aberration from the scanner's optics. While tetrahedral artefacts have already been developed to verify 3D optical scanners [17], NPL's tetrahedral is designed to hold the Bessel plate artefact and allow simultaneous resolution, colour and measurement volume tests.

To test a 3D optical scanner for dimensional changes within the measurement volume, the tetrahedral is built to an appropriate size for the instrument's measurement volume and placed onto a rotation stage. The NPL tetrahedral and Bessel plate are then measured by the scanner through a series of rotations. The measurement point clouds are analysed to identify changes in artefact dimensions (sphere diameter and sphere centres separation distances) and any dimensional sensitivities to the colours of the spheres.

2.1.8 Laser Scanning Articulating Arm Scan Velocity, Height and Joint Encoder Angle

Industrial measurements using laser scanning articulating arms may be a compromise between scan velocity and measurement quality; slower movement of the laser scanner may result in higher quality data and more dimensionally accurate scans, but at a time cost. On the contrary, moving the scanner more quickly over the measurement artefact may result in faster completion of the scan, but at a cost to the measurement data quality and the dimensional accuracy.

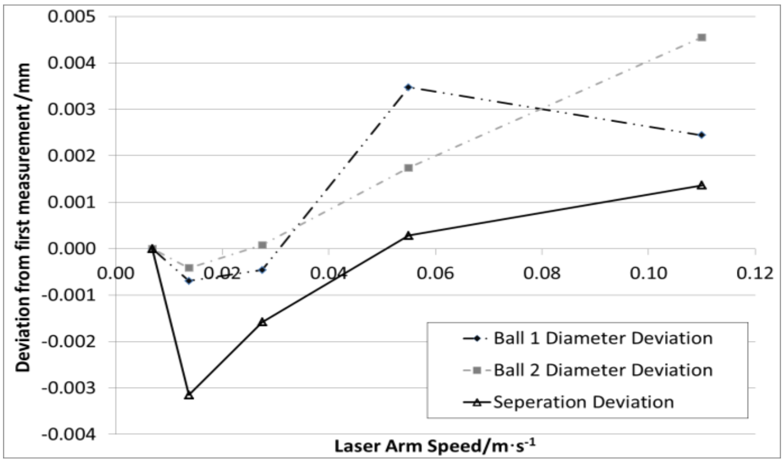

Figure 7: Preliminary measurement results showing increasing deviation in measured sphere diameter and separation with scan velocity.

To find the optimum balance between scan velocity and measurement quality, NPL's National FreeForm Centre have developed a system where the articulating arm's scanning head is placed within an adjustable frame and moved along by a precision carriage. To isolate the arm's individual encoders the frame can be moved relative to the scanner's base and adjusted for height and angle. A motor maintains a constant scanning head velocity during the scan, thus removing operator effects such as varying velocity and height during measurement. The effects of scan velocity, height and joint encoder angle on data quality and data quantity are determined from the measurement point clouds, by analysing the sphere dimensions, the separation between their centres and the number of points that form them in the point cloud. Figure 7 presents preliminary results from the system that shows increasing deviation in the measured sphere diameters and the separation of their centres with increasing scan velocity, the results from this study will be published in a future paper.

3 Summary

NPL's National FreeForm Centre have developed a dimensional verification facility to provide global industry with greater confidence in 3D optical scanners, which are rapidly replacing traditional Cartesian CMMs as they offer point-cloud data capture, portability and speed. When compared with CMMs, 3D optical scanners are a relatively new technology, their limitations are still being understood and international standards regarding their use are still to be developed. In addition, future ISO standards will involve the acceptance and verification of 3D optical scanners, but will not address the range of issues that NPL's facility covers, such as the measurement of freeform surfaces.

NPL's 3D optical scanner dimensional verification facility comprises a purpose-built environmentally-controlled laboratory, artefacts, tests and test equipment. The laboratory provides control over temperature and illumination to assess environmental effects on scanner measurements. Artefacts have been developed to assess scanner ability to measure the dimensions of objects with different colours, reflectances, roughness, and materials of particular industrial interest and to determine how these measurements are affected by angle. Other artefacts have been designed to measure scanner resolution, their sensitivity to orientation and their sensitivity to the object's position within the measurement volume. Tests to verify laser scanning articulating arm performance are being developed to identify sensitivities to scan velocity, height and joint encoder angle.

Work is ongoing within the facility which is to be launched within the year. However, preliminary tests are already showing the effects on fringe projector measurements with increasing temperature and laser scanning articulating arm sensitivities to scan velocity. The results from both of these investigations and other tests will be reported in future papers.

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