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Metrological comparison of CMM & structured-light 3D scanner

Special Course Report

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1 Introduction

Structured light 3D scanning is an important imaging technique which allows for quick, precise and accurate acquisition of 3D geometry for a variety of purposes ranging from metrology to reverse engineering. In recent years the costs of optical 3D scanners have decreased significantly, which has increased the adoption of the technology.

The aim of this report is to perform a metrological comparison between a structured light 3D scanner, the 'Shining 3D Autoscan Inspec' and a 'Zeiss PRISMO' coordinate measuring machine (CMM). Given that the uncertainty in measurements from the CMM is an order of magnitude lower than that stated on the 3D scanner, it is possible to use the CMM as a benchmark for evaluating the 3D scanner's performance.

2 Structured Light 3D Scanning

2.1 How does it work?

Structured light 3D scanning operates on the principle of projecting known patterns of light onto an object and analyzing their deformation to reconstruct its three-dimensional shape. The process typically involves three main components: a light projector, one or more cameras, and specialized software for data processing.

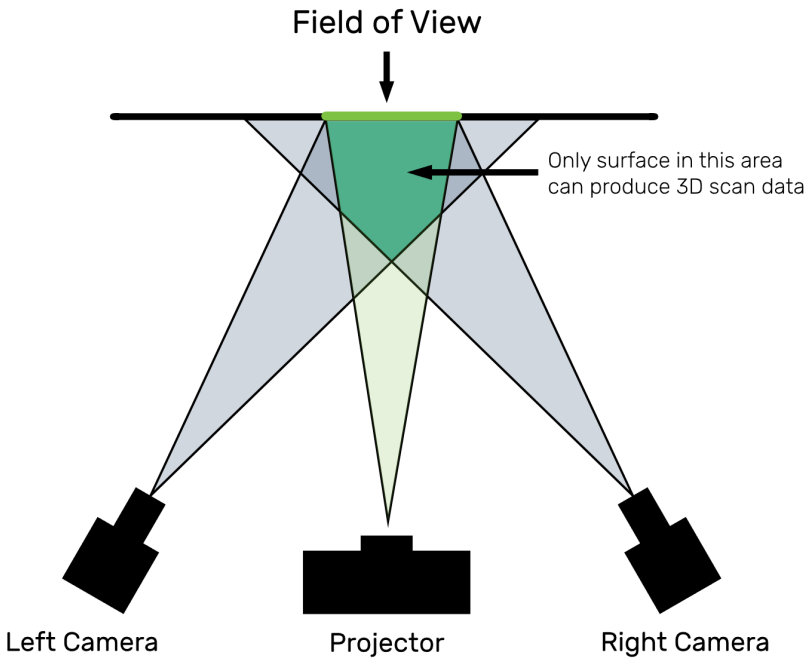


Figure 1: Slice of the scanned volume[1]

The projector emits a precise pattern, usually in the form of a grid or lines. As this structured light falls on the object's surface, it becomes distorted by the object's contours, curves, and irregularities. Simultaneously, one or more cameras, positioned at known angles relative to the projector, capture images of the distorted light patterns as they reflect off the object's surface.
The core mathematical principle underlying this technique is triangulation. By knowing the precise geometry of the projector-camera system and analyzing the distortion of the projected patterns, the scanner can calculate the depth and surface coordinates of each point on the object. The fundamental triangulation equation, $Z = \frac{B \cdot f}{d}$, calculates depth Z based on the baseline distance B, focal length f, and pixel disparity d.

2.2 Comparison to other 3D scanning methods

Compared to laser scanning, structured light systems generally offer faster capture speeds, excelling at capturing fine details and textures, especially for smaller objects. However, laser scanners perform better in varied lighting conditions and outdoor settings. In contrast to photogrammetry, structured light provides more consistent surface information but requires specialized hardware, whereas photogrammetry can be done with standard cameras and often excels in capturing color and texture for larger objects or environments.

3 Equipment Specifications

This section contains the specifications of the equipment used. Full specifications provided by the manufacturers can be found online. The equipment is located in the Metrology Lab at DTU. The laboratory is temperature and humidity controlled at 20°C and 50% respectively. This ensures proper operating conditions for the equipment used and very low thermal expansion related measurement errors.

3.1 Zeiss PRISMO

The Zeiss PRISMO is a 3 axis CMM with a measurement volume of 700 x 900 x 500 mm and an maximum permissible error (MPE) of:

$$\text{MPE} = 0.9 + \frac{L}{350}\mu\text{m}$$

The DTU Metrology Lab has a large selection of steel ruby tipped styli for this CMM.

3.2 Shining 3D AutoScan Inspec

The AutoScan Inspec is a desktop optical measurement system employing blue light structured light technology combined with dual 5.0 MP cameras. Designed for dimensional analysis of small industrial components, it utilizes automated multi-axis positioning to capture

[1]Source: `https://www.polyga.com/blog/3d-scanning-101-structured-light-3d-scanning/`.

Parameter	Value
Maximum permissible error	$\leq$ 10 µm
Measurement volume	100 × 100 × 75 mm
Measurement principle	Structured light triangulation
Light source wavelength	460 nm (blue spectrum)
Camera resolution	2 × 5.0 MP
Positioning system	3-axis automated rotation
Environmental requirements	10°C - 30°C operating range
Data output	STL mesh format

Table 1: Specifications of the Autoscan Inspec structured light 3D scanner[1]

surface geometry through phase-shift pattern projection and optical triangulation. The specifications are displayed in Table 1.

The system projects phase-shifted fringe patterns using a blue LED source, with surface geometry reconstructed through disparity analysis between synchronized camera captures. The 5.0 MP global shutter sensors provide a theoretical lateral resolution of 0.05 mm across the 100 mm field of view [1]. The system is equipped with a dual axis rotation stage and a camera angle adjuster for fully automated positioning and data acquisition.

4 Measured Objects

This section describes the objects that were chosen for measurement, and explains the choices. Two FDM 3D printed objects are chosen for the study. Both are well known FDM 3D printer calibration objects - the Voron Calibration Cube and the 3D Benchy. They offer a good blend of detail and simple surfaces to perform a variety of measurements on. Additionally, both objects are open source [2, 3]. A simple prism is added below each of the objects for easier work-holding on both the CMM and structured light scanner.

[2] https://www.printables.com/model/758730-voron-design-calibration-cube

[3] https://www.3dbenchy.com/license/

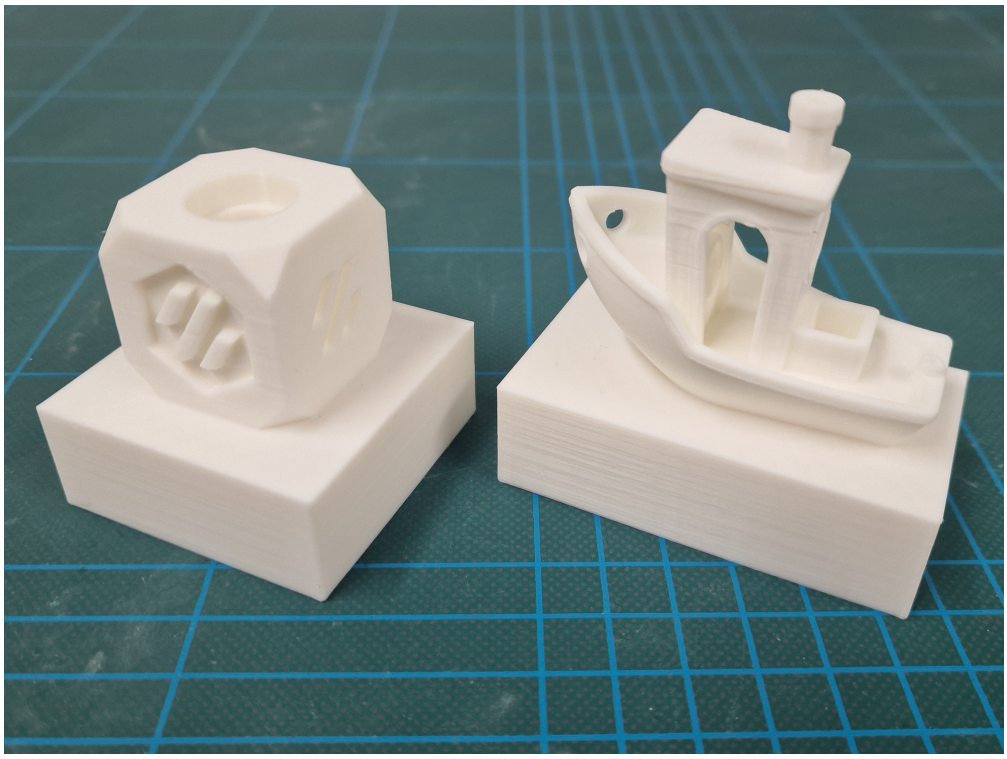


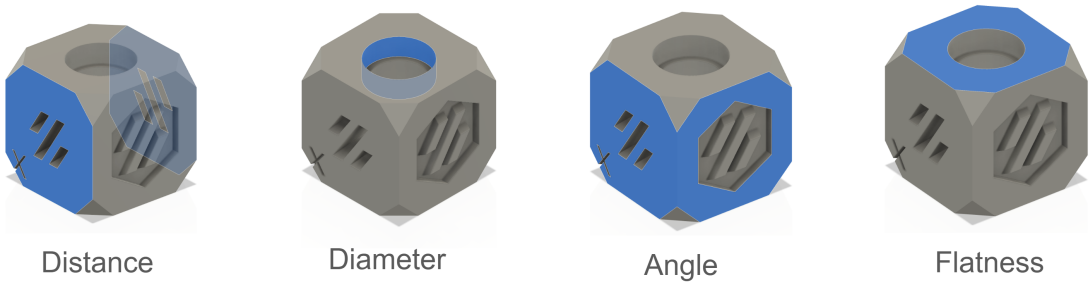
Figure 2: 3D printed calibration objects - Voron calibration cube (left) and 3D Benchy (right)

The objects shown in Figure 2 were printed in white PLA so that they do not have to be sprayed for scanning. The color has no effect on the CMM measurement. The 3D printer used was a Bambu Lab X1 Carbon, and the material was PLA Basic Jade White from the same manufacturer. A 0.12mm layer height and a 0.4mm diameter nozzle were used.

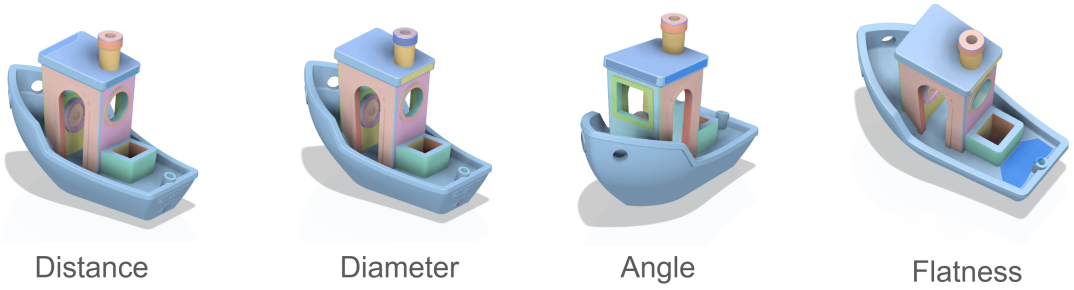
The objects each have several features that would would work well for a metrological comparison of the 3D scanner to the CMM. The features must be accessible by both machines, and should have different quantities measured. For the purposes of this comparison I have chosen to measure:

- The distance between two parallel faces
- The angle between two faces
- The diameter of a cylinder
- The flatness of a level surface

The features chosen for measurement on both objects are shown on their CAD models in Figure 3. They are chosen to represent the set of features listed above on each object, and to be easily accessible by both CMM and 3D scanner. It should be noted that the Voron Cube features an internal cylinder, and the 3D Benchy an external cylinder.



(a) Features measured on the Voron Cube

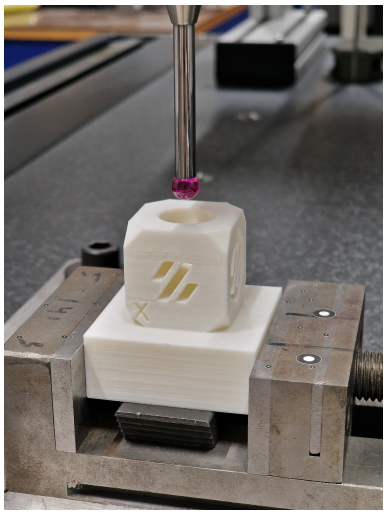


(b) Features measured on the 3D Benchhy

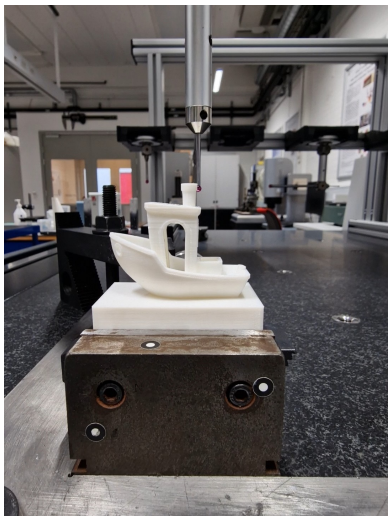
Figure 3: Features measures on the CMM on both objects

4.1 CMM measurements

Each object was measured 5 times using the same measurement program. The Voron Cube was measured using a 4mm radius ruby sphere as a larger sphere reduces the influence of surface waviness on the measurement. The 3D Benchy was measured using a 0.75mm radius ruby sphere, as the model has many more small features unsuitable for measurement with the larger probe. The objects fixed to the CMM are shown in Figure 4. The measurement strategy avoids any details present on the measured faces, and leaves a margin from the edges of the measured features as to not catch any filleting or defects present at sharp edges.



(a) Voron cube during measurement

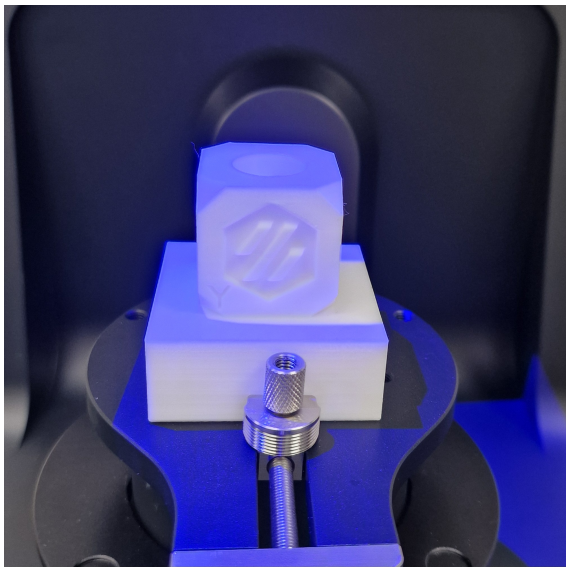


(b) 3D benchy during measurement

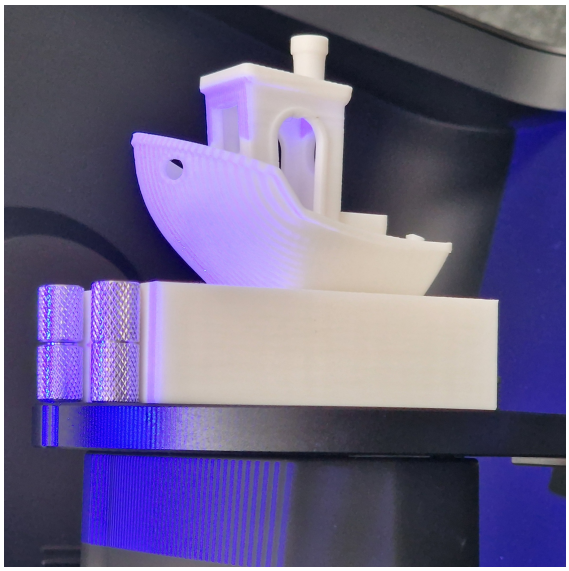
Figure 4: Both objects mounted to the Zeiss Prismo during measurement

4.2 3D scans

Each object was scanned 5 times using identical settings. The scans of the Voron Cube were done using 17 frames and the 3D Benchy was captured using 21 frames. The objects as mounted on the scanner are shown in Figure 5. With the bases of the parts entirely removed, the resulting meshes for the Voron Cube contain an average of 1904649 triangles with a standard deviation of 2%, while the 3D Benchy scans contain an average of 2456375 triangles with a standard deviation of 0.43%. The meshes with the bases removed are shown in Figure 6.

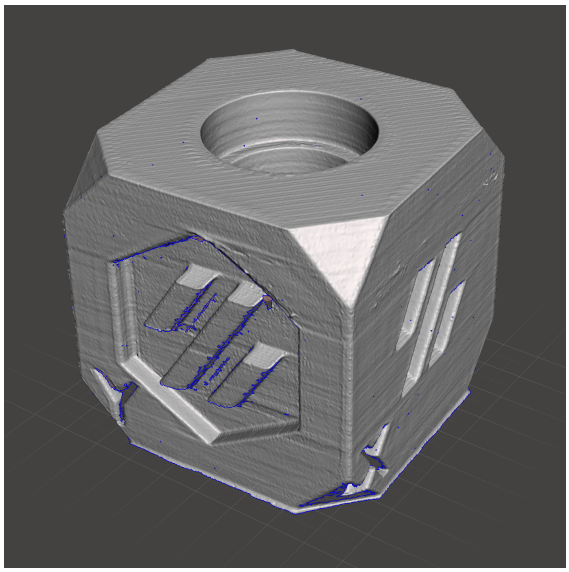


(a) Voron Cube during scanning

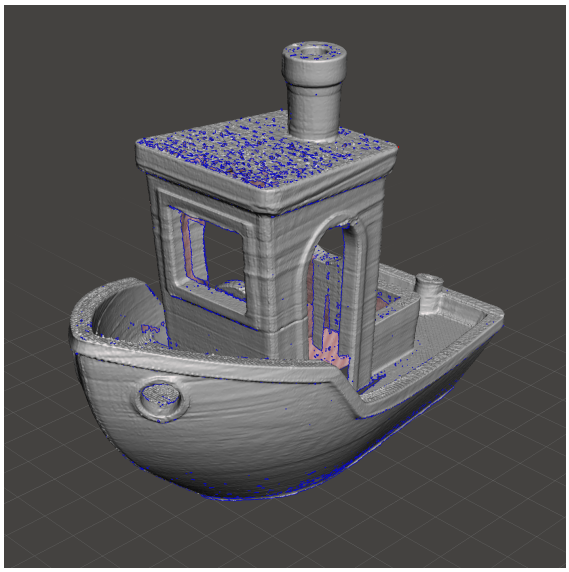


(b) 3D Benchy during scanning

Figure 5: 3D printed objects during the scanning process



(a) One of the Voron Cube scans



(b) One of the 3D Benchy scans

Figure 6: Meshes of the scanned objects with the bases removed

4.3 Scan analysis

The meshes of the scans were imported into GOM Inspect for analysis. In GOM inspect, the user can manually select geometries on the meshes, and construct best fit features (ex. lines, planes, cylinders) to the mesh fragments. These constructed features can then be used to make measurements. The process for extracting the information from the scans is shown in

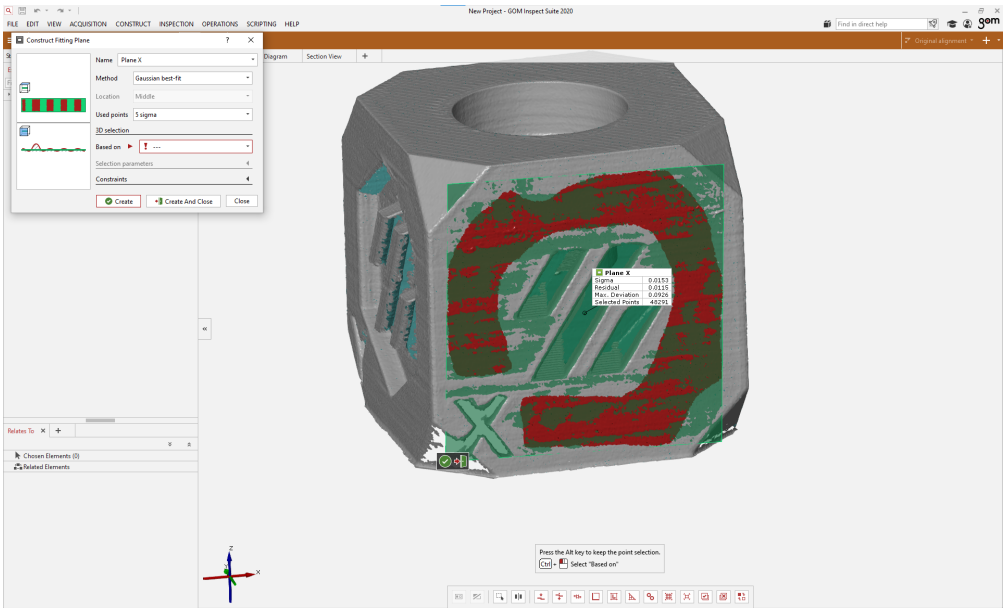


Figure 7: Constructing a Gaussian best fit plane for the X face on the Voron Cube in GOM Inspect

this subsection. The geometry construction process is shown in figures 7 and 8. The selected areas clear any details present on the face and leave a margin to the edges. This is the same for the CMM measurements. Since the area is selected manually each time, the exact area used for the calculation varies slightly from scan to scan.

For the measurements of the distance and angle, a work around in GOM Inspect is needed since the software does not support measuring the distance or angle between two planes in any way. For the distance measurement the planes need to be parallel for the measurement to be unambiguous. Therefore one plane is constructed as a best fit plane, and the other as a constrained parallel best fit plane. On the Voron Cube the face containing the X symbol is the best fit and the opposite face is the parallel best fit. On the 3D Benchy the front of the roof is the best fit plane and the rear of the roof is the constrained best fit plane. The distance between the faces can then be found by constructing a point at the centroid of the best fit plane, and constructing a projected distance from that point to the opposite plane. The measurement is shown in Figure 9.

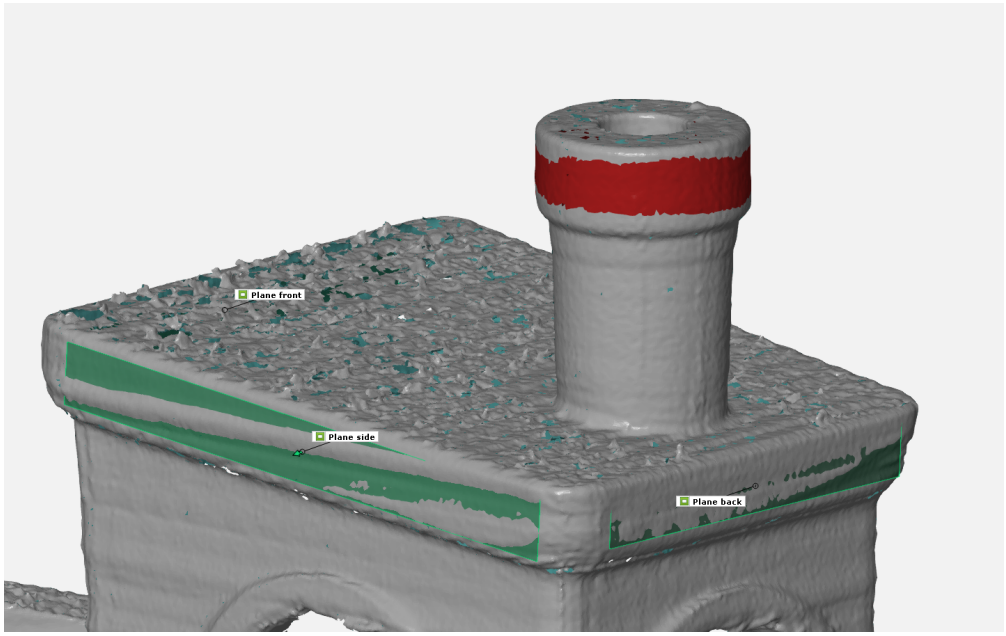


Figure 8: The selected area for a gaussian best fit cylinder on the 3D Benchy in GOM inspect

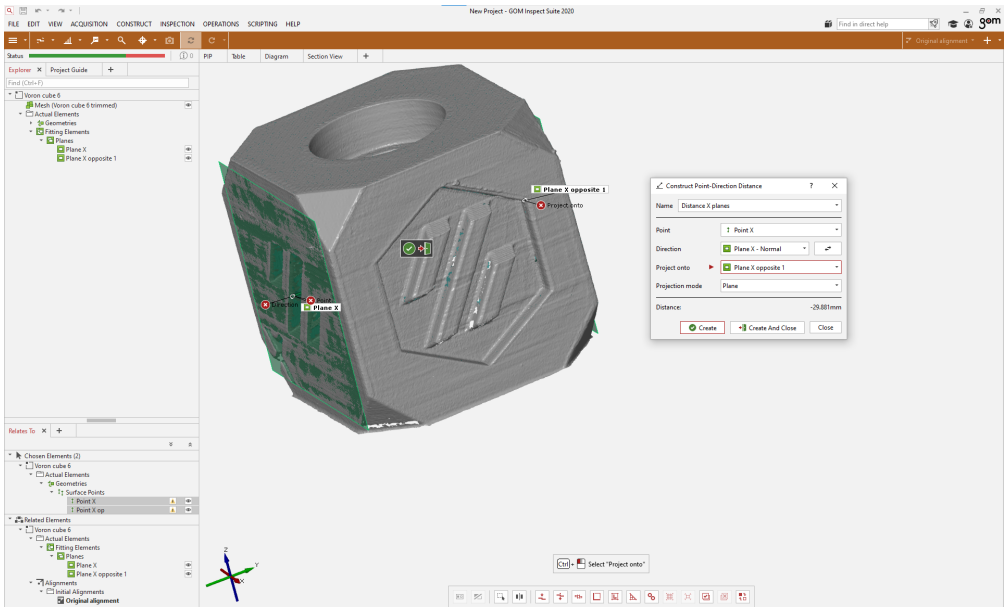


Figure 9: The distance between planes measurement in GOM inspect

To measure the angle between two planes, the 3 point angle tool can be used, however it requires two points and a center point, which are not readily available on the models. The solution is as follows:

a. Construct a point at the centroid of each plane.

b. Construct a line originating at the point on the X plane in the direction of the normal

vector of the Y plane

c. Construct a line originating at the point on the Y plane in the direction of the normal vector of the X plane

d. Construct a point on the intersection of the two lines

e. Construct a 3 point angle measurement using the intersection point as the vertex and the points at the centroids of the planes as the vectors

The angle measurement construction is shown in Figure 10.

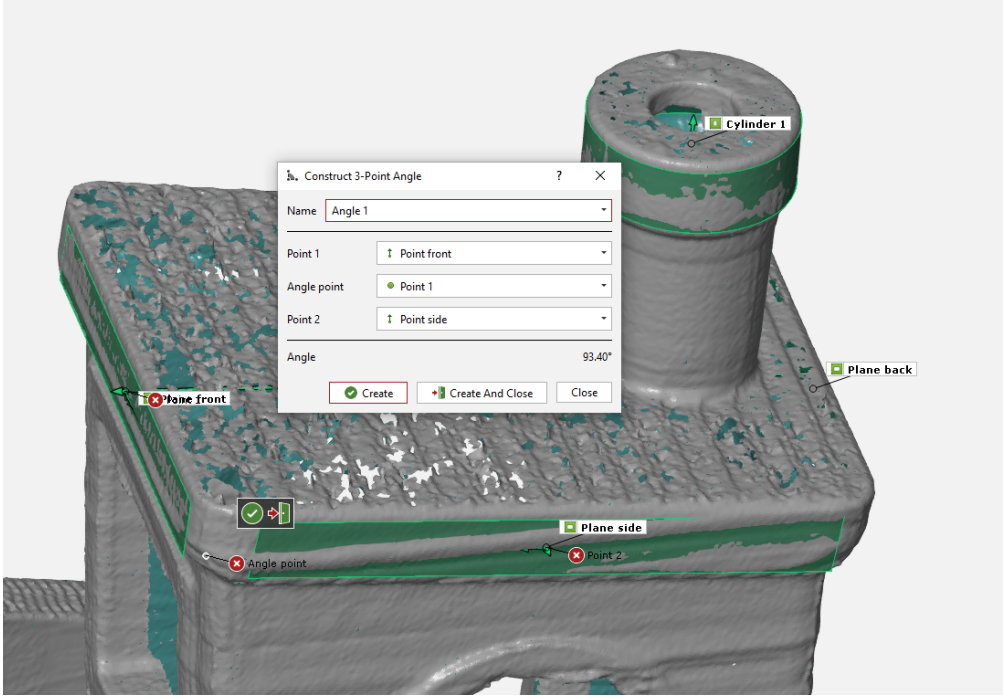
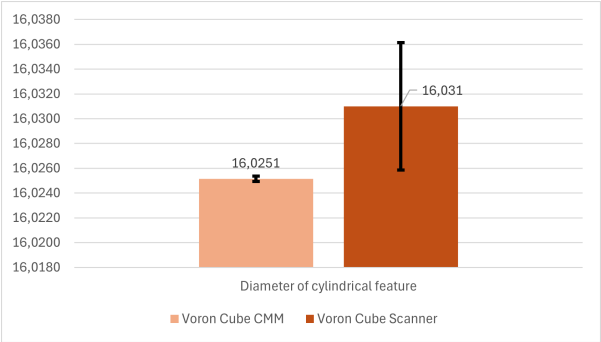


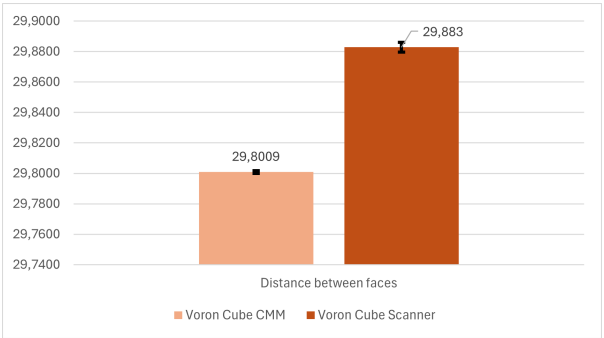
Figure 10: Angle measurement construction on the 3D Benchy in GOM Inspect

5 Results

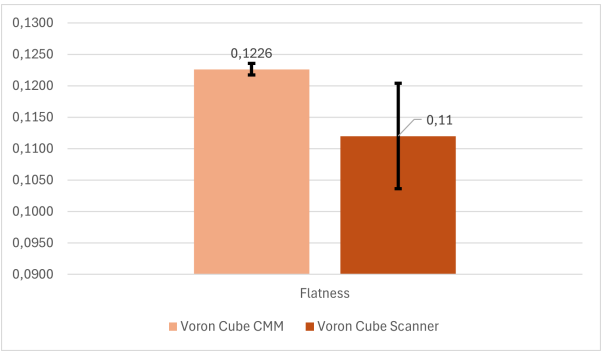
The results from the CMM and 3D scanner measurements of the 3D printed objects are visible in the Figure 11 and Figure 12. The vertical axis is in mm and the uncertainty is the standard deviation of the measurements.



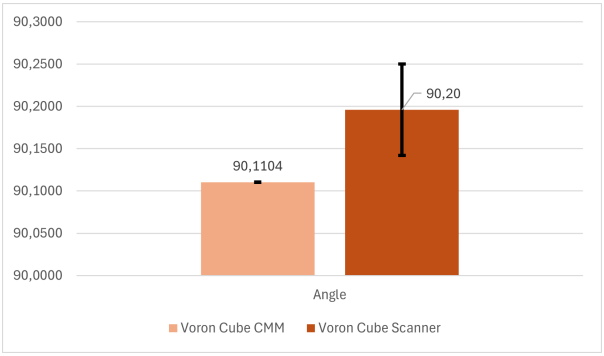
(a) Diameter of the hole



(b) Distance between the X faces

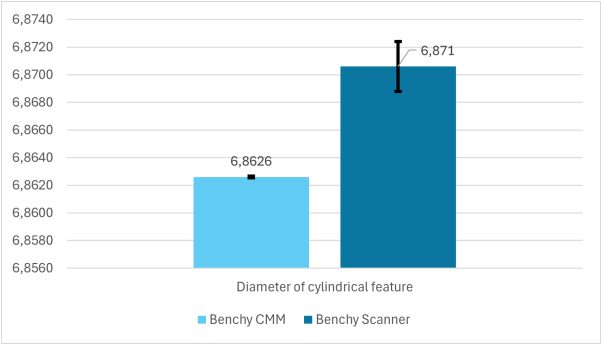


(c) Flatness of the top face

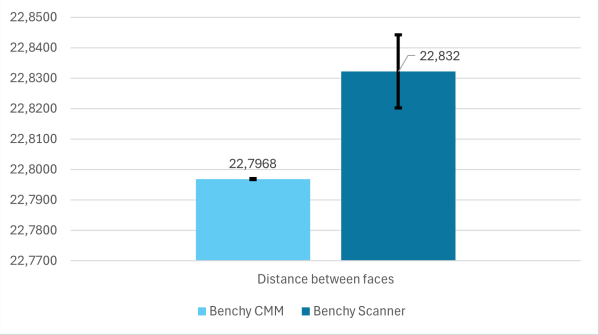


(d) Angle between X and Y opposite faces

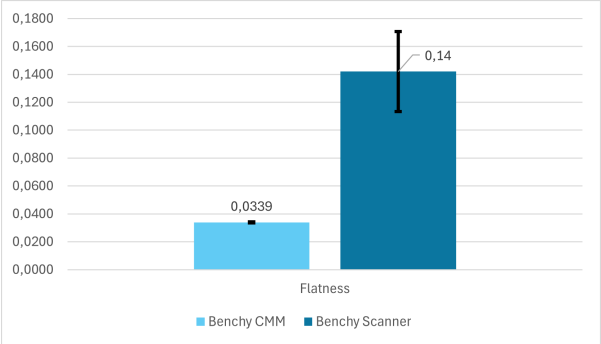
Figure 11: Comparison of the CMM and 3D Scanner measurements of the Voron Cube



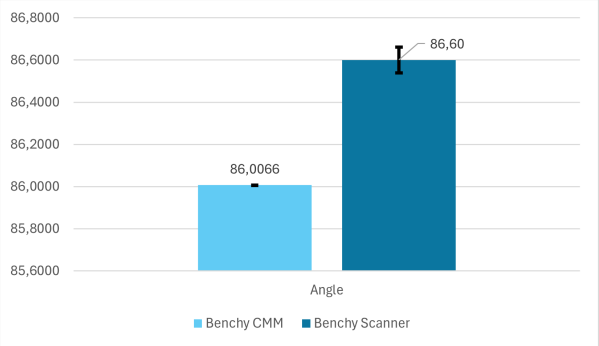
(a) Diameter of the chimney



(b) Distance between the roof faces



(c) Flatness of the deck



(d) Angle between roof faces

Figure 12: Comparison of the CMM and 3D Scanner measurements of the 3D Benchy

It is clear from the measurements that the scanner not only has a greater uncertainty, but it also exhibits a bias in the results, which is shown in Figure 13. The 3D scanner claims an MPE of 10 μm according to its specifications, while the CMM has MPE $= 0.9 + L/350\mu$m. Since the CMM is calibrated, the MPE on the 3D scanner is underestimated according to the results presented in this report.

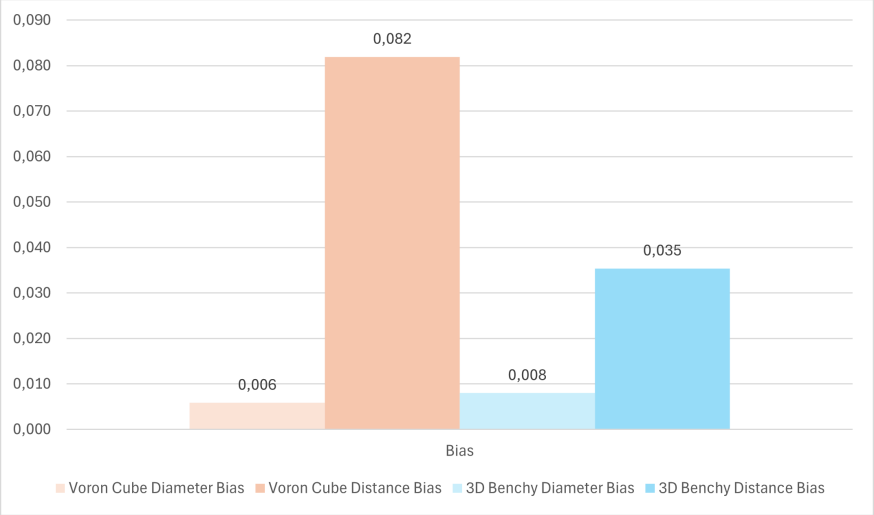


Figure 13: Bias exhibited by the 3D scanner relative to the CMM

6 Discussion

The flatness measurements revealed a pronounced discrepancy: for the Voron Cube flatness measurement shown in Figure 11c the CMM measured a larger value of 0.1226 compared to the 3D scanner at 0.11. For the 3D Benchy measurement the inverse it true (Figure 12c), the scanner measured a much larger value of 0.14 compared to the CMM's 0.0339. This is an unexpected result as the Voron Cube was scanned with a larger probe (r=4mm) than the 3D Benchy (r=0.75mm). A larger probe during a sweep measurement acts as a wider mechanical filter, missing more of the fine ripples in the surface, which should result in a lower flatness value for the Voron Cube compared to the 3D Benchy. An illustration of the mechanical filtering can be seen in Figure 14.

A similar flatness is expected from both objects as the top surfaces of all parts are printed with the same settings, and the objects were made in one 3D print job. In this case the results from the 3D scanner are in relatively good agreement between the parts. A bias for the scanner to measure less flat surfaces in both cases was expected (due to the mechanical filtering of the CMM probe). The result for the flatness of the deck of the 3D Benchy as measured by the CMM is considered anomalous. The exact measuring strategy chosen for the 3D Benchy flatness measurement on the CMM may have been the cause, as due to the repeating pattern on the top surfaces, the direction in which the flatness is measured has an effect on the obtained value.

Overall the Autoscan Inspec is an instrument that is fast and easy to use, and provides an accuracy better than 100 μm which is usable for some applications. Additionally, it provides a more complete measurement of the part, where exact features to be measured can be determined after the fact, which is not the case with a CMM measurement. Due to the mesh output, it has high potential for reverse engineering when the CAD files of a mechanical

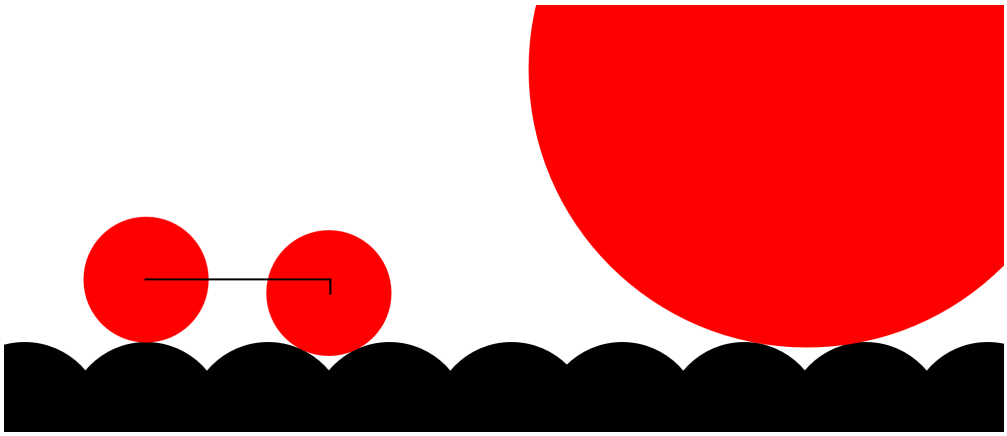


Figure 14: Schematic showing a small and large probe over the 3D printed top surface

part are not available, which could be complemented by more accurate and precise CMM measurements for some critical features or mating surfaces.

7 Conclusion

This report has presented a direct metrological comparison between the Zeiss PRISMO CMM and the Shining 3D AutoScan Inspec structured-light scanner, using two FDM-printed objects (Voron cube and 3D Benchy). Distances between parallel faces, angles between faces, cylinder diameters and surface flatness were measured five times on each instrument, and uncertainties were assessed as the standard deviation of repeated measurements. The flatness measurement of the 3D Benchy made on the CMM is considered anomalous, potentially due to the specific measurement path chosen.

The Zeiss PRISMO CMM consistently achieved repeatability within its specified maximum permissible error, $\mathrm{MPE}_{\mathrm{CMM}} = 0.9 + L/350\mu\mathrm{m}$, while the structured-light scanner exhibited standard uncertainties up to an order of magnitude larger and systematic biases of tens of micrometres relative to the CMM (see Figure 13). Moreover, the observed bias exceeded the scanner's claimed MPE of 10 μm, indicating that its specification underestimates its true error.

Accordingly, for applications demanding sub-10 μm precision, the Zeiss PRISMO remains the instrument of choice. The Shining 3D AutoScan Inspec, however, offers rapid, non-contact digitization and is suitable for workflows where moderate accuracy (tens of micrometres) is acceptable. Future work should focus on assessing the scanner's uncertainty when measuring objects made of different materials as the surface finish and material may have an influence on the precision and accuracy of the measurement.

References

[1] SHINING 3D Tech. Co., Ltd., *AutoScan Inspec Technical Specifications*, version 3.25 ed., Hangzhou, China, 2025, product Brochure.