A CONTEST OF SENSORS IN CLOSE RANGE 3D IMAGING: PERFORMANCE EVALUATION WITH A NEW METRIC TEST OBJECT

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ABSTRACT:

An independent means of 3D image quality assessment is introduced, addressing non-professional users of sensors and freeware, which is largely characterized as closed-sourced and by the absence of quality metrics for processing steps, such as alignment. A performance evaluation of commercially available, state-of-the-art close range 3D imaging technologies is demonstrated with the help of a newly developed Portable Metric Test Artefact. The use of this test object provides quality control by a quantitative assessment of 3D imaging sensors. It will enable users to give precise specifications which spatial resolution and geometry recording they expect as outcome from their 3D digitizing process. This will lead to the creation of high-quality 3D digital surrogates and 3D digital assets. The paper is presented in the form of a competition of teams, and a possible winner will emerge.

1. INTRODUCTION

Greater accessibility of affordable sensors and software in recent years enable consumers and non-engineering users to start investigating and investing in the use of 3D technologies; but this hard- and software is largely characterized by being closed-sourced and by the absence of numeric or metric feedback of quality metrics in acquisition and subsequent image processing steps. Therefore an independent means of 3D image quality assessment for 3D acquisition is needed.

The aim of this paper is to validate performance of commercially available, state-of-the-art close range 3D imaging technologies with the help of a purpose built portable metric test artefact. An outline of the procedure to perform acceptance tests will be described. The non-professional user will be able to assess whether a 3D imaging system complies with the limits for quality parameters specified by the manufacturer, and also if the 3D imaging system is performing to a degree that the 3D image quality outcome is ‘fit for purpose’.

This paper is presented in the form of a friendly competition between high-resolution expensive sensors, a widely used medium priced sensors, and known robust photogrammetry strategies. The format is inspired by the paper of (Förstner 2002) with a ‘question & answer’ conversation between computer vision and photogrammetry. All sensors need to compete by 3D imaging the same challenging test object with a known geometry features and challenging surfaces.
The applied procedure will confirm principal test methods and provide a tool 3D image sensor evaluation for the end user.

This paper includes measurement outcomes of comparative 3D imaging with different sensors undertaken in 2012 and 2013, in-house at UCL, UK and in Belgium with the Agora3Dproject (RBINS) (Hess 2013).

2. HISTORY AND RULES OF THE GAME (BACKGROUND)

Ideally, sensor evaluation and assessment of the overall 3D system must be based on a systematic approach. Metrology provides a framework by which a measurement instrument can be characterized and compared to other instruments. Usually testing should be conducted in a dedicated metrology laboratory, with controlled temperature, air humidity level and known laminar airflow. The performance is evaluated using quantities like resolution, uncertainty and accuracy, with particular attention to the effects of object material and local surface features.
Testing should take existing standards into account and use certified artefacts (Beraldin et al. 2007, chap.2). An overview of existing artefacts has been published by (Robson et al. 2011) and a good overview over metrology standards and also insight into test objects has been given by (Guidi 2013).

Two main methodologies for evaluating sensor capabilities are adapted for the assessment procedure in this paper:

1. The guidelines VDI2634 which serves optical probing for acceptance and re-verification measurements, based on ISO10360 for CMMs (Coordinate Measurement Machines). In this research particularly part 2 (area scanning) and part 3 (multiple view systems based on area scanning) are used (VDI/VDE 2634-2 & VDE-GMA 2002).
2. Geometric Dimensioning and Tolerancing (GD&T) by (The American Society of Mechanical Engineers (ASME) 2009). Expressions and variables are used.

3. DESCRIPTION OF THE GAME

3.1 The game board - Metric test object for independent sensor assessment

Characterizing and validating a 3D imaging system is done by the use of certified material reference bodies, called ‘geometric features’ or ‘objects’ in this research. To enable manufacturer independent quality control assessment of 3D imaging sensors, a portable metric test artefact was developed. It was designed and built at UCL CEGE (first authors principal PhD research) on the basis of engineering metrology guidelines, and was introduced in 2012 (Hess & Robson 2012). This test object is used for quantitative assessment of commercially available, state-of-the-art technologies. It enables an assessment of sensor form recording and spatial resolution evaluation from adapted photographic procedures. It includes known surface and geometric properties which support comparative imaging on different 3D imaging systems.

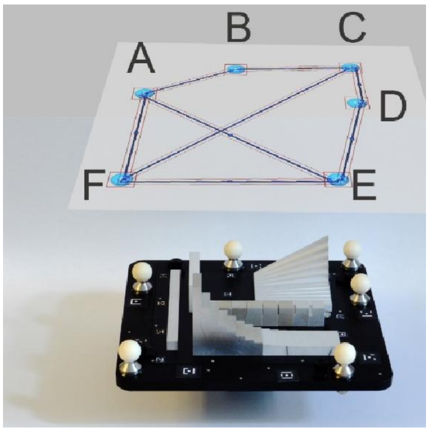

Figure 1 The portable metric test object. Base plate with calibrated spheres as datum and geometrical features to conduct dimensional tolerancing tests and geometric evaluation. Inserted is the secondary plate with geometric features.

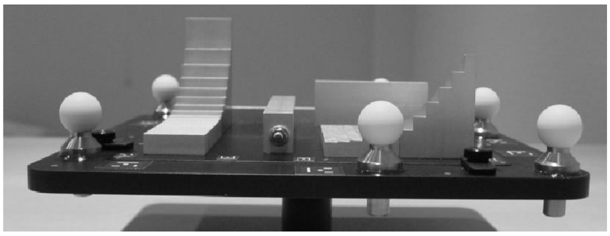

Figure 2. The portable metric test object. Base plate seen from the side, surrounded by calibrated lambertian tooling balls raised on a stainless steel collar, for consistent registration.

Figure 3. The portable metric test object. Secondary plates with colour and resolution targets.

The test object includes reinforced carry-case for portability and is of small size (close to A4 standard page size). Materials have been chosen for thermal stability (15-25 C). Situated around the base plate is an irregular array of six 20mm diameter individually calibrated tooling balls mounted onto conical aluminium bases, to provide an independent datum for spatial registration. As the white matt surface of the ceramic balls provides a good surface for optical measurement the conical base allows a high degree of sensor access to obtain maximum sphere surface coverage. The frame then provides the physical reference onto which a series of secondary plates can be reproducibly attached.

All geometric reference features on the test object are grouped on the same secondary **'geometry plate'** supporting step, gap, angle and length evaluation. The surface finish of the aluminium features was treated to be diffusely reflecting by etching.

The '**2D photographic target plate'** includes established photographic test materials designed to assess spatial resolution (ISO-16067-1), colour recording capabilities (x-rite Mini-Macbeth) and gloss recording. It supports the assessment of resolution, colour and gloss.

The test object is designed for the evaluation of short-range (50mm to 500mm) optical surface recording systems.

4. TEAMS (DATA ACQUISITION)

The use of a validation procedure is demonstrated on different surface measurement principles which include photogrammetric multi-view stereo (MVS), 3D colour laser scanner, structure from motion (SfM), medium cost 3D laser scanner.

4.1 Team 1: Photogrammetric Multi-view stereo (MVS) – longstanding team

Photogrammetric Multi-view Stereo method has proved its ability to be a serious rival for laser scanners for accurate and dense 3D reconstruction of both cultural heritage and industrial objects (Hosseininaveh Ahmadabadian et al. 2012).

The test object was set up in a photographic lab. To aid recording of the surface features a structured pattern was projected onto the test object. Next to the test object a set of calibrated Brunson scale bars were installed for the correct adjustment of scale. Similar to the method presented in (Hosseininaveh Ahmadabadian et al. 2013), after geometrically correcting the images known as 'image undistortion', corresponding image measurements extracted from the network were used to compute approximate 3D coordinates in Bundler (Snavely et al. 2008). A photogrammetric network adjustment with the relative orientation parameters of the stereo camera as geometric constraints was then computed to estimate the length of the stereo baseline within the network. This length was compared with the calibrated baseline to estimate a scale factor, which was then applied to the camera locations and 3D coordinates. After resolving the scale, these data were input into PMVS processing software to generate a dense point cloud.

4.2 Team 2: 3D colour laser scanning – champions league

The data was recorded with a 3D colour laser scanner, an expensive but high-performing system. This laser scanner is designed for recording small objects with volumes of the order of 0.5m$^{3.}$ It records 3D coloured point data at a sampling interval of 100µm at an accuracy of the order of 25µm over the surface of an object. The scanner collects 3D geometry information through the use of a laser triangulation system, whilst colour is collected by analysis of the reflected light from three lasers. The object profile is recorded within the depth of field (9x8x5cm) while moving the scan head laterally and vertically by a Coordinate Measuring Machine (CMM). The laser spot diameter is nominally 80µm, the sampling rate was at 100µm, the RMS and the accuracy of its CMM positioning is 6µm.

4.3 Team 3: Structure from motion (SfM) – newcomer

Structure from Motion uses the principle that movement through a scene allows an understanding of the shape of the scene in three dimensions. This methodology has become very popular in different domains like archaeology field work, and can be used by non-professional users with a regular pocket camera; it even can even be computed on a mobile phone with wireless network connection.

In this case a very controlled recording of the scene has been conducted. To record the metric test object a SLR camera (18 Mpx camera with a macro 50 mm lens) was set up on a tripod with two-directional lighting. The camera is set up in two heights (45º and 60º looking down onto the object), while being turned fully around its own axis. Approximately 100 photographs are taken and processed in a commercially available software.

After a night's of processing the software produces a model with a high polygon count. No metric outcomes of the quality of the bundle adjustment or quality of alignment is given. The 3D model now needs to be scaled and is exported in polygon (.stl) format.

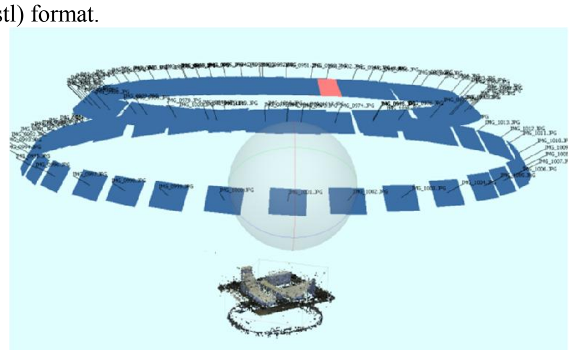

Figure 4. Team 2. Structure from motion on the Metric Test Object (Image and processing courtesy of Agora3D).

4.4 Team 4: 3D laser scanning – mid-division

This affordable 3D laser scanner is very popular different communities, amongst them scientific use for morphometric surface analysis and the 'maker movement'. This is an attractive tool for museum professionals, palaeontologists and other fans of 3D digitization of surface and colour. (Mathys et al. 2013). The manufacturer specifies that for the specific set-up used the accuracy is at 0.38mm.

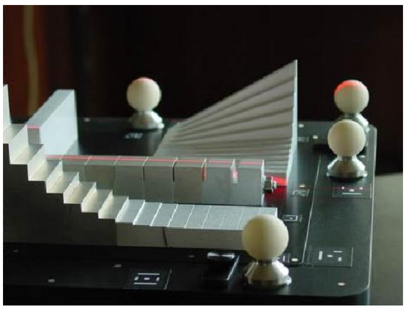

Figure 5. 3D imaging of the test artefact with a laser scanner in action.

5. THE GAME (EXPERIMENTS)

5.1 Recording environment

Testing by non-engineering users is usually not conducted in a metrology laboratory and users will need a clear guideline and procedure how to perform tests. Therefore a realistic scenario will be shown, where users will record a complete 3D model in one single session or scan from the top of the test object (will be treated as area scanning), and proceed to the evaluation, or in the round (and sensors will be treated as multiple view systems based on area scanning).

5.2 Evaluation tools

GOMInspect is a certified software, currently freely available. It also includes "Geometric Dimensioning & Tolerancing" (GD&T) strategies for evaluation, and is using ISO 1101 and Y14.5 as guidelines for computations (GOM GmbH 2013). The software package used usually gives numeric feedback about number of points selected and the quality of the fit. Actual data versus nominal (e.g. reference) values can be conducted in the software (diameter, distance, etc. including tolerances).

5.3 Pathway through the game

To conduct the test, the user is encouraged to select the levels of testing appropriate to evaluate the sensors, which will be from top down for a preferred geometry evaluation, and from bottom up for a preferred spatial resolution evaluation using the ISO 16067-1 Chart, see Figure 6. The user will also be able to choose to evaluate the results with a pass/fail, based on the calibrated values and the expected sensor specifications.

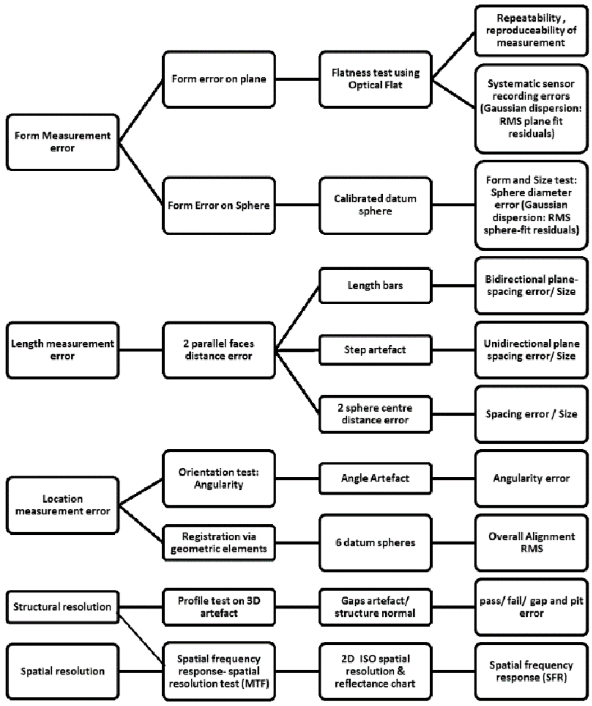

Figure 6. Decision making tree for sensor tests.

Let's play! Here following criteria for form errors are demonstrated: sphere diameter error, sphere distance error, plane spacing errors. The structural/spatial resolution evaluation is also demonstrated.

5.4 Sphere Diameter error

The Diameter Error is the difference between the measured diameter of a sphere and the reference diameter of the same sphere provided on the calibration certificate. The uncertainty associated with the reference diameter should be provided.

An unconstrained least squares sphere is fitted to the collected data of each sphere (Gaussian fit, 5 sigma) and compared to the known certified sphere diameter (accuracy 0.001). The diameter deviations from the reference of the six datum spheres of each team were computed. The data plot in Figure 8 shows the deviation from the diameter in mm, while Table 1 provides overall values of each team (min, max, and standard deviation, mean).

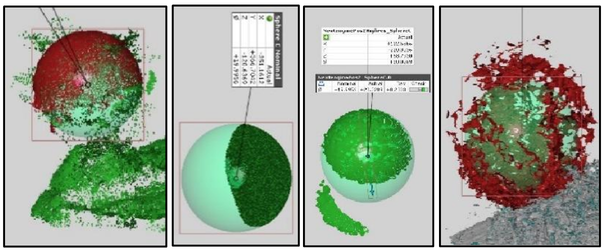

Figure 7. The four images show the sphere fitting.
From left to right: a) Team 1 b) Team 2, c) Team 3 d) Team 4.

While for Team 2 and 3 a clear selection of data was easy to select, for Team 1 a significant manual (de)selection of outlier points was necessary, see Figure 7a. Sphere fitting for Team 4 was not achievable due to the inconsistent surface mesh with many outliers, see Figure 7d. An approximated sphere was nevertheless fitted, always significantly smaller than the expected diameter, was applied and used for Sphere distance error, see section 5.5. Team 4 therefore failed the Sphere Diameter challenge.

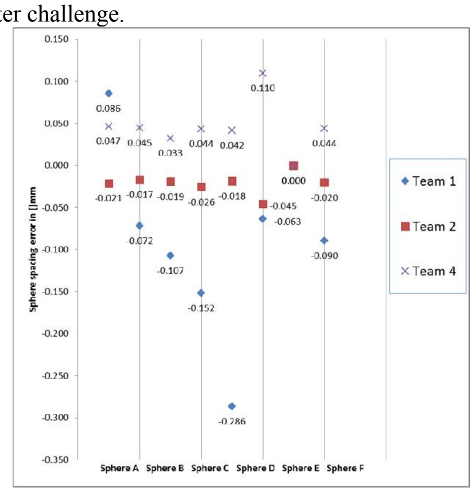

Figure 8. Sphere diameter error of Team 1, 2 and 4.

Sphere Diameter Error	Team 1	Team 2	Team 3	Team 4
mean/ media	-0.09	-0.02	n/a	0.04
standard deviation	0.12	0.01	n/a	0.03
max	0.09	-0.02	n/a	0.11
min	-0.29	-0.05	n/a	0.03

Table 1. Overall values of team for Sphere Diameter error.

While Team 1 (blue diamond) had considerable difficulties to keep up with this task and shows an inconsistent set of values (sphere fit from a point cloud with many outliers), and Team 4 (purple sphere) is keeping up well, Team 2 (red square) was - with one minor forgivable exception - consistently performing to their specifications, but Team 2 is clearly winning the challenge here.

5.5 Sphere Distance Error

The mounted tooling balls are intentionally irregular to produce a registration and alignment datum. The spheres have been named with letters, and the distances with two letters describing the distance for example sphere A and B is the sphere distance ‘A-B’ from sphere centre to sphere centre. The test distances and sphere positions are shown as diagram in Figure 1. For this challenge the following lengths have been tested: C-D (79.9mm mm = first column of values in Figure 9), A-B (106.96mm = second column), B-C (125.03mm = third column), D-E (143.31mm = fourth column).

The reference distances have been measured with digital callipers with an uncertainty of +/- 0.01mm.

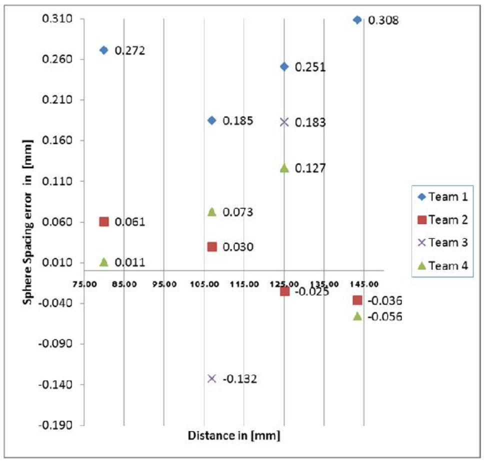

Figure 9. Sphere spacing error for Teams 1-4.

Sphere spacing error	Team 1	Team 2	Team 3	Team 4
mean/ media	0.26	0.00	0.26	0.04
standard deviation	0.05	0.05	0.56	0.08
max	0.31	0.06	1.18	0.13
min	0.19	-0.04	-0.13	-0.06

Table 2. Overall values of team for Sphere Spacing error.

Team 3 has had difficulties from the start (sphere fitting) and is represented graphically only for two values (green triangle). While the values for C-D and B-C are displayed, the values of A-B (0.34mm) and D-E (1.17mm) are beyond the scale of this graph. Table 2 is showing the large standard deviation for Team 3. Team 1 is at the upper fringes of the field (blue diamond), and Team 2 (red square) and 4 (purple circle) are competing for the best place with only a minor difference. Team 2 manages to keep ahead with a Standard deviation of 0.046mm, and a maximum deviation of 0.061mm. It is followed by team 4 with a standard deviation of 0.079mm. We can consider team 2 the winner for this competition.

5.6 Plane Spacing Error

Bidirectional and unidirectional plane spacing error can be conducted with the test object, with the following features: step and length gauges. Here we demonstrate the bidirectional plane spacing error on the length gauges. These are particularly challenging due to their placement in relation to other features on the geometry plate (occlusion), and for systems with a fixed recording position. For each team a least-square plane was fitted into the selected area on the faces of the end gauges on the metric test object, as in Figure 10b.

For Team 4 a combined 3D image had to be aligned from multiple scans (high resolution and medium res.) in the proprietary software without control or option for improvement over alignment quality/ metrics; the deviation from the reference value is quite high with 0.65mm for this. While for team 3 the polygon mesh needed to be scaled, an outcome of a standard deviation of 0.00mm is not astonishing. Team 1 is performing to its specifications, but Team 2 is performing very well. Full points to team 3 and team 2.

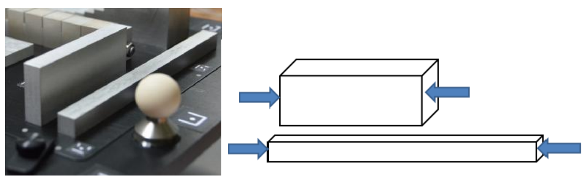

Figure 10. a) Length gauge on the test object; b) Bidirectional Plane spacing error measurement schematically.

		Did your system record both faces of length bars 1 and 2?	Reference measurement in [mm]	Measured length	Difference = Plane Spacing error [mm]	Deviation in % of Total	Standard Deviation	Median
Team 1	Length bar	Yes	74.94	74.35	-0.59	-0.01	0.50	-0.24
Team 1	Length bar	Yes	149.87	149.75	0.12	0.00		
Team 2	Length bar	Yes	74.94	75.07	0.13	0.00	0.03	0.15
Team 2	Length bar	Yes	149.87	150.03	0.16	0.00		
Team 3	Length bar	Yes	74.94	74.94	0.00	0.00	0.00	0.00
Team 3	Length bar	Yes	149.87	149.87	0.00	0.00	used for scaling	
Team 4	Length bar	Yes	74.94	75.62	0.68	0.01	0.04	0.65
Team 4	Length bar	Yes	149.87	150.49	0.62	0.00	alignment / 3 scans	

Table 3. Bidirectional Plane Spacing error.

5.7 Structural resolution using the gap feature as structure standard

Structural resolution is defined by lateral resolution of distance sensors (VDI/VDE-GMA 2617-6-2 2007, p. 26). A pit with calibrated depth and diameter is measured to determine if the smallest structure (gap) are resolved. The feature to be tested is a right angled edge structure.

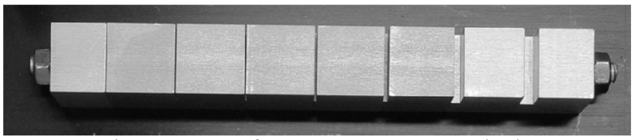

Figure 11. Gap feature as structure standard.

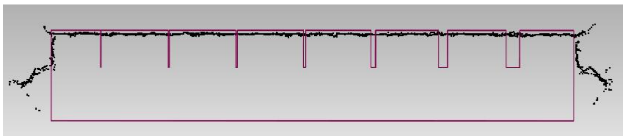

Figure 12. Team 1: point cloud in black, in purple is the as-built geometry in CAD. No gaps could be detected.

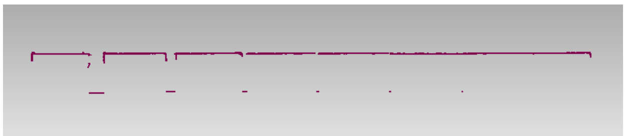

Figure 13. Team 2: Single point cloud recorded from the top Clear detection of pits for the geometry and the gap at the top of the structure from 3mm gap to 0.2mm gap.
Gaps could be measured and a pass/fail for dimensions analysis could be conducted.

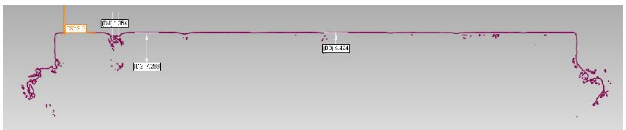

Figure 14. Team 3: the 3mm gap could be detected, and some further indentations which did not count as proper gap.

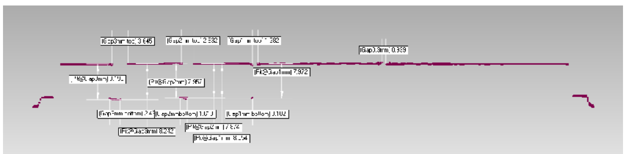

Figure 15. Team4: A good detection of gaps from 3mm to 1mm can be shown. This figure shows the numeric evaluation of the gaps and pits.

Gaps (from large to small)	Before etching [mm]	Team 1	Team 1	Team 2 Pit (imaged to the bottom)	Team 2 Gap	Team 3 Pit at Gap	Team 3 Top	Team 4 Pit at Gap	Team 4 top
Gap 1	3.00	0	0	1	1	0	1	1	1
Gap 2	2.00	0	0	1	1	0	0	1	1
Gap 3	1.00	0	0	1	1	0	0	1	1
Gap 4	0.50	0	0	1	1	0	0	0	0
Gap 5	0.30	0	0	1	1	0	0	0	1
Gap 6	0.20	0	0	1	1	0	0	0	0
Gap 7	0.10	0	0	0	1	0	0	0	0
		0	**0**	**6**	**7**	**0**	**1**	**3**	**4**

Table 4. Detected gaps in the structure. The number 1 indicates whether a gap could be identified on the 3D cross section through the longitudinal section of the gap structure.

The gap feature on the metric test object is constructed from eight individual blocks of the same height in combination with a series of seven blocks which present seven slots with reference depth (pit) of 8mm and widths of: 0.1mm, 0.2mm, 0.3mm, 0.5mm, 1.0mm, 2.0mm, and 3.0 mm.

Looking at the numbers in Table 4, Team 2 hit by far the most goals and is a clear winner with 13 goals (and earns 3 points), followed by Team 4 with 7 goals (earns 1 points). Team 1 and 3 could not score any competitively (earn 0.5 and 0 points respectively).
Even though team 1 and 3 did not score much in this competition, the rendering of the geometric feature in colour is suggesting that the sensor has recorded the gaps. The colour of the shadows and surface normal artefacts caused by a systematic error caused by a shift in the centroid of the laser spot due to a step or gap discontinuity, or through a filtering and smoothing in photogrammetry suggest geometric evidence, where there is none.

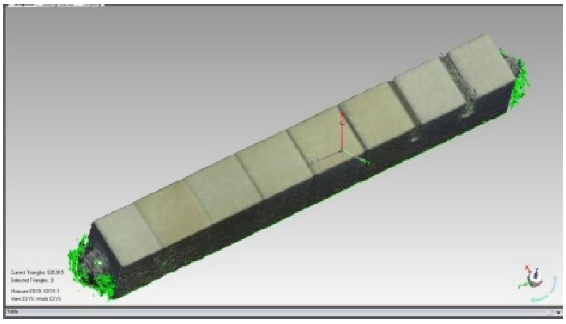

Figure 16. Team 3: Rendering of the gap feature in colour, displaying all gaps/pits.

5.8 Spatial Resolution/ MTF/ SFR

To determine the spatial frequency response of a sensor it is possible to use conventional photographic test procedures. Spatial resolution (and the ability to record greyscales) is of importance for both conventional photography and 3D object recording. Therefore the relation of spatial resolution capabilities through photogrammetric matching strategies on the one hand and through point based laser scanning on the other hand will be determined through sensor spatial frequency response (SFR) on the ISO-16067-1 chart, and will be related to the results by the structure standard, e.g. by the use of the gap feature.

The method to establish values for the MTF (modulation transfer function) and SFR (spatial frequency response) are numeric tests for flat photography prints and 2D image scanning capabilities, but can be extended into 3D imaging sensor evaluation. (Goesele et al. 2003) have proven that MTF of a 3D range scanner can be used for robustly determining using a slanted edge technique.

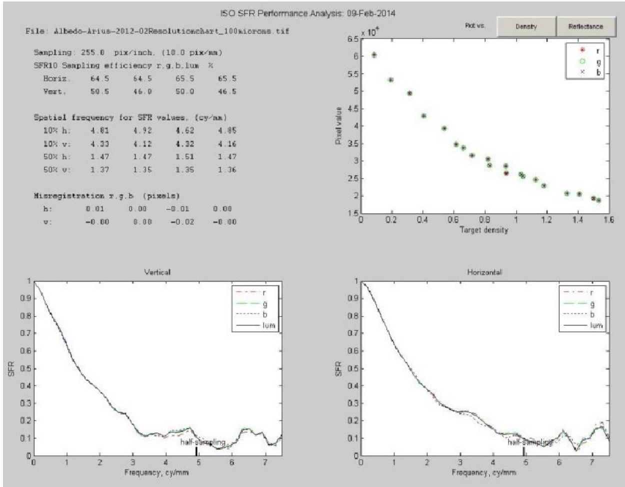

Figure 17. Spatial Frequency Response evaluation for Team 2.

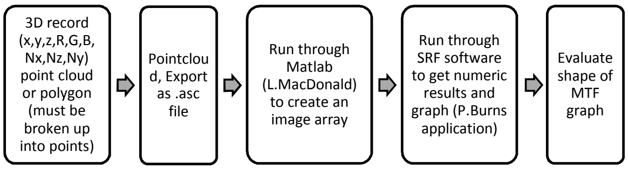

Figure 18. Process 2: Evaluation pathway for spatial resolution evaluation for 3D images.

In this research this is possible by two additional computational elements:

1. Firstly, (Burns 2003) has developed a software application for the second measurement classification method for Spatial frequency response (SFR) by Slanted edge MTF software utility that can also be used on images and 3D scans of ISO-16067-1 charts. It requires the Matlab(R) Compiler Runtime 7.9 (SourceForge.net 2008).
2. Secondly, and essentially, as shown in Figure 18 above, a Matlab script was developed by (MacDonald 2010) at UCL CEGE using 3D colour laser data, that enabled the mapping of a 3D point cloud onto a two-dimensional image array. The resolution can be changed according to the sensor sampling rate but was initially programmed with a resolution of 20pixels/mm.
3. The SFR of this exported image of a 3D coloured point cloud can now be analysed with the Slanted edge software by Burns applying the 'QA-61 Scanner target' analysis as shown in Figure 17.

Values can be computed for a) the initial 2D photograph which is used to produce the photogrammetry for Team 1 and 3, and b) evaluations for the outcome in the 3D model. The latter is taken into evaluation.
Team 2 has performed at ca. 4.8 cy/mm (cycles per mm) as Nyquist limit. Tests for the other teams need to be reconfirmed (therefore score 0), but from a visual inspection Team 2 is winning this contest (score 1 for this challenge as not comparative values are presented).

6. "THE COMPETITION IS ON" (EVALUATION)

6.1 Comparison of the performance of Teams under test.

All teams have performed with great fervour and we are going to look at the score the teams could bring home.
In this competition the most efficient team wins: scores for technical abilities are considered while keeping a balance to user requirements for cost and time.
The maximum score is 3 points per criterium.

Firstly we look at the technical capabilities of the team:

	Team 1	Team 2	Team 3	Team 4
Sphere diameter, probing	2	3	0	2
Sphere spacing error	1	3	3	0
Plane spacing error	1	3	3	0.5
Structural resolution/ gap	0	3	0.5	1
SFR (spatial frequency response)	0	1	0	0
Score 1	**4**	**13**	**4**	**3.5**

Table 5. Scores for technical capabilities for all teams.

Secondly we look at the tactics the team are using to get to their results, the 3D images.

	Team 1	Team 2	Team 3	Team 4
Time for 3D imaging on site	3	1	3	2
Cost	3	0	3	3
Portability of sensor	3	0	3	3
Score 2	**9**	**1**	**9**	**8**

Table 6. Scores for tactics and strategy for all teams.

	Team 1	Team 2	Team 3	Team 4
Combined Score (Score 1 + Score 2)	**13**	**14**	**13**	**11.2**

Table 7. Combined scores for the competition

6.2 Who's the winner?

From the overall score we see that Team 2 is the winner for overall performance, closely followed by Team 1 and 3 (Table 7). Team 2 is excelling in technical capabilities (Table 5), while Team 4 is somewhat behind but has reached a good score for strategy, Table 6.

We can see that advantages of easy portability and affordability counterbalance the excellence in geometric, spatial and colour recording accuracy. Team 4 was quite slow in playing the game (data acquisition), but the ratio between the cost of the equipment (fairly affordable), and the consistent quality of 3D imaging results are certainly to their favour. The system has many fans internationally and is very popular for research applications.

The use in the practical application in a consumer and non-metrology environment and the aims of the end user will decide whether one is happy with an affordable but consistent solution (Team 4) or a high-quality delivering team like our Team 1. The emphasis might be on the quick and affordable delivery of 3D models, with the additional advantage to produce calibrated colour models from camera raw data (Team 1 and 3). The next section will briefly outline user requirements by the audience.

7. AUDIENCE

7.1 Find a match

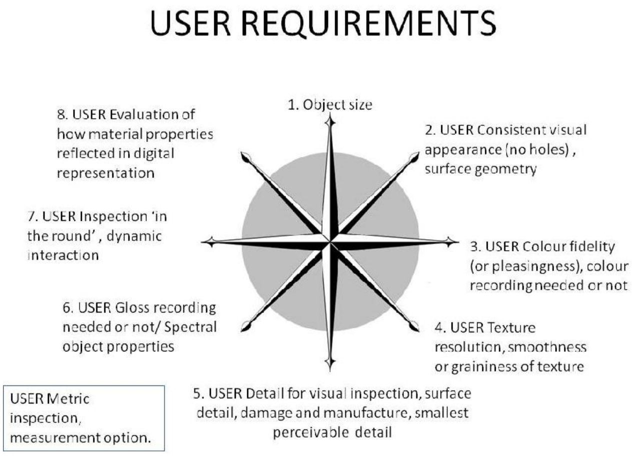

Figure 19.User requirements for 3D imaging.

User testing at UCL CEGE was able to isolate a set of criteria to be able to establish a project brief for the non-professional user to help define user requirements and sensor specifications.
Through the use of multivariant data the criteria are displayed on a compass rose. Each criterium is normalized and plotted on its own axes, arranged radially as equi-angular spokes around a central point. The lowest value with 0 is in the center, increasing to the maximum value to the outer edge.
Figure 19 above shows a template how to graphically evaluate user requirements, which can then be matched to sensor capability profiles,

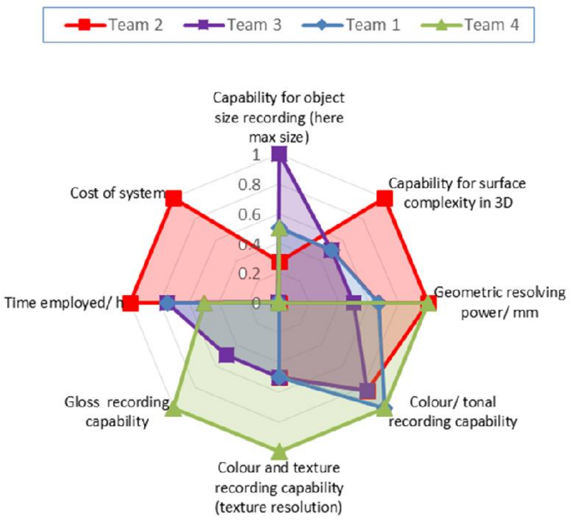

Figure 20 Sensor criteria (normalized) are echoing the user requirements in Figure 19.

8. THE FINAL WHISTLE (CONCLUSION OF THE GAME)

This paper has briefly described a new Portable Metric Test Artefact developed at UCL CEGE, for the independent assessment of 3D imaging sensors for non-professional users.
The capabilities of the Metric Test Artefact and its evaluation protocol based on guidelines from VDI2634 and GD&T have been demonstrated in a friendly contest. Participants in this match were three commercially available 3D imaging technologies, including laser scanning, photogrammetry and structure from motion and a 3D colour laser scanner at UCL CEGE.

The following tests have been successfully demonstrated with the test object: sphere diameter error, sphere spacing error, structural resolution, and spatial frequency response.
The metric test object also aimed at testing for colour performance, gloss recording with the targets on the 2D plate, which have not been demonstrated in this paper.

In summary, the use of the metric artefact produces quality control by assessment of 3D imaging sensors and should enable non-engineering users to give precise specifications for what they expect as outcome from a 3D digitizing process. This will lead to the creation of high-quality 3D digital surrogates and 3D digital assets.

8.1 Preparation for the next game! / Further work

The evaluation procedure was effective for the practiced user of 3D technologies and 3D evaluation software. The next step is to try a knowledge transfer of the procedure with non-metrology users, for example in a 3D imaging lab in a museum or institutions. Furthermore a re-iteration and optimization of the design of the test object is planned.

3D image quality in relation to spatial resolution and geometric capabilities of a sensor can be assessed and scientifically evidenced through quantitative metrics by the metrologist - and as here demonstrated - by the non-metrology user; but the perception of image quality of digital 'visual' or 'virtual surrogates' are influenced by other aspects, see Figure 19. The author has conducted qualitative user testing of 3D image quality with cultural heritage professionals, adapting psychophysical experimental methods from 2D to 3D for estimating image quality. This image quality assessment is usually applied in design and publishing industries for 2D images, and is conducted with a standard display under controlled viewing conditions.
The detailed outcomes of this qualitative investigation should be the described in another paper.

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