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Metrological evaluation of Structured Light 3D scanning system with an optical feature-based gauge

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Abstract

This work evaluates the dimensional accuracy that is able to reach a commercial Structured White-Light scanning (SWL) equipment. This technology is widely used in many Reverse Engineering applications. It allows to quickly capture and create pointclouds from photographs (taken from different orientations) of a fringe projection pattern. For the survey, a novel optical feature-based gauge has been used. The gauge is endowed with basic geometrical features made of matt white ceramic material, and located on a Carbon Fiber Reinforce Polymer (CFRP) structure. The reference measurements of the gauge are obtained using CMM by contact, which makes possible to compare the measurements obtained by the SWL sensor with those obtained by the CMM. In the experimentation, two different tests were carried out: long-distance test, searching for the global capture of the gauge (at the maximum range of the SWL) and short-distance test, looking for the maximum attainable precision. The survey offers some practical values of the accuracy affordable in each case.

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Keywords: Structured White Light Scanning; Metrological evaluation; Feature-based gauge; Fringe Projection SensorIntroduction

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1. Introduction

This work presents an experimentation aimed at analyzing the accuracy of a photogrammetry sensor based on Structured White-Light scanning (or fringe projection scanning) technology in GD&T verification. This type of equipment is vastly used for capturing dense pointclouds over different surfaces of a part in very short times [1]. However, the attainable accuracy still remains as hard to evaluate or quantify, due to several errors and involved factors [2-4]. In fact, there are factors derived from the equipment itself (camera resolution, mathematical model and intrinsic calibration procedure [3-6], the angles between part, camera and projector [7,8]), or even derived from the ambient light at the measurement time [9], the surface finish, etc. All of them explain why industrial deployment has been produced without the development of evaluation -or conformity- standards, either checking the quality of the pointclouds, or even assigning measurement uncertainty to the reconstructed geometrical features. In this work, a Structured White Light scanning equipment (Mephisto EX-PRO, 4ddynamics®) is evaluated by using a brand new optical prototype artefact (Fig. 1).

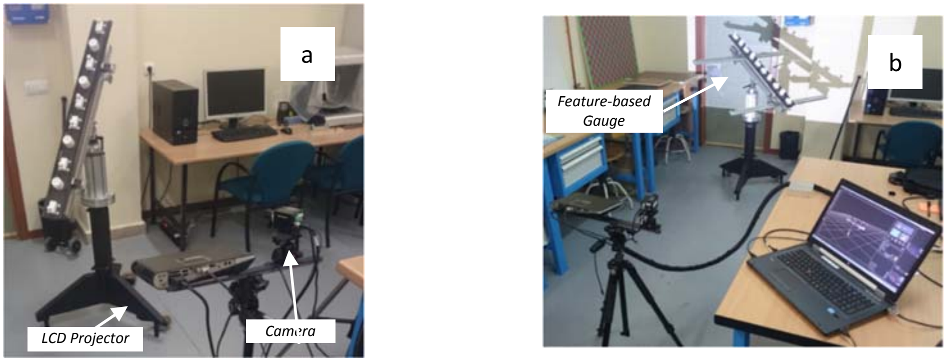

Fig. 1. An overview of the Structured White Light Scanning and the feature-based gauge. (a) One orientation of a short-distance test; (b) Another orientation in a long-distance test.

Undoubtedly, in recent years the equipment aimed at non-contact reverse engineering based on photogrammetry have raised enormously. The possibility of capturing very dense high-quality pointclouds over different surfaces in short times makes this equipment ideal for a diversity of tasks. Modern software tools for transforming pointclouds into surfaces have also aided in their industrial deployment. Amongst their main applications, surface reconstruction, CAD comparing, statistical analysis (SPC), cataloguing or simply inspection and metrological verification of prototypes and batch production units can be cited. Nevertheless, the optic nature of this equipment involves certain disadvantages. Talking about photogrammetric techniques exclusively, there are multiple devices based on different principles and that employ different algorithms for point capturing and for surface reconstruction. Even when referring to the same principle (structured white light, fringe pattern, or reference target image analysis), these systems can be equipped with one or two cameras of very different range and resolution (from 2 Mpx to 12 Mpx), with rotary tables, etc. which lead to a very diverse range of 3D scanners.

Table 1. Structured White Light Sensor (Mephisto EX-PRO).

LCD Projector (Optoma ML1500 E)		Camera (Sony XCD H280E)		SWL Scanner (Mephisto)	
Contrast	20000:1	Geo. Resolution	1920 x 1080	Range Near	0.4 m
Projection distance	520-3000 mm	Standard lens	Pentax C1614-M (Ricoh)	Range Far	4.5 m
Resolution (pixels)	1280 x 800	Focal Length	16 mm	Pixel Size	4.54 µm
Resolution type	WXGA	Iris range	1.4 – 1.6	Point Accuracy	0.05 mm (Average)
Aspect ratio	16:10 (native), 16:9/4:3	Focussing Range	0.25 m - infinity	Point-to-Point distance	0.43 – 2.8 mm
Projection Lens	F/1.5; f = 13.92 mm, Fixed	Framerate	30 – 60 Fps	Acquisition Time	0.1 – 0.5 s (depend. on settings)
Brightness	2200 ANSI Lumens	Texture camera*	12.4 Mpx	*(Optional, not used in the experiment)	

However, this commercial deployment has not been followed by the development of standards universally accepted, nor by procedures and artefacts that permit the evaluation of conformity, or even the assignment of uncertainty to the measurement results obtained from the captured pointclouds.

It is precisely in this area where this work is focused, aimed at evaluating the accuracy that a fringe pattern projection equipment is capable to attain. Specifically, a model Mephisto EX-PRO equipped with a LCD projector and a 1920×1080 px photographic camera has been used. It is intended for low accuracy captures at short (from 0.4 m) and large distances (up to 4 m) under not very constrained light conditions.

2. Equipment. Hardware and software resources

The available equipment for evaluating its accuracy is a Structured White Light (SWL) mobile scanner model Mephisto EX-PRO (4ddynamics®). It consists of a LCD projector, Optoma ML1500E with a resolution of 1280x800 pixels, and a camera Sony XCD H280E with a resolution of 1920x1080 pixels. Table 1 collects all of the characteristics of the different components (the projector and the camera) as well as the characteristics of the equipment as a whole SWL scanner. As it can be deduced from the characteristics, this scanner is intended for medium and large work ranges, capturing objects from a distance of 0.4 m up to 4 m. It is not a high resolution scanner, as in the best of the cases the closest distance between captured points is 0.43 mm, whereas reaches 2.8 mm if the object being scanned is located at a distance of 4 m. According to the manufacturer, point accuracy is 0.05 mm for optimal conditions of working distance and ambient light. It is precisely this value what is questioned in this work, that tries to determine an objective value for the accuracy in function of the surface being scanned, the working distance, the number and orientation of the capture shots, etc.

The reference part chosen for studying the measurement accuracy of the scanner is an experimental artefact: an Optical Feature-based gauge. Its design is based on a previous research oriented to evaluate Articulated Arm Coordinate Measuring Machines (AACMM or CMA). Now the actual version of the artefact is specifically developed for the evaluation of optic and reverse engineering metrological equipment. At first, its development was focused on the evaluation of Laser-based Triangulation Sensors (LTS) mounted on Coordinate Measuring Arms. The artefact satisfies to a great extent the indications of a patent regarding the design and use of a feature-based gauge aimed to CMA calibration purposes [10]. The main innovation consist of using several ceramic features mounted on top of a supporting base, now made in Carbon Fibre Reinforced Polymer (CFRP) of high elastic modulus (solid bars: E = 150 GPa; supporting plate: E = 450 GPa). The different geometrical features available are planar surfaces, outer cylinders, inner cylinders, cones and spheres.

The gauge is shown in the Fig. 2. Its consists of six prismatic volumes (50x25x25 mm) manufactured, with high dimensional precision, in machinable ceramic of the commercial trade MACOR®, as well as four cylindrical volumes machined in the same material. The surfaces of the prismatic volumes constitute the planar-type features. The gauge is endowed with 4 cylindrical surfaces of 40 mm nominal outer diameter and 40 mm of height. The two furthest cylinders encloses 2 inner cylinders machined by straight turning, whereas two inner cones have been machined inside the other two outer cylinders. The nominal angle of these inner cones is 24°, and the nominal diameter of their bases is 32 mm. At the top of each one of the prismatic volumes (6 units), a precision sphere of 20 mm nominal diameter, manufactured in a ceramic mixture of Aluminum Oxide (Al_2O_3) and Zirconium Oxide (ZrO_2), has been mounted. Spheres have been elevated relative to the prismatic volumes by means of Carbon Fibre-Reinforced cylindrical stems.

The disposal of all the features along the length of the gauge can be seen in Fig. 2. A fixture designed for locating and orientating the gauge supports the gauge at the Bessel points (very close to the Airy points) in order to minimize the deflection of the neutral axis of the bi-supported gauge. In fact, certain measurements have been made selecting the point of the feature that lies closest to the neutral axis.

The feature-based gauge has been calibrated by measurements made with a CMM (DEA Global Image), whose Maximum Permissible Error (ISO 10360-2) is $MPE_E[\mu m]=2.2 + 0.003\cdot L$, being L in [mm], enough accuracy for the purpose of this survey. Besides, several techniques have been applied for compensating the usual errors arising in calibration with CMMs, like inversion methods, multiposition measurements, and several (12 times) measurement repetitions. Among others, the GD&T dimensions considered were: diameters and form errors (cylindricity) of both

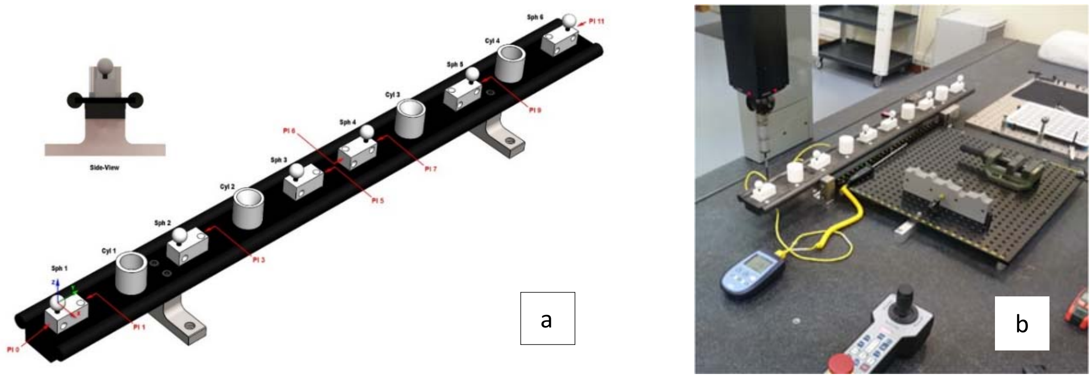

Fig. 2. (a) Nominal CAD of optical feature-based gauge; (b) Overview of the gauge during its Calibration with CMM.

outer and inner cylinders, diameters and form errors (sphericity) of spheres, form errors (flatness) of planes, distances between cylinders (between axes), distance between spheres (between centres), distances between parallel planes, angles and form errors of the inner conical features, and others.

3. Methodology for metrological evaluation

The methodology applied for the metrological evaluation is summarised in Fig. 3. Once the feature-based gauge was manufactured, it was measured and calibrated with a CMM (Fig. 2a), hence providing reference values for the different GD&T dimensions considered. Those same dimensions were subsequently measured with the white fringe projector equipment (SWL scanner). A further comparison between these results with regard to the reference values (GD&T comparison in Fig. 3) allows for evaluating the accuracy of measurements performed with the SWL equipment.

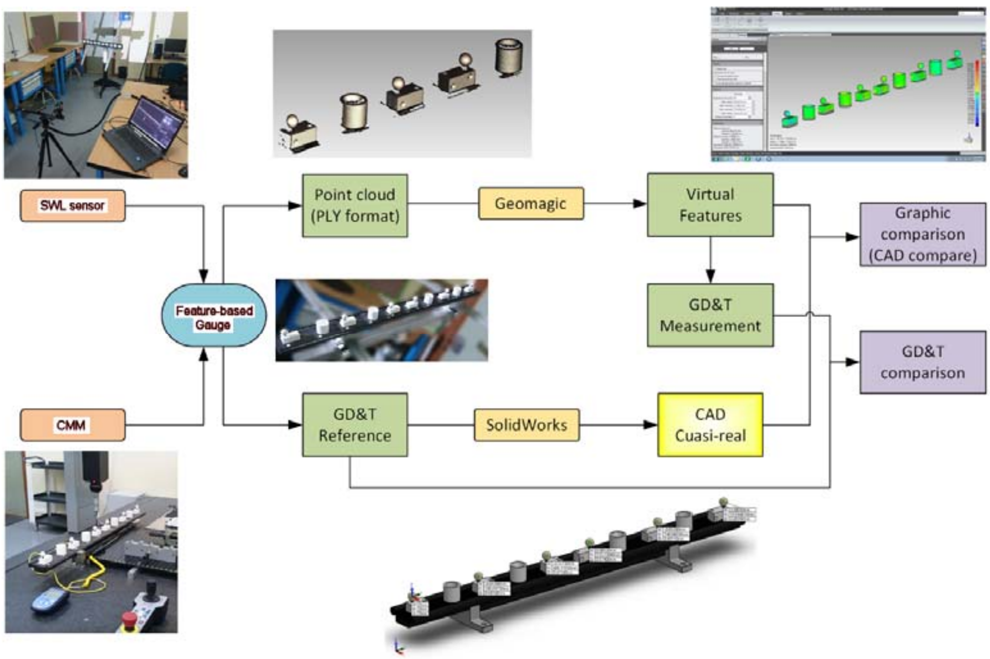

Fig. 3. Experimentation Methodology.

Simultaneously, a global comparison was carried out between the pointcloud captured with the SWL scanner and a modified CAD model of the gauge in order to check the agreement of measurement results between the scanner and the gauge. The original CAD model was modified by replacing the nominal values of its dimensions by the reference values measured with the CMM, leading to a “quasi-real” CAD model. Specifically, the size (diameters, heights, and other dimensions) and the distances between different geometrical entities were modified for adapting the CAD model to the actual geometry as much as possible (with errors between 0.003 and 0.005 mm, given the specification of the CMM). In this sense, corrections in the order of the hundredths of mm were applied to dimensions derived from ceramic elements (as they were machined by milling and turning) whereas they raised to orders of tenths of mm for the entities location as the ceramic elements were joined to the carbon fibre baseplate by adhesive bonding with epoxy-based glue. After configuring the “quasi-real” CAD model, a new comparison (graphic comparison) was accomplished between the global pointcloud acquired with the SWL scanner and the new CAD model. Although form deviations were not corrected in the CAD model, the comparison does allow for studying the degree of agreement between the SWL and the CMM performances.

Either the method selected, that is, performing the analysis entity by entity or globally, an evaluation procedure has been defined that simulates the “in-situ” working conditions. Firstly, the procedure involves performing an intrinsic calibration of the equipment with the equipment positioned at the same distance from the object as in the subsequent captures, and under the same ambient light conditions. After calibrating the camera, the gauge entities were captured with a high number of shots, taken from different angles in order to achieve a sufficiently widespread covered area for defining geometrically each entity (i.e., a covered area greater than 70% of the whole area for axisymmetric entities, and greater than 90% for planar entities).

Captured pointclouds (in *.ply format) were subsequently cleaned up and filtered to define each geometric entity as accurately as possible. For each entity, all the pointclouds obtained from different angle shots were merged into a unique pointcloud after a registration process carried out with the aid of Geomagic® software. Then, a substitute geometry was obtained by applying a Least Squares fitting algorithm to the pointcloud, in order to subsequently evaluate its dimensions (and geometrical errors in some cases) and finally compare the results with the reference values.

4. Experimentation

After the intrinsic calibration, the proposed evaluation procedure includes capturing numerous scans of the gauge features, shot from different angles, simulating the non-optimal in-situ working conditions.

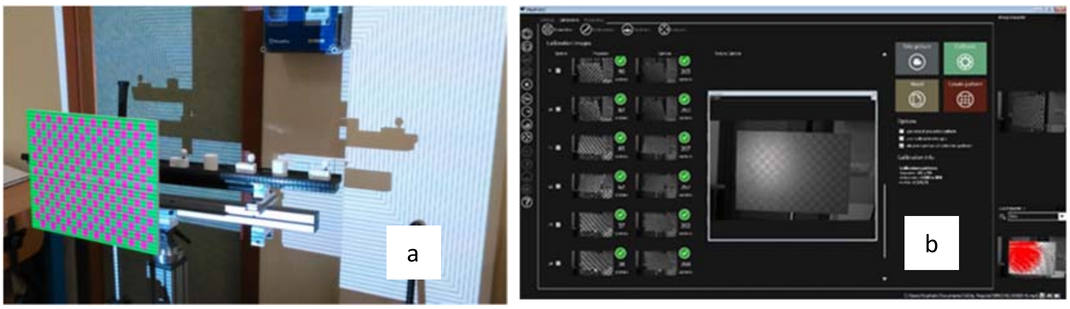

Fig. 4. (a) Intrinsic Calibration for short-distance tests; (b) Mephisto software screenshot.

Previously to the capture of an object, either for measurement or for reverse engineering, the camera must be calibrated for a determined focal distance and the actual ambient light conditions. Fig. 4 shows several images of this process. The camera calibration procedure has been well-defined by the manufacturer. In the case of the SWL scanner of Mephisto®, the procedure consists in taking shots of a 300x500 mm checkerboard with 15x21 squared cells (18.85 mm of side length), and coloured in green and orange to highlight the contrast between cells (Fig. 4a). The calibration procedure (camera set-up) establishes a minimum number of 9 shots (although 16 shots were taken) of the checkerboard from different angles (Fig. 4b), that were later used for calculating a radiometric correction of the volume surrounding the checkerboard and for providing an evaluation of the accuracy achieved by default.

This procedure enabled to qualify the equipment under the same conditions than in the subsequent capturing of the feature-based gauge. As the measurement tests included both captures taken at short and long distances, two camera calibrations were made using checkerboards of two sizes, and producing different results for the calibration accuracy (Table 2). In this sense, the calibration accuracy is better when captures are shot at short distances while accuracy decreases when working with a greater depth-of-field.

In short-distance tests (Table 2), the centre of the gauge was located at a distance of about 0.7 m from the scanner. Depending on the spatial orientation, in the same capture some entities were located at a distance so close to the scanner as 0.4 mm whereas other entities were at distances about 1 m. Anyway, in each capture only three spheres were taken at a time (and in the best case), including three ceramic prisms and two elements of revolution between them (cylinders and/or cones). In long-distance tests, the centre of the gauge (centre of rotation between orientations) was positioned at about 3 m from the scanner, so that all the entities might be captured in the same shot. However, as the gauge spatial arrangement is linear, some spatial orientations gave rise to wide areas covered in shadow, due to the occlusion of some entities by others, reason why these “extreme” orientations were discarded.

Table 2. Type of evaluation tests.

	Short distance	Long distance
Measuring Range	0.4 – 1 m	2.5 – 3.5 m
Number of features per capture	3+3+2 (3 spheres, 3 planes and 2 cylinders or cones between them)	All (of those visible from each perspective)
Type of evaluation	Form error, short distance (between adjacent spheres & planes)	Large Distances (between spheres, planes & cylinders)
Number of different orientations	4	25
Number of captures per orientation (total captures)	4 (total: 16*) *Discarding low quality pointclouds	1 (total: 25*)
Chessboard size (Camera Set-up)	300×500 mm	700×1000 mm
Calibration (Set-up) precision (pixel RMS error).	Camera: 0.343 px Projector: 0.445 px System (Equipment): 0.367 px	Camera: 0.336 px Projector: 0.456 px System: 0.415 px

In any case, for both type of tests (short and long distance), strategies were defined for selecting orientations that enabled to cover all the control features throughout a series of captures, with enough overlap between them. The experimentation implied several series of both tests, short and long-distance tests (Table 2). In each short-distance test (Table 2, Fig. 1a) a minimum of 16 high-coverage captures were taken, that is, at least 4 captures were shot in each one of the 4 different gauge orientations. Similarly, in each long-distance trial, a minimum of 25 high-coverage captures (Table 2, Fig. 1b) were taken, all in different orientations. In fact, more captures were taken, but those with low coverage were discarded before the next steps.

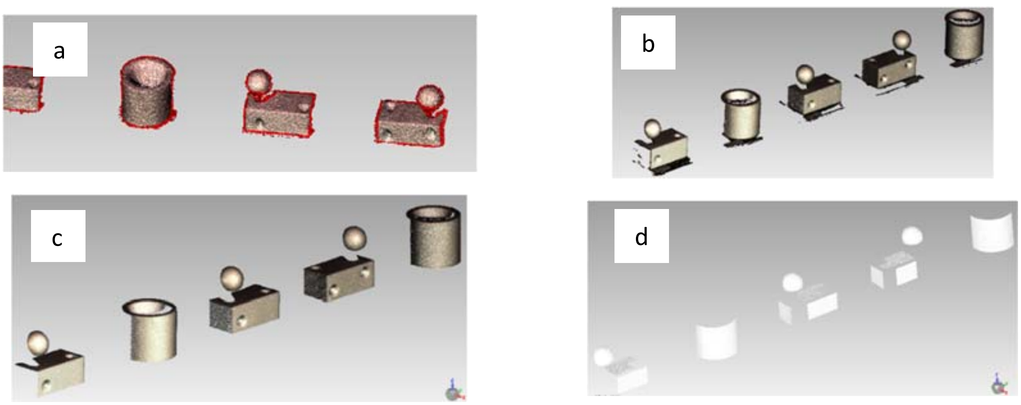

Fig. 5. Point Clouds Treatment; (a) y (b) Original pointcloud & outliers filtering; (c) Filtering of the false points originated in the horizon of each perspective; (d) Cleaned pointclouds once trimmed and filtered.

With these "complete" pointclouds, derived from different scanning angles (spatial orientations), a single pointcloud was obtained by merging using the manufacturer software, Mephisto®. Then, the following operations were carried out using the Geomagic® software to post-process the resulting pointcloud (Fig. 5):

- Filtering of outliers points. Points not belonging to ceramic entities (that materialize the features to be measured) were removed, such as points belonging to carbon-fibre rods, to supports of spheres, to stickers (used to reference the entities), or to the multiposition fixture. In addition, false points caused by reflections were also removed. Fortunately, the black colour of these entities simplified this phase, since few points were captured in them.
- Filtering of the false points originated in the boundary of each perspective. This type of equipment has problems in the borders of the entities digitized in a particular view, often creating clouds of false points in those zones. This issue required a lot of effort and was practically mandatory in all captures.
- Elimination of border points at edges resulting of intersection of planar surfaces between them, or planar surfaces with cylindrical and conical surfaces.
- Trimming the pointcloud in order to match the area of captured surfaces and the area of the surfaces measured by contact (CMM). In this sense, areas extending 2 mm from edges, 3 mm in cylinders and cones and below the equator in spheres were removed.

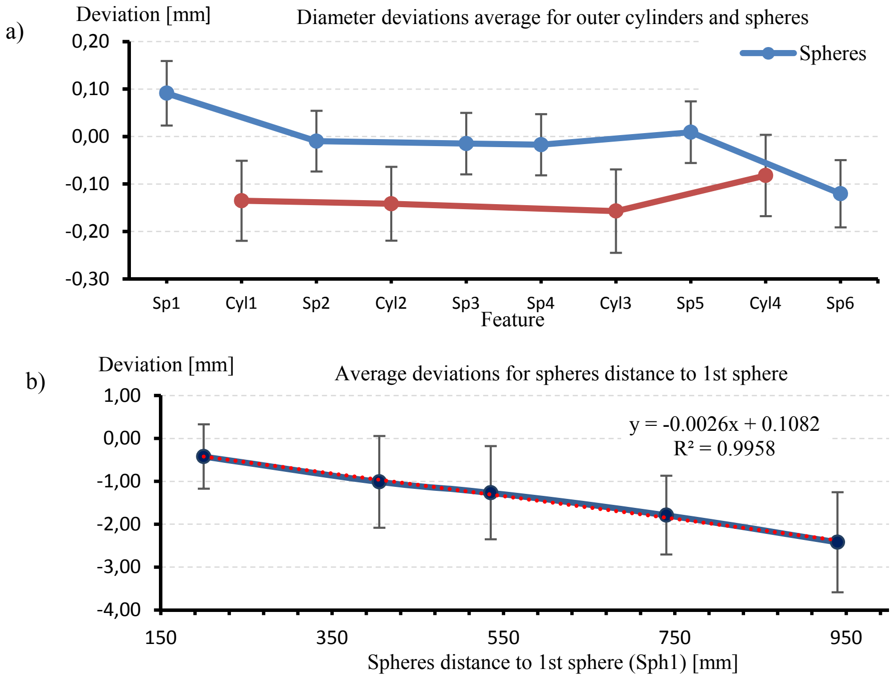

Fig. 6. Comparison between the SWL sensor data versus CMM reference values; (a) Short distance test; (b) Large distance test.

Once the pointclouds were processed (Fig. 5d), the different geometric entities were reconstructed using Geomagic®. Finally, values of the dimensions, form errors and distances between entities were evaluated from the reconstructed entities. Due to their evident greater accuracy, short distance tests were used to evaluate dimensions and form errors concerning a single feature. On the other hand, long distance tests were used for evaluating certain distances, such as those between cylinders or spheres located furthest apart. In this case, another evaluation was considered that only employs pointclouds from short-distance tests merged into a "best-fit" pointcloud. However, this option gave worse results due to the excessive linear arrangement of the features within the gauge, which caused poor adjustment of the pointclouds, especially in the alignment of pointclouds from different spatial orientations. Although the standard deviation of the fitting from the long distance trials, considering 25 captures, were high (from 0.75 to 1.16 mm), the addition of all captures in short-distance tests gave rise to a worst global "best-fit" adjustment.

This standard deviation was obtained from a CAD-compare procedure between the pointclouds and the quasi-real CAD model.

5. Results and conclusions

Fig. 6 shows some of the results obtained. In these graphs, deviations between the results measured with the SWL scanner and the reference values calibrated with the CMM are represented. For example, in Fig. 6a, which corresponds to the short distance tests, the interval of deviations obtained in the diameter measurement for outer cylinders and spheres was [-0.082, -0.141] and [0.009, -0.121] mm respectively. The error bars represent two times the standard deviation (2σ) given by the Geomagic® software from the pointclouds adjustment (16 different spatial orientations) once the control feature was created. The higher value of 2σ was 0.181 mm for cylinders and 0.161 m for spheres. The pointclouds used to create the control features contained about 2000~4000 points for the spheres case, and 10000~14000 points for the case of the outer cylinders. This pointcloud density, even after the filtering operations mentioned above, can be considered enough for a correct definition of the entities.

Similarly, values obtained with the long-distance tests are shown in Fig. 6b. In this case, graph shows the mean value of the distance between the different spheres centres to first sphere (Sph1) centre. The deviation behaviour is clearly linear with the distance, from -0.421 mm to -2.410 mm in the case of spheres located furthest apart (950 mm spacing). The error bars also represent two times the standard deviation (2σ) of the 25 captures (thus, the 25 different spatial orientations considered).

The analysis performed have led to reliable results about the accuracy of measurements derived from captures of several geometric entities shot by a SWL scanner. The experimentation has been carried out under the usual working conditions of this type of equipment in terms of “in-situ” measuring procedures. The relatively high distance between the part (which is about 1 m between the farthest entities) and the scanner leads to define two different types of tests: at a long and at a short distance from the scanner. This analysis has been performed entity-by-entity (aiming at comparing form errors) and by considering the global gauge (aiming at comparing distance deviations). As a result, this work have permitted to establish reliable values for the accuracy that this type of equipment can attain for metrological tasks rather than for Reverse Engineering tasks.

On the other hand, this work has allowed the validation, although only partially, of the developed optical feature-based gauge. Even though it has proved appropriate for the generation of high-quality pointclouds (white and matte ceramic elements), the linear arrangement of the geometric entities is not the most suitable for a photogrammetry equipment based on SWL, as the location of spheres in a straight line avoid an accurate fitting of the pointclouds.

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