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METROLOGICAL CONCEPTS AND APPLICATIONS OF 3D OPTICAL SCANNING

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Abstract: This text presents some of the state of the art and technical and metrological aspects of 3D optical scanners (also commonly called digitizers). Optical digitizers create point clouds from data on an object's surface, which are used to build digital three-dimensional models. It has become essential equipment for dimensional analysis, reverse engineering, free-form surface evaluation, quality control, prototyping, etc. Some physical principles of the types of optical scanners are presented, and important aspects in the calibration of a 3D optical scanning system. Comments on surface texture and color are provided, as well as the difficulties inherent in scanning reflective surfaces and translucent objects. At the end, examples of scans with metrological applications are presented.
Keywords: 3D scanning; 3D optical scanners; metrology.

INTRODUCTION

The 3D optical scanners (Figure 1) have become one of the great innovations in the industrial sector with increasing application especially in the last decade.

From a metrological point of view, 3D measurement technology has presented several evolutions over time that represented substantial solutions for the development of the industry: in the middle of the last century (~1960) with the emergence of the first coordinate measuring machines, in end of the last century (~1990), with the introduction of articulated measuring arms onto the market, at the beginning of this century (~2005), through the incorporation of tomographic technique into the gantry system of a coordinate measuring machine, and finally, with the popularization of 3D optical scanners, around 2010.

The increase in the use of these digitizers is due to several relevant factors, particularly when comparing with equivalent metrological systems. With massive application in the industrial area (HALEEM et al., 2022), it has also become widely used in several other sectors, such as in the medical and dental areas, in museums (sculptures, cultural relics, archaeological objects), in forensic applications, etc. (JAVAID et al., 2021).

Figure 1: Optical digitizers

Source: prepared by the authors

Particularly in the industrial sector, the optical digitizer currently has two widespread applications. The first would be scanning and obtaining a point cloud from the surface of an artifact for reverse engineering purposes. A recurring example is additive manufacturing, which has benefited from the resources that digitalization offers in terms of obtaining data from geometric surfaces.

The second consists of using the equipment to scan an artifact for metrological purposes, that is, for dimensional measurement and analysis of results for inspection and quality control.

Despite not yet offering equivalent levels of accuracy, the optical digitizer has been replacing traditional measuring machines with Cartesian coordinates as it performs data acquisition from a volume in point cloud format extremely quickly, is portable and can be stored in a case, that is, it is extremely practical for transportation to carry out activities in the field or in industrial installations, in addition to being relatively easy when measuring free-form surfaces (DURY, 2016).

In this context, this text provides a glimpse into the state of the art of 3D optical scanners. Scans with some metrological applications are presented, as well as other topics (calibration, texture, reflective surfaces, etc.) relevant and intrinsic to this technology are also presented and discussed.

SCANNING TECHNOLOGIES

PHOTOGRAMMETRY

In photogrammetry, several photographs are taken from different angles of an artifact, and through the detection of pixels corresponding to the same two-dimensional information from the various photos, the shape and location of the points are determined and the object is reconstructed three-dimensionally, establishing the exact position of points on the surface.

LASER TRIANGULATION

Three elements are fundamental in this technology: the emitting laser, the incident point on the surface, originating from the emitting laser, and a camera. This technique is called triangulation because these three elements form a triangle. Initially, the light falls on the object, and the reflected light is directed to a CCD camera, which locates the position of the light incident on the surface. The laser appears in different positions in the camera's field of view, depending on the distance at which the light reaches the surface.

The distance between the camera and the emitting laser is known, being the length of one side of the triangle. The position angle of the emitting laser is also known. The angle of the camera position is determined by the location of the laser spot in the camera's field of view. These three pieces of information determine the shape and size of the triangle, providing the location of the laser point in the triangle (adapted from EBRAHIM, 2015).

STRUCTURED LIGHT

Structured light 3D optical scanners project a series of linear or continuous patterns of light or laser onto the object. A camera analyzes the deformations of each line pattern on the object, and the calculation of the distance between the 3D scanner and the object's surface uses a technique similar to triangulation to calculate the distance to each point on the line. Using the distance values, the artifact object is reconstructed in 3D (adapted from EBRAHIM, 2015).

There are also other scanning technologies, such as time-of-flight, phase shift, or even hybrids, which are combinations of other 3D scanning technologies.

CALIBRATION OF OPTICAL SCANNERS

Calibration of digitizers is described in standards VDI/VDE 2634-2 (VDI 2012) and VDI/VDE 2634-3 (VDI 2008), which establish guidelines for acceptance testing and rechecking the performance of a 3D optical measurement system, based on surface scanning. The suggested verification pattern (Figure 2) is shaped like dumbbells (technically known in the industry as a ballbar, or ball bar, in free translation), whose diameters and shape errors of the left and right spheres, the distance between the centers of the spheres and the total length of the artifact constitute the important metrological parameters for analysis.

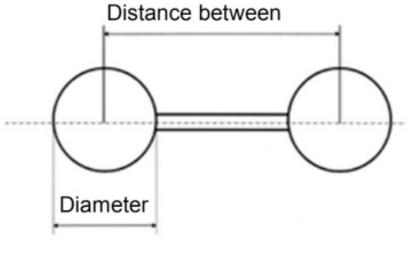

Figure 2: Standard for digitizer calibration

Source: adapted from VDI/VDE 2634-2 (2012)

Below are the formulas for calculating the parameters:

Form error (PF):

$$PF = R_{max} - R_{min}$$

where Rmax = Maximum shape deviation, and

Rmin = Minimum shape deviation.

Diameter calibration error (PS):

$$PS = D_a - D_r$$

where: D_a = Diameter measured with the digitizer, and

D_r = Reference diameter.

Error in calibrating the distance between the center of the spheres (SD):

$$SD = l_a - l_r$$

where; l_a = Distance measured between centers of the spheres with the digitizer, and l_r = Reference distance between sphere centers.

TEXTURE AND COLOR

An interesting feature incorporated into the data acquisition system of optical digitizers is the possibility of obtaining the texture and color of the scanned surface, that is, the scanning result can present only the geometry of the artifact of interest or the geometry with the texture and the natural color of the object. Below (Figure 3), an example of the scanning of a prismatic part is presented, with a photo of the steel prism on the left, the resulting scan in the center, only with the geometry of the part and on the right the same scan presented previously in the center, with the addition of texture and color.

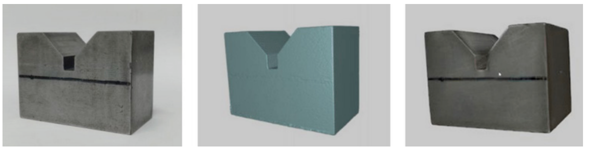

Figure 3: Prism (left), scan (center) and with texture and color (right)

Source: prepared by the authors

REFLECTIVE SURFACES AND TRANSLUCENT OBJECTS

Besides, regarding the topic of surface, but in the case of a completely different panorama, a common method when scanning artifacts with reflective surfaces is the use of an anti-reflective coating in order to reduce glare or even eliminate the reflection of incident light. about the piece.

An example of an anti-reflective coating application is shown in Figure 4. It is a contoured pattern, made of steel with a reflective surface. The Figure on the right shows the scan performed on this artifact with the application of such a coating.

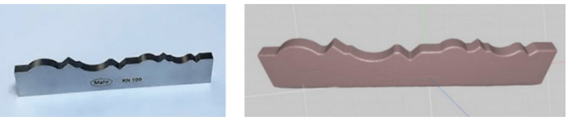

Figure 4: Contour pattern (left) and scanning (right)

Source: prepared by the authors

In recent work, after investigating anti-reflective coatings from different manufacturers, Mendřický concluded that the addition of such coatings produces significant variations (on the order of a few micrometers to a few hundredths of a micrometer) in optical measurement systems, after measuring the incremental variation of dimensional measurements depending on the coatings analyzed. It complements by reiterating that the use of matting agents has a significant influence on the accuracy of the digitizer (MENDŘICKÝ, 2018).

An example of a translucent material, a circular pattern made of crystal is shown in Figure 5, and was also scanned using the same coating used previously.

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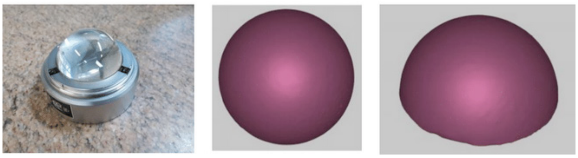

Figure 5: Circularity pattern (left) and respective scans (Figures on the right)

Source: prepared by the authors

APPLICATIONS

Four (4) examples of scans carried out with the Space Spider model optical digitizer are presented, which consists of a structured light system with three cameras to capture the projected light pattern, in addition to an RGB camera to capture the surface texture, with resolution of 0.1 mm and accuracy of 0.05 mm. With a 3D reconstruction rate of 7.5 frames per second, it has a data acquisition speed of 1 million points per second (ARTEC 3D, 2023).

ARTIFACT 1

In the first example, a cylindrical-shaped artifact with a diameter of 8 mm was scanned, whose region of interest was the semi-spherical shaped end. Figure 6 shows the respective photos of the cylindrical artifact and the image of the scan performed.

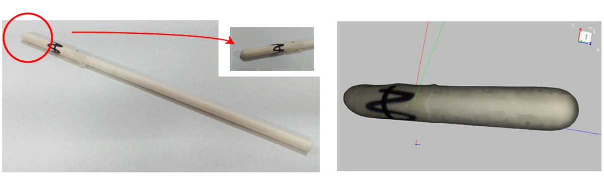

Figure 6: Artifact (left) and scan (right)

Source: prepared by the authors

Only the end of interest was scanned, on the side of the marking indicated in the photo in Figure 6 on the left, which is why the total length of the scan presented in Figure 6 on the right appears to be shorter in relation to the total length of the scanned part.

For metrological evaluation, several circles were constructed starting from the end (Figure 7), with steps (distance between circles, considering the cylinder axis) equal to 0.25 mm. From these circumferences, information regarding the diameter at a given distance in relation to the end, as well as the determination of the circularity error for each circumference, can be obtained.

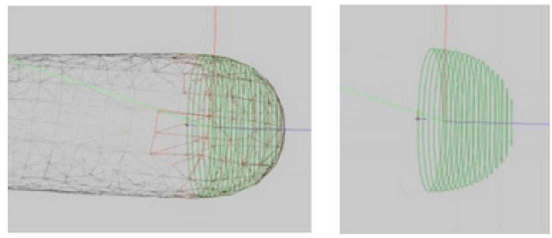

Figure 7: Analyzed region (left) and circumferences with steps of 0.25 mm (right)

Source: prepared by the authors

ARTIFACT 2

In the second example, the artifact also consisted of a cylindrical shape with an external diameter of 19 mm and a length of 23 mm, but with a through hole in the axis of the cylinder. Figure 8 presents a photo of this artifact and the image of the scan performed.

Figure 8: Artifact (left) and scan (right)

Source: prepared by the authors

In the image of this scan, it is possible to detect an intrinsic fault that exists when using this type of equipment (Figure 9). Sometimes, when the diameter of a hole to be scanned has a diameter in which the light cannot reach the surface to be scanned and collect information for image reconstruction, the scan of the final surface becomes incomplete, presenting flaws in the model. Final. In these situations, in order to obtain a closed-loop scan, the reconstruction software corrects surface defects using artificial intelligence. In the Figure, it is possible to visualize the reconstructed diameter, however the imperfection in the cylindricity of the hole is evident and pronounced, when compared to the artifact. For metrological purposes, evidently any information extracted from this cylindrical hole in the artificially reconstructed region will present a very high degree of uncertainty, and it is therefore recommended, if possible, to use other equipment to map holes with diameters on which the digitizer light cannot fall. in a satisfactory manner.

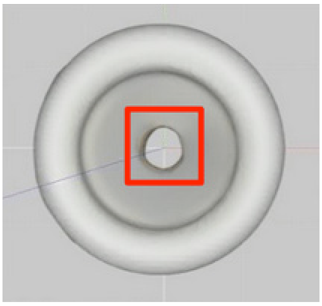

Figure 9: Scan failure region (highlighted in red)

Source: prepared by the authors

As in the previous example, several circles were constructed starting from the end (Figure 10), with steps equal to 0.25 mm and also with steps equal to 0.1 mm, but with a sample length equal to 75 mm.

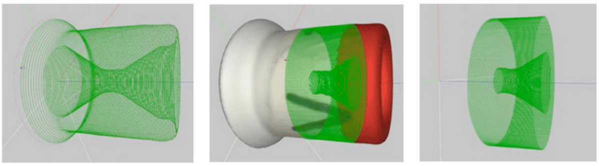

Figure 10: Circumferences with steps of 0.25 mm (left) and 0.1 mm over a length of 75 mm (center and right)

Source: prepared by the authors

An existing tool in the data processing software is the feature that simulates x-ray effects on the sample, which is interesting for visual inspection purposes of rotating solids. Figure 11 presents two examples of this image analysis mechanism.

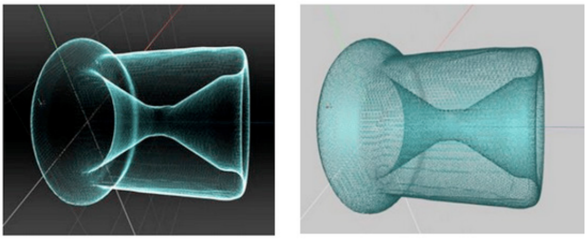

Figure 11: Two images that simulate x-ray effects

Source: prepared by the authors

ARTIFACT 3

The analyzed artifact consisted of an architectural model, with approximate dimensions of (523 x 195 x 128) mm. Figure 12 shows the respective photo of this artifact and the images of the scan performed. On the left the artifact is presented and in the middle the scan is presented.

Figure 12: Mockup (left), scan (center) and dimensional measurement (right)

Source: adapted from Yamanaka (2023)

In the third Figure, a linear measurement between opposite planes is shown on the blue line. Values of results with respective uncertainties are presented in YAMANAKA et al., 2023.

ARTIFACT 4

A resource for analyzing 3D geometries that presents interesting results for quick and very detailed inspections consists of combining scanned data with the generating design of the manufactured artifact. Known as best-fit, this is a mathematical adjustment between measurement data in relation to the CAD model, using different strategies to determine the optimal alignment condition (by the coordinate system, by geometric entities). In Figure 13 we have an example of the CAD model of a part (first Figure on the left) that was machined (second Figure) and digitized (third Figure).

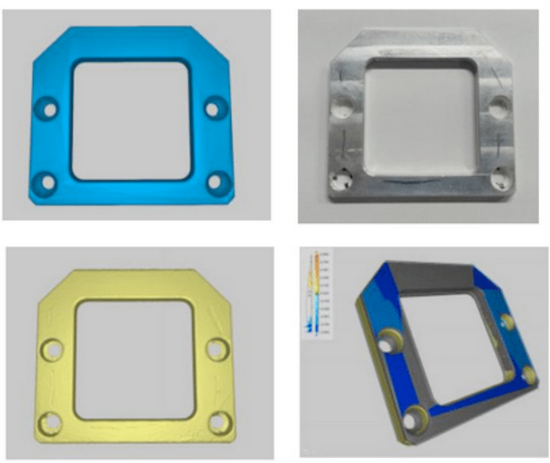

Figure 13: From left to right: CAD drawing, manufactured part, scanning and best-fit

Source: prepared by the authors

The fourth figure shows the best-fit between the CAD model and the point cloud of the scan performed. The color legend in the upper left corner indicates the lack or excess of material, with warm colors representing excess material and cold colors representing lack of material. In this example, the predominant blue color indicates a lack of material in relation to the generating design.

CONCLUSION

Optical scanning for various purposes such as reverse engineering and best-fit represent a new trend at the beginning of this century, especially when it comes to metrology for dimensional control. Advantages and disadvantages can be pointed out in this last aspect. Regarding advantages, we can first point out the issue of time, as the acquisition of points is independent of preparation, creation of a coordinate system, programming of sensor movement, etc., inherent to the process of using a measuring machine by coordinates. Simply positioning the scanner (respecting the working distance recommended by the manufacturer) already makes it possible to instantly collect points on the surface to be scanned. Another positive point is the acquisition of a large volume of surface points and their distribution and representativeness after processing. Comparatively, scanning a part in its entirety, considering all its geometries and details, including internal ones, is only possible using metrotomography. Any other method, such as a contact coordinate measuring machine with continuous scanning, an optical coordinate measuring machine or a contact measuring arm, will not have obtained as complete a point cloud as we would have with optical scanning. Furthermore, all technology for 2D and 3D analysis (best-fit, GD&T, statistical techniques, mathematical adjustments, etc.) developed over time were incorporated into the metrological processes post-processing the scan, and justify and strengthen the use of the optical scanner for laboratory purposes, for research and in industrial environments.

However, there are disadvantages that are intrinsic to this equipment. The main one lies in the fact that it cannot penetrate holes, depending on their diameter and depth. Another negative point is the scanning resolution, since the best scanners on the market have a resolution of a few micrometers, while coordinate measuring machines (tactile and optical) have a resolution of a tenth of a micrometer. However, in this issue we see the increasing advancement of research related to optical scanning and the incorporation of new optical and image processing technologies into data acquisition systems by manufacturers, and the most likely trend will be for the scanner to at least match the resolution traditional coordinate measuring machines. Furthermore, comparing metrotomography with an optical scanner, because the scanner only obtains superficial data, it is not possible to visualize the interior of a part, analysis techniques such as detection of internal defects (cracks, discontinuities, etc.), and porosity analysis, are not possible activities to carry out with optical scanning, with such techniques being restricted to metrotomography. Finally, a large volume of data is also not a favorable condition operationally from a post-processing point of view, as data processing software demands a considerable amount of memory, requiring robust machines to work in conjunction with the scanner.

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