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The importance of a correct alignment in contactless inspection of Additive Manufactured parts

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KEYWORDS : Additive manufacturing, Contactless inspection, Reference frame, Alignment

Nowadays products having complex freeform custom-made shapes can be fabricated without any tool by means of additive manufacturing processes. Additive manufactured parts must be inspected for quality to verify that they meet dimensional and geometrical specifications among other requirements just as any other product. Contactless inspection carried out with optical 3D scanners is preferred to traditional pointwise measurements because of the higher amount of data retrieved in short times. A key step of the contactless inspection process is the definition of the part reference frame for the alignment of scan data. This paper considers different 3-2-1 alignments and analyze their influence on the inspection results, putting in evidence that an inattentive or inaccurate definition of the part reference frame can lead to incorrect evaluations of real part deviations.

1. Introduction

Additive manufacturing processes allow the tool-less fabrication of complex freeform custom-made products in relatively short times directly from the virtual CAD model. From an economic point of view, if compared to other traditional manufacturing processes, it was proven that additive manufacturing is convenient for the fabrication of unique pieces or low volume productions[1,2]. After fabrication, Additive Manufactured (AM) parts have to be inspected to assess their quality in terms of dimensions and geometrical tolerances.

Additive process tolerances and subsequent finishing operations inevitably induce a deviation of real part geometry from the original virtual model. Furthermore, prior to sending the geometric data to the manufacturing machine, the CAD model is converted into an STL (Solid To Layer) file. The STL model is obtained through a slicing operation that converts a solid model into a group of triangular facets. Thus it is a tassellated and approximated version of the CAD model. It reproduces the theoretical geometry of an AM part with certain errors that depend on slicing parameters.

For the above reasons, the CAD model or STL file do not accurately represent the real geometry of the final product. Hence the approval of the customer is often granted on the real piece and not on its virtual model. In the case of multiple copies, the real geometry of a customer-granted AM part can be acquired by means of Reverse Engineering (RE) techniques in order to obtain a reference model for quality control of the copies.

Today the quality control of freeform geometries and complex parts is carried out using 3D optical scanners and contactless inspection procedures[3-8]. These techniques are slightly replacing traditional pointwise contact measurements, even though 3D scanners are not as accurate as Coordinate Measuring Machines (CMMs).

Actually AM parts do not have tight tolerance requirements, so optical measuring instruments are suitable for inspecting such kind of products. In pointwise contact measurements an issue that cannot be disregarded is the roughness and staircase effect of the surface of AM parts. The surface finish affects the measurements results since the probe tip can slip from one stair step (layer) to the adjacent one, depending also on the approaching direction. Consequently, contact measurements could be inaccurate, whereas the problem is warded off by using optical digitisers. Moreover contactless digitizing does not require the use of any fixture to firmly hold the part during the inspection. Potential deformation that can be caused by probe tip contact on plastic parts or deformable bodies is also avoided[9].

The main advantage of using optical 3D scanning is that a large amount of data about the part geometry is retrieved is short times. Consequently the whole surface of the part can be inspected by high density point clouds, if compared to some scattered points that can be measured on a CMM in the same time. Among other factors, quality control results depend not only on the accuracy of the contactless digitizer used, but also on the definition of the part reference frame for the inspection alignment.

The aim of this paper is to highlight that the definition of the alignment plays a crucial role in contactless inspection, particularly if the scanning device accuracy is low. Specific works

on the influence of the part alignment from scan data on the quality control results of AM part could not be found in technical literature. Little attention has been given to it so far, because the use of contactless scanners for inspection of AM parts is quite a recent issue.

The paper is organized as follows. Section 2 outlines the methodology used to investigate the influence of the data alignment on inspection results. Section 3 describes the application of the proposed methodology to an AM part. The results are presented in Section 4 and then discussed in the conclusions.

2. Methodology

An AM part was selected as case study and two different optical scanners were used for contactless inspection activity. Each device retrieved a point cloud that completely represents the geometry of the fabricated AM part. Different inspection alignments were defined on the two scan data by selecting different points for the calculation of the same Cartesian reference frame. The influence of points selection on the results of the inspection activity was examined in the following ways:

1) by the software-based comparisons of the differently-aligned point clouds;

2) by the CMM inspection of the real part.

The first analysis considers the distances between couples of homologous points of the two-by-two compared point clouds. The average distance is a measure of the relative deviation between the compared couple of scan data, but it does not allow discriminating which point cloud is the most accurate and reliable representation of the real part.

The second analysis assumes the coordinates of the points of each scan data as nominal values for the pointwise measurement of the real part by a CMM. Consequently the deviation between the real geometry and the scan data is evaluated in absolute terms, allowing to distinguish the most accurate representation of the AM part. A CMM is used for this purpose because such a machine has an accuracy that is of one order of magnitude better than the one of the two optical scanners used for contactless inspection.

In either analysis, before the comparison, the compared scan data have to be aligned one to another. In the inspection activity the alignment operation is extremely important and plays a key role. The reference coordinate system on the part has to be defined coherently with the blueprint and all the features are normally dimensioned from the origin point. Thus any error made during the alignment operation leads to an incorrect measurement that results in an unreliable inspection of the part.

As regards software-based comparisons, different point clouds can be aligned by minimizing the distance between couples of homologous points. This procedure is widely known as “best fit” and is carried out by means of the Iterative Closest Point (ICP) algorithm and its variations or similar methods[10-16]. The best fitting operation aligns the compared point clouds through the minimization goal, disregarding any fixed reference frame. The algorithm finds a unique solution, so it is possible to define only one part reference frame and one alignment for the compared point clouds.

On the contrary, the designer of mechanical components sets the requirements in terms of features location and tolerances with respect to a unique reference frame that has to be accurately reproducible. The reference frame is also very important in assembly operations.

A Cartesian reference frame is very often used. Such a reference frame can be defined by means of a plane, a vector and an origin point. The 3-2-1 alignment rule allows the registration of a point cloud into the defined reference frame.

The 3-2-1 rule is commonly used in the traditional pointwise measurements by CMMs. Operators who are accustomed to traditional inspection procedures may run into alignment errors through applying the same methods to contactless inspection. The issue with high density scan data is that each feature is defined by several points, so the definition of the reference frame by the 3-2-1 alignment could be influenced by which point is selected. Of course the influence is also related to the accuracy of the optical scanner and to the quality of the resulting point cloud.

To deeply investigate this aspect, the 3-2-1 rule was used to define the reference frame on the scan data of the AM part selected as case study. On the two point clouds, the 3-2-1 alignment was then replicated four times. Each time, during the replication, different points were selected on the same aligning features. The methodology followed for the analysis by pointwise measurements is outlined by the flow chart in Fig. 1.

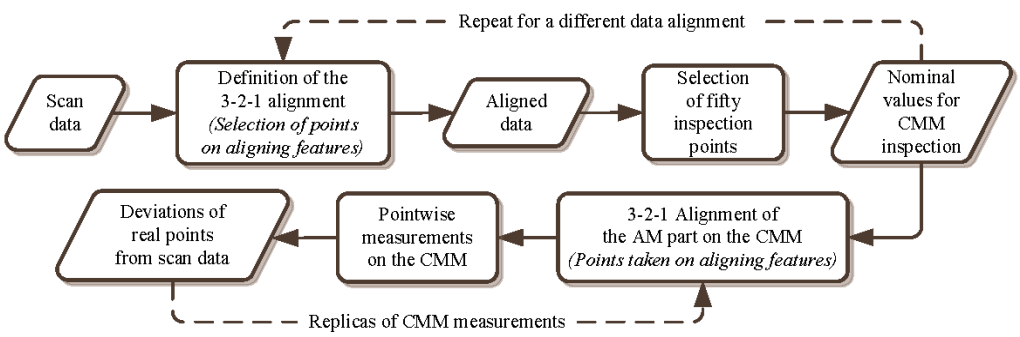

Fig. 1 Flow chart of the methodology followed for the analysis by CMM inspection

Starting from the same scan data (scanning is not repeated), the selection of different points on the aligning features leads to the definition of a different part reference frame, so the nominal coordinates of the inspected points change. In other words, from the quality control perspective, differently-aligned point clouds correspond to different parts although the original data is the same.

After the replications of the alignment, the eight differently-aligned scan data were first compared one to another to compute the deviation of the whole point cloud. Subsequently, fifty scattered scan points were selected on each differently-aligned point cloud. The Cartesian coordinates of these points were set as nominal values for the inspection by a CMM.

The analysis by CMM measurements is carried out in an uncommon way. As a matter of fact the Cartesian coordinates of the fifty points on scan data were assumed as nominal (theoretical) values for the contact measurements on the physical part. Thus it is possible to evaluate the error of the differently-aligned scan data with respect to the real physical part, not to the theoretical virtual model (CAD or STL). The 3-2-1 alignment of the physical part on the CMM was defined coherently with the one of the scan data by using the same aligning features. In other words, the reference frame should be defined in the same way for the scan data and the physical AM part in order to avoid systematic errors.

3. Case Study

The AM part that was selected as case study is a holder for a hydraulic cylinder (Fig. 2a). The holder was manufactured by Fused Deposition Modelling (FDM) on a Stratasys Dimension Elite machine using a layer thickness of 0.178 mm of ABS plastic.

The overall dimensions of the part are 107 x 93.7 x 60.5 mm and its surface was not finished nor polished after fabrication not to alter the staircase effect. The stair case effect is generated by the layer manufacturing process mainly on inclined and curved surfaces. The effect is not present on the original STL model (Fig. 2b).

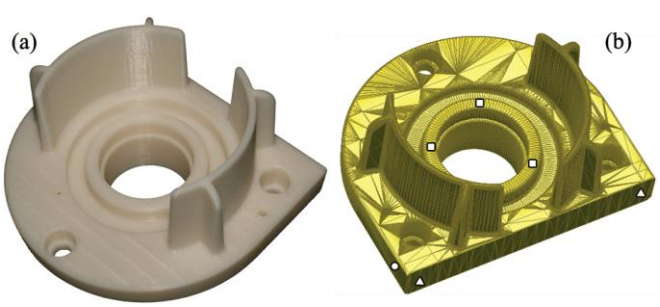

Fig. 2 AM part selected as case study (a), STL model and points for the definition of part reference frame by 3-2-1 alignment (b)

3.1 Contactless Digitising

Two different optical scanners were used for contactless inspection of the case study. The former is the structured light scanner ATOS (Advanced TOpometric Sensor) Standard produced by GOM[17].

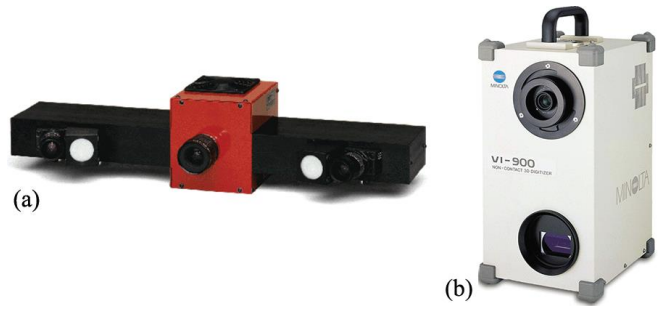

Fig. 3 ATOS Standard structured light scanner (a) and Minolta Vivid 900 triangulation laser scanner (b)

It has a declared accuracy of 0.05 mm and it was calibrated for a working area of 200 x 160 mm. The ATOS Standard (Fig. 3a) has a mean acquisition rate of about 40,000 points per second. The acquisition of the case study was completed by forty scans taken from different view angles at a distance of about 650 mm with a spatial resolution of one point every 0.26 mm.

The latter is the triangulation laser scanner Vivid 900 (Vi-900) by Konica-Minolta[18] (Fig. 3b). The device has a declared accuracy of 0.08 mm and it was used with the tele lens for a scan area of 111 x 84 mm. The Vi-900 has a mean acquisition rate of about 60,000 points per second. Twelve scans of the case study were taken every 30 degrees by using a synchronized rotary table at a distance of about 600 mm with a spatial resolution of one point every 0.18 mm.

According to author's experience[19,20], the ATOS Standard performance in terms of accuracy and reproducibility is better than that of Vi-900. The difference can also be appreciated by looking at Fig. 4, which shows that Vi-900 data is less accurate and more noisy.

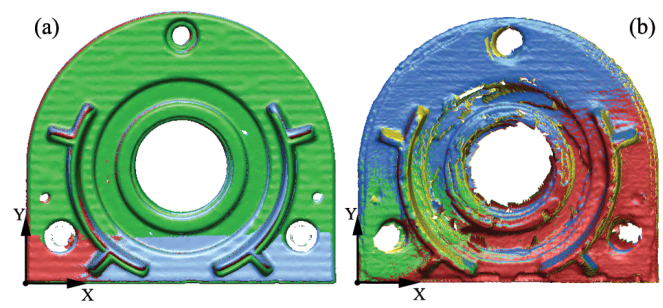

Fig. 4 Superposition of differently-aligned ATOS data (a) and differently-aligned Vi-900 data (b)

3.2 Reference Frame Definition

After digitization, the 3-2-1 rule was applied on scan data to define the part reference frame in the following way (Fig. 2b):

1. three points (square symbol) were selected on the top plane of the central hole to set the Z axis direction and Z axis origin;
2. two points (triangle symbol) on the front plane were selected to set the X axis direction and Y axis origin;
3. one point (circle symbol) was selected on the left side plane to set the X axis origin.

The 3-2-1 alignment was replicated four times on the ATOS scan data (157,682 points) and four times on the Vi-900 data (222,098 points). At each replications, different points were selected on the aligning

features (top plane, front plane and side plane) as indicated by the top dashed loop of Fig. 1.

For the definition of a 3-2-1 alignment on scan data, Reverse Engineering software packages generally requires that the operator manually selects the points by clicking on them by the mouse. While carrying out this operation on the two point clouds of the case study, an error was intentionally introduced by selecting points that were far from the ideal aligning planes (top plane, front plane and side plane). The points were chosen on a peak or a valley of the triangular mesh corresponding to the aligning feature. Such an error aims to increase the difference between two different 3-2-1 alignments of the same data set. The error introduction was easier for the Vi-900 scan data because the mesh is more irregular and noisy (Fig. 4b). In the case of ATOS data (Fig. 4a), the points are much more closer to the ideal aligning planes, so the error introduction is less effective.

The difference between the differently-aligned scan data of the same scanner can be visually checked by super-positioning the point clouds one to another. Fig. 4a shows the super-position of the four differently-aligned ATOS point clouds, while the four alignments of Vi-900 data are super-positioned in Fig. 4b.

Therefore eight differently-aligned point clouds were available for comparison as a result of the replications of the Cartesian reference frame: four alignments for ATOS data and four others for Vi-900 data. For convenience and readability, later on in the text the corresponding cardinal number will be used to refer to each different alignment of the two scanners. For instance the term “Alignment 1” refers to the first alignment and so forth.

4. Results

4.1 Scan data comparison

The differently-aligned point clouds were compared to the theoretical STL model by means of Rapidform 2006 software. The CAD model could be assumed as reference for the comparisons as well. However, by setting the STL model as reference, the results of the comparisons do not keep into account the errors introduced by the slicing operation. The values of deviation are the sum of FDM process tolerances, scanning accuracy and alignment errors.

The average absolute distance from the theoretical STL model and the standard deviation of distance distribution for the eight differently-aligned point clouds are listed in Table 1. If the CAD model was used as reference, the values in the table would have increased by the error induced by the slicing operation. Nevertheless considering each single column of Table 1, that refers to one of the scanners, the difference between one row and the others would not have varied because it is only due to the alignment error. FDM process tolerances, slicing error and scanning accuracy do not change.

The first line of the table refers to the best fit alignment, that provides the lowest distance from the original STL file, but it is not replicable if the scan data changes. Using a fixed reference (i.e. the STL model), it is possible to notice similarities between the different alignments of the same scan data. For example, the alignments 2, 3 and 4 for ATOS data are similar, since the absolute average distance is 0.27 mm and the standard deviation is 0.22 mm for all of them. In the case of the Vi-900 data, the alignments 1 and 3 are similar, while the alignment 2 is the worst one. The comparisons results can also be visualized as coloured distance maps with associated statistical distribution as the one in Fig. 5.

Table 1 Comparisons of differently-aligned scan data with respect to the STL file: average absolute distance and *standard deviation* (All values are in millimetres)

Comparison			ATOS data	Vi-900 data
Best Fit	Vs.	STL	0.19 *(0.17)*	0.31 *(0.39)*
Alignment 1	Vs.	STL	0.28 *(0.22)*	0.36 *(0.41)*
Alignment 2	Vs.	STL	0.27 *(0.22)*	0.42 *(0.43)*
Alignment 3	Vs.	STL	0.27 *(0.22)*	0.36 *(0.41)*
Alignment 4	Vs.	STL	0.27 *(0.22)*	0.37 *(0.43)*

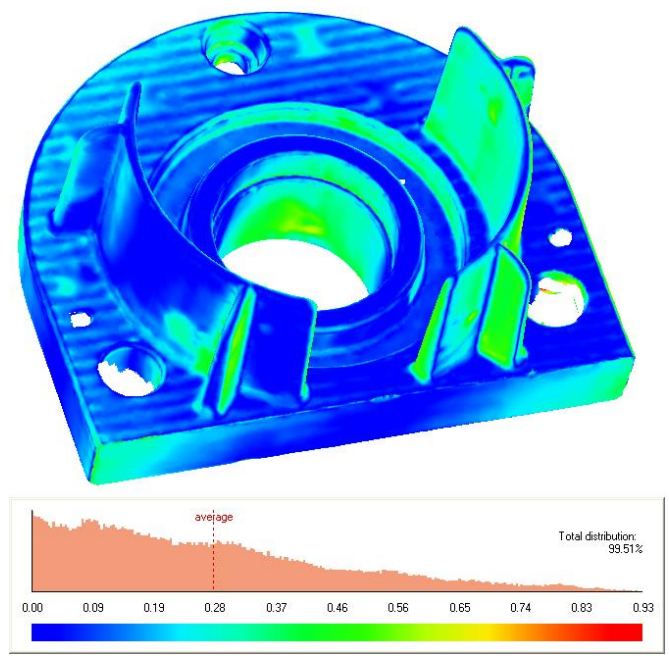

Fig. 5 Deviation map of the comparison of ATOS data 1st alignment versus the original STL model

In addition to this, the four differently-aligned point clouds of the same digitizer were compared in couples by means of Rapidform 2006 software to compute the reciprocal distances. The results of the comparative analysis are shown in Table 2 and Table 3 for ATOS data and Vi-900 data respectively.

Table 2 Comparisons of differently-aligned ATOS data

Compared alignments			Average absolute distance (mm)	Standard deviation (mm)
1	Vs.	2	0.04	0.03
1	Vs.	3	0.02	0.01
1	Vs.	4	0.05	0.03
2	Vs.	3	0.03	0.03
2	Vs.	4	0.02	0.02
3	Vs.	4	0.03	0.03

Table 3 Comparisons of differently-aligned Vi-900 data

Compared alignments			Average absolute distance (mm)	Standard deviation (mm)
1	Vs.	2	0.20	0.16
1	Vs.	3	0.01	0.03
1	Vs.	4	0.15	0.12
2	Vs.	3	0.19	0.16
2	Vs.	4	0.20	0.16
3	Vs.	4	0.15	0.12

As regards ATOS data, the two-by-two software-based comparisons of the different alignments denote a difference between the compared point clouds that is lower than 0.05 mm in all of the cases. This means that the difference is consistent with the declared accuracy of the digitizer.

In the case of Vi-900 data, the alignment 1 is very similar to the alignment 3, since the distance between the corresponding point clouds is in the order of a few hundredth of millimetres. In all other comparisons, the average absolute distance ranges from 0.15 mm to 0.20 mm, so it is higher than the accuracy of the triangulation laser scanner.

4.2 CMM inspection

To further investigate and validate the results of the software-based comparisons, fifty scattered points were selected on similar locations of each differently-aligned point cloud (Fig. 6a).

The single point to be inspected was selected in Rapidform 2006 software by clicking on it with the mouse. The software retrieves and displays the point position in terms of X, Y and Z coordinates and the cosines of the normal to the surface at that point. The surface normal is computed from the triangular mesh by considering all the triangles that share the selected point as common vertex. Subsequently the Cartesian coordinates of the points were set as nominal values for the pointwise inspection of the AM part and the CMM probe path was programmed with an approaching direction that was coincident with the point normal. With the purpose of getting comparable results from the CMM inspection, the fifty points were selected in homologues positions on the two scan data (ATOS and Vi-900).

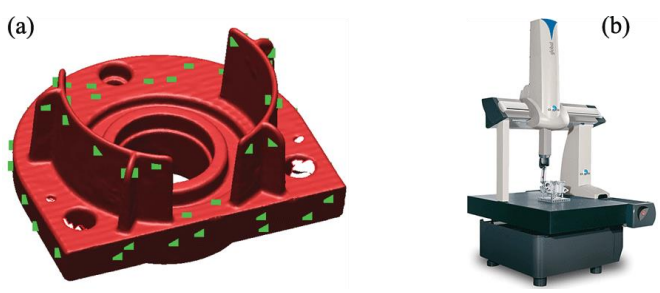

Fig. 6 Location of the fifty inspection points on ATOS scan data (a) and CMM DEA Global Image model 07.07.07 (b)

The sample set was inspected by a probe tip of 2 mm on a DEA CMM model GLOBAL Image 07.07.07 (Fig. 6b), that was equipped with an indexable swinging head and a touch trigger probe whose resolution is 1 μm. The volumetric length measuring uncertainty MPE of the machine according to ISO-10360/2 is 1.5 + L/333μm, where MPE is the acronym for Maximum Permissible Error and L is the measured length.

The pointwise measurements were replicated three times on the nominal values of each differently-aligned point cloud. Before each replication, the physical alignment of the AM part on the DEA CMM was repeated. In doing so the 3-2-1 rule was applied by taking the points with the touch trigger probe on the same aligning features used for the point clouds alignment. Hence the CMM alignment of the part in each replication does not change. Instead the nominal coordinates of the inspection points are different for each point cloud, but do not change for the three replications.

The results of the inspection of ATOS data are shown in Table 4, those of Vi-900 data in Table 5. The values in the tables represent the mean absolute distance between the nominal position on the point clouds of the fifty inspected points and their real position on the physical AM part.

Table 4 Results of CMM inspection of the AM part with 3-2-1 alignment of ATOS scan data (All values are in millimetres)

	Average Distance and *(Standard Deviation)*		
	1st Measure	2nd Measure	3rd Measure
Alignment 1	0.26 *(0.27)*	0.26 *(0.28)*	0.27 *(0.26)*
Alignment 2	0.23 *(0.27)*	0.24 *(0.28)*	0.25 *(0.26)*
Alignment 3	0.25 *(0.26)*	0.25 *(0.28)*	0.27 *(0.25)*
Alignment 4	0.23 *(0.26)*	0.24 *(0.28)*	0.24 *(0.25)*

Table 5 Results of CMM inspection of the AM part with 3-2-1 alignment of Vi900 scan data (All values are in millimetres)

	Average Distance and *(Standard Deviation)*		
	1st Measure	2nd Measure	3rd Measure
Alignment 1	0.28 *(0.21)*	0.24 *(0.17)*	0.31 *(0.24)*
Alignment 2	0.39 *(0.27)*	0.34 *(0.26)*	0.41 *(0.30)*
Alignment 3	0.26 *(0.19)*	0.23 *(0.17)*	0.28 *(0.20)*
Alignment 4	0.36 *(0.24)*	0.33 *(0.22)*	0.39 *(0.27)*

The average absolute distance for the differently-aligned point clouds retrieved by the two scanners is greater than two tenths of a millimetre. For ATOS data, all the values are similar and very close to 0.25 mm. In the case of VI-900 data, the highest values are observed for the alignments 2 and 4: they are about 50% greater than those of the alignments 1 and 3. On one hand such a result confirms once again that the alignment 1 and 3 of Vi-900 data are very similar. On the other hand the choice of the points for the 3-2-1 alignments on Vi-900 data is extremely important, because the higher distance of the alignments 2 and 4 depends on the part reference frame only.

The results can also be analysed in terms of absolute error distribution. Three examples are given for the second replication of CMM measurements for the alignment 1 of ATOS data (Fig. 7) and for the alignments 1 (Fig. 8) and 2 (Fig. 9) of Vi-900 data. The vertical dashed line on the graphs indicates the mean absolute distance. It can be observed that the histogram for ATOS point cloud (Fig. 7) denotes a decreasing trend: the distribution becomes thinner

as the distance value grows, since a great distance was measured for a few points only. This is the more logical and common trend for a distribution of inspection results that are non uniform, but not affected by systematic errors or singularities.

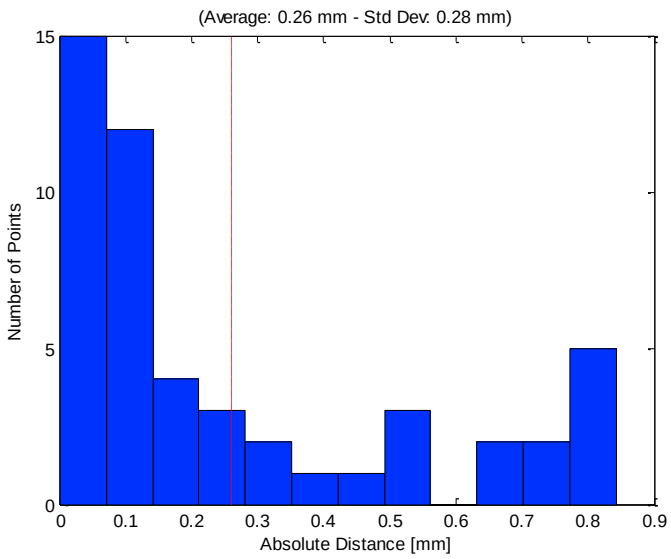

Fig. 7 Absolute distance distribution in the second replication of alignment 1 of ATOS data

On the contrary, for Vi-900 data (Fig. 8 and Fig. 9) it can be noticed that the histogram is different and do not shows the same decreasing trend: the worse accuracy of the scanner generates a more uniform distribution of the distance. In particular, this aspect is more evident for the alignment 2 of Vivid data (Fig. 9), because the distribution of the distance is also affected by the worse definition of the part reference frame.

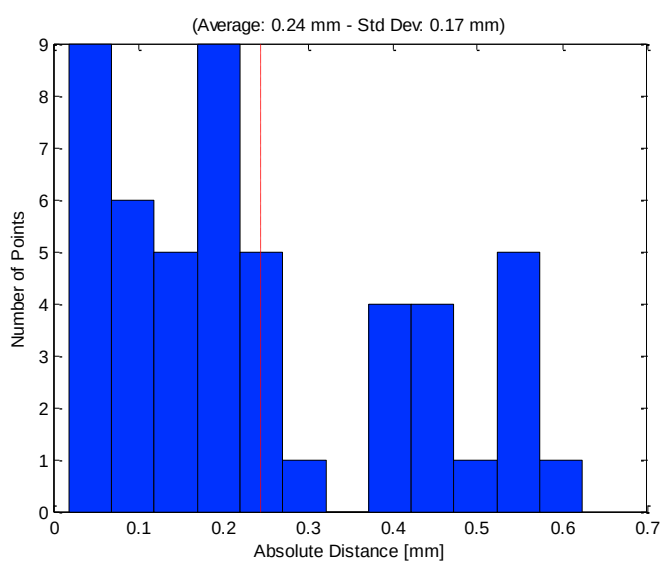

Fig. 8 Absolute distance distribution in the second replication of alignment 1 of Vi-900 data

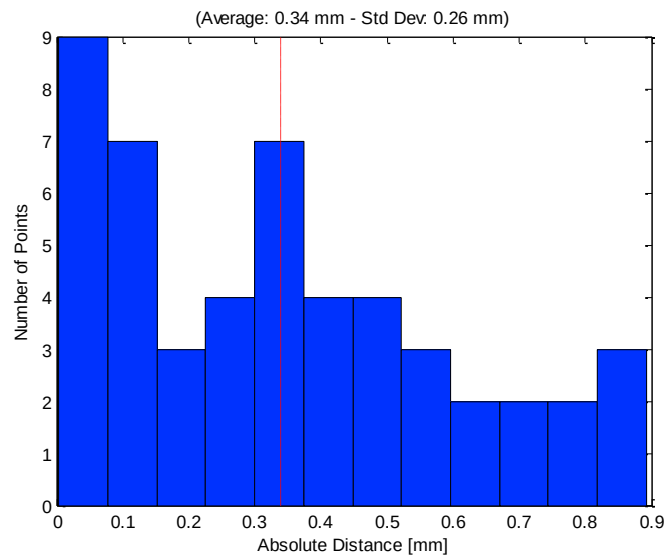

Fig. 9 Absolute distance distribution in the second replication of alignment 2 of Vi-900 data

5. Conclusions

Mechanical components have been inspected by contact measurements by CMMs for a long time. Quality control procedures and plans were coherently developed for CMM measurements. Switching to contactless inspection, those procedures can still be used, but operators should be aware of differences and new issues.

This paper deals with the application of the widely-used 3-2-1 rule for the alignment of range data in contactless inspection. An ABS part manufactured by FDM was selected as case study. The part was scanned by means of the structured light scanner ATOS standard and the laser triangulation scanner Vi-900.

The digitising by ATOS standard took about one hour and forty scans of the AM part were acquired. To change the point of view between one scan and the following one, the part was manually repositioned in the working volume or the scanner position was modified. No further data processing was necessary, since the ATOS software merges multiple scans in one point cloud automatically and accurately by using fixed targets on the part surface.

In the case of Vi-900, the scanning phase was faster because of the use of the synchronized rotary table, that did not require the manual repositioning of the part. It took almost a quarter of an hour to completely digitise the ABS holder, but then the automatic software-based merging of the multiple scans was not very accurate. A semi-automatic registering procedure was then used to improve the merging accuracy. The twelve scans were registered into one point cloud in one hour.

Subsequently, the 3-2-1 rule was used to align the ATOS point cloud and the VI-900 one in the same Cartesian reference frame prior to inspection. Different points were selected on each aligning feature for each replication with the purpose of investigating the influence of point selection with respect to inspection results. The definition of the Cartesian reference frame for contactless inspection is very fast and took only a few minutes. Four differently-aligned point clouds were

available from each scanner as a result of the alignment replication. Although the starting data set is the same, each differently-aligned point cloud represents a different part in the same Cartesian reference frame.

The influence points selection was first carried out by software-based comparisons of the differently-aligned point clouds. Secondly the positions of fifty points were selected on each differently-aligned scan data as nominal coordinates for the contact pointwise measurement of the real part on a CMM.

The inspection by the CMM requires fixturing the part on the machine, defining the Cartesian reference frame on the physical part, programming the probe path and executing the measurements. The activity took about one hour for a set of fifty inspection points. The higher the number of points to be inspected, the longer the inspection time on the CMM.

The results of the software-based comparisons between the differently-aligned point clouds (Tables 2 and 3) were confirmed by the CMM inspection of the fifty scattered points (Tables 4 and 5). The mean distance between all points of the four alignments of ATOS data was lower than 0.06 mm (Table 2). Such value is smaller than the layer thickness of the FDM process. Due to the staircase effect of the part surface, contact inspections by CMM (Table 4) show no difference for the four alignments of ATOS data.

On the contrary, the mean distance between all points of the four aligned Vi-900 point clouds computed by Rapidform software is around 0.17 mm (Table 3). Contact pointwise measurements by CMM confirmed a difference between the four alignments for Vi-900 data (Table 5). With respect to the results of software-based comparisons (Tables 2 and 3), higher values for the differences between the ATOS data and Vi-900 data were obtained in the fifty points inspection by CMM (Table 4 and Table 5): this is probably due to the staircase effect on the real part surfaces that influences contact measurements.

On the whole, both software-based comparisons and CMM inspection of differently-aligned point clouds demonstrate that the selection of the points on reference features during the definition of the same part reference frame can influence the results of non contact quality control, leading to incorrect evaluations. The influence is more evident if the accuracy and quality of the scan data is worse, as for the Vi-900 device.

In conclusion, for the AM part selected as case study, the inspection time was almost comparable for contactless inspection by 3D scanner and pointwise measurements by CMM. Nonetheless contactless inspections considers hundred thousands points, whereas only fifty points were measured by the CMM. This number is not sufficient for an accurate inspection of the whole geometry of the part. This limit is even more evident in the case of free form sculptured surfaces which normally characterise AM parts .

When multiple copies of the same AM part have to be inspected for quality, a robotized procedure can be used. If the 3D scanner is mounted at the end of robot arm, the scanning phase can be automated by programming the robot configuration and measuring positions. The programming step is similar to the one of a CMM and should be carried out only once when the first copy is inspected. Moreover the robot could be coupled with a synchronised rotary table for automatically reposition the part, but costs would also increase.

Awareness of the differences to traditional CMM methodologies is needed when switching to contactless inspection for the first time. The higher number of points available in range data does not necessarily represents an advantage. The results of this analysis show that in 3-2-1 alignment the inspection results are different by simply changing the point selected on an aligning feature.

Traditional procedures can still be used and there are also opportunities for defining new methods for the part alignment and for the inspection process itself. Future research activity will consider the use of a large number of points on scan data for the definition of the Cartesian reference frame. The influence of best fitting procedures on aligning features will be examined.

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