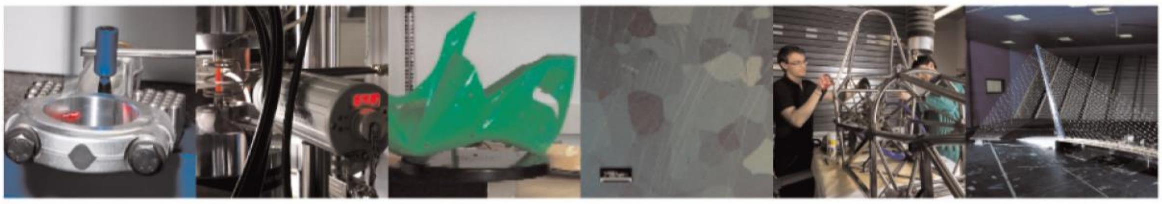

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Segmentation-free geometrical verification of additively manufactured components by X-ray Computed Tomography

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X-Ray Computed Tomography sets the stage for geometrical verification of additive manufacturing components, thanks to its ability in measuring complex shapes. Being a volume measurement technique, usually segmentation/thresholding is adopted to turn volume to coordinate measurement enabling the use of well-known computational algorithms: this transformation significantly contributes to measurement uncertainty.

We propose a segmentation-free approach for geometrical verification of additively manufactured components based on "mutual information", an information theory concept adopted for the comparison of inhomogeneous data. This is part of a comprehensive model for the design, (additive) manufacturing, and verification of products by an "enriched voxel representation".

Inspection; Additive Manufacturing; 3D X-Ray Computed Tomography

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1. Introduction

Additive manufacturing (AM) sets a new standard in manufacturing, thanks to its ability of providing 'complexity for free': the greater benefits come from the possibility to control both the shape and material complexity of a product, as deeply discussed in [1]. However, to completely take advantage of AM, the process chain needs a lot of development with respect to geometric dimensioning and tolerancing. About the tolerance verification step, conventional coordinate measuring systems are not characterized by a flexibility comparable to AM, in particular when internal geometries, one of the strengths of AM, are involved.

The only well-developed measurement technique able today to carry geometric measurements on complex-shaped parts is 3D X-Ray Computed Tomography (3DXCT) [2, 3]. Currently, 3DXCT is applied to scan components to verify, and then the scan is segmented to generate a cloud of points to be analysed with the conventional geometric metrology software.

In a previous work [4], we proposed an 'enriched voxel-based representation' as the way to approach the problem of representing additive manufacturing parts. This is coherent with how AM systems work [5, 6], but also with the output of 3DXCT: a voxel representation of the X-ray absorption. The possibility of a completely volumetric representation and verification of parts is open then.

In this work a simple volumetric representation of geometric tolerances will be proposed, based on the concept of minimum and maximum material continuum [4]. Starting from the alignment of the nominal and measured part, a criterion for stating the conformity of the additively manufactured part with the specifications will be proposed. Both the alignment and the comparison will be based on the concept of 'mutual information'. As the comparison is directly applied to the volumetric representation of the tolerance and 3DXCT scan, there is no need to define a segmentation approach and approximate the measured part with a cloud of points. The proposed approach will be illustrated and validated on two simple case studies.

2. Volumetric specification of a 'geometric tolerance'

In general, the limits to the geometry of AM parts should be defined only by a minimum material continuum (enabling the satisfaction of the functional requirements) and a maximum material continuum (still guaranteeing the functional requirements but avoiding exceeding the use of material and the weight of the part) [4]. Anselmetti et. Al. [7] discussed the possibility of representing the two by applying the conventional geometric tolerances [8], but only constant tolerance zones can be represented this way.

Now, consider a generic volume representation of an object. In a volumetric representation, each point/portion of the volume is defined by some characteristic. For example, to represent the nominal geometry of a part it is sufficient to define each point of the volume as belonging or non-belonging to the part. The problem of representing the geometric tolerance zone can be easily solved by applying a volumetric representation. In practice, it is sufficient to state, at each location of the volume, if we are inside the surface defining the minimum material continuum, outside the maximum material continuum, or in the tolerance zone, which is found between the two (Figure 1).

Starting from this theoretical definition of a tolerance zone in a volumetric representation, we need to translate it in a conventional representation. The simplest volumetric representation is a voxel representation. A voxel-based representation of a nominal part is nothing else than a 3D grid: each element (voxel) $x_{i,j,k}$ of the grid contains a value representing some characteristic of a portion of the volume represented. In the case of a nominal geometry, the characteristic is the presence or absence of material at the specified coordinates. If the voxel is cubic, of size s, then the element $x_{i,j,k}$ is located at coordinates $(s \cdot i, s \cdot j, s \cdot k)$. If at coordinates $(s \cdot i, s \cdot j, s \cdot k)$ no material is expected, then $x_{i,j,k} = 0$, else, if there is material, $x_{i,j,k} = 1$. It is worth noting that multi-material components can be defined by simply indicating different values of $x_{i,j,k}$ for different materials. In this study we will consider only the single-material case.

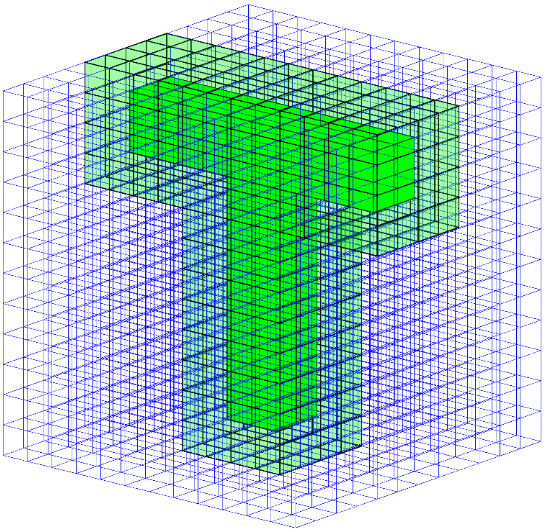

Figure 1: Volumetric representation of the tolerance zone (transparent green volume elements).

The representation of a tolerance zone is straightforward if the tolerance zone itself is defined by a maximum material continuum and a minimum material continuum. In this case, we can (arbitrarily, as this does not influence the rest of the discussion) assume that voxels inside the area of minimum material continuum assume the value 2, those outside the maximum material continuum assume the value 0, and remaining points assume the value 1. As such, the set of voxels equal to 1 represent the tolerance zone. We define this representation as the voxel-based model of the geometric tolerance (VMGT).

3. Tolerance verification

When checking geometric conformity by means of 3DXCT the typical procedure is depicted in Figure 2. As one can see, segmentation is among the fundamental steps, and is aimed at defining the boundary between the part and the air (or other materials). However, segmentation is recognized among the main contributors to uncertainty [9]. Even small variation in the parameters, or the choice of different segmentation approaches, can yield significantly different measurement results [10].

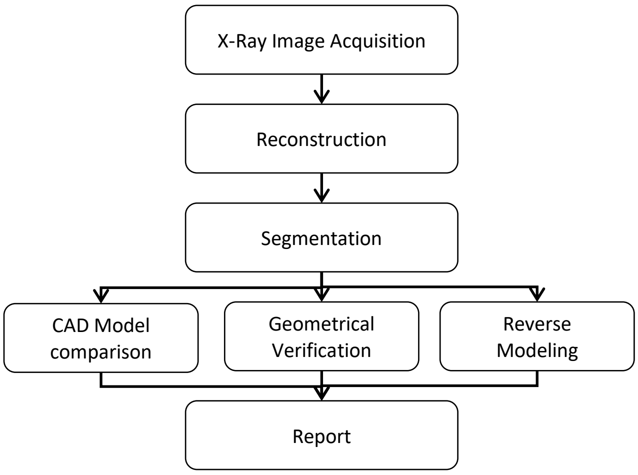

Figure 2: Inspection by 3DXCT workflow

This contribution to the uncertainty can be eliminated if the 3DXCT scan and the VMGT are directly compared. Two steps are needed: at first the nominal geometry and the 3DXCT scan must be registered, then they can be compared.

Registration has already been discussed in our previous work [4]. Briefly, the problem we are facing is the registration of two inhomogeneous 3D images. The images are inhomogeneous because one is a scan of an object, while the other is a theoretical representation of the same object. In this case the literature suggests the maximization of the mutual information [11] as the best criterion to register the images.

Suppose now that we have registered the 3DXCT scan and the nominal geometry, so that we have two voxel representations of the same size. This means that also the VMGT is registered.

The problem is: how can it be stated that the 3DXCT scan complies with the VMGT?

If 3DXCT was able to define without ambiguity what is material of the part and what is not, it would be sufficient to verify that all the voxels of the 3DXCT scan corresponding to the '2' value in the VMGT (points in the minimum material continuum) are filled with material, and all the voxels of the 3DXCT scan corresponding to the '0' value in the VMGT (points outside the maximum material continuum) are with no material. However, due to measurement noise, the 3DXCT scan is not able to unambiguously identify the material. Furthermore, the transition between material and air is not sharply identified, but progressive. As such, a more complex criterion must be developed.

First, we suggest not to consider all the voxels in the considered representations. Even a small 3DXCT scan is constituted by billions of voxels. Considering all of them could lead to a huge computational burden, and even a good deal of uncertainty originating from computational errors. Furthermore, not all voxels are equally relevant for verifying the tolerance. For example, voxels corresponding to the tolerance zone are not relevant at all. It is not relevant whether these voxels are filled with material or not, from the point of view of the geometric conformity. In this work, we propose to consider only the voxels adjacent to the tolerance zone, inside the minimum material continuum and outside the maximum material continuum.

Let's give a univocal definition of these 'shells'. Define the neighbourhood of a voxel as the set of voxels adjacent to it:

$$N\{x_{i,j,k}\} = \bigcup_{o,p,q\in\{-1,0,1\}} x_{o+i,p+j,q+k} - x_{i,j,k} \qquad (1)$$

Let's consider the VMGT, the shells can be defined as:

$$x_{i,j,k} : x_{i,j,k,} = d \wedge \exists x_{o,p,q} \in N\{x_{i,j,k}\} | x_{o,p,q} = 1 \qquad (2)$$

where $d = 2$ for the inner shell and $d = 0$ for the outer shell. The voxels of the inner shell should be set equal to '3' and the voxels in the outer shell to '4'.

We can define NSN the sorted set of the voxels belonging to both the inner and outer shell (a sequence of '3' and '4') in the VMGT (nominal representation of the part), and NSM the identically sorted set of the corresponding voxels in the 3DXCT scan.

The reason for not considering the voxels not belonging to the shells is robustness. Voxels outside the outer shell often present 3DXCT artefacts, which could mislead the criterion. Similarly, the voxels inside the inner shell are affected by any lack of homogeneity of the material, like the presence of porosity or even cavities. As geometric conformance is the focus, these defects should not affect the decision rule. Considering the shells is sufficient, as if any geometric deviation 'exits' the tolerance zone they include the first affected voxels.

Having selected the shells as portion of the volume to study to assess the geometric conformance, a criterion can be developed. The criterion we propose is based on the information content of NSN and NSM, as measured by their entropy H [11]. In general, we can expect that $H(NSN) < H(NSM)$. This is due to the presence of noise in NSM, while NSN is a pure binary theoretical representation of the shells. However, this does not guarantee that all the information in NSN is contained inside NSM.

But what is the information inside NSN? The only information it conveys is 'the inner and the outer shell are completely separated'. As such, if comparing NSN and NSM we find that NSM contains all the information of NSN, this means that NSM contains the information that the shells are completely separated.

We suppose that this condition corresponds to the geometric conformance. In fact, if the shells are separated, any transition from air to material must happen between the two, i.e. in the tolerance zone. From a mathematical point of view, the concept of 'NSM containing all the information of NSN' is related to the mutual information shared by NSN and NSM. Mutual information is a statistical property of two 'signals'. It is defined as

$$\mathrm{I(A,B) = H(A) + H(B) - H(A,B)} \qquad (3)$$

where $H(A)$ and $H(B)$ are the entropies of A and B 'signals', while $H(A,B)$ is their joint entropy. It can be demonstrated that $I(A,B) \le \min\big(H(A), H(B)\big)$. The limit condition:

$$\mathrm{I(A,B) = \min\big(H(A), H(B)\big)} \qquad (4)$$

represents the situation in which one of the two signals contains all the information of the other signal (the shared information is equal to the information in the signal containing less information).

One could be interested in measuring how 'close' we are to the complete separation. This can be obtained by considering the 'normalized mutual information' proposed by Yao [12]:

$$NMI(A,B) = \frac{I(A,B)}{\min\big(H(A),H(B)\big)} \qquad (5)$$

This is the ratio between the information shared by the signals and the information of the less informative signal. It is impossible that the less information-rich signal contains all the information, but it is possible that the most information-rich signal contains all the information, thus including the information of the other signal. This is the complete separation condition, represented by:

$$NMI(NHN, NHM) = 1 \qquad (6)$$

This condition is the tolerance verification decision rule we propose. It is worth noting that this condition is equivalent to state that there is no overlap between the values in the voxels of the 3DXCT scan in the inner shell and those in the outer shell (**Errore. L'origine riferimento non è stata trovata.**).

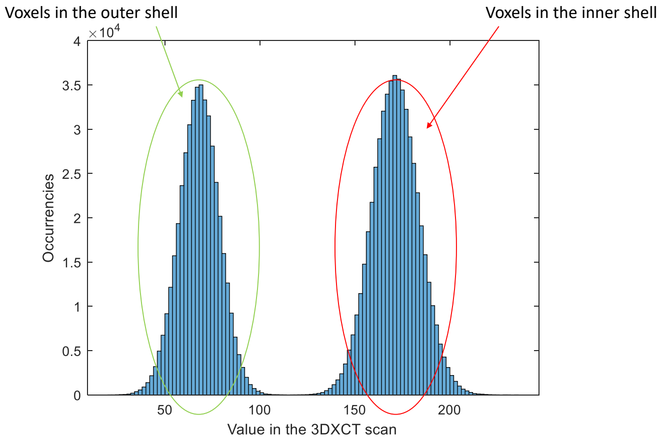

Figure 3: Separation between the inner and the outer shell when the geometric tolerance is verified.

This introduces the main peculiarity of the method: there is no measurement result. NMI is not a measurement result, it is a synthetic indicator, which can give only a qualitative indication of how 'far' we are from . As there is no measurement result, there is no measurement uncertainty. However, considering uncertainty in decision rules aims at controlling the probability that a non-conforming item will be accepted (global consumer's risk) and the probability that a conforming item will be rejected (global producer's risk) [13]. These risks have to be considered in any kind of decision rule to cope with the consequences of an incorrect decision. The discussion of consumer's and producer's risks will be the subject of further studies.

4. Validation of the approach

Two case studies will be considered for the validation: a simple cylindrical sample and a multi-hole cylindrical sample.

4.1. Cylindrical sample

The first case study is a simple titanium calibrated cylinder, chosen as the simplest possible geometry, so the simplest to understand. The diameter of the cylinder is equal to 6,0760(4) mm, and the global cylindricity deviation is equal to 10,1(3) µm. The sample was scanned on a NSI X25 computed tomography scanner. The parameters of the scan were set as follows:

- X-ray source voltage: 160 kV;
- X-ray source target intensity: 24 µA;
- Integration time: 0,66 s;
- Voxel size: 13,25 µm.

To study the behaviour of the proposed approach, a simple VGMT has been built, that is the voxel representation of a perfect cylinder characterized by the nominal diameter, around which a tolerance zone of defined amplitude has been added. Then, after the VGMT and the 3DXCT scan have been registered, the NMI has been calculated for different values of the amplitude of the tolerance zone.

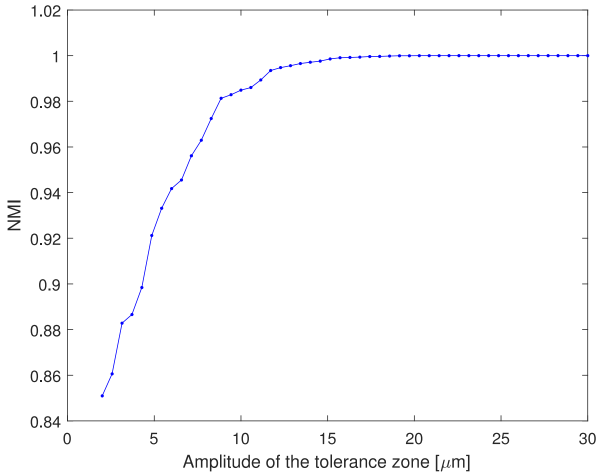

Figure 4: NMI as a function of the amplitude of the tolerance zone for the cylindrical sample.

Figure 4 shows the NMI as the tolerance zone grows larger. As expected, if the tolerance zone is small, there is not a complete separation of the shells, so $NMI < 1$. One can point out that the NMI reaches the critical value of 1 when the tolerance zone is about 20 µm wide, while the cylindricity deviation is about 10 µm. This can be explained by the fact that the voxel size is about the same size of the cylindricity deviation. As such, if the width of the tolerance zone is about 10 µm, due to the presence of a transition in the 3DXCT scan from the material to the air one cannot expect a complete separation is found. Complete separation is found instead when the tolerance zone is large enough.

4.2. Multi-hole cylindrical sample

An aluminium multi-hole sample has been manufactured (Figure 5). The pattern of Ø4 mm holes of its geometry should mimic a portion of a possible complex shape used in additive manufactured parts, but still very easy to calibrate. The sample has been calibrated for the hole diameter and position, and the form error (with uncertainties respectively equal to 0.5, 2, and 2 µm). The total geometric deviation is approximatively equal to 700 µm. This high value is intentional, allowing the simulation of an out-of-tolerance state. The sample was scanned with the following parameters:

- X-ray source voltage: 90 kV;
- X-ray source target intensity: 60 µA;
- Integration time: 0,33 s;
- Voxel size: 11,03 µm.

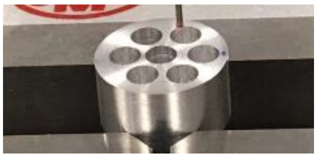

Figure 5: Multi-hole sample.

Two different VGMT have been considered in this case. The first one has been developed based on the nominal geometry, while the second one is based on the calibrated geometry. Again, these VGMTs have been registered to the 3DXCT scan. In the case of the nominal geometry, the registration was poor, as expected. This is due to the large amount of geometric error of the sample. If the calibrated geometry is considered the registration improves (Figure 6).

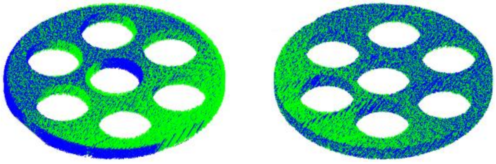

Figure 6: Registration of the multi-hole sample. Green points belong to the 3DXCT scan, blue points belong to the VGMT. On the left, nominal geometry, on the right calibrated geometry.

Again, the NMI was calculated for both the nominal and calibrated VGMT (**Figure 7**). As one can see, in the case of the nominal geometry the NMI is equal to 1 only when the tolerance zone is very large. This is coherent with the large geometric deviation. In the case of the calibrated geometry instead the NMI grows faster. In practice, in this case mainly the form error of the holes is tested, while their position error is not considered.

5. Conclusions

AM and 3DXCT are emerging technologies in manufacturing and verification thanks to their ability to take advantage of the 'complexity for free'. This is enabled by a volumetric-based approach. Therefore, a new paradigm for designing, manufacturing, and verifying products is needed.

In this work we have shown how it is possible to verify by 3DXCT geometric tolerances without a segmentation step. The main idea is to compare 3DXCT scan to an enriched voxel-based representation of the part tolerance zone, and then to consider the NMI as indicator of the conformity of the real part to the design.

The main drawback of the approach is its inability in providing a measurement result for the geometric deviation, but just a conformance statement.

Several improvements can be considered for this work. Volumetric representations more efficient than a voxel representation could be considered. The NMI could be statistically characterized to estimate consumer's and producer's risks in the proposed conformance decision rule. Anyway, the authors of this paper think that volumetric representation will become predominant for AM.

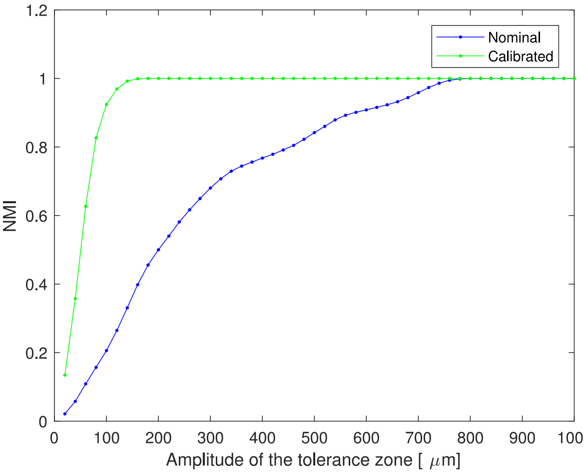

Figure 7: NMI as a function of the amplitude of the tolerance zone for the multi-hole sample.

Acknowledgements

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