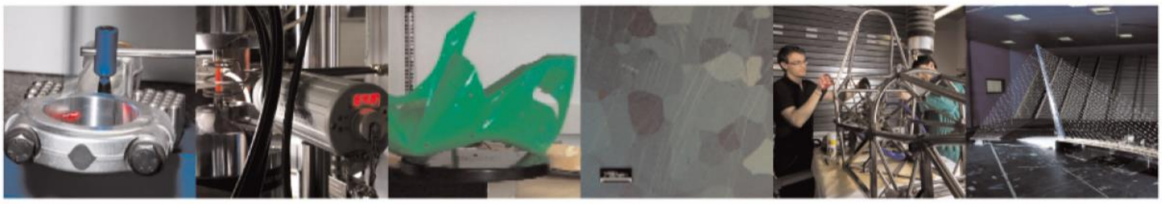

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This is a post-peer-review, pre-copyedit version of an article published in CIRP Annals. The final authenticated version is available online at: http://dx.doi.org/10.1016/j.cirp.2017.04.043

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Rev. 0

Geometrical Product Specification and Verification in Additive Manufacturing

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The geometric freedom associated with additive manufacturing (AM) processes create new challenges in defining, communicating, and assessing the dimensional and geometric accuracy of parts. Starting from a review of the ASME-GD&T and ISO-GPS current practices, a new approach is proposed in this paper. The new approach combines current tolerancing practices with an enriched voxel-based volumetric representation scheme to overcome the limitations of standard methods. Moreover, the new approach enables a linkage between product design optimization and product verification with respect to the AM process chain. A case study is considered to demonstrate the concept.

Tolerancing, Quality, Additive manufacturing.

1 Introduction

It is well established that additive manufacturing (AM) is a historical breakthrough in manufacturing and deeply impacts the overall design and manufacturing process chain as well as the entire life cycle of a product [1].

The greater benefits of AM come from the fact that by adding material point-to-point and layer-by-layer, it is possible to control both the shape and material complexity of a product. This "complexity for free" requires alterations to current methods to describe and communicate complex design.

This need is particularly true and well recognized with respect to the specification of geometry, material, tolerances, surface finish, and any additional functional requirements of the product.

This paper proposes a new approach for dealing with geometrical specifications of a product in the additive manufacturing context.

Two seminal works have detailed the actual difficulties of geometric dimensioning and tolerancing (ASME GD&T [2]) and geometrical product specification (ISO GPS [3]) standards.

Ameta et al. [4] addressed the specification issue in additive manufacturing by distinguishing between process-driven issues and issues highlighted by the capabilities of additive manufacturing.

Process-driven issues are related to the following:

1. Build Direction – By adding material point-to-point or layer-by-layer, the direction of growth has an influence on the behavior of the material due to the resulting anisotropic structure.
2. Build Location – This is an issue related to the position of the growing part inside the machine's working envelope and to the relative influence if a multiple-part production is performed. The performance of an AM machine may vary inside the working envelope, and the local heating due to the simultaneous fabrication of different parts may have an effect on the material micro-structure.
3. Layer Thickness – This is an important parameter related to the quality of a product and may be a fixed parameter or a parameter that is changeable from layer to layer.
4. Support Structure – Supports are used in many AM processes, and their location, shape, and size are usually directly linked to the build direction. They also have a relevant influence on the final quality of both the macro- and micro- geometry and the material structure of a part. One issue is the post-processing requirement to remove the supports, while another is due to the heating and cooling effects of the support material with respect to the part itself.
5. Heterogeneous Material – This issue is related to the fabrication of parts with multiple or graded materials. The transition among them is a design intent that should be described and communicated.
6. Scan/Track Direction – The material deposition direction or the energy-beam trajectories have a relevant influence on the final quality of the part and the material structure.

The new capabilities of an AM process generate the following issues:

a. Tolerancing Freeform Complex Surfaces;
b. Tolerancing Topology-Optimized Shapes/Features;
c. Tolerancing Internal Features.

Even if the authors distinguished these three issues, they all have a commonality: the "complexity for free" that is related to an AM process has an impact on how to define the allowable variability that guarantees the final quality and functionality of the part. The authors pointed out that the actual GD&T and GPS standards are not able to adequately address this issue. Moreover, the authors underlined a relevant issue in tolerance communication: in AM, all geometry is converted into a tessellation before processing a layer. During this conversion, all features and tolerances information are lost.

Starting from a similar consideration, Witherell et al. [5] summarized the issues into three main points:

1. Complex Geometries – They note that only the traditional surfaces can be toleranced using GD&T, while free-form surfaces with varying thickness and/or tolerances cannot.
2. Material-Process Interaction – They note how the final behavior of either a material, a multi-material, or a graded material will depend on the process parameters, i.e., on the way the product growth and the thermal cycles are applied to the material. All of this is far beyond the actual GD&T/GPS standard.
3. Internal Features – They underline that the ability to create internal features that are not possible with other technologies brings about issues related to their definition, tolerancing, and verification.

The authors pointed out that the actual GD&T and GPS practices have their foundation in two-dimensional space. Model-Based Engineering (MBE) has been considered in the evolution of the standards through the Model-Based Definition (MBD) as the technique to communicate a product using 3D solid models and 3D annotations. Nowadays, the transition to digital manufacturing, as for AM, is rising in importance to incorporate Product and Manufacturing Information (PMI) in the MBE packages. To this extent, the authors conclude that, with respect to AM, there is a need of developing methods to perform the following:

a. Tolerance complex freeform surface;
b. Communicate and tolerance heterogeneous materials and internal feature;
c. Communicate dimensioning and tolerancing requirements throughout the product lifecycle;
d. Facilitate machine-readable dimensioning and tolerancing from design to manufacturing, conformance, and verification.

All of these considerations are the fundamental motivation for this work. We now present a new approach in dealing with geometrical specifications to mitigate these issues.

2 Proposed Approach

Considering that additive manufacturing is a digital technology, we propose mitigate all of the previously highlighted issues with the introduction of a hybrid PMI system. The system should combine the 3D annotations of the actual GD&T or GPS standards using a solid model boundary representation, with a voxel-based volumetric representation that is enriched with product and manufacturing information.

The need of a hybrid system is related to the fact that, generally, a component of a complex product may or may not be fabricated using additive manufacturing, and, despite the fabrication technique used, the different components must be assembled into the final product. This means that, even if the topological optimization is applied to take advantage of additive manufacturing, a single AM component usually has some geometrical features that are used to constrain different degrees of freedom; therefore, the standard GD&T/GPS annotation gives a clear and unique representation of all the possible requirements. Meanwhile, the non-mating features that are usually complex geometrical elements/surfaces that derive from the fully exploited topological optimization could be properly represented through an enriched voxel-based volumetric representation.

2.1 Enriched voxel-based volumetric representation

The use of a voxel-based volumetric representation has been already demonstrated to be an adequate representation of AM components [6,7,8]. A voxel-based representation of a component is a volumetric representation in which a prismatic volume surrounding a part is subdivided into elementary cubic elements that are classified as belonging or not belonging to the part (solid material or air). The union of the solid voxels is the representation of the part.

Being an approximated representation of a continuous $\mathbb{R}^3$ space, the dimension of the voxel should be sufficiently small to adequately represent the part and all of its external and internal features.

This representation is compatible with any possible topological optimization method that, starting from a first guess of a part structure, will add or remove material in order to find the best material continuum that satisfies the part functional requirements.

It is worth noting immediately that this representation enables the representation of porous micro-structures [6] and thus any kind of complex structure typical of graded materials.

Moreover, the coordinate reference system of this volumetric representation can be directly associated with the build direction of the part; for example, considering the positive z-axis as the growth direction, it is possible to immediately understand the intent of the designer without any ambiguity.

The need to enrich this volumetric representation aims to fully describe and communicate an AM part. An enriched representation is a representation in which some information is associated with each single voxel. Examples of possible pieces of information are listed here:

- Layer ID – If the dimension of the voxel is small enough to represent the smallest layer, this information is related to a representation enabling the control of the layer thickness. The actual layer has a thickness that is equal to the sum of the dimension of the voxels that have the same ID along the build direction.
- Material ID – This information enables one to represent not only a multiple-material part but also the location, shape, and size of the support structure, if needed.
- Mating Surface ID – This information is needed to create a link between the two solid representations of the part. This ID identifies all of the voxels that approximate a mating surface involved in a GD&T/GPS classical annotation.

2.2 Voxel based tolerance representation

We did not distinguish between freeform complex surfaces, topology-optimized shapes/features, and internal features. In fact, to fully take advantage of AM, topological optimization should be applied considering constraints related to design for additive manufacturing. This means that, apart from the mating features, the final structure of a part will be a composition of complex features and surfaces, which are both internal and external.

From our point of view, the topological optimization should give us two pieces of information:

1. The minimum material continuum that enables the satisfaction of the functional requirements (therefore, the minimum material volume);
2. The maximum material continuum that still guarantees the functional requirements but avoids exceeding the use of material and the weight of the part (therefore, the maximum material volume).

If this assumption is correct, this statement is equivalent to simultaneously guaranteeing a minimum amount of material and a maximum amount of material. This is very close to the semantic of the surface profile tolerance, whose tolerance zone is not centered on the nominal surface. Anselmetti et al. [9] discussed the need of this representation and proposed a method to use the classical annotation to this purpose. An issue remains: the possibility to have a variable tolerance zone depending on the position in the optimized part.

We propose to use the enriched voxel-based representation for this purpose. The same voxel-based volumetric representation may hold the information of both the set of voxels that represent the minimum material continuum and the set of voxels that represent the maximum material continuum.

This explicit representation of the tolerance zone of all of the part features may be used in both the tolerance analysis, as it is possible to randomly generate different instances of the part skin model compliant to the tolerances [10], and in part inspection, as discussed in the following section.

3 Volumetric-Based Tolerance Verification

Once the tolerance model has been established, we need an effective way to verify that the tolerance has been obtained. Traditional approaches to geometric tolerance verification may not be effective in doing this: surfaces generated by AM plus topological optimization are usually complex. As such, conventional approaches to geometric measurement are not effective, and we need to consider different approaches, like volume measurements. This kind of measurement does not yield a cloud of points as a raw measurement result, but it yields a volumetric representation of the part, e.g.. a voxel-based representation. Comparing a volumetric measurement to a boundary representation of the part is not straightforward. In fact, in a volumetric measurement, the boundary between the part and the surrounding medium is usually fuzzy. The definition of the surface of the part is then based on a threshold whose correct definition is very difficult. Instead, a direct comparison between a volumetric measurement and a volumetric model of the part avoids this drawback. This requires the definition of a synthetic indicator of the coherence between the theoretical volume representation of the part and the actual volumetric measurement.

In (2D and 3D) image manipulation, the comparison of images taken in different conditions requires, in general, an initial step of image registration. Usually, two situations are considered: images that come from homogeneous sources (e.g., captured at different times) or heterogeneous sources (e.g., from computed tomography and nuclear magnetic resonance). In our case, a theoretical representation of an object is compared to a measurement of it: it is clear that the two representation cannot be homogeneous. To better understand this, one can consider that the color depth of a nominal model is usually 1 bit, while the color depth of images measured by, e.g., computed tomography, is usually around 12-16 bit: comparing a volumetric model and a volumetric measurement and considering them to be homogenous is not correct. Probably, the most often adopted similarity measure for the comparison and registration of two heterogeneous images A, B is mutual information $I(A,B)$ [11]. Mutual information is a statistical property of two signals. It is defined as

$$I(A,B) = H(A) + H(B) - H(A,B) \qquad (1)$$

where $H(A)$ and $H(B)$ are the entropies of A and B images, while $H(A,B)$ is the joint entropy of the A and B images. The entropy of an image—or in general of a signal—is a probabilistic measure of the information content of the image itself, while the joint entropy is a measure of the total information in the two. The mutual information is then a measure of the information shared by the images (Figure 1): when it is maximum, if an arbitrary rigid transformation is applied to one of the two images, the two images are registered. Although the maximization of the mutual information has been shown to be very effective for the registration of heterogeneous images, it is strongly influenced by several factors, like the size of the images or their color depth. As such, several 'normalized mutual information' (*NMI*) definitions have been proposed. Among others, the one proposed by Yao [12] treats the mutual information similarly to the Pearson correlation coefficient, thus making it dimensionless:

$$NMI(A,B) = \frac{I(A,B)}{\min(H(A),H(B))} \qquad (2)$$

Due to the properties of entropy and mutual information, it is always $0 \leq NMI(A,B) \leq 1$. Higher values of NMI denote more coherent images.

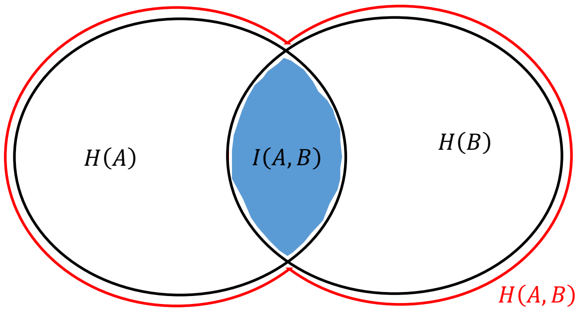

Figure 1. Relationship among entropy, joint entropy, and mutual information.

3.1 *Validation of the proposed approach*

To validate the proposed approach, a very simple part has been considered (simplified bracket [1], Figure 2). Although this part is, by itself, quite simple, it is nonetheless an adequate demonstration of what an additive manufactured part looks like. It presents a series of thin ribs that substitute a bulky structure, plus a series of holes on the hinges and in the base, representing functional mating features. A very basic mating scheme is defined using actual standards. A maximum/minimum condition has been defined for the structural part using the voxel-based volumetric representation (Figure 3). The bracket has been represented using approximately 780 million voxels.

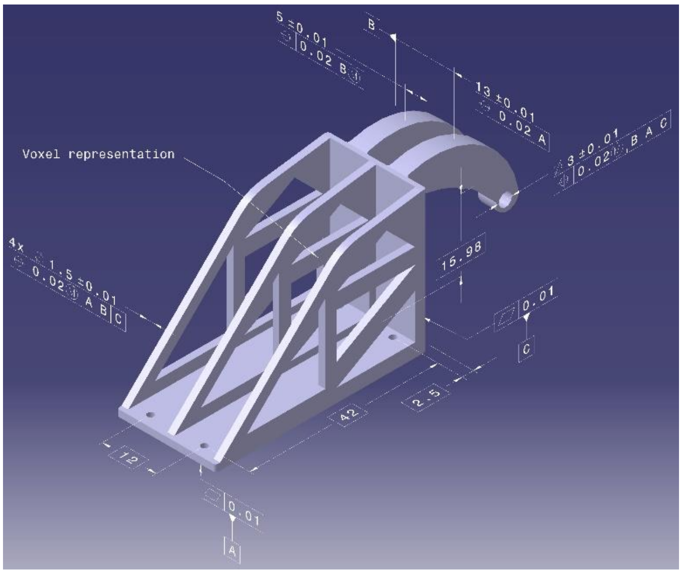

Figure 2. An example part used to validate the approach.

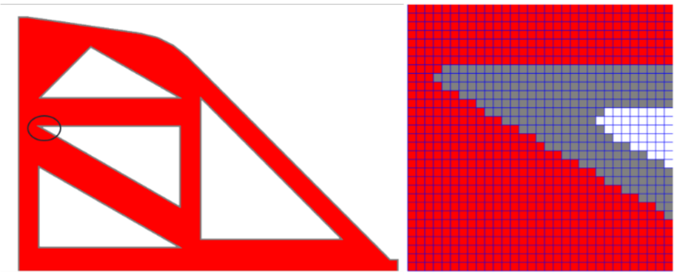

Figure 3. Detail of the voxel-based volumetric representation of the tolerance zone.

The part has then been manufactured by means of fused deposition modelling on a Sharebot 42 machine. The material is PLA, and the layer thickness is 0.2 mm. In particular, the hinges were quite difficult to manufacture because of their overhanging position. As such, one can expect that their accuracy is not optimal.

Finally, the bracket has been scanned by means of a NSI X25 computed tomography scanner. The parameters of the scan were set as follows:

- X-ray source voltage: 40 kV,
- X-ray source target intensity: 200 μA,
- Integration time: 0.075 s,
- Voxel size: 40.71 μm.

The CT scan and the nominal volumetric model were finally registered by maximizing the mutual information. As expected, Figure 4 shows a very good overlap of the stiffening branches of the bracket, while the hinges do not overlap very well. The value of NMI is equal to 0.715, which denotes a significant similarity between the two but not a complete overlap. Starting from this result, it is possible to compare the volumetric measure to the allowed part variability.

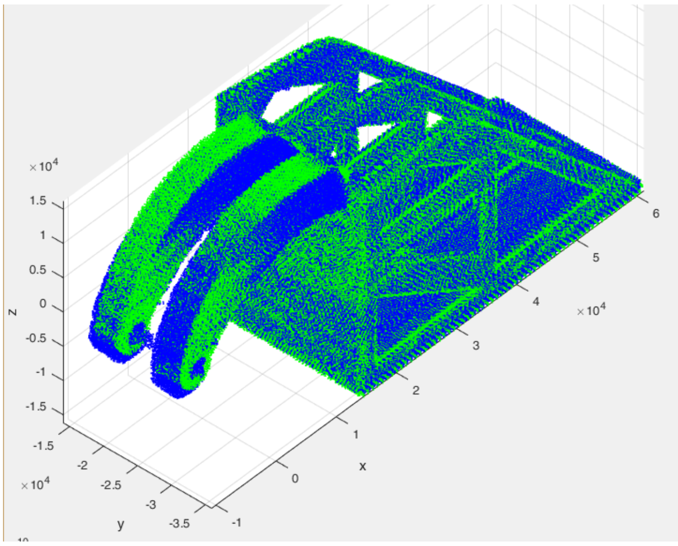

Figure 4. Comparison between the measured (blue) and nominal (green) volumetric representation after registration.

4 Conclusions

The proposed hybrid PMI system, which combines the 3D annotations of the actual GD&T/GPS standard using a solid model boundary representation with a voxel-based volumetric representation enriched with product and manufacturing information, mitigates all of the issues discussed in [4,5], except for the build location and the scan/track direction, which we consider as a process-planning issue that is not related to the design. Please note that these two issues could be mitigated by considering a voxel-based volumetric representation of the AM machine working envelop.

Moreover, even if not discussed in this paper, it should be possible to perform the following:

- Represent an assembly that is directly fabricated by additive manufacturing by adding a Part ID to each voxel.
- Generate different synthetic "points of view" through voxel-based representation of a property of a single part. In this case, it should also be possible to obtain a multi-resolution representation of the part property using an octree representation scheme [13].

In this paper, we also highlight the possibility to use mutual information to generate a direct link between part design and verification using a voxel-based volumetric representation scheme and a volumetric measuring system (e.g., a 3D X-ray CT). Further studies are needed to explore the possibility to directly use the mutual information to state the conformity of a part with respect to its allowed variability.

The main limitation of this proposed method is related to the vastness of the information associated with this representation scheme. The amount of this information directly corresponds with the tolerance requirement and the number of voxels that are required to properly represent the part. Therefore, an appropriate coding should be defined.

5 Acknowledgements

Financial support for this work has been provided as part of the project AMALA – Advanced Manufacturing Laboratory, funded by Politecnico di Milano (Italy), CUP: D46D13000540005.

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