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Design for X-Ray Computed Tomography

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Abstract

The search for higher and higher performance is pushing part geometry to increased complexity. A significant contribution to this trend has been given by the diffusion of additive manufacturing technologies: substituting a simple additive manufacturing part with a complex one does not significantly affect the production cost.

The diffusion of complex geometries has made geometric inspection more and more complicated. However, in recent years a new technique for geometric verification has emerged, which is not affected by the complexity of the geometry: X-Ray Computed Tomography (XCT). XCT substitutes the point probing of geometric metrology with a volumetric scan of the X-Ray absorption of the material. As the whole volume is (even internally) scanned without any accessibility issue, complex geometries are easily acquired.

Even if XCT is totally flexible, this does not mean it can scan any geometry with the same degree of accuracy. In many cases, the part can be measured but the required degree of accuracy cannot be reached. In this work we will try to highlight which are the geometries the most suitable for XCT scanning. This can serve as guide to design parts which can be easily measured by XCT, and simultaneously avoid the generation of scan defects and artifacts which could negatively affect the measurement result. These indications can also serve as an input to develop new rules for topological optimization software.

Keywords: Design for Metrology; Geometric Verification; X-Ray Computed Tomography.

1. X-Ray Computed Tomography for Geometric Verification

Complexity has always been a problem in engineering. Manufacturing complex parts is of course more difficult than simpler ones. The manufacture of complex parts usually requires the definition of complex tool paths. This can be at tool manufacturing level (for casting and forming, where the mold/pattern has to be manufactured) or directly on the part (chip removal). Complexity of surfaces adds to the global uncertainty of parts, both at design and inspection level [14]: proper techniques of "design for manufacturing" and "design for metrology" are needed.

In recent years the rise of additive manufacturing technologies has suggested that this paradigm could change. Additive manufacturing is said to allow "complexity for free" [22]. Although complexity makes part manufacturing design more complicated, the increase of difficulty for additive manufacturing is far less than for traditional manufacturing. Furthermore, given the volume of the part, manufacturing complex parts by additive manufacturing is approximately as expensive as manufacturing simple parts: the deposition time is not significantly affected by complexity. This is made possible by the layer-by-layer process additive manufacturing is based on. Then complex surfaces are no more a taboo, and complex parts require less joining operations to be manufactured. Additive manufacturing allows an almost direct translation of solid models into real parts.

When dealing with complex surfaces, not only manufacturing, but also inspection is badly affected by complexity. In recent years, many authors [1, 4, 6, 7, 15, 17–19, 21, 23, 24] faced this problem and proposed solutions. In general, the classical coordinate measuring machine (CMM) is not a very suitable measuring system for inspecting free-form surfaces. Their surface generates intrinsic accessibility issues, which can currently be faced by articulating probing CMM [9], but this kind of system is in general less accurate than rigid ones. The varying slope of the surface can significantly affect the accuracy of the single points, as the direction of approach changes. Finally these parts often need a different degree of measurement accuracy in different portions of their surfaces (see e.g. turbine blades, requiring a higher accuracy on the entrance and exit surfaces rather

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than on the middle surface), leading to difficult-to-plan inspection strategies. In practice, the approaches found in literature are mostly based on adaptive inspection, but still adaptivity is not possible at shop-floor level, even if the diffusion of the Industry 4.0 concept pushes this way [11]. It worth noting that accessibility issues affect both contact and non-contact CMM. If it is easier for non-contact systems to acquire sculptured surfaces, which are difficult for contact systems, the first ones cannot measure undercut surfaces nor deep holes.

But now, as additive manufacturing has made complexity for free feasible in manufacturing, the use of these approaches, which require complex planning operations for part inspection, can be a bottleneck in complex part manufacturing. To cope with additive manufacturing challenges also a "complexity for free" approach to inspection is needed. Furthermore, an advantage of additive manufacturing is its ability in manufacturing internal surfaces. Conventional non-contact measuring systems, being based on light projection, are usually limited to the measurement of external surfaces.

Up to now, the inspection technology the closest to the concept of "complexity for free inspection" is X-Ray Computed Tomography (XCT) [3, 5, 10]. This characteristic makes XCT probably the most suitable measurement technique for additive manufacturing parts [12, 13]. XCT is based on the acquisition of several radiographic projections of the part to inspect, and then the reconstruction of its volume based on a "back-projection" algorithm [8]. The raw output an XCT scan offers differs form the typical output of a coordinate measuring system: instead of a discrete representation of the surface based on a cloud of points, a volumetric (voxel) representation of the X-Ray absorption in the whole scanning volume is produced. As such, before the measurement result can be analyzed by the conventional coordinate metrology tools, it must undergo a "segmentation" step, which turns the volumetric representation into a surface one by defining a border between the part and the surrounding medium. Finally, it is possible to compare the measurement result to a CAD representation, verify geometric tolerances, or doing some reverse engineering (Fig. 1).

Planning an XCT scan requires a series of parameters to be selected:

- X-Ray source voltage;
- X-Ray source intensity;
- number of projections;
- geometric magnification;
- physical filter.

The choice of these parameters affects the accuracy of the scan and the time required to perform it, so it is essentially an inspection optimization problem. Once these parameters have been set, all the following steps are almost automatic and carried out by some software. In general, defining these parameter and obtaining a scan is not particularly difficult.

However, "obtaining a scan" differs form "obtaining a *good* scan". Obtaining a scan sufficient for the qualitative identification of defects is not difficult, but a obtaining a scan adequate for geometric metrology is not as simple. Actually, the characteristics of the part (geometry, material) affect the quality of the XCT scans that can be obtained. Even if the part can still be scanned, the quality of the scan (noise, contrast) can be too poor, and then geometric measurements extrapolated form the scan can be characterized by an excessive uncertainty to verify geometric tolerances.

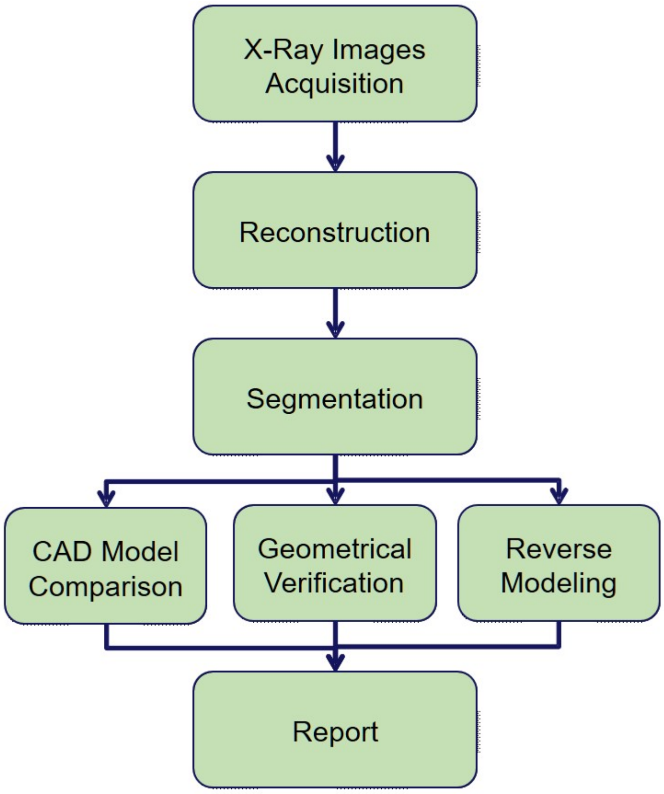

Fig. 1. Work-flow for the use of XCT in coordinate metrology.

In this work, we aim at highlighting a few characteristics of a part that can badly affect an XCT scan. These characteristics then set a series of rules that one should consider when designing a part (made e.g. by additive manufacturing) which is expected to be inspected by XCT: the operator should try to avoid them. In the specific case of additive manufacturing parts, these rules should be turned into constraints of the eventual topological optimization [20] algorithm adopted.

2. Rules for an easy-to-XCT scan part

Although XCT measurement does not require a particular planning of the scan, as it is sufficient to put the part on the rotary table of the scanner and then let several radiographic projection be taken from different points of view, not all parts are easily measurable by XCT. Some geometric features of the part can badly affect the quality of the scan. As XCT is gaining importance in part verification, developing parts that can be scanned obtaining good quality scans is important.

The reader is addressed to specific works on XCT [3, 5, 8, 10] to better understand the process of XCT scanning. Here, a very simple description is given.

An XCT system is essentially constituted by three components:

- An X-Ray source, which generates an X-Ray beam. Most industrial X-Ray sources generate a conic beam (so the projection of the scanned object is conic and characterized by some magnification), with a continuous spectrum of emission.
- A rotary table on which the object to scan is put. This way, different X-Ray projections can be taken from different points-of-view as the object rotates.
- A detector capable of turning the projections into digital images. Most X-Ray industrial detectors are constituted by a scintillator plus a CCD array of given resolution.

Taking an XCT scan means taking a series of projections of the object to scan at different rotation angles of the table. Once the projections have been acquired by the detector, a filtered back-projection algorithm reconstructs them into a voxel representation of the X-Ray absorption in the reconstruction volume.

Here are a few rules to be taken into account when designing a part which is expected to be scanned by XCT.

2.1. Reduce the maximum thickness of the part

Probably the main limitation of XCT is related to the capability of X-Ray to penetrate dense materials. To obtain radiographic projections, X-Rays must be capable of passing through the part to measure. If low density materials, like polymers and aluminum, are easily pierced by the X-Rays, when denser material like titanium, ceramics, steel, and other special nickel, chromium, zinc, tungsten, copper, etc. alloys are considered obtaining projection is not so easy. But if a single pixel of the detector is not hit by X-rays, this can cause artifacts in the XCT scan.

One could then think to solve this problem by using an X-Ray source with a higher voltage and intensity. However, this cannot always solve the problem. In most cases, the part to inspect does not intercept the whole X-ray beam: a portion of the detector is directly hit by the unattenuated X-Rays. But if the X-Rays are too intense, they can saturate the detector: like a pixel which is not hit by the X-Rays, a saturated pixel can also generate artifacts in the XCT scan. Furthermore, increasing the voltage of the X-Ray source broadens the X-Ray spectrum. This adds to the so called "beam hardening" artifact, which causes the external hull of the part to seem denser than the inside. Although many approaches have been proposed to correct beam hardening during reconstruction [2], still the only way to obtain high accuracy scans is to use low voltage X-Rays coupled with a physical philter which cuts out the low-energy X-Rays.

Table 1 gives a general indication of the maximum thickness of parts that can be scanned with X-Ray sources characterized by different voltages. These values refer to continuous materials. It is worth noting that most parts are not massive, and this is particularly true for additive manufacturing parts, which are usually constituted by lattice structures.

Table 1. Maximum material thickness as a function of the X-Ray source voltage.

	130 kV	**150 kV**	**190 kV**	**225 kV**
Steel - Ceramics	5 mm	8 mm	25 mm	40 mm
Aluminum	30 mm	50 mm	90 mm	150 mm
Polymers	90 mm	130 mm	200 mm	250 mm

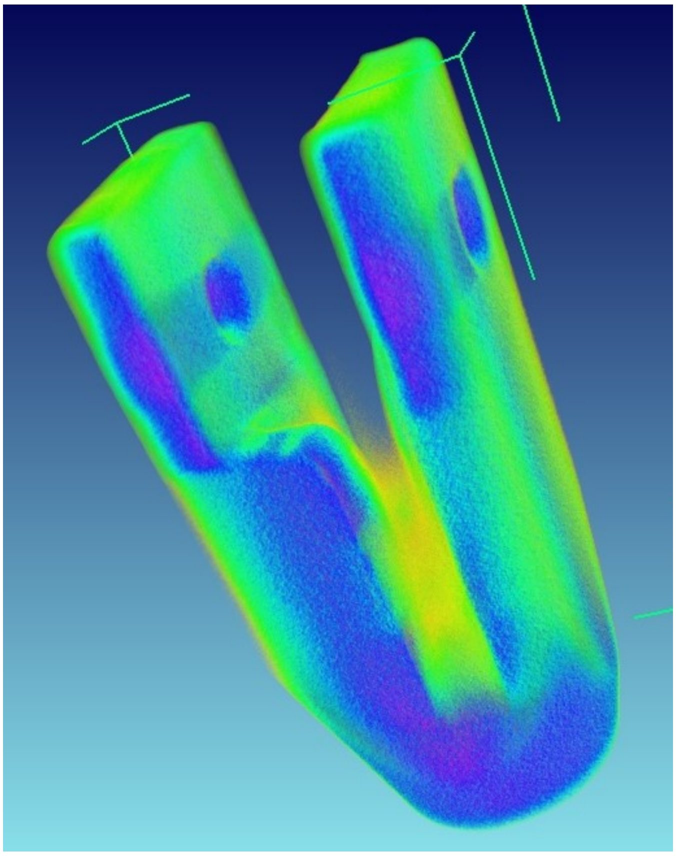

Fig. 2. XCT scan of a Zamak joint. The yellow area presents a sever beam hardening due the variation of the thickness of the part, which causes what seems like a "fog" around the part.

2.2. Avoid thickness variability

Industrial X-Ray sources are polychromatic. Unfortunately, this makes the X-Ray absorption strongly non-linear: low-energy ("soft") X-Rays are absorbed quickly by the material, while high-energy ("hard") X-Rays can pass through it almost unaltered. This phenomenon is known as "beam hardening" [8].

Beam hardening generates several defects in the reconstructed volume. Among the others, one should consider that, in parts characterized by different thicknesses, thinner features are pierced by the soft X-Rays, while thicker ones are not Fig. 2. As such, thinner parts seem less dense than thicker ones. This can generate issues in the correct choice of the threshold, leading to underestimate of the size of thin feature and overestimate of thick features. As such, parts easy to scan by XCT should be characterized by a thickness as constant as possible.

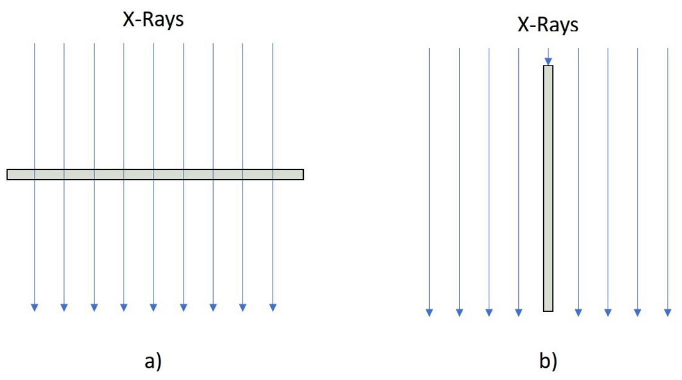

Fig. 3. Interaction of X-Rays with thin layers of materials. a) the X-Rays pass almost unaltered. b) only a small portion of the X-Rays is completely absorbed.

2.3. Avoid thin layers of materials

Scanning very thin layers of materials can be tricky. If a sheet structure is scanned, when the X-Rays are perpendicular to it, they can pass through it almost unaffected, while when they are parallel, a small portion of them will encounter a very thick layer of material, which will block them, and the remaining X-Rays will pass completely unaltered (Fig. 3). Even if the part is not so thick in any projection to deny penetration, this in general reduces the quality of the scan. In particular the inner part of the thin structure seems less dense than the external one, as exemplified in Fig. 4. Even if these images can be sufficient for a qualitative inspection, obtaining quantitative measurement from them is impossible with a good degree of accuracy.

2.4. Avoid sharp edges

Sharp edges of the part can cause scatter of the X-Rays [8]. This alters the straight propagation of the X-Rays, causing in general blurred images, and a lack of definition of the sharp edges themselves, which can seem denser or less dense, depending on the specific scanning conditions. In this condition, performing a good segmentation is difficult: edges tend to look rounded. This has been in part solved by the so-called "local thresholding" algorithms; however, the solution is still non optimal. An example of this is shown in Fig. 5.

2.5. Consider the required resolution

The resolution of XCT scans is mainly limited by two factors: the size of focal spot, and the combination of the geometric magnification and the size of the detector (Fig. 6).

The first one is a characteristic of the X-Ray source, and as such is a hardware constraint to the maximum resolution that can be obtained by a specific XCT scanner. This limits the XCT capability of measuring small parts.

The second one is typical of conic projection XCT scanners, which are the current industrial standard, and is usually more relevant. This effect can at least in part be controlled by the operator.

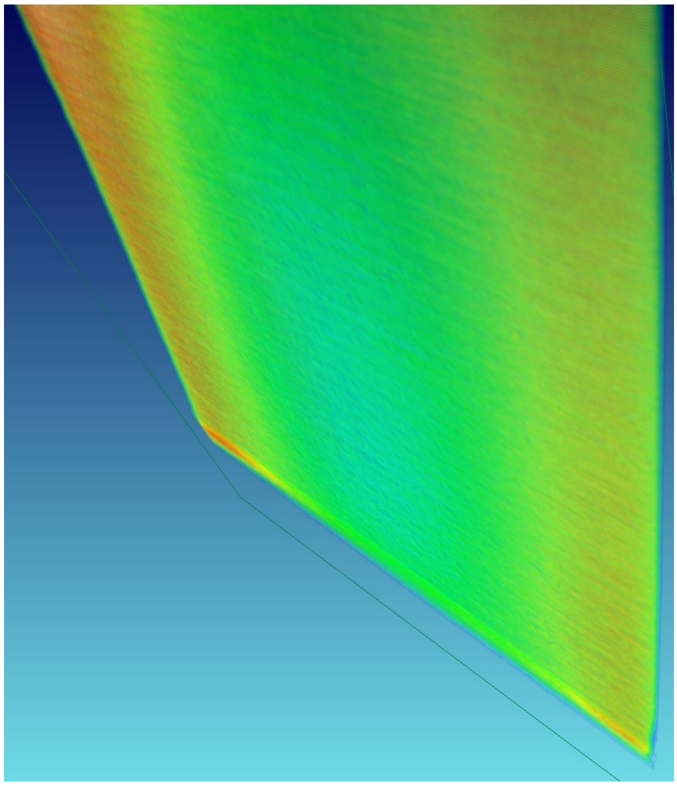

Fig. 4. A thin structure scanned by XCT. Hot colors should denote a higher density of the material, but the material is actually homogeneous.

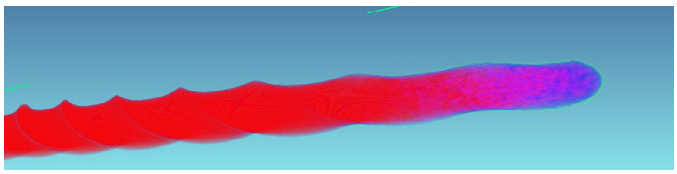

Fig. 5. Sharp edges scanned by XCT. Hot colors should denote a higher density of the material, but the material is actually homogeneous.

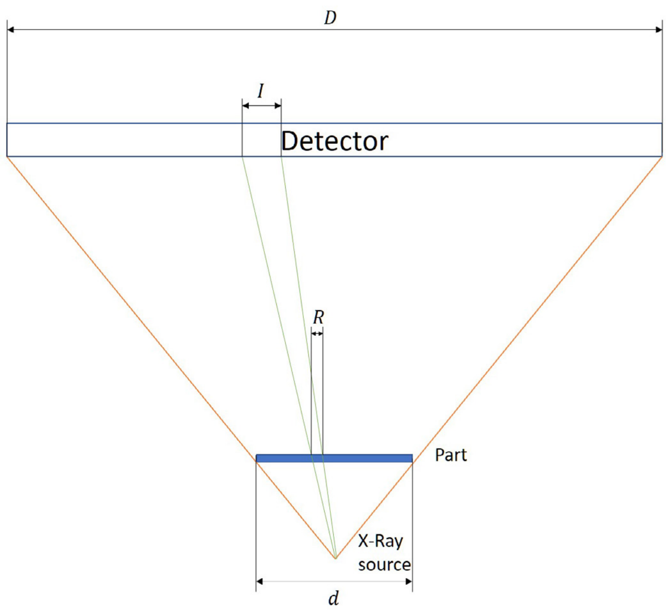

Fig. 6. Real and projected size of the part. Limit to the maximum magnification.

In order to avoid "partial volume" artifacts [8], the part must be completely projected in all views. But if the magnification is excessive, part of the projection could fall outside the detector. As such, the maximum size of the projection is limited by the part and detector width (Fig. 6). The maximum magnification is then

$$M_{max} = \frac{D}{d} \quad (1)$$

where D is the width of the detector and d is the (maximum) width of the part. Supposing it is possible to obtain such projection (which usually is not the case, as a projection exactly fitting the detector is difficult to obtain), then the same projection is digitized into n pixels, n being the number of pixels of the detector. Each pixel covers then a

$$R_{max} = \frac{l}{M_{max}} \quad (2)$$

portion of the object (l is the pixel width). This R_{max} value, which can be easily shown to be equal to $R_{max} = \frac{d}{n}$, is approximately equal to the minimum voxel size that can be obtained by the considered XCT scanner. As the voxel size influences the resolution of the XCT scan, when designing a part, one should consider that the maximum resolution that can be obtained when scanning it is inversely proportional to its size. Scanning large parts at high resolution is still impossible.

2.6. Avoid the use of multiple materials

One of the typical application of XCT is the analysis of multi-material objects. As different material are characterized by different X-Ray absorption, after the reconstruction it is possible to distinguish them, allowing the verification of assemblies, the observation of the structure of composites, or the investigation of the homogeneity of concretes. Additive manufacturing shares this suitability for multi-material parts, as with some technologies different materials can be deposited simultaneously.

But the presence of multiple materials creates additional difficulties for geometric verification. Due to the different X-Ray absorption, the different materials require different thresholds for the correct segmentation from the background, and the separation of the two materials from each other requires a further threshold. In the case the X-Ray abortions of the materials are almost identical, defining a boundary in the XCT scans is very difficult and prone to an incorrect choice of the threshold. As such, a more careful segmentation is required, and automatic methods can fail in perform the correct segmentation [16].

Scanning materials of very different X-Ray abortion generates different problems. In this case, finding parameter which can lead to a perfect scan of both materials is difficult (Fig. 7). This leads to severe beam hardening artifacts when one concentrates on the softer material, or makes the latter almost "transparent" if one concentrates on the denser material. In the case the denser material forms only small inclusions, then a "metal" artifact [8] is generated, too. These problems can be reduced with the use of the monochromatic X-Rays generated by a synchrotron, but the adoptions of synchrotrons is not feasible in industry.

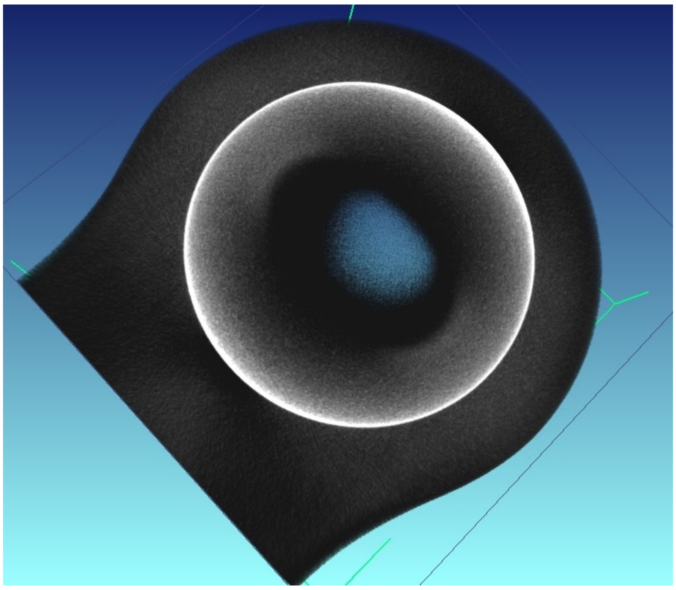

Fig. 7. XCT scan of an aluminum rod with a brass bearing. The section highlights the lack of contrast, in particular in the bearing, and a serious beam hardening artifact at the boundary between the aluminum and the brass.

3. Conclusions

XCT is spreading as technique for geometric inspection, and this is mainly due to its flexibility when facing complex parts. However, even if complex parts can be easily scanned, this does not mean that the result is always optimal. Choosing the correct scan parameters is of course fundamental to obtain optimal scans. But there are parts which are intrinsically difficult, or even impossible, to scan with very high accuracy.

In this paper a series of indications have been given regarding which are the characteristic of a part to avoid to obtain geometries which can be easily inspected by XCT. In most cases, the suggestions regard the total size of parts: middle-sized parts are usually easier to scan than small and large parts. The other crucial factor is the presence of voids inside the part. This reduces the total thickness of material that has to be crossed by the X-Rays. It is worth noting that often the presence of voids is considered a problem in the measurement by means of conventional measuring systems.

The proposed indications could also be translated into constraints for topological optimization software.

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References

[1] Ascione, R., Moroni, G., Petrò, S., Romano, D., 2011. Adaptive inspection of free-form surfaces in coordinate metrology, in: Proceedings of the ASPE 2011 Spring Topical Meeting - Structured and Freeform Surfaces, American Society for Precision Engineering, Charlotte, NC. pp. 49–55.

[2] Boas, F., Fleischmann, D., 2012. CT artifacts: Causes and reduction techniques. Imaging in Medicine 4, 229–240. doi:10.2217/iim.12.13.

[3] Carmignato, S., Dewulf, W., Leach, R., 2017. Industrial X-ray computed tomography. 1 ed., Springer International Publishing, Cham, Switzerland. doi:10.1007/978-3-319-59573-3.

[4] Colosimo, B.M., Senin, N. (Eds.), 2011. Geometric Tolerances - Impact on Product Design, Quality Inspection and Statistical Process Monitoring. Springer-Verlag, London, UK. doi:10.1007/978-1-84996-311-4.

[5] De Chiffre, L., Carmignato, S., Kruth, J.P., Schmitt, R., Weckenmann, A., 2014. Industrial applications of computed tomography. CIRP Annals - Manufacturing Technology 63, 655–677. doi:10.1016/j.cirp.2014.05.011.

[6] He, G., Huang, X., Ma, W., Sang, Y., Yu, G., 2017. Cad-based measurement planning strategy of complex surface for five axes on machine verification. International Journal of Advanced Manufacturing Technology 91, 2101–2111. doi:10.1007/s00170-016-9932-2.

[7] He, G.Y., Jia, H.Y., Guo, L.Z., Liu, P.P., 2012. Adaptive sampling strategy for free-form surface based on cad model. Advances in Materials Research 542, 541–544. doi:10.4028/www.scientific.net/AMR.542-543.541.

[8] Hsieh, J., 2009. Computed Tomography. 2 ed., SPIE Digital Library, Bellingham, Washington. doi:10.1117/3.817303.

[9] International Organization for Standardization, 2000. ISO 10360-1: Geometrical Product Specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) - Part 1: Vocabulary.

[10] Kruth, J., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L., Weckenmann, A., 2011. Computed tomography for dimensional metrology. CIRP Annals - Manufacturing Technology 60, 821–842. doi:10.1016/j.cirp.2011.05.006.

[11] Moroni, G., Petrò, S., 2018. Geometric Inspection Planning as a Key Element in Industry 4.0, in: Lecture Notes in Mechanical Engineering. Springer International Publishing, pp. 293–310. doi:10.1007/978-3-319-89563-5_21.

[12] Moroni, G., Petrò, S., 2018. Segmentation-free geometrical verification of additively manufactured components by x-ray computed tomography. CIRP Annals - Manufacturing Technology 67, 519–522. doi:10.1016/j.cirp.2018.04.011.

[13] Moroni, G., Petrò, S., Polini, W., 2017. Geometrical product specification and verification in additive manufacturing. CIRP Annals - Manufacturing Technology 66, 157–160. doi:10.1016/j.cirp.2017.04.043.

[14] Morse, E., Dantan, J.Y., Anwer, N., Söderberg, R., Moroni, G., Qureshi, A., Jiang, X., Mathieu, L., 2018. Tolerancing: Managing uncertainty from conceptual design to final product. CIRP Annals 67, 695–717. doi:10.1016/j.cirp.2018.05.009.

[15] Obeidat, S., Raman, S., 2009. An intelligent sampling method for inspecting free-form surfaces. The International Journal of Advanced Manufacturing Technology 40, 1125–1136. doi:10.1007/s00170-008-1427-3.

[16] Borges de Oliveira, F., Stolfi, A., Bartscher, M., De Chiffre, L., Neuschaefer-Rube, U., 2016. Experimental investigation of surface determination process on multi-material components for dimensional computed tomography. Case Studies in Nondestructive Testing and Evaluation 6, 93–103. doi:10.1016/j.csndt.2016.04.003.

[17] Poniatowska, M., 2012. Deviation model based method of planning accuracy inspection of free-form surfaces using cmms. Measurement 45, 927 – 937. doi:10.1016/j.measurement.2012.01.051.

[18] Rajamohan, G., Shunmugam, M.S., Samuel, G.L., 2011. Effect of probe size and measurement strategies on assessment of freeform profile deviations using coordinate measuring machine. Measurement 44, 832 – 841. doi:10.1016/j.measurement.2011.01.020.

[19] Savio, E., De Chiffre, L., Schmitt, R., 2007. Metrology of freeform shaped parts. CIRP Annals - Manufacturing Technology 56, 810 – 835. doi:10.1016/j.cirp.2007.10.008.

[20] Sigmund, O., Maute, K., 2013. Topology optimization approaches: A comparative review. Structural and Multidisciplinary Optimization 48, 1031–1055. doi:10.1007/s00158-013-0978-6.

[21] Stojadinovic, S., Majstorovic, V., Durakbasa, N., Sibalija, T., 2016. Towards an intelligent approach for cmm inspection planning of prismatic parts. Measurement 92, 326–339. doi:10.1016/j.measurement.2016.06.037.

[22] Thompson, M., Moroni, G., Vaneker, T., Fadel, G., Campbell, R., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., Martina, F., 2016. Design for additive manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals - Manufacturing Technology 65, 737–760. doi:10.1016/j.cirp.2016.05.004.

[23] Yu, M., Zhang, Y., Li, Y., Zhang, D., 2012. Adaptive sampling method for inspection planning on cmm for free-form surfaces. The International Journal of Advanced Manufacturing Technology , 1–9doi:10.1007/s00170-012-4623-0.

[24] Zhang, X., Zhang, H., He, X., Xu, M., Jiang, X., 2013. Chebyshev fitting of complex surfaces for precision metrology. Measurement: Journal of the International Measurement Confederation 46, 3720–3724. doi:10.1016/j.measurement.2013.04.017.