Joint Special Interest Group meeting between euspen and ASPE
Dimensional Accuracy and Surface Finish in Additive Manufacturing,
KU Leuven, BE, October 2017
www.euspen.eu

Metrological design of calibration and benchmarking artefacts for an additive manufacturing system

Vicente M. Rivas Santos[1], Danny Sims-Waterhouse[1], Samanta Piano[1], Ian Maskery[2], Richard K. Leach[1], Manolis Papastavrou[3], Adam Ellis[3] and Peter Woolliams[4]

[1]Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, UK
[2]Centre for Additive Manufacturing, Faculty of Engineering, University of Nottingham, UK
[3]Xaar plc, Nottingham, UK
[4]National Physical Laboratory, Teddington, UK

Vicente.RivasSantos@nottingham.ac.uk

Abstract
Quality control of additively manufactured (AM) parts can include the measurement of freeform surfaces, cellular structures, cavities and internal features, which challenge the capabilities of current measurement technologies. The complexity of some AM parts can make the measurements time-consuming, difficult, or even impossible to perform non-destructively. In this paper, we propose designs of calibration and benchmarking artefacts with the aim of facilitating their measurement, therefore promoting the concept of "Design for Metrology". Two artefacts were designed for a newly developed powder bed fusion AM system using high-speed sintering (HSS) technology: a benchmarking artefact for quality testing and a calibration artefact for machine calibration and adjustment. The design process takes into account the instruments used to measure the artefacts. In particular, the measurement principles of a contact coordinate measuring machine (CMM), a vision CMM system and a photogrammetry setup are considered, in order to achieve optimised designs that facilitate the measurement process. The benchmarking artefact is used to test the limits of the HSS system, such as its ability to produce different surface forms and textures, while the calibration artefact allows the testing of the accuracy and precision of the AM system, compared to the nominal values supplied by the CAD model.

Metrology, Design for Metrology, Benchmarking, Dimensional measurements.

1. Introduction

Quality control of AM parts includes measurements of freeform geometries, lattice structures, cavities and internal features which challenge the currently available measurement systems [1]. Measurements can be expensive, time-consuming, difficult or damaging to the part being measured. To overcome some of these limitations, new measurement systems are being developed at the University of Nottingham using, for example, structured light techniques [2] and X-ray computed tomography [3]. In addition to new measurement systems, we are exploiting the AM design freedom to help overcome some of the measurement challenges. Our aim is to produce a new methodology to facilitate quality control: "Design for Metrology".

The role of Design for Metrology is to ensure that the characteristics, limitations and standard procedures of the available measurement systems are taken into account at an early design stage. In this paper we present case studies for Design for Metrology as proofs of concept, the final objective is to produce a series of methodologies and guidelines for the AM design process. Another reason for focusing this new methodology on AM is the low volume and high customisation of the parts produced, in contrast with the large-scale production of traditional manufacturing techniques. The unique nature of each part makes it difficult to adapt the measurement process.

In this paper, we apply Design for Metrology to the development of calibration and benchmarking artefacts for a newly-developed AM process: high-speed sintering (HSS) [4]. Since the early stages of AM development, users have required reference designs to test a system's performance. Several test parts for benchmarking, calibration and monitoring control have been developed [5], but none have been established as industrial standards. This lack of standardisation demonstrates the potential for improvements on the proposed designs.

2. Design methodology

We present the design of two artefacts for the calibration and benchmarking of an AM system. The design methodology proceeded in several steps.

As a first step, a design requirements document was created in order to outline the functions of the AM product. The characteristics of the manufacturing process are then introduced. This is necessary, as despite the design freedom of AM processes, every process presents a unique set of characteristics (build volume limit, need to generate support structures, build direction considerations, minimum feature resolution, etc.) [6] that limit the design and need to be taken into account.

Moreover, we also study and analyse the characteristics of the measurement systems that will be used to measure the final part. In particular, in this project, we will consider a contact coordinate measuring machine (CMM), a vision-based CMM and a photogrammetry system. Each measuring instrument has a specified working range and a known precision. For this reason, it is important to choose the most appropriate measuring instrument in order to improve the accuracy of the measurements and reduce the uncertainty. On the other hand, the designer has to ensure that the part characteristics are compatible with the instrument.

There are also other factors that can be considered for the design process, i.e. size, cost, material, fabrication time, number of parts to be produced, mass, etc. [7] .

2.1. Design requirements

For this work, our final goal was to produce artefacts that will be able to test the capabilities of the high-speed sintering (HSS) system. HSS is a powder bed fusion process in which a polymer is sintered using an infra-red lamp. A layer of powder is spread over the building area, then an inkjet printhead is used to jet ink composed of a radiation absorbent material (RAM) in areas determined by the CAD file. Once the ink is deposited, the infrared lamp provides the energy to sinter the areas with the RAM ink (see Figure 1). The powder bed is then lowered for a new layer of unsintered powder to be spread on top. The powder bed is kept just below sintering temperature throughout the process.

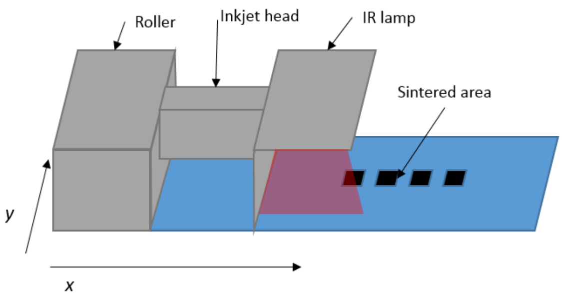

Figure 1. Diagrammatic representation of the HSS system.

Our first aim is to assess the accuracy of the system to sinter material at the required position and potentially obtain information for HSS system recalibration in case of deviations. In this case, accuracy is the closeness of agreement between the printed part and the CAD model. Accuracy in the horizontal (*xy*) plane is affected by the ink deposition, which is related to the precision of the inkjet head movement, speed control, jetting frequency and ink absorption by the powder bed.

A flat area with several markers can be used as a feature to identify the accuracy of the machine in the horizontal plane. The accuracy in the *y* direction is expected to be better than in the *x* direction because the distance between ink droplets only depends on the distance between nozzles, rather than the head movement and the jetting frequency. Moreover, because the thermal lamp is aligned parallel to the *y* axis, no thermal gradient is present in this direction. The thermal gradient in the *x* axis can cause thermal stress as the material cools and contracts, resulting in material deformations.

The height accuracy, or accuracy in the *z* direction, is more difficult to assess, due to the layer thickness and residual stress from the layer bonding. The design needs to assure that the points to be measured are not located between layers, because this would add an uncertainty of the size of the layer. With the points to be measured exactly on the surface of a layer, the accuracy only depends on the displacement of the building volume in the *z* direction and the layer bonding.

The other design requirement needs to assess the capabilities of the process and relate them to different parameters (e.g. speed, layer thickness, temperature). For this, knowledge of how well the machine is able to produce basic geometric forms is required; some of them as pass/fail tests and others as quality assessments of the printing.

A pass/fail test can be used to understand the minimum feature size that the machine is able to produce. This test consists in printing a number of features with decreasing size, until the HSS system is no longer able to produce them. These features are meant to deliver a qualitative and not quantitative result; if they are successfully printed, then the machine has passed the test. This can be assessed without the need of measurements. An example of this kind of pass/fail test would be a set of walls or slots with reducing thickness. Therefore, in order to test the minimum feature size, a decreasing feature with a sharp end can be included. Examples of this decreasing features are a taper, a decreasing radius end of a cone, or a wall ending on a sharp edge. These features allow understanding of the behaviour of the HSS system when reproducing small sharp features and the minimum resolution that can be achieved.

Another test to assess the performance of the HSS system is a flatness test, in which the deviation of an extracted surface is compared against a fitted plane. The layer-by-layer process of AM results in a staircase effect that alters the surface of the part. The texture of AM parts is known to be complex and can present overhangs, voids or un-sintered particles [8]. To analyse these features, the artefact needs to have a flat surface over which measurements can be taken. As the texture can change with the manufacturing angle, several surfaces with different build angles should also be included.

A roundness test evaluates a circular profile made by the HSS system against a reference profile provided by the CAD (nominal profile). The absorption of the ink by the powder bed and the drop spacing will affect the ability of the HSS system to create a perfect circle. If we are testing roundness in a vertical plane, it will be also be affected by layer bonding and thickness which results in a staircase effect [9]. To analyse the roundness, we need to add cylindrical features with axes on the horizontal and vertical planes. The analysis of the cylindrical features should also provide information on the ability of the HSS system to produce spheres and its behaviour with changing slopes.

The artefacts were required to fit in the building volume of the HSS system (145 mm × 65 mm × 75 mm) and have the shortest manufacturing time. The material used to fabricate the artefacts was PA12 and no cost limit was assigned to the parts. The artefacts would require to be scalable to be used in larger HSS systems.

2.2. Design restrictions: the available measurement systems

The available measurement systems are a Mitutoyo Quick Vision system located at Xaar, which is equipped with a contact and an optical CMM sensors, and a photogrammetry setup at the University of Nottingham (see [10] for details).

For the contact CMM, the main geometric limitations are a result of the probe requiring access in the *z* axis. Access from the *y* or *x* directions is not possible with this system, due the lack of a star probe. In order to make lateral measurements, the artefacts need to be rotated. Another limitation is the size and the length of the probe: if there is a step with a depth larger than the probe length, the probe mount may collide with the artefact. The CMM vision system has a working distance of 30 mm, a field of view of 2.5 mm and can provide three types of illumination: upper, lower and ring illumination. For a better understanding of the correct procedure to conduct dimensional measurement with these systems, two National Physical Laboratory (NPL) good practice guides were used [11,12].

Photogrammetry is based on the triangulation of common points between three or more images and is able to provide form measurements with expanded uncertainties of around 20 µm [10] (compared to the CMM, which has an estimated maximum permissible error of less than 10 µm). The level of surface roughness found on samples produced by the HSS system is particularly suitable for the photogrammetry system, as correspondences between images can be easily found. Although the reconstruction process can be time consuming, the fast acquisition time and dense point clouds produced by the photogrammetry system provide an ideal measurement procedure for the artefact. Due to the nature of the measurement procedure, photogrammetry methods are also significantly less limited by artefact geometry than contact probes. The only geometry prerequisite for the photogrammetry system is that the regions of interest not be occluded in the field of view.

3. Artefact design and measurement plan

After several iterations, designs for a calibration and a benchmarking artefacts were produced.

The calibration artefact (figure 2a) consists of a semi-random distribution of columns in which their top surfaces form part of a virtual sphere. The centre of each column is designed to coincide with a specific powder layer. Measurements can be made with the three measurement systems and through a least-squares method, a virtual spheroid with the following equation can be fitted to the data:

$$\alpha(x-x_0)^2+\beta(y-y_0)^2+\gamma(z-z_0)^2=R^2 \qquad (1)$$

where x, y and z are the coordinates of the spheroid surface; x_0, y_0 and z_0 are the coordinates for the centre of the spheroid; α, β and γ are the coefficients of the spheroid axes; and R is the spheroid radius. The study of this spheroid provided information about the distortion of the sintering mechanism through the build volume. The spheroid can also be compared with the CAD model to test whether the dimensions of the printed artefact match the nominal values. A model of the artefact was printed with a selective laser sintering printer and preliminary measurements were performed. A point cloud was obtained using the photogrammetry setup and compared with the CAD model, showing height dependant distortions on the z axis (Figure 2b). The measured results and the nominal CAD values are shown in table 1 with 95% confidence bounds. The adjusted correlation coefficient was 0.9997 and α = 1.013, β = 1.015 and γ = 0.9771.

Table 1. Results of the photogrammetry measurements.

	Measured spheroid/mm	Nominal sphere/mm
x_0	49.92 ± 0.01	50
y_0	50.03 ± 0.01	50
z_0	-60.00 ± 0.17	-60
R	99.06 ± 0.01	100

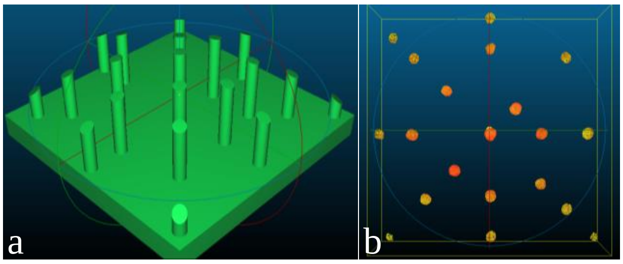

Figure 2. a) CAD model of the calibration artefact. b) Point cloud obtained from the top surface. The red points are higher than the nominal sphere while the yellow points are lower than the nominal sphere.

The benchmarking artefact is a cube with spheres in each corner (Figure 3). The sphere centres define a reference plane. This cubic design allows the rotation of the sample in order to take measurements with the available instruments. The repetition of the sphere configuration in each of the faces allows for a fast measurement with the programmable CMM. Several faces with different features are provided: a minimum feature test with walls and slots, holes, cylinders, sharp edges, surfaces with different angles, solid faces and empty faces, so the manufacturer can select the features that are of interest and they can be added to each artefact.

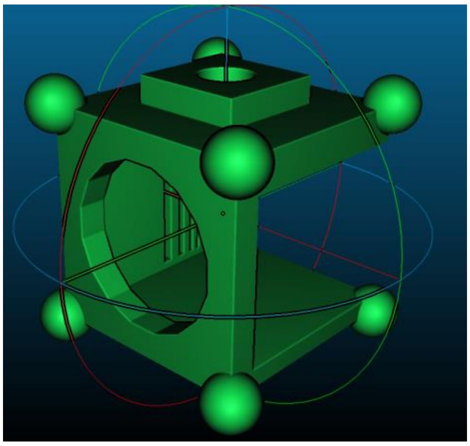

Figure 3. CAD model of the benchmarking artefact.

4. Summary, conclusions and future work

In this paper, we introduced the concept of Design for Metrology, which provides a new vision to help the measurement of complex AM parts. The design concept has been applied to two case studies in order to provide reference artefacts for calibration and benchmarking of a new AM system. An analysis of the required functions for the part was carried out and the limitations of the measurement systems were considered to set the design guidelines.

Future work includes detailed measurements of the printed artefacts, in order to investigate the ability of the proposed design to provide the required information about the HSS system. A set of guidelines and a methodology for Design for Metrology will also be developed to provide a generic approach that can be applied to an arbitrary AM system.

Acknowledgements

The Nottingham authors would like thank EPSRC (Grants EP/M008983/1 and EP/L01534X/1), NPL and Xaar for funding this work.

References

[1] Thompson M K, Moroni G, Vaneker T, Fadel G, Campbell R I, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B and Martina F 2016 Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints *CIRP Annals* **65** 737–60

[2] Stavroulakis P I, Chen S, Sims-Waterhouse D, Piano S, Southon N, Bointon P and Leach R 2017 Combined use of a priori data for fast system self-calibration of a non-rigid multi-camera fringe projection system *Modeling Aspects in Optical Metrology VI* (Munich: SPIE)

[3] Thompson A, Maskery I and Leach R K 2016 X-ray computed tomography for additive manufacturing: a review *Meas. Sci. Technol.* **27** 72001–18

[4] Ellis A, Noble C J and Hopkinson N 2014 High Speed Sintering:

Assessing the influence of print density on microstructure and mechanical properties of nylon parts *Addit. Manuf.* **1**–**4** 48–51
[5] Moylan S, Slotwinski J, Cooke A, Jurrens K and Donmez M A 2014 An additive manufacturing test artifact *J. Res.NIST* **119** 429–59
[6] Gibson I, Rosen D W and Stucker B 2010 *Additive Manufacturing Technologies* (Boston, MA: Springer US)
[7] Corbett J, Dooner M, Meleka J and Christopher Pym 1991 *Design for manufacture: strategies, principles and techniques* (Wokingham, England: Addison-Wesley)
[8] Townsend A, Senin N, Blunt L, Leach R K and Taylor J S 2016 Surface texture metrology for metal additive manufacturing: a review *Precis. Eng.* **46** 34–47
[9] Paul B K and Baskaran S 1996 Issues in fabricating manufacturing tooling using powder-based additive freeform fabrication *J. Mater. Process. Technol.* **61** 168–72
[10] Sims-Waterhouse D, Piano S and Leach R 2017 Verification of micro-scale photogrammetry for smooth three-dimensional object measurement *Meas. Sci. Technol.* **28** 055010–6
[11] Flack D 2001 CMM Measurement Strategies *Good Practice Guide* (National Physical Laboratory)
[12] Rodger G 2001 Dimensional Measurement using Vision Systems *Good Practice Guide* (National Physical Laboratory)