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A Preliminary Investigation on Surface Roughness Assessment of Complex Additive Manufactured Parts Scanned by X-ray Computed Tomography

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Abstract

The additive manufacturing (AM) technologies bring in a number of benefits over traditional subtractive manufacturing technologies. However as-built surface finish of AM produced components is often not satisfactory and usually needs further post-process. Surface roughness is vitally important to the product's functional performance. However, the measurement and characterization of the complex functional AM surfaces is difficult due to their complicated shape or intricate internal geometries. XCT is current the only valid method that can measure complete internal and external geometry without constraints of traditional tactile and optical techniques. Nonetheless, XCT measurement posts two obstacles to standard roughness characterisation: the measured surface form and the non-uniform sampled measurement data structure. Aiming for a holistic and reliable roughness assessment, it is proposed to use the linear diffusion equation to achieve a Gaussian filtering effect on complex surfaces and to extend the roughness areal parameters on a triangular mesh.

Keywords: surface roughness, computed tomography, additive manufacturing, diffusion filtering, triangular mesh

1 Introduction

By building products through the selective addition of materials in layers directly from digital model, AM processes have the potential to produce highly complex, customisable and multifunctional parts at lower material and energy costs and with lower environment pollution than conventional (subtractive) manufacturing techniques. Despite a number of significant benefits of AM, many technical limitations still hinder its full version [1-3]. One major issue is that AM processes are not robust enough, which consequently brings various shortcomings that are commonly seen in AM products, such as poor as-built surface finish, low quality and large variance between components. These issues lead to the awareness that AM requires measurement methods to control its process as well as verify its product quality.

The complexities of AM geometry and surface topography have caused many problems to conventional geometrical metrology techniques, including both tactile and optical measurement. Tactile measurement suffers from the high asperity of AM surfaces due to the probe mechanical filtering effect. Optical measurement is restricted by multiple reflections because of the high local slope angles of AM surface topography. Moreover, both optical and tactile techniques are not able to measure some of the more complex AM geometries, whose intricate forms do not permit line-of-sight. In contrast, X-ray computed tomography (XCT) can measure both internal and external surfaces of such objects. However, the systematic errors, when employing XCT as a dimensional measurement technique, are not fully understood and its application in surface texture measurement is still in its infancy. Although XCT has a limitation on surface texture measurement due to limited resolution and a number of uncertainties, it might be qualified for that of most of the additive processed surfaces (usually at the roughness level of ten of micrometres).

It is planned to investigate the use of XCT to assess the surface texture of AM produced components. The proposed research work is composed of two parts. The first part is to explore the capability of XCT on measuring surface texture. The scanning resolution, surface determination, data decimation as well as other factors that are associated with XCT measurement system are the main concerns. The second part is surface texture characterisation using XCT measurement data. The measurement data generated by XCT is not straightforward applicable to the standard characterisation techniques, e.g. filtration and parameterisation. This paper mainly deals with the second part.

2 Roughness characterisation strategies for XCT measurement

The XCT measurement relies on the object's material absorption of high-energy radiation. An X-ray source emits radiation, passing through the object under measurement and captured by an X-ray detector. A sequence of projection is generated from rotating either the X-ray source or the measurement object, resulting in a sequence of 2D greyscale image slices. Thereafter the 3D volumetric data is reconstructed as a cube of 3D voxels, each of which is associated with a grayscale value indicating the amount of radiation absorption. To perform the dimensional measurements of geometrical quantities, those voxels representing the surface of the measured object is extracted out from the volumetric data. It is done by setting a global thresholding on voxel grayscale values, e.g. ISO 50% or using more advanced local adaptive methods to distinguish between the object materials and the air. Finally, these surface voxels in form of point cloud are usually converted into a polygonal surface (normally triangular mesh), better representing the geometry of the measured object [4, 5].

XCT can measure the whole geometry of the part and its measurement data is in the format of point cloud or triangular mesh, both derived from the reconstructed volumetric data. However, one of barriers that hinder XCT from being useful for surface texture assessment is that XCT generated measurement data structures for the object geometry, are not straightforward compatible with the standard surface texture characterisation, which requires uniform sampled grid data structure and also requires measured surface is basically planar [6]. The comparison and analysis of different measurement data structures are given in Table 1.

	Pros	Cons
Grid data (Uniform sampling)	- Default data structure for surface texture evaluation. All surface texture analysis software can deal with it. - The connection of measured points is well defined. - A special case of polygon mesh (4 connection).	- Not straightforward available from XCT. - They are specified by heights over the sampling plane, e.g. $z = f(x, y)$. Not suitable for surfaces with complex geometry.
Triangular mesh	- More general data structure. Specified by (x, y, z) and point connections. Suitable for surfaces with complex geometry. - Available from XCT. - The connections of measured points are well defined.	- No commercial surface texture analysis software support triangular mesh. - Not clear how triangular mesh is generated from point cloud by XCT software.
Point cloud	Directly available from XCT and most "reliable".	- Raw data structure. Purely discrete points specified by (x, y, z) without point connection. - Have to estimate where the surface is. - Surface texture analysis software does not support point cloud.

Table 1. Comparison of different measurement data structures.

A straightforward solution is to convert the XCT measurement data into the one that can cope with the traditional surface characterisation methods. To enable that, two issues should be well managed. First, the surface portion of interest needs to be taken out from the XCT measurement data. The extracted portion should be planar or nearly planar to avoid any possible distortion caused by the surface form. Second, the point cloud needs to be interpolated into a regular sampled grid structure. Thereafter conventional surface analysis techniques are applicable to this kind of converted data. The following example illustrates the conversion procedure. Figure 1a presents a portion of planar surface that is taken out from the XCT scanned data of a selective laser melting (SLM) produced component. An orthogonal least square plane is fitted to level the point cloud (see Figure 1b and 1c). Then the cubic interpolation is applied to generate a uniform sampled grid data structure so that it can be handled by the common filtration techniques (see Figure 1d). Figure 2a shows the resulting reference surface generated by the Gaussian filtering (λ_{cx} and λ_{cy} both 0.8 mm) and the corresponding roughness surface is presented in Figure 2b. The roughness parameters S_a and S_q are 20.7 μm and 31.6 μm respectively.

The above strategy is a fast and easy way and is feasible in some cases. However, it cannot give a holistic assessment of the surface roughness of the component since it takes only a small portion of the whole geometry. To achieve more comprehensive and reliable assessment, the same procedure will have to be repeated over a number of different locations on the part's surface. In comparison, another strategy is investigated aiming for a holistic, consistent and reliable roughness assessment of complex functional AM components, e.g. the 3D scaffold/lattice structures which play a vital role in tissue engineering. In this strategy, the whole surface information generated from the XCT scanning can be taken into roughness assessment if necessary. The filtration is applied on the triangular mesh data and finished in one turn. To achieve these goals, the aforementioned technical barriers arise from the traditional roughness characterisation, i.e. complex surface form and triangular mesh data structure, have to be addressed. On one hand, directly applying the Gaussian filter without taking into the consideration the surface form will induce serious distortions. On the other hand, if the surface texture were to be projected to a planar grid, the flattening process will cause compression of surface and will result in smaller implied distances between neighbouring points than their actual geodesic distance on the surface. Both effects will yield an inaccurate characterization of surface roughness.

It is proposed to use the linear diffusion equation to achieve a Gaussian filtering effect on the surfaces with complex geometry and to extend areal surface texture parameters on a triangular mesh. Both two techniques will need to extract the surface texture aforehand. This can be done by comparing the XCT measured surface with the original CAD model (STL file) of the AM part. Then the 'residual' after alignment will be regarded as surface texture, which resides over the triangular mesh.
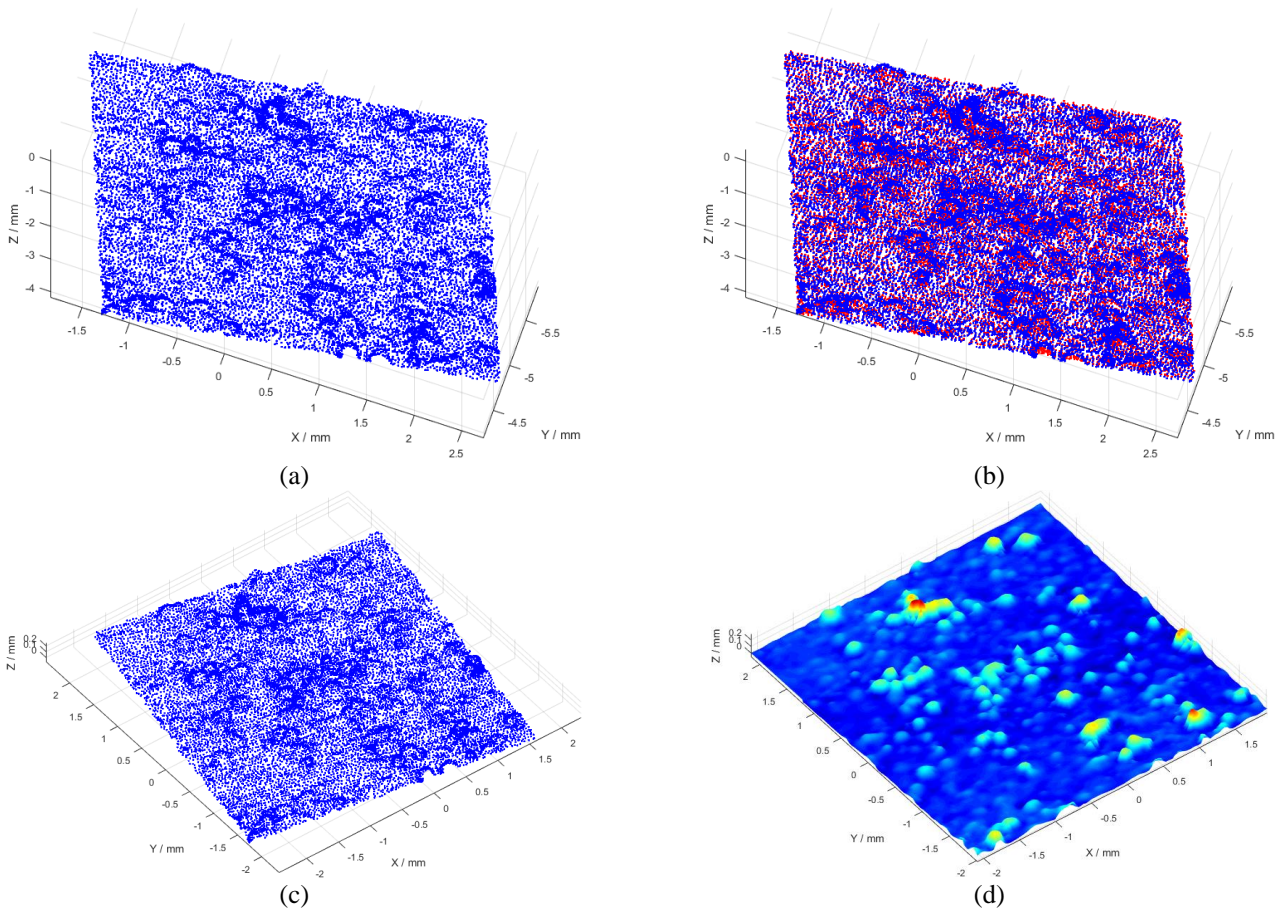
Figure 1. Point cloud interpolated into uniform sampled grid: (a) Point cloud extracted out from XCT measurement data; (b) Orthogonal least square plane fitting; (c) Levelled point cloud; (d) Surface in grid structured generated by cubic interpolation.
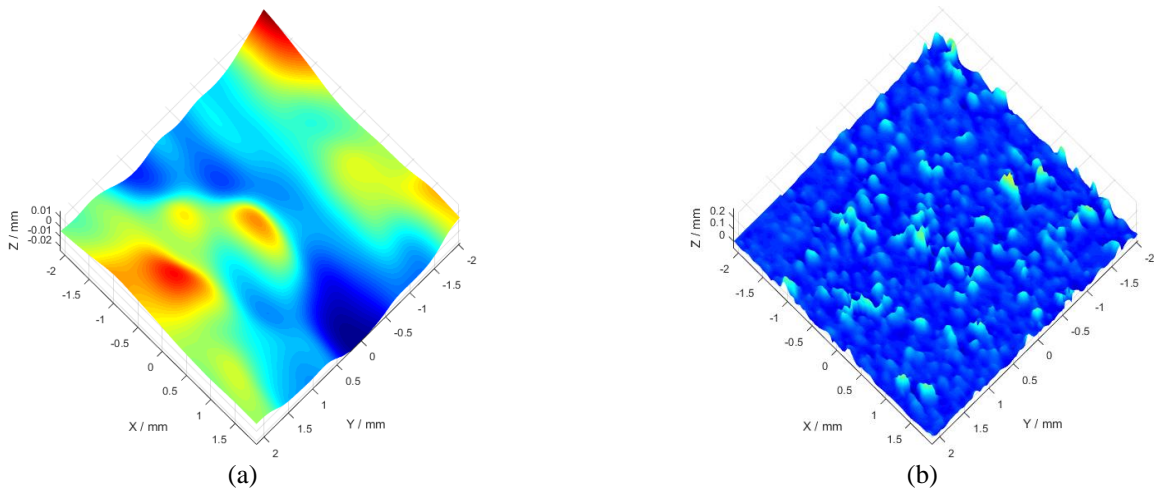

Figure 2. Gaussian filtering: (a) Reference surface; (d) Roughness surface.

3 Linear diffusion equation based Gaussian filtration

The Gaussian filter is the standard method to separate the roughness component from the surface texture in a planar surface [7]. In actual, it is the convolution of the measured data f with the Gaussian function g, i.e. $f * g$. In the areal case g is

given by $g(x,y) = \dfrac{1}{\alpha^2 \lambda_c^2} \exp\left[-\dfrac{\pi}{\alpha^2}\left(\dfrac{x^2+y^2}{\lambda_c^2}\right)\right]$ with λ_c being the cut-off wavelength for the roughness filtration. It is valid for Euclidean geometries, however no longer immediately applicable on geometries that are non-Euclidean; otherwise serious distortion occurs.

Aiming for a distortion-free Gaussian filtering on complex surfaces, the linear diffusion equation can be involved, which is given by:

$$\frac{\partial f(p,t)}{\partial t} - \Delta f(p,t) = 0 \tag{1}$$

where

$f(p,t)$ indicates the position of a particular point in space at a specific time,

Δ is the Laplacian operator defined on a continuous function in Euclidean space.

A link exists between the linear diffusion process and the Gaussian filtering process. Suppose $f(p,0)$ is the initial status of p, i.e. $t=0$. Then after the t time, the diffused p will be at the location $f(p,t)$, which can be solved by Equation (1). Its solution can be given by a continuous convolution of the function $f(p,0)$ with a Gaussian function g of standard deviation $\sigma = \sqrt{2t}$ [8]. The relationship between the time parameter t to the diffusion process and the cutoff wavelength λ_c to the standard Gaussian filter is $\lambda_c = \pi\sigma\sqrt{\dfrac{2}{\ln 2}} \approx 5.336\sigma = 7.546\sqrt{t}$ or $t \approx 0.0176\lambda_c^2$.

The discrete implementation of diffusion filtration can use the Laplace-Beltrami operator, which extends the Laplace operator from the functions defined in Euclidean space to the functions defined on surfaces. One approximate solution of Equation (1) in discrete case is given by the following iteration system [9]:

$$f(p,t) = (I - \delta t \Delta) f(p,t+\delta t) \tag{2}$$

where

δt is the time increment for each iteration.

Δ is the Laplacian weighting matrix with the size n by n (n indicates the number of vertices of triangular mesh).

Δ is a sparse matrix, only having non-zeros values at the vertices and edges [10]:

$$\Delta_{ij} = \begin{cases} \displaystyle\sum_{l \in N(i)} \frac{1}{2A_M(p_i)}(\cot \alpha_{il} + \cot \beta_{il}) & i = j \\[2ex] -\dfrac{1}{2A_M(p_i)}(\cot \alpha_{ij} + \cot \beta_{ij}) & i \in N(i), j \in N(i) \\[2ex] 0 & i \notin N(j) \end{cases} \tag{3}$$

where

$A_M(p_i)$ is the neighorhood area defined by the mixed Voronoi cell, which is formed by connecting the Voronoi centres. In case a Voronoi centre is outside the triangle face, it will be replaced by the middle point of the edge opposing the centre vertex p_i. See Figure 2.

α_{ij} and β_{ij} are the two angles opposing the edge $p_i p_j$ of two triangles that share the edge $p_i p_j$.
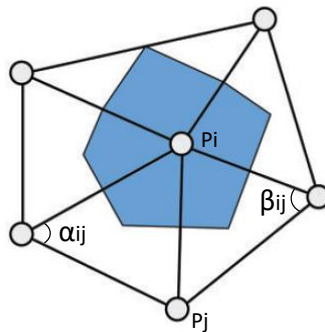

Figure 2. Calculation of the Laplacian weighting matrix.

4 Roughness parameterisation for triangle mesh data structure

Moving from uniform sampled grid case to 3D triangular mesh case requires the extension of surface parameters to fit the new data structure. A pioneering work on extending surface height parameters have been proposed to fit the 3D triangular mesh case [11]. In the case of uniform sampled data, the roughness parameter S_a is defined as the arithmetic mean of the absolute value of surface heights; S_q on the other hand is the root mean square value of surface heights. The formal definitions of S_a and S_q are given by ISO 25178-2 [12]:

$$S_a = \frac{1}{A} \iint_A |z(x, y)| dxdy, \tag{4}$$

$$S_q = \sqrt{\frac{1}{A} \iint_A z^2(x, y) dxdy} \tag{5}$$

Their dicrete implementations can use the follow formulae:

$$S_a = \frac{1}{nx \cdot ny} \sum_{i=1}^{nx} \sum_{j=1}^{ny} |z_{i,j}|, \tag{6}$$

$$S_q = \sqrt{\frac{1}{nx \cdot ny} \sum_{i=1}^{nx} \sum_{j=1}^{ny} z_{i,j}^2} \tag{7}$$

where nx and ny are the number of points in X and Y direction in the sampling plane respectively.

Note that the area of each individual squares (pixels) in the discrete formulae is omitted in Equation (6) and (7) because it is always the same and therefore it will be cancelled out. However for the case of 3D triangular meshes, each individual face of the mesh has a different area than the others and therefore these areas cannot be cancelled out and should be taken into the consideration. For example, S_a in the case of triangular mesh can be perceived as calculating the total sum of all volumes between the surface and residuals, and then dividing that total volume by the total area of the surface [11]. It is given by:

$$S_a = \frac{\sum_{t \in \Omega} \left(A(t) \cdot \sum_{k=1}^{3} \frac{|z_{t,k}|}{3} \right)}{\sum_{t \in \Omega} A(t)}, \tag{8}$$

where

$A(t)$ is the area of the triangle t in the parametric domain Ω;

$z_{t,k}$ is the residual value of the vertex k in the triangle t;

$\sum_{k=1}^{3} \frac{|z_{t,k}|}{3}$ is the mean value of the surface residual (texture) for the three vertices of the triangle t.

The S_q parameter can be extended similarly: the root mean square value of the surface heights in the normal direction within the whole parametric domain.

$$S_q = \sqrt{\frac{\sum_{t \in \Omega} \left(A(t) \cdot \sum_{k=1}^{3} \left(\frac{z_{t,k}^2}{3} \right) \right)}{\sum_{t \in \Omega} A(t)}}, \tag{9}$$

5 Simulation example

A computer simulation is made to initially verify the proposed diffusion filtration technique and parameterisation methods. The simulated data is composed by an enclosed spherical ball (triangular mesh with 2306 vertices and 4608 faces) to represent the reference form of the component, the sinusoidal waves to represent the waviness and the random noise to act as the roughness.

See Figure 3a for the simulated data. Then the diffusion filter with the diffusion time 1.126s (equivalent to the Gaussian cutoff wavelength 8 mm) is applied to obtain the reference surface. Figure 3b evidently shows that the random noise ('roughness') is efficiently suppressed and the resulting surface is basically the combination of the spherical form and the sinusoidal waves ('waviness'). Further increasing the diffusion time will gradually smooth the sinusoidal waves.

The roughness component is obtained by comparing the filtered surface to the original surface. The height residuals are calculated in the normal direction at each vertex, i.e. each vertex on the triangular mesh will be associated with a roughness height value. These numbers are shown as a colormap on the filtered surface (See Figure 4). The commonly used roughness parameters S_a and S_q are solved using Equation 8 and 9. They are 25.4 µm and 31.7 µm respectively.

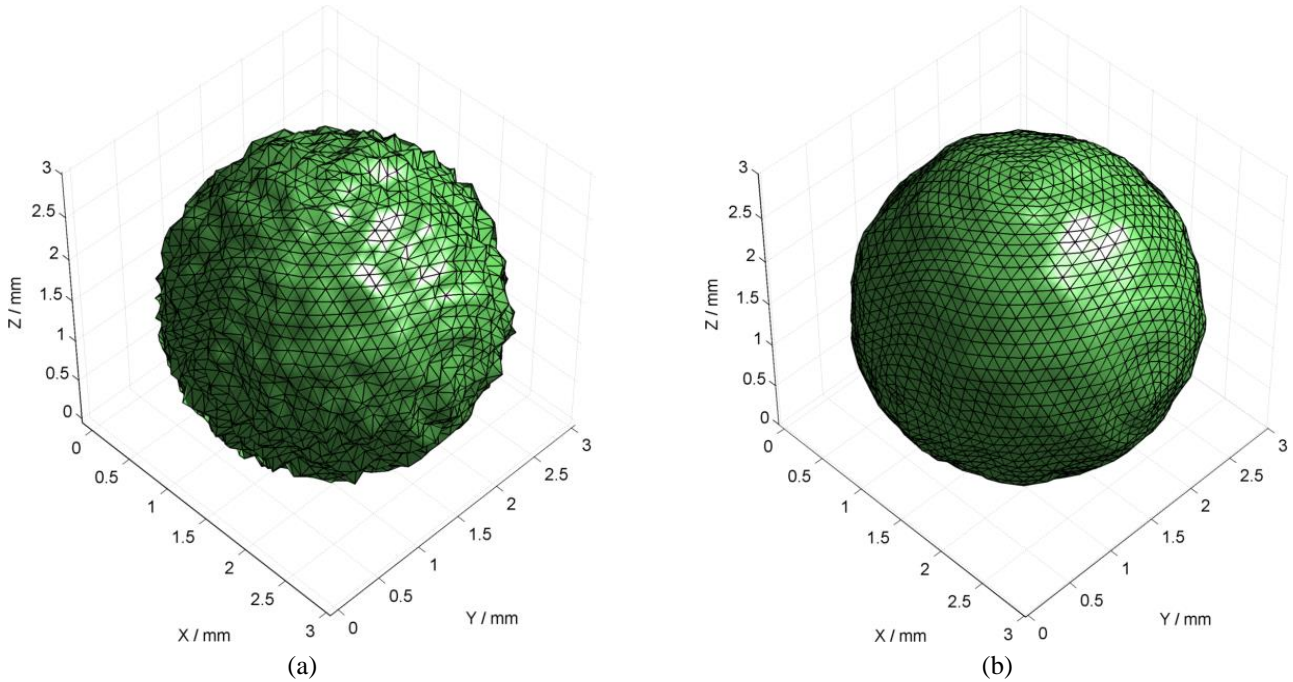(a)   (b)

Figure 3. The diffusion filtration of a simulated spherical ball: (a) The original simulated surface; (b) The filtered surface.
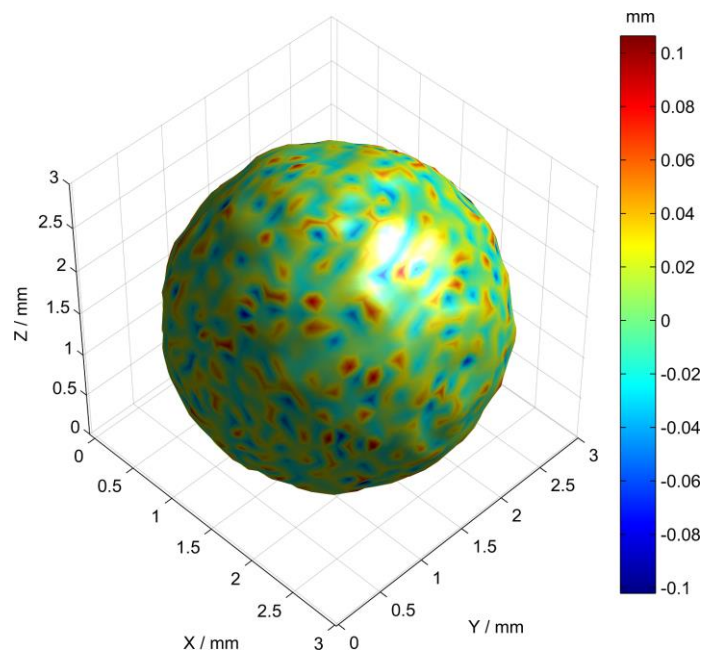

Figure 4. The roughness shown as the colormap on the filtered surface.

6 Conclusion and future work

XCT has the capability to measure AM products with complex internal and external geometries, but posts the obstacles to traditional surface roughness characterisation methods, i.e. the measured surface form and the triangular mesh measurement data structure. Based on the link between the Gaussian cutoff wavelength and the diffusion time, the linear diffusion equation is used to achieve a Gaussian filtering effect on complex surfaces. The roughness height parameters defined on the uniform sampled grid structure are extended to triangular mesh. With these two enhancements, it is possible to have a holistic and reliable surface roughness assessment of complex functional AM products.

Further work includes full implementation and verification of the proposal methods as well as experiments on measuring and characterising complex functional AM parts.

Acknowledgements

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