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

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Abstract
Additive manufacturing technologies have many advantages over conventional subtractive counterparts. X-CT is currently the unique way to measure both the internal and external geometries of complex AM products, which is not possible using either the tactile or optical measurement methods. However one of the barriers that restrict X-CT usage from being useful for surface texture assessment is that X-CT generated data structure is not compatiable with the standard procedures of roughness characterization which requires uniform sampled data and also takes the prerequite that measured surface is basically planar. It is proposed to use the Gaussian filter based on the linear diffusion equation to achieve the ability for a distortion free filtration on non-Euclidean surfaces as well as the compability with X-CT generated triangular mesh measurement data. The widely used roughness parameters, such as Sa and Sq, are also extended for the same purpose.

Keywords: X-CT metrology, surface roughness, additive manufacturing, triangular mesh

1 Background

The development of additive manufacturing (AM) technologies, moving from a prototype and pilot technology into a mature manufacturing, have the potential to change the paradigm for manufacturing [1]. 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 [2]. Despite of a number of significant benefits of AM, many technical limitations hinder its full version from being realized today [3]. Chief among these is increasing the precision of 3D manufacturing. AM production machines lack sufficient process control to ensure parts stay within the design tolerance [4]. Inherit to the AM process itself, the produced surfaces of AM parts tend to be very rough, showing significant defect features. Higher quality product requires improvement to AM processes, including methods for improving as-built surface finish.
While offering the benefit of building very complex geometry structures that conventional manufacturing methods cannot do, the complexities of AM geometry and surface topography have caused many problems to existing geometrical metrology techniques, including both tacile 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 internal structures of complex AM parts are inaccessible using both tactile and optical sensors.
In recent years X-CT metrology becomes more popular as a promising geometrical measurement technique. In comparison to tactile and optical metrology techniques, X-CT has the unique advantage: it is a non-destructive method which can measure the complete internal and external geometry without constraint. Although X-CT has a limitation on surface texture measurement due to limited resolution and also suffers from a number of uncertainties, it might be qualified for that of most of additive processed surfaces (usually at the roughness level of ten of micrometers). However one of barriers that hinder X-CT from being useful for surface texture assessment is that X-CT generated data structures for the object surface, point cloud or triangular mesh, are not straightforward compatiable with the standard surface roughness characterization, which requires uniform sampled data and also takes the prerequite that measured surface is basically planar [5]. To enable that, point cloud needs to be interpolated into grid structure, or surface analysis techniques enhanced to support triangular mesh. Grid interpolation is a faster and easier way but its usage can be limited to simple geometries (Euclidean). The point connection of triangular mesh can better determine the surface especially in the case of complex geometry (non-Euclidean), e.g. the AM fabricated 3D scaffold/lattice structures which play a vital role in tissue engineering [6]. The later method is more capable but challenging, because both traditional filtration methods and roughness parameterization are no longer valid.
Prelimary research has been carried out by the authors for the facilitation of the second strategy, i.e. filtration and parameterization on the X-CT generated triangle mesh data for surface roughness assessment of complex AM surfaces.

2 Proposed surface roughness assessment for X-CT measurement

2.1 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. Actually it is a convolution of the measured data with the Gaussian function, which in the areal case is given by

$s(x,y)=\frac{1}{\alpha^2\lambda_c^2}\exp\left[-\frac{\pi}{\alpha^2}\left(\frac{x^2+y^2}{\lambda_c^2}\right)\right]$ with λ_c being the cut-off wavelength for the roughness component. 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 using of the Gaussian filter on complex surfaces, the linear diffusion equation $\frac{\partial f}{\partial t}-\Delta f=0$ can be involved, where the position of a particular point in space and time is decribed by f. Its solution at time t is given by a contionous convolution of the function $g(x,y)$ with a Gaussian function of standard deviation $\sigma=\sqrt{2t}$ [7]. The relationship between the time parameter t of the diffusion process and the cutoff wavelength of the standard Gaussian filter can be drived as: $\lambda_c=\pi\sigma\sqrt{2/\ln 2}\approx 5.336\sigma=7.546\sqrt{t}$ or $t\approx 0.0176\lambda_c^2$. The discrete implementation of diffusion filtering can use the Laplace-Beltrami operator, which is compatiable with triangle meshes.

2.2 Roughness parameterization extension

The traditional roughness parameters are defined on the uniform sampled measurement data. For example, S_a is defined as the arithmetic mean of the absolute value of surface heights; S_q is defined as the root mean square value of surface heights. Their dicrete implementations are given by:

$S_a=\frac{1}{nx\cdot ny}\sum_{i=1}^{nx}\sum_{j=1}^{ny}\left|z_{i,j}\right|$ and $S_q=\sqrt{\frac{1}{nx\cdot ny}\sum_{i=1}^{nx}\sum_{j=1}^{ny}z_{i,j}^2}$, where nx and ny are the number of points in X and Y direction in the sampling plane respectively.

S_a can be understood as calculating the total sum of all volumes between the surface and residues, and then dividing that total volume by the total area of the surface [8]. In the case of triangular mesh, it can be extended as $S_a=\frac{\sum_{t\in\Omega}\left(A(t)\cdot\sum_{k=1}^{3}\left(\frac{\left|z_{t,k}\right|}{3}\right)\right)}{\sum_{t\in\Omega}A(t)}$ and similarly S_q extended as $S_q=\sqrt{\frac{\sum_{t\in\Omega}\left(A(t)\cdot\sum_{k=1}^{3}\left(\frac{z_{t,k}^2}{3}\right)\right)}{\sum_{t\in\Omega}A(t)}}$, 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 ; $\sum_{k=1}^{3}\left(\left|z_{t,k}\right|/3\right)$ is the mean value of the surface residues (texture) for the three vertices of the triangle t .

3 Summary

X-CT provides the capability to measure AM products with complex internal and external geometries. A prelimary research is presented on using the diffusion equation based Gaussian filter and also the extended roughness parameterization for achieving the compatablity of X-CT to surface texture measurement. Further work includes full implementation, verification of the proposal methods as well as experiments on measuring and charactersing real AM lattice structures.

References

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