Contributed Papers from Materials Science and Technology 2018 (MS&T18)
October 14–18, 2018, Greater Columbus Convention Center, Columbus, Ohio, USA

DOI 10.7449/2018/MST_2018_149_156

Characterizing Surface Defects in Additively Manufactured Components Using Smart-Phone Imaging

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Abstract

Surface defects can be extremely detrimental to performance of fabricated components due to strain concentrations that are known to shorten life due to wear, fatigue, and corrosion. Unfortunately, surface defects are challenging to characterize due to their small size and require advanced equipment such as white-light interferometers. This is not a viable approach when high throughput is of the essence. The present work shows a novel methodology of characterizing surface defects. The method relies on optical imaging of components and characterizing gradients in surface velocities that result from topographical undulations. These gradients naturally arise due to foreshortening, i.e. parallax and can also be artificially introduced to amplify visibility of surface gradients by rigid body rotation. The present work attempts to calibrate these effects using scalable smart-phone imaging as well as advanced optical imaging. Applications on additively manufactured materials are shown. Analytically obtained process limitations are discussed.

Keywords: Smart-Phone, Imaging, Geometry, Topography

Introduction

Topography and roughness of surfaces play important roles in governing the mechanical and functional response of engineered components. These component features can be tuned to endow enhanced bio-compatibility [1], tribological properties, e.g. friction [2] and wear [3], and hydro-phobicity [4], among others. However, poorly controlled surface topography on fabricated components can compromise tolerances, and thereby require subsequent post-processing and finishing. In fatigue limiting components, uncontrolled roughness can result in premature and unpredicted fatigue crack growth and failure. Unfortunately, quantification of surface topography is a challenging task. This requires creation of a specimen that will fit inside, or be compatible with the instrument that is used for measuring topography. While this can be trivial in small to medium sized simple part geometries featuring flat faces, challenges associated with characterization of topography are amplified when part geometries are complex, or too large. In fact, creation of specimens in such cases can often be only done sacrificially. Such challenges dominate additively manufactured components.

Additive manufacturing (AM) has emerged as an extremely important process for creating arbitrarily complex geometries. The process involves building parts in a layer-by-layer fashion. This provides AM with unmatched capabilities for fabricating large and complicated machine components, e.g. impellers. Unfortunately, the physics underlying AM naturally promotes formation of uncontrolled topographical roughness [5]. Hence, there is a need for trustworthy and scalable methodologies for characterization of surface roughness topographies. If available, such tools could be used for on-line monitoring as well as in-situ post-mortem inspection.

The objective of this article is to present the proof of concept of two such methodologies. These methodologies rely on optical imaging. For the present study, this is performed using standard smart-phone cameras, as well as more sophisticated optical systems. It will be seen that nature of the optics used and characteristics of the surface directly govern the fidelity and resolution of characterization. Some limitations of the proposed approaches are also described in subsequent sections.

Kinematically characterizing topography and roughness

The first approach towards characterization of surface roughness is motivated from kinematics of rigidly rotating bodies. This concept is illustrated in Fig. 1a that shows a component rotating at an angular speed ω. Naturally, a component feature at a distance r from the axis of rotation will feature a surface speed:

$$V = r\omega \tag{1}$$

It can be deduced from this kinematic relation that a pit on the surface featuring a hight δh will feature a smaller speed:

$$V' = V - \delta V = (r - \delta h)\omega \tag{2}$$

Characterization of surface topography features using this concept therefore relies on charac-

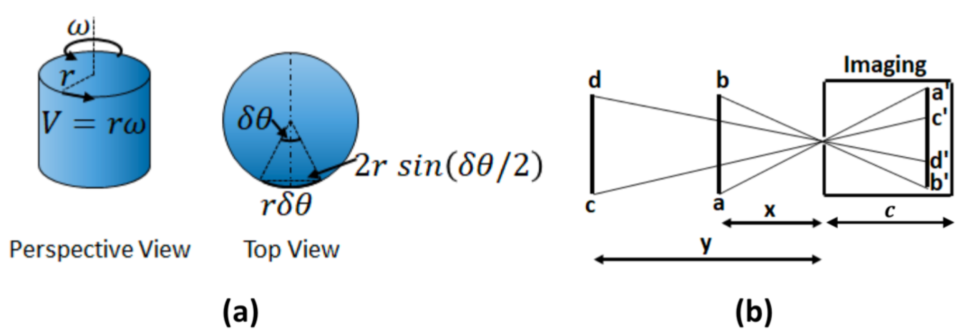

Figure 1: (a) Kinematic characterization of topography and roughness (b) Foreshortening resulting from parallax

terization of surface speeds and calibrating them with respect to resolution of the optical system. Towards this, it is noted that the displacement vector caused by rotational motion features an out-of-plane component, which cannot be characterized by a 2D imaging camera. Errors in characterized speeds were corrected to account for the same by realizing that the normalized error $\frac{\delta V_{error}}{V}$ amounts to:

$$\frac{\delta V_{error}}{V} = \frac{2(\delta\theta/2 - \sin(\delta\theta/2))}{\delta\theta} \tag{3}$$

This equation prescribes that the real speed is given by:

$$V_{real} = V + \delta V = V + V\frac{2(\delta\theta/2 - \sin(\delta\theta/2))}{\delta\theta} \tag{4}$$

Here, it is assumed that $\delta\theta$, i.e. the rotation angle across a given time step is known a-priori, i.e.

$$\delta\theta = \omega\delta t \tag{5}$$

The real speed is thereafter converted to the real radius of the component feature using the kinematic relation:

$$r_{real} = \frac{V_{real}}{\delta\theta} \tag{6}$$

By compiling radii traces as a function of rotational position, geometry, and surface topography are characterized. This geometry is subsequently corrected for parallax induced foreshortening.

Foreshortening by parallax is an optical effect due to which, dimensions at greater distances are perceived to be smaller. Figure 1b illustrates foreshortening due to parallax, wherein, two equally sized objects ab, and cd, are projecting images $a'b'$, and $c'd'$ in an imaging system. It is evident that dimensions of these images depend on distances of the corresponding objects from the imaging system. For instance, object ab at distance x from the imaging system projects image $a'b'$ whose dimensions $d_{a'b'}$ are larger than dimensions of image $c'd'$, i.e. $d_{a'b'} > d_{c'd'}$ as distance of object cd, y is smaller than that of object ab, i.e. $x < y$. This phenomenon results in an apparent slow-down of perceived speeds of objects in motion at large distances. In this manner, this effect can significantly distort characterized surfaces speeds, and therefore the shape and topography that are characterized using rigid body rotational kinematics.

Correction for foreshortening by parallax is complicated by the fact that real dimensions as well as geometry of the object of interest are a-priori unknown in most circumstances. This can be mitigated by assuming that the resolution of the camera $N(d)$ varies slowly with respect to increasing distance d. This is true during imaging of most geometries featuring modest aspect ratios. With this assumption, it is realized that the resolution of the camera system can be specified as:

$$N(d) = \frac{V_d}{V_{d_p}} \tag{7}$$

Here V_d is the real surface speed of the component feature at real distance d units from the optical system and V_{d_p} is the pixel surface speed of the component feature at pixel distance d_p units from the optical system. With a change in axis, the aforementioned equation can be rewritten as:

$$N(d_A - r) = \frac{V_r}{V_{r_p}} \tag{8}$$

Here $V_r,\ V_{r_p}$ are surface speeds in real and pixel units of the component feature at real r and pixel r_p radii from the axis of rotation, respectively. Further d_A is the distance between axis of rotation and the optical system used. As stated above, the real shape of the component is unknown. Therefore by our assumption of constant resolution, we change this equation to:

$$N(d_A - N(d_A)V_{r_p}) = \frac{V_r}{V_{r_p}} \tag{9}$$

It will be seen that this correction provides exceptionally small errors.

Characterizing topography using parallax induced foreshortening

Characterization of the shape and topography of a component kinematically is clearly based on rotation motion and hence requires a rotational stage. While this can be a trivial requirement in many AM platforms that come equipped with a rotational stage, this may be unfeasible in several situations when such a stage is unavailable. Towards mitigation of this shortcoming, parallax induced foreshortening presents an opportunity for characterization of shapes and topographies as well. This methodology shares the principal underlying human depth perception, which involves simultaneous acquisition of two images of the same object from two different perspectives. By comparing these images and accounting for difference in their perspectives, the shape of the object is characterized.

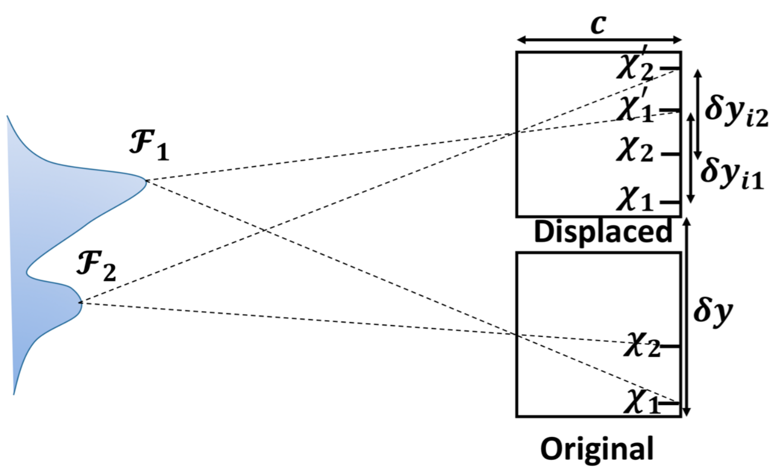

Figure 2: Pinhole model for predicting displacement in image due to displacement in object

To delineate this principal for digital characterization of component features, Fig. 2 schematically illustrates a scene comprising a component with two features $\mathcal{F}_1$ and $\mathcal{F}_2$ at distances x_1 and x_2, respectively, from a pinhole camera that is moving along the y direction. By the pinhole camera principal, a displacement δy of the camera results in a corresponding displacement of the image of feature $\mathcal{F}_1$ from location χ_1 in the original image to location $\chi_1^{'}$ on the image as given by:

$$\frac{\delta y_{i1}}{c} = \frac{\delta y}{x_1} \tag{10}$$

Here, $\delta y_{i1},\ c$ are recorded displacements of the image of feature $\mathcal{F}_1$ and the distance between imaging plane of the camera and its lens. Similarly, the corresponding displacement of the image of $\mathcal{F}_2$ from location χ_2 in the original image to location $\chi_2^{'}$ is given by:

$$\frac{\delta y_{i2}}{c} = \frac{\delta y}{x_2} \tag{11}$$

These relations then suggest:

$$\frac{\delta y_{i2}}{\delta y_{i1}} = \frac{x_1}{x_2} \tag{12}$$

In this relation, the ratio on the right hand side, i.e. $\frac{x_1}{x_2}$ signifies component feature aspect ratios. Hence, the LHS of this relation, i.e. $\frac{\delta y_{i2}}{\delta y_{i1}}$ can be used to characterize component geometries. This can be done by simply hovering the phone over the component features of interest and characterizing their digitally recorded motion. It is hypothesized that by sufficiently increasing the resolution of the optical system, e.g. by using a high magnification objective lens, fine topographical features on the component of interest can also be characterized. This hypothesis is tested, as described in the forthcoming sections.

Optical characterization of displacements using digital image correlation

A vital component towards characterization of shape and topography optically as described in sections and is the digital characterization of surface displacements. This was done using digital image correlation, which involves recording displacement in a series of images and subsequent characterization of the correlation function. The correlation function quantifies the correlation coefficient given by the formula [6]:

$$\gamma(x, y) = \frac{\Sigma_{u,v}\left[f(x+u, y+v) - \bar{f}_{x,y}\right]\left[t(u, v) - \bar{t}\right]}{\left(\Sigma_{u,v}\left[f(x+u, y+v) - \bar{f}_{x,y}\right]^2 \Sigma_{u,v}\left[t(u, v) - \bar{t}\right]^2\right)^{0.5}} \tag{13}$$

Here, high values of the correlation coefficient $\gamma(x, y)$ signify a good match between the original and final image at locations (u, v) and $(x+u, y+v)$, respectively. This implies that the point in the original image at location (u, v) has displaced to location $(x+u, y+v)$ in the final image, thereby suggesting a pixel displacement: $\delta s = \sqrt{u^2 + v^2}$ and a pixel velocity: $V_{r_p} = \frac{\delta s}{\delta t}$. For this work, a correlation template of size $T_x = T_y = 15$ pixel units was chosen. Further,

$$\bar{t} = \frac{\Sigma_{u=0,v=0}^{T_x,T_y} t(u, v)}{T_x T_y} \tag{14}$$

is the mean intensity of the template, and

$$\bar{f}_{x,y} = \frac{\Sigma_{u=0,v=0}^{T_x,T_y} f(x+u, y+v)}{T_x T_y} \tag{15}$$

is the mean intensity of the offset image. Normalization with respect to the standard deviations in the denominator ensures robustness with respect to arbitrary fluctuations in density. Additional details involving digital image correlation can be found in ref. [6].

Experimental Work

The rotational stage required for kinematic characterization of surface topography was fabricated using a simple gear assembly featuring a 72:1 reduction that was coupled to a stepper motor. This assembly was controlled using an arduino controller. Rotation was performed at 2 RPM. Imaging was performed using two optical systems. The first optical system involved a standard smart-phone camera that was equipped with a f/2.2 lens. Imaging was performed at full resolution, i.e. 1920x1080 pixles using this camera. The component was illuminated using ambient lighting. For imaging on the rotation stage, the camera was aligned vertically in a tripod using its inbuilt electronic gyroscope and accelerometer. Talcum powder was sprinkled on the specimens to enhance their imaged texture and accuracy of characterization using digital image correlation. Complementary experiments were performed using a manual rotation stage through a high resolution sophisticated optical system. The focus of these experiments was to detect topographical defects on the surface of AM components. Towards this, a polymer cylinder featuring a diameter of 50.8 mm was fabricated using fused deposition melting.

Characterization of geometry using parallax induced foreshortening was performed by recording displacement of component features in a video at 31 frames per second while hovering the smart-phone over it. A reasonable distance $\sim 40mm$ was maintained from the component center of mass. Errors in characterization resulting from fluctuations in angular orientation in camera or its distance from the component center of mass were ignored. Clearly, this is a simplistic approach to imaging for characterization of geometry and topography, which does not even require a tripod. This was implemented in the spirit of testing the limits this approach to characterization of geometry and topography. Both, arbitrary shapes and engineered AM components were imaged.

Results

Characterization of component geometry using rigid body rotational kinematics

Proof of concept investigations towards characterization of arbitrary shapes using kinematic rigid rotation relationships were performed using a standard smart-phone camera. A rotation stage was fabricated and arbitrarily shaped objects were placed on it. Their rotational motion of these objects was recorded in a video. Subsequently, images were extracted from this video from which, surface speeds were characterized, which were then processed as described in section . Figure 3 shows the results. It is evident this characterization process was able to capture component details such as surface curvature and defects. The accuracy of this characterization methodology was delineated by: (i) characterizing the dimensions of a cylindrical shape with known diameter, and (ii) performing laser based scanning using a Makerbot laser scanner and comparing point clouds obtained from the two methodologies to produce a absolute error field d_q. Results are shown in Fig. 3d and these exhibit a maximum, mean and standard deviation of $|d_q| = 4.85\ mm$, $\langle d_q \rangle = 0.89\ mm$, $\sqrt{d_q^2 - \langle d_q \rangle^2} = 0.43\ mm$, respectively.

Characterization of Surface Defects in Additively Manufactured Components

Results illustrated in the previous section suggest that if the resolution of the imaging system is sufficiently increased, the imaging methodology can become capable of characterizing surface topographical defects. To test this hypothesis, imaging was performed using a PCO SCMOS high speed camera that was equipped with a telescopic microscope with a maximum resolution of $1.4\mu m/pixel$. A cylindrical specimen was fabricated by fused deposition modeling (FDM). Characteristics of components produced by this process are strongly governed by process parameters. For instance, if the starting locations e.g. (x, y) coordinates of subsequent build layers are kept constant, a marginally raised vertical build direction defect results in the component. This is illustrated in Fig. 4a, wherein a closeup of this defect is shown. Theoretically, surface speed of the zone within this defect must exhibit a local maximum with respect to the surround-

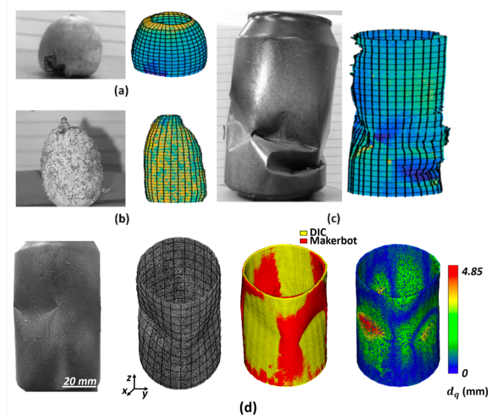

Figure 3: Kinematic characterization of surface geometry of arbitrary objects

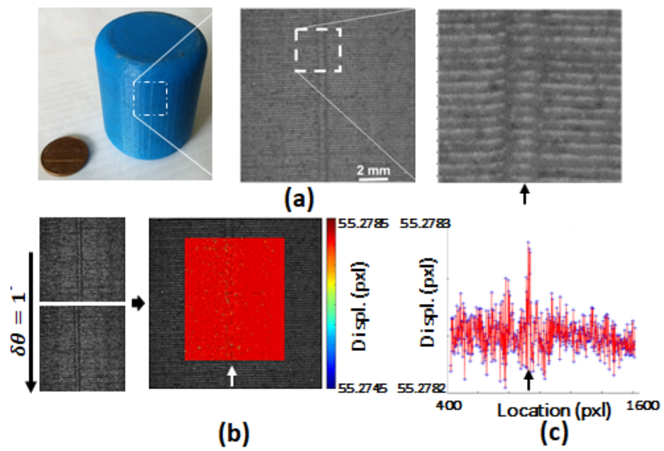

Figure 4: Characterization of surface defects using kinematics. (a) Surface defect on component fabricated by fused deposition modeling. (b) Surface displacement field obtained from rotaiton by $\delta\theta = 1^{\circ}$. (c) Mean surface displacement.

ing zones. Therefore, presence of this local minimum in the characterized surface speeds will provide a proof of concept with regards to ability of this methodology in capturing surface topographical defects. To test this, the cylindrical FDM component was rotated on our rotational stage. Characterized surface speeds near the defective zone indeed exhibit a local maximum, representative of the aforementioned defect, as shown in Figs. 4b, c.

Characterization of component geometry using parallax induced foreshortening

Foreshortening resulting from parallax was used to characterize geometry of an additively manufactured component. The component is shown in Fig. 5 and features six limbs that come together in the central zone. Towards characterization of this component geometry, the smartphone was hovered over it at a distance $\sim 40mm$. Simultaneously, a video was recorded. Frames from the video file were subsequently extracted using Matlab. Two adjacent frames were arbitrarily picked from this sequence. These frames are shown in Fig. xa and xb. Although these frames look identical, they feature subtle differences due to motion of the camera during imaging. These differences were characterized as described in section . Figure xc shows the result of this analysis, clearly exhibiting reconstruction of the component features.

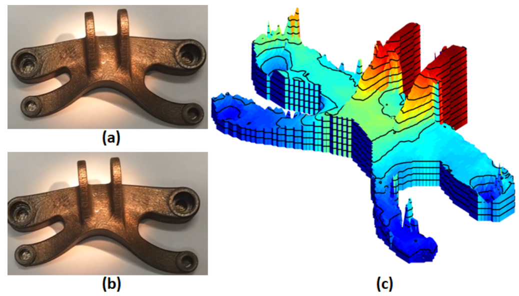

Figure 5: Characterization of geometry from foreshortening due to parallax

Conclusion

Proof of concepts of methodologies based on optical imaging were demonstrated for characterization of surface geometry and topographical defects using smart-phone as well as more sophisticated high resolution imaging. These methodologies were based on rigid body rotational kinematics and foreshortening induced parallax. It was shown that even minuscule surface defects can be characterized by sufficiently increasing resolution of the optical system.

Acknowledgements

The authors would like to acknowledge the support from faculty startup funds from The Harold and Inge Marcus Dept. of Industrial and Manufacturing Engineering at Penn State, Univ. Park, PA, USA. SB would like to acknowledge support from the College of Engineering Multidisciplinary Seed Grant program at PSU.

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