Single-shot areal profilometry: towards real-time surface quality control in additive manufacturing

Tobias V. REICHOLD[1a], Dr Pablo D. RUIZ[a] and Prof Jonathan M. HUNTLEY[a]
[a] *Loughborough University, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough, Leicestershire, LE11 3TU, UK*

Abstract: Hyperspectral Interferometry (HSI) is a recently-proposed technique for measuring 3-D point clouds from an opaque object in a single shot. We propose a new application of HSI enabling single-shot 3D surface measurements of optically rough surfaces commonly found on additively manufactured and machined components. Using an additively manufactured sample, single-shot surface profiles were taken at a fixed distance to capture and reconstruct the surface profile. This enables the single-shot measurements of rough surfaces over many independent channels in a short time.

Keywords. Rough surface quality control, Single-shot, Hyperspectral interferometry, Dimensional metrology

1. Introduction

Over the past few years, additive manufacturing (AM) has developed into an increasingly useful technology which enables the production of complex-shaped components that could never be made by conventional subtractive machining. For heavy duty applications, metallic printing using selective laser melting (SLM) and electron beam melting (EBM) has grown more popular. Regardless of the printing method, a prime concern is the surface roughness, dimensions and quality of the finished part. Achieving an even/smooth surface from an AM process is difficult due to the inherent layering of the base material. Factors such as layer thickness, local surface slope, material used and particle size and distribution (for SLM and EBM) are primary factors that determine the surface roughness and the inclusion of defects in the main body of the structure [1].

A common non-contact inspection method is focus-variation microscopy where the object or apparatus is moved along the optical axis and focus variation is evaluated. All depth slices are then combined to build up a 3D height map [1]. Imaged regions are evaluated on for example and root mean square surface roughness, S_a and S_q.

---

[1] Corresponding Author. T.Reichold@lboro.ac.uk

Recent metrological developments are driving towards *in-situ* process analysis to capture potential material defects, surface roughness/quality and monitor laser-generated melt pool size, shape and intensity during printing. An example of in-situ process analysis is co-axial sensing as shown in figure 9 under section 3.2.1 in [2].

A new technique called single-shot areal profilometry using Hyperspectral Interferometry (HSI) has been developed for measuring 3-D point clouds from an opaque object [3]. From a single image, up to 100 independent points are sampled simultaneously giving the surface profile over the field of view with an accuracy of <0.5 µm and effective unambiguous depth range of up to 1300µm [4, 5]. The procedure to obtain a surface height map from the experimental data is described in [4].

2. Experimental setup and data acquisition

The optical system uses a modified micro optic array compared to the microlens array hyperspectral interferometry (MLA HSI) setup as shown in figure 1. It is separated into two major subsystems: a balanced Linnik interferometer and a hyperspectral imaging system.

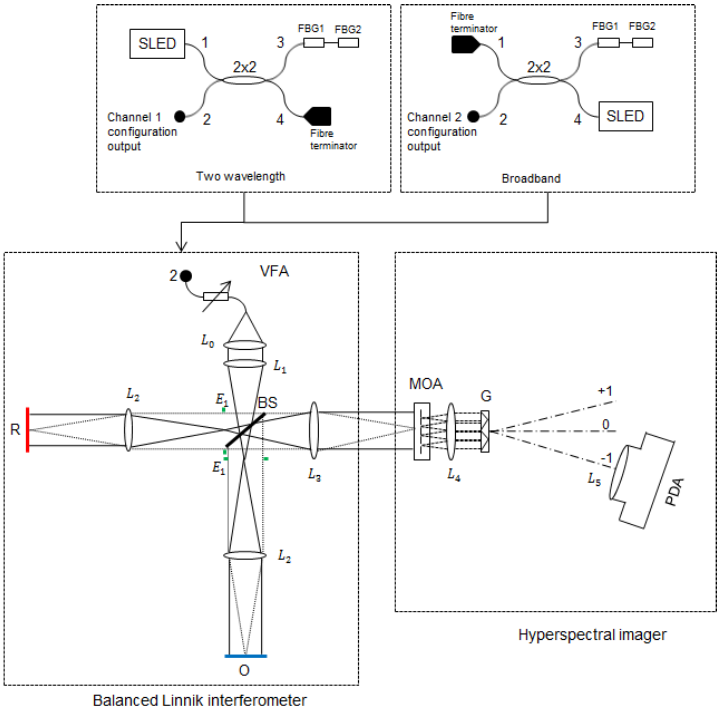

Fig. 1: Optical setup, showing: SLD: Super-luminescent light emitting diode; FBG$_1$, FBG$_2$: Fibre Bragg gratings; L0: collimator; BS: beam splitter; O: object; R: reference mirror; L$_0$, L$_1$, L$_2$, L$_3$, L$_4$and L$_5$: NIR achromatic lenses; E$_1$: aperture stop; MOA: micro-optics array; G: diffraction grating and PDA: photodetector array. At the top of the Linnik interferometer box, two alternative input illumination configurations ('two wavelength' and 'broadband') are shown.

The top left part of the figure shows the two wavelengths illumination configuration of the light source which is used for spectral calibration. The broadband illumination configuration is used for absolute height measurements. The lower diagram portion shows the interferometer and spectrometer subsystems.

Using a broadband superluminescent diode (SLED), the balanced Linnik-type interferometer forms a broadband interferogram which is spatially sampled by a micro optic array (MOA) in the hyperspectral imager. The resulting array of pupils is imaged with a doubly telecentric system formed by lenses L4 and L5 onto a large format PDA. The diffraction grating G diffracts the light coming from L4 to form a line spectrum of the light from each measured point onto the PDA [4].

An additively manufactured dimple-structured part, as shown in figure 2, was used as the sample. The component is printed from steel powder with size 20 by 20 mm. The red area on figure 2 indicates the region which was sampled by a 10×10 array of channels.

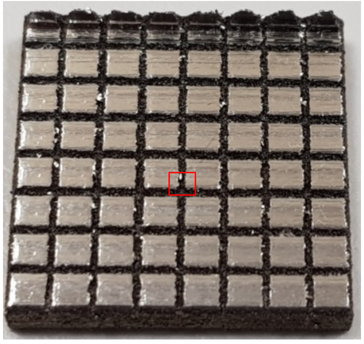

Fig. 2. Steel powder additively manufactured sample with protruding 8 by 8 square sections; red square shows area captured by HSI system.

3. Results

Figure 3 shows a portion of the interference signal measured by the system from the sample shown in Fig. 2. Each horizontal 1-D fringe pattern is the signal from a single channel from the HSI system. The spatial frequency of a given fringe pattern measures the distance from the interferometer to the corresponding point on the sample and thus contributes a single co-ordinate to the areal scan. The results show that HSI measurements on such samples are clearly possible, despite the rough surface (Sa approx. 3.62 μm).

All data was acquired in a single shot, the duration of which was ~1 s due to the weak source and weak reflection. The acquisition time could have been reduced to much lower values through the use of a higher power pulsed light source such as a pulsed supercontinuum laser.

The resulting single-shot surface profile of the additively manufactured dimple-structured part is shown in Fig. 4.

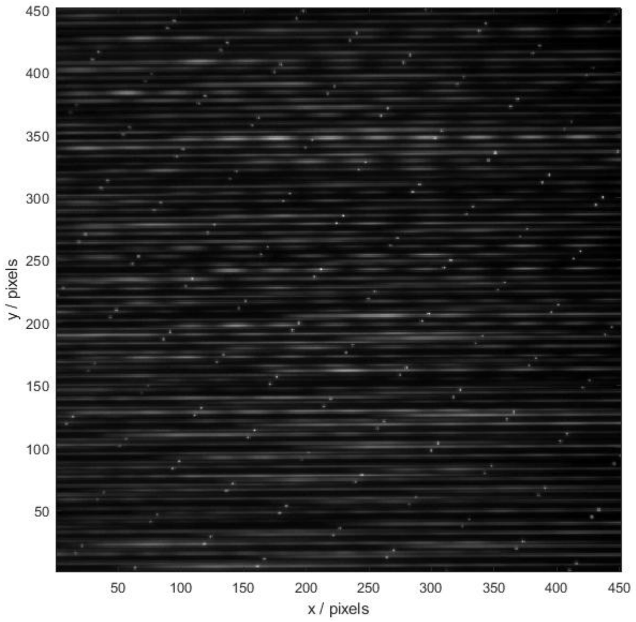

Fig. 3: Small 450 by 450 pixel region within the 16 megapixels image showing approximately 60 individual 1-D spectra encoding surface height.

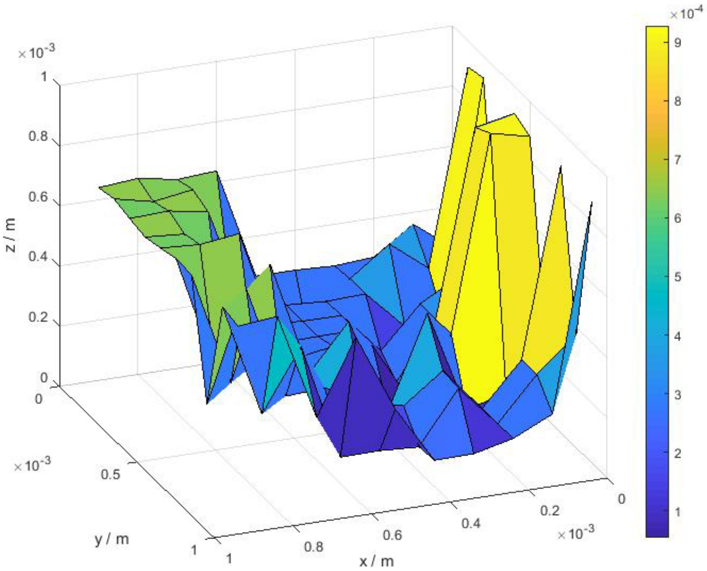

Fig. 4: Reconstructed surface height profile of AM component with colour bar (units: m).

The sampled region contains two edges of opposite dimples and a T-section of the valley separating the dimples as shown in figure 2 and 5. Despite the rough surface nature of the sample, no channels show loss of signal and all features are clearly visible on the reconstructed surface. Each HSI channel is an independent depth sensor, therefore the phase unwrapping errors that can occur on samples with height discontinuities when measured by single wavelength interferometers do not occur here, despite the steep side walls of the grooves on the top surface of the measured sample. The measured height difference from the dimples to the valleys is between ~341-609 µm which is consistent compared to a reference measurement on a focus variation Alicona Infinity focus instrument as shown in figure 5.

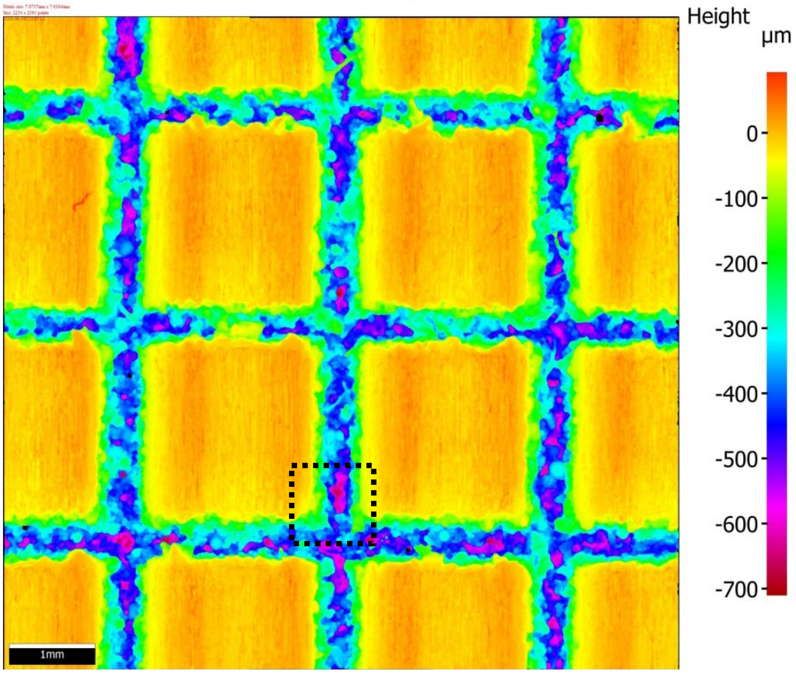

Fig. 5: Alicona Infinity focus reference image; black dotted grid denotes equivalent captured area by HSI system as shown in figure 2.

4. Conclusion

We have demonstrated single shot areal profilometry capabilities on additively manufactured components allowing the acquisition of 100 discrete surface points within a ~1s camera exposure. With a sufficiently short pulsed illumination source such as a supercontinuum laser and increased PDA, in excess of 10000 points can potentially be captured in ≤ 1 ms.

Acknowledgements

Tobias V. Reichold gratefully acknowledges support from the EPSRC Centre for Doctoral Training in Embedded Intelligence (EPSRC Reference: EP/L014998/1) and industrial partner Renishaw PLC.

References

1. Triantaphyllou, A., et al., *Surface texture measurement for additive manufacturing.* Surface Topography-Metrology and Properties, 2015. **3**(2).
2. Grasso, M. and B.M. Colosimo, *Process defects and in situ monitoring methods in metal powder bed fusion: a review.* Measurement Science and Technology, 2017. **28**(4): p. 044005.
3. Huntley, J.M., T. Widjanarko, and P.D. Ruiz, *Hyperspectral interferometry for single-shot absolute measurement of two-dimensional optical path distributions.* Measurement Science and Technology, 2010. **21**(7): p. 075304.
4. Ruiz, P.D. and J.M. Huntley, *Single-shot areal profilometry using hyperspectral interferometry with a microlens array.* Optics Express, 2017. **25**(8): p. 8801-8815.
5. Widjanarko, T., J.M. Huntley, and P.D. Ruiz, *Single-shot profilometry of rough surfaces using hyperspectral interferometry.* Optics Letters, 2012. **37**(3): p. 350-352.