Metrology for additive manufacturing

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What is today about?

• To inform the community about the research at Nottingham – including the results of recent reviews
• To highlight research at University of Huddersfield, NPL and MTC
• To get feedback on our approach
The fellowship

• EPSRC Manufacturing Fellowship
• March 2015 to March 2020
• Total of £1.5m funding + leverage (£4.2m)
• Supports fellow (60%), 2 research fellows, equipment and impact activities
• Faculty support for 1 research fellow (2 years), 1 lecturer, 7 PhD students
• Letters of support from 5 academics, 3 research institutes and 14 industrials
Partners - academic

- Loughborough University
- University of Huddersfield
- Aston University
- UNC Charlotte
Partners - industry

Nikon  TOYOTA  3T

RENISHAW  ZEEKO  Lein

BRUKER  alicona  Neuteq

ZEISS  LOXHÅM  Calon Cardio
Partners – national institutes

- National Physical Laboratory
- Science & Technology Facilities Council
- Manufacturing Technology Centre
- Central Laser Facility
Equipment and labs

- 2 main labs up and running (one temperature controlled), 1 lab being finalised, 1 lab due early 2016
- Alicona G5 focus variation microscope installed, Advanced Real3D ordered
- Nub3D fringe projection system installed
- Bruker Form & Texture (5 axis CSI) due February 2016
- Nikon XCT ordered for delivery February 2016
- HIT confocal microscope in proposal
- Also have access to stylus, chromatic confocal, 3 x CSI, CMM, micro-CMM, vision-CMMs, SEMs, AFM, dual-beam FIB
- Plus facilities in Nottingham Nanotechnology & Nanoscience Centre
- Full access to precision and additive machining facilities
Plans

• Develop the next-generation of techniques for measuring complex form of AM parts
• Develop techniques for measuring surface texture of AM parts and move towards a mapping of process variables to texture
• Develop x-ray computed tomography for the measurement of internal form and texture of AM parts
• Develop in-process/in-line techniques for dimensional and defect measurement (existing work = OCT, SRAS, fringe projection, plastic & metal)
• Develop a calibration and performance verification infrastructure for the techniques above, including uncertainty estimation
Early outputs


• Everton S K, Hirsch M, Stavroulakis P, Leach R K, Clare A T 2016 Review of in-situ process monitoring and in-situ metrology for additive manufacturing *Materials and Design* under review

• Thompson A, Maskery I, Leach R K 2016 X-ray computed tomography for additive manufacture: a review *Meas. Sci. Technol.* to be submitted by Christmas

• Townsend A, Senin N, Blunt L A, Leach R K, Taylor J 2016 Review of surface texture measurement for additive manufacturing, to be submitted by Christmas
How can you engage?

- Support PhD research (so far NPL, MTC, 3T RPD, Nikon, Bruker, RAL, Alicona)
- Support research fellows
- Supply equipment
- Allow access to equipment (metrology and manufacturing)
- Industrial internships, including KTPs
- Feedback metrology requirements
- Provide case studies (especially components to be measured or in-line scenarios)
- Get involved in the research (especially towards joint publications)
10:00-10:20  Arrival and coffee
10:20-10:30  Introduction and purpose of the meeting (*Richard Leach*)
10:30-11:00  The UK Strategy for AM (*Phil Dickens*)
11:00-11:30  Introduction to AM metrology at Nottingham (*Richard Leach*)
11:30-12:00  Co-ordinate metrology for AM (*Petros Stavroulakis*)
12:00-13:00  Lunch
13:00-13:30  Surface texture measurement for AM (*Nicola Senin, Andrew Townsend*)
13:30-14:00  AM metrology at NPL (*Stephen Brown*)
14:00-14:30  Internal feature metrology for AM (*Adam Thompson*)
14:30-15:00  In-process metrology for AM (*Sarah Everton, Ben Dutton*)
15:00-15:20  Coffee break
15:20-15:40  Open forum
15:40-16:00  Tour of MTC AM and metrology facilities
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An apology...
Additive Manufacturing
Manufacturing – Phase 1
Manufacturing – Phase 3?
Why all the interest?

1. Enabler for **LOW VOLUME** production
2. Maximising **DESIGN COMPLEXITY**
   - Key enabler
3. Additional **FUNCTIONALITY**
   - Single and multi-material
4. Customisation and **PERSONALISTION**
5. **BUSINESS REORIENTATION**
   - new business models, **SUPPLY CHAINS, LOGISTICS**
6. Potential **ENVIRONMENTAL** benefit
   - Very application dependent
Metrology
With AM we can make some highly-complex components and even assemblies

But what about QUALITY?

So far, most people involved in AM have never heard of the word TOLERANCE

All mature production processes have suitable quality systems in place

Why should this be different for AM?
Why measure?

- To know whether a part is fit-for-purpose – tolerances and functionality
- To allow assembly of complex components
- To allow control of a manufacturing process
- To avoid unnecessary scrap material and redundant processing time - cost, environment
- To improve energy-efficiency
- To give “customers” confidence in a product
Metrology for Additive Manufacturing
Current metrology in manufacturing

- Contact co-ordinate measuring machines (CMMs)
  - Very common in modern manufacturing industry
  - Accurate but slow

- Optical co-ordinate measuring machines
  - Becoming more popular
  - Fast but inaccurate

- X-ray co-ordinate measuring machines
  - New kid on the block
  - Holistic: external and internal
  - Accuracy questionable
State-of-the-art in dimensional measurement for AM

• **Form**: contact CMMs, fringe projection, laser triangulation – slow, lack of access, difficult in-process

• **Texture**: contact, optical – slow, difficult surfaces – see later

• **Internal features**: X-ray CT – expensive, slow, difficult in-process

• **Defects in-process**: thermal cameras, imaging systems – limited information content (not 3D), little tolerance information
Why is AM an issue for metrology?
Why is AM an issue for metrology?

• With almost infinite design freedom, comes almost infinitely complex shapes to measure!
• Complex surface texture – very high slope angles
• Huge range of materials – plastics, metals, ceramics, ... growing daily
• The need for speed!
Back to Basics
Surface measurement – all about spatial frequencies

The “mechanical surface”: analytical solutions
Why use optical and not contact?

• Contact always causes damage, although this is often over-emphasised
• Optical can be much faster – in-line solutions become practical
• For coordinate metrology, optical systems give a large set of point cloud data rather than a few carefully-chosen points
• Optical instruments can be easier to use – this is a critical point – see next slide
Why use optical and not contact?

• Work of art piece of precision engineering

• But
  – Difficult to use
  – Fragile, easily broken
  – Lack of access
  – Expensive, to buy and to maintain

F25 micro-CMM at Nottingham and NPL
Optical instruments - basics

• Light reflected from a surface and the returned amplitude (and phase) data interrogated

• Can vary depending on:
  – Incident angle (spatial bandwidth)
  – Source spectrum (temporal bandwidth)
  – Degree of coherence
  – Polarisation state
Optical instruments - limitations

- Finite spatial frequency bandwidth due to diffraction limit and/or pixel size/density
- Finite range due to imaging and detection apertures
- Slope limitation due to finite angular collection system
- Aberrations in the optics leading to “optical artefacts” – these are often due to non-linear affects and difficult to predict and/or correct
- Speed issues due to need for scanning (mechanical or wavelength)
- Big data!
- Lack of standardisation
- ....
So why can’t we stride forward?
So why can’t we stride forward?
... and compromise
Numerical aperture – slope limitation

Objective lens

To detector

Not detected

Surface

$\alpha$
Numerical aperture – slope limitation
Information-rich Metrology
Can we do anything about these issues?
“Information-rich metrology” (IRM)

IRM = Rigorous models of the instrument-surface interaction, often including all the nasty non-linear parts + Information about the object being measured, e.g. CAD data, course measurements, manufacturing specifications, ...
New paradigm: Information-rich metrology (IRM)

- Exploit all *a priori* information (e.g. CAD, models, course measurement data, etc.)
- Use of probe and measurand modelling
  - increase measurement bandwidth
  - decrease measurement times/information content
- Akin to super-resolution techniques

Optical instrument \(+\) A *priori* information \(=\) A good model \(\Rightarrow\) Result with higher bandwidth
The imaging process
The imaging process
What about high slopes?

- Nice linear theory only works for surfaces with slopes within the spatial bandwidth (aperture limit)
- What about slopes outside this limit?
- The linear filtering model no longer applies in this case because of multiple reflections
- But, with Loughborough University, we are developing a rigorous model which seems to be able to correctly predict results from various instruments
- Computational speed is the issue rather than physics...
We know we can produce outputs that show the surface related problems of instruments to solve the forward problem.

Q. Can we calculate the surface accurately from one or more outputs?

This is the inverse problem. Mathematically it is the solution that minimises an error function such as,

$$\text{Error} = \sum (E_S^m - E_S^{\text{calc.}})^2$$

A. Sometimes!
What about high slopes?
What about high slopes?
Object: 15 μm step with a 5 μm x 1 μm groove. Illumination from the top.

CSI results: top and bottom surfaces are found

New object calculated from CSI data using updated model shows the profile of the “vertical wall”
Conclusions
“It's never too late to start over!”

- The use of *a priori* manufacturing data gives us a wealth of information to exploit
- Combine this with rigorous modelling and we can significantly enhance measurements
- Often this involves non-linear optimization and 3D solvers -> need to look at fast approaches
- IRM will form the focus to build a world-leading, game-changing team at Nottingham
Open forum
Questions

• Are we taking the right approach?
• Have we got the appropriate team and partners?
• Have we missed anything critical?
• What about the materials metrology?
• Is the UK appropriately embedded in the standards infrastructure?
• Should we do something like this regularly? If yes, how regularly?