Session 1: state-of-the-art review

**Dimensional metrology & NDT for additive manufacturing**

Filippo Zanini, Simone Carmignato

Department of Management and Engineering, University of Padova, Vicenza, Italy

---

**Precision manufacturing engineering group**

25 researchers:
- 6 faculty members,
- 2 technicians,
- 17 PhDs and post PhDs.

1600 m² labs in Padova and Rovigo with state-of-the-art equipment.

labtesi.dii.unipd.it
Dimensional measurements & NDT for additive manufacturing

# Outline

- **Introduction**
  - AM technical challenge areas
  - Challenges in quality assessment of AM parts

- Performance verification of AM machines

- Dimensional measurements for AM
  - Coordinate measuring machines (CMMs)
  - Optical measurements
  - X-ray computed tomography (CT)

- Non destructive testing (NDT) for AM

---

## AM technical challenge areas

- Understanding of material properties
- Limited types of material suitable for AM
- Process understanding and performance
- Need for *in-situ* monitoring
- Surface finish of contoured surfaces
- Fabrication speed
- Lack of AM standards
- Data formats
- Need for qualification and certification of AM processes and parts
- Part accuracy
- Adequate measurement techniques

---

[NIST Measurement Science Roadmap for Metal-Based Additive Manufacturing 2013]
[Bourell et al.; Roadmap for Additive Manufacturing – Identifying the Future of Freeform Processing 2009]
AM technical challenge areas

Introduction AM performance verification Dimensional measurements Non destructive testing

- **Lack of standards and protocols**: Standards, protocols, and guidelines for all the aspects: from materials design and use to part build, inspection, and certification.

<table>
<thead>
<tr>
<th>Part Quality, Consistency, and Conformance to Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Standards and guidelines for part conformance, qualification, and certification, including:</td>
</tr>
<tr>
<td>o Geometric accuracy, material properties, defects, distortion, surface characteristics, and variation in these characteristics</td>
</tr>
<tr>
<td>o Microstructure quantification, artifacts to test microstructure</td>
</tr>
<tr>
<td>o Characterization of multi-material parts</td>
</tr>
<tr>
<td>• Standardized measurement test pieces and sets and testing standards</td>
</tr>
<tr>
<td>• Standardized part validation tools</td>
</tr>
<tr>
<td>• Post-process standards and specifications for parts (e.g., internal, surface roughness, measurements)</td>
</tr>
<tr>
<td>• Standards for building (e.g., orientation) and repairing of parts</td>
</tr>
<tr>
<td>o Round-error testing for building and testing parts</td>
</tr>
<tr>
<td>o Test protocols for materials testing and reporting of results</td>
</tr>
<tr>
<td>o Repair protocols</td>
</tr>
</tbody>
</table>

[NIST Measurement Science Roadmap for Metal-Based Additive Manufacturing 2013]

- **Measurement and monitoring techniques and data**: Current technologies and techniques for measurement, monitoring and control are inadequate and can significantly impact part quality, functionality, and performance. New sensors, integrated models, and measurement methods will be needed to enable integration of materials and processing control and feedback.

**Innovative metrology solutions are needed for AM**

Challenges in quality assessment of AM parts

AM parts quality issues

- Complex freeform shaped parts
- High surface roughness
- Internal geometries and undercuts
- Voids and entrapped particles

Metrology challenges for AM

Typical applications for freeform surface

[Guo, Leo; Mech. Eng. 2013] [Savio et al.; CIRP Annals 2007]
Challenges in quality assessment of AM parts

AM parts quality issues

Complex freeform shaped parts  High surface roughness  Internal geometries and undercuts  Voids and entrapped particles

Metrology challenges for AM

SLM texture

FDM texture

EBM part with internal channels

Octet test part

[Townsend et al. – Precision Engineering 2016]
Dimensional measurements & NDT for additive manufacturing

Challenges in quality assessment of AM parts

AM parts quality issues

Complex freeform shaped parts
High surface roughness
Internal geometries and undercuts
Voids and entrapped particles

Metrology challenges for AM

SEM image of a pore with entrapped unmelted powder

Ti6Al4V SLM micro-valve

Performance verification of AM machines

Benchmark parts

[Tesile: Journal of Research of the National Institute of Standards and Technology 2014]


[Teeter et al.; Journal of Engineering in Medicine 2014]

[Uhlmann et al.; ASPE 2015]
Requirements for benchmark parts design

- Large enough to test the performance of the system over the entire platform
- Substantial number of small, medium, and large features
- Presence of both holes and protruding features
- Fast building enabled
- Reduced material quantity required
- Many features of a “real” part (e.g., thin walls, flat surfaces, holes, etc.)
- Simple geometrical shapes, allowing perfect definition and easy control of the geometry
- No post-treatment or manual intervention required
- Repeatability measurements allowed
- Easy to be measured

Parts used for different manufacturing technologies

- Circle-diamond square part
- Parts with internal features

Parts from metrology experience

- Parts with internal features

References:

- Cooke, Soons; 21st Annual Solid Freeform Fabrication Symposium: An Additive Manufacturing Conference 2010
- Hansen H.N. et al; ASPE 2014
- Kim F. H. et al; ASPE 2016
- Jansson A. et al; CIRP Procedia (28) 2015
- Möhring H.C. et al; CIRP Procedia (28) 2015
Coordinate Measuring Machines (CMMs)

- **Introduction**
- **AM performance verification**
- **Dimensional measurements**
- **Non destructive testing**

**Dimensional measurements & NDT for additive manufacturing**

- **Contact CMMs**
  - Contact CMMs can measure form with high accuracy
  - Limited number of measured points on an object’s surface.
  - Relatively slow (not ideal for in-line inspection)

- **Optical CMMs**
  - Non-contact probing systems based on optical principles (i.e. like autofocus, triangulation and conoscopic holography) allows non-contact and faster acquisition of a larger number of points
  - Optical CMMs are less accurate than contact CMM

---

**Contact CMMs**

- Flatness of the top surface: 12 points
- Cylindricity of the center hole: 3 levels with 8 points each
- Pins and holes: 6 points, 3 mm from the top of the feature
- Height of each stair step: 1 point
- Straightness measurements: 1 line segment with at least 15 points distributed over at least 80 % of the feature’s length
- Parallelism and perpendicularity: at least 10 points, also distributed over a line at least 80 % of the length of the feature
Coordinate Measuring Machines (CMMs)

**Contact CMMs**

- Hole plate produced by FDM technology
- Application of a calibration artefact for CMMs
- Developed to create a connection with the traditional calibration method of CMMs
- The design of the hole plate has been used to measure its geometry with acceptable accuracy using standard CMMs

Roundness measurement (25 points for each hole)

[Hansen H.N. et al; ASPE 2014]

Optical measurements

- The two main types of optical form measurement systems which can be the most useful for industrial AM are those currently used in conventional manufacturing industry, namely, **laser triangulation (LT)** and **structured light projection (SL)**.

- LT and SL are **active systems**, i.e. they recreate a 3D model of the object’s form by detecting the modulation of projected illumination caused by the object’s shape.

- **SNR improves on parts featuring optically rough surfaces**, since smooth surfaces (e.g. obtained by subtractive manufacturing) can produce specular reflectance.

- However, the roughness remains a measurement challenge on the accuracy of the final result, especially when it is too fine to resolve.

[Stavroulakis P I, Leach R K et al.; Review of Scientific Instruments 2016]
Laser triangulation

- Laser triangulation systems project a laser spot or a line onto the part.
- The spot or line is scanned across the object by deflecting the beam using a mirror. At each mirror position, triangulation is performed to calculate the height of the scanned points.
- The most fundamental source of measurement uncertainty in laser triangulation is the roughness of the surface.

Structured light projection technique

Sinusoidal fringe projection is the most promise: high speed, pixel-level resolution, highest accuracy

Other optical measurements

Focus variation principle (Alicona)

Confocal profilometry (Sensofar) to measure the height of AM thin-walls.
**Non-Cartesian measuring instruments**

- Unaffected by thermal variations in the production environment
- Located directly on the production line
- Pass/fail criteria based on an AM ‘gold standard’, validated using a CMM

Equator™ Non-Cartesian digital gauge.  

---

**X-ray computed tomography**

- Holistic three-dimensional reconstruction of the scanned object
- High surface digitalization
- **Non-destructive** and **non-contact** measurement of external and internal geometries, features and micro-features
- Traceability still challenging
X-ray computed tomography

- Quality control and dimensional metrology:
  \[ \text{AM} \rightarrow \text{CT} \rightarrow \text{Report} \checkmark \]

- Product development and process optimization:
  \[ \text{AM} \rightarrow \text{CT} \rightarrow \text{AM} \]

- Reverse engineering for rapid prototyping:
  \[ \text{Object} \rightarrow \text{CT} \rightarrow \text{AM} \]

Lattice structures
CAD comparison
Lattice structures
Wall-thickness analysis

[Van Bael S. et al; Materials Science and Engineering 2011]

External and internal geometries
CAD comparison
Wall-thickness analysis

Ti6Al4V SLM micro-valve

Chess rook

[Villaraga H. et al; ASPE 2015]
Dimensional measurements & NDT for additive manufacturing

**Comparison of different technologies**

- Different Coordinate Measuring Systems (CMSs) have different measuring principles
- Influence of specific material properties (e.g. surface roughness, optical properties, type of material, etc.)
- Different error sources
- Functional properties of parts are mainly mechanically determined

**Tactile CMM**

**Laser sensor**

**X-ray CT**

---

**Comparison of different technologies**

**Introduction**

**AM performance verification**

**Dimensional measurements**

**Non destructive testing**

**AM performance verification**

**Dimensional measurements**

**Non destructive testing**

---

**CMM vs CT**

**List of features and tolerance allocation.**

<table>
<thead>
<tr>
<th>Feature</th>
<th>L.D.</th>
<th>U.L.D.</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Angle/ity</td>
<td>SA</td>
<td>SA1</td>
<td>Angularity</td>
</tr>
<tr>
<td>Cut-out helix parallelism</td>
<td>CPE</td>
<td>CPE1-4</td>
<td>Perpendicularity</td>
</tr>
<tr>
<td>Cut-out helix cylinder</td>
<td>CC</td>
<td>CC1-4</td>
<td>cylindrical</td>
</tr>
<tr>
<td>Inner surface parallelism</td>
<td>BCP</td>
<td>BCP1-4</td>
<td>Parallelism</td>
</tr>
<tr>
<td>Inner surface cylinder</td>
<td>BC</td>
<td>BC1-4</td>
<td>Sphericity</td>
</tr>
<tr>
<td>Hemispherical parallelism</td>
<td>HS</td>
<td>HS1-4</td>
<td>Sphericity</td>
</tr>
<tr>
<td>Inner surface cylinder</td>
<td>PC</td>
<td>PC1-3</td>
<td>Sphericity</td>
</tr>
<tr>
<td>Cut-out helix flanges</td>
<td>CF</td>
<td>CF1-4</td>
<td>Flatness</td>
</tr>
<tr>
<td>Inner surface flanges</td>
<td>BF</td>
<td>BF1-4</td>
<td>Flatness</td>
</tr>
</tbody>
</table>

**Percentage error % of CT measurements using reference results (lower is better):**

<table>
<thead>
<tr>
<th>Feature</th>
<th>FDM CT1</th>
<th>FDM CT2</th>
<th>SLS CT1</th>
<th>SLS CT2</th>
<th>SLA CT1</th>
<th>SLA CT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>47.43</td>
<td>46.27</td>
<td>42.55</td>
<td>59.15</td>
<td>28.33</td>
<td>41.53</td>
</tr>
<tr>
<td>CCPe</td>
<td>57.86</td>
<td>56.92</td>
<td>24.56</td>
<td>23.97</td>
<td>50.81</td>
<td>60.14</td>
</tr>
<tr>
<td>CCPa</td>
<td>36.61</td>
<td>26.71</td>
<td>73.17</td>
<td>76.7</td>
<td>88.88</td>
<td>86.05</td>
</tr>
<tr>
<td>CC</td>
<td>39.52</td>
<td>40.88</td>
<td>30.50</td>
<td>31.81</td>
<td>24.49</td>
<td>13.64</td>
</tr>
<tr>
<td>BCPE</td>
<td>44.69</td>
<td>48.02</td>
<td>70.63</td>
<td>18.89</td>
<td>53.84</td>
<td>37.04</td>
</tr>
<tr>
<td>BCPO</td>
<td>42.34</td>
<td>37.52</td>
<td>85.21</td>
<td>65.28</td>
<td>74.81</td>
<td>55.77</td>
</tr>
<tr>
<td>BC</td>
<td>23.12</td>
<td>24.18</td>
<td>18.59</td>
<td>16.39</td>
<td>73.81</td>
<td>47.02</td>
</tr>
<tr>
<td>HS</td>
<td>32.46</td>
<td>32.74</td>
<td>36.82</td>
<td>31.30</td>
<td>24.23</td>
<td>35.34</td>
</tr>
<tr>
<td>PC</td>
<td>60.81</td>
<td>60.75</td>
<td>45.44</td>
<td>46.22</td>
<td>66.77</td>
<td>11.87</td>
</tr>
<tr>
<td>CCF</td>
<td>27.56</td>
<td>27.89</td>
<td>14.48</td>
<td>13.82</td>
<td>69.06</td>
<td>29.99</td>
</tr>
<tr>
<td>BCF</td>
<td>56.53</td>
<td>58.37</td>
<td>29.31</td>
<td>26.15</td>
<td>36.07</td>
<td>22.00</td>
</tr>
</tbody>
</table>

[Shah P. et al.; CSNDT 2016]
**Dimensional measurements & NDT for additive manufacturing**

### CMM vs CT vs Optical

**Design criteria**
- Typical issues in AM manufacturing, e.g. distortion due to the layer by layer building
- Both external and internal features, accessible to every measuring instrument
- Features have a simple form
- 3 ceramic balls: diameters and centers were used to enable scale and surface determination of different techniques to be compared

Depending on the metrology system being used to capture the measurement data and the construction of the part being measured, systems can behave differently. As tactile, optical and XCT systems use different data capturing techniques, a systematic difference in dimensional measurements may exist that will invalidate the chain of traceability.

[Brown et al.; ASPE 2016]
Non destructive testing (NDT) for AM

- Internal defects and surface flaws
- Geometric accuracy
- In-situ process monitoring

<table>
<thead>
<tr>
<th>Methods</th>
<th>Internal defects</th>
<th>Surface flaws</th>
<th>Global(G) / Local(L)</th>
<th>Surface sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual testing</td>
<td>N</td>
<td>Y</td>
<td>L</td>
<td>N</td>
</tr>
<tr>
<td>Radiography</td>
<td>Y</td>
<td>Y</td>
<td>L</td>
<td>Y</td>
</tr>
<tr>
<td>X-ray CT</td>
<td>Y</td>
<td>Y</td>
<td>G, L</td>
<td>N</td>
</tr>
<tr>
<td>Archimedes method</td>
<td>Y</td>
<td>N</td>
<td>G</td>
<td>N</td>
</tr>
<tr>
<td>Gas pycnometry</td>
<td>Y</td>
<td>N</td>
<td>G</td>
<td>N</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Y</td>
<td>Y</td>
<td>G, L</td>
<td>Y</td>
</tr>
<tr>
<td>Eddy current testing</td>
<td>Y/N slightly subsurf.</td>
<td>Y</td>
<td>L</td>
<td>Y</td>
</tr>
<tr>
<td>Magnetic methods</td>
<td>Y/N slightly subsurf.</td>
<td>Y</td>
<td>L</td>
<td>Y</td>
</tr>
<tr>
<td>Penetrant testing</td>
<td>N</td>
<td>Y</td>
<td>L</td>
<td>Y</td>
</tr>
</tbody>
</table>

NDT defect detection

Archimedes method

- Non-destructive
- Fast and simple to perform with commercial instrumentation
- Only total fraction of porosity
- No information about porosity distribution
- Nominal density may be not accurate for non-homogeneous parts, such as the AM parts.

Gas pycnometry

- Non-destructive
- Fast and simple to perform
- Limited detection volume
- Only total fraction of porosity
- No information about porosity distribution
- Nominal density may be not accurate for non-homogeneous parts, such as the AM parts.
NDT defect detection

**Ultrasonic technique**
- Non-destructive
- Detection of surface and subsurface defects
- Detection of cracks and inclusions
- Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.
- Reduced accuracy for high porosity content (>10%)

**X-ray CT**
- Non-destructive
- Pore size, distribution and morphology
- Detection of surface defects
- Inability to reliably detect cracks.
- High cost
- Traceability establishment is still challenging
- Influence of artefacts, thresholding and resolution

Eddy current testing
- Electric current is created in the sample in the presence of an alternating magnetic field. Features that interrupt the current are detected.
- Useful for finding cracks
- Surface finish and grain structure play a huge role in the success of the method in finding critical defects (high background noise due to surface roughness).

Magnetic particle testing
- A ferromagnetic material with surface cracks or discontinuities “leaks” magnetic field. Magnetic particles are attracted by these locations. Visual inspection identifies these locations.
- Surface sensitive

Penetrant testing
- Detection of surface defects:
- Require a relatively smooth inspection surface, so it may not be a realistic for rough AM parts without special post-process machining and polishing (high background noise due to the as-manufactured surface roughness).
- Many techniques applied to reduce surface roughness close up surface flaws and cracks.
Comparison between porosity methods

- Introduction
- AM performance verification
- Dimensional measurements
- Non destructive testing

**Archimedes vs X-ray CT**

- [Slierings A.B. et al; Rapid Prototyping Journal 2011]
- [Slotwinski J.A. et al; Journal of Research of the National Institute of Standards and Technology 2014]

**Ultrasonic vs X-ray CT**

- [Slotwinski J.A. et al; Journal of Research of the National Institute of Standards and Technology 2014]
**Reference objects with internal features**

**Introduction**

- **AM performance verification**
- **Dimensional measurements**
- **Non destructive testing**

**Dimensional measurements & NDT for additive manufacturing**

Filippo Zanini

---

- **Internal features built using AM**
- **Measurement by CT**
- **Aim: understand PoD of CT porosity analysis**

---

**Optimized design**

[Kim F. H. et al; ASPE 2016]

---

**Reference objects with internal features**

- **Internal spherical features and external hemispherical features with same nominal diameters**
- **CMM calibration of the external features**
- **CT measurement of both external and internal features**

---

[Jansson A. et al; DIR 2015]
Components:
- 4x M6 polyamide screws
- 4x soft rubber washers
- 4x aluminum pin

Assembled:
- Cylindrical aluminum body

Pin:
- Ø15 mm cylindrical aluminum body
- 4x Ø5 mm cylindrical pin with artificial defects
- Various height position of pins (defects)
- 72 artificial defects of hemispherical shape
- Defect size range: 100 – 500 µm

[Reference: Hermanek P. et al; CSNDT 2016]