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CIMP-3D

In-situ monitoring of processing defects and avenues for control/correction in laser-based metal additive manufacturing.

Abdalla R. Nassar

Contributions by: Chaitanya Bakre, Stephen W. Brown, David Corbin, Peter Coutts, Corey Dickman, Christopher Kube, Wesley F. Mitchell, Cliff J. Lissenden, Matthew Pantano, Jan Petrich, Andrew Przyienmski, Edward (Ted) Reutzel, Jason Scherer, Zack Snow, Edward Reutzel, Christopher Stutzman

Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D)
Applied Research Laboratory at The Pennsylvania State University

AMSC Virtual Event on AM Standardization to Highlight Inspection/Monitoring to Meet Regulatory Requirements, January 7, 2021

Bio

- Department head within the Materials Science Division of the Applied Research Laboratory (ARL) & Associate Research Professor at Penn State.
- Graduate Faculty appointments with
  - Engineering Science and Mechanics Department,
  - Additive Manufacturing & Design (AMD) Graduate Program, &
  - Department of Mechanical Engineering.
- Worked in the field laser processing of metals for >13 years. Focus on laser-based AM of metals since 2012.
  - Earned PhD, from Penn State, in 2012. Thesis on *laser-sustained plasma and the role of plasma in carbon dioxide laser nitriding of titanium.*
  - As part of PhD, completed Post-Baccalaureate Program in Laser-Materials Processing.
  - >35 journal articles, >10 invention disclosures (>5 provision or current patents).
- In 2020, awarded the International Outstanding Young Researcher in Freeform and Additive Manufacturing (SFF FAME JR) Award.

Dr. Abdalla R Nassar

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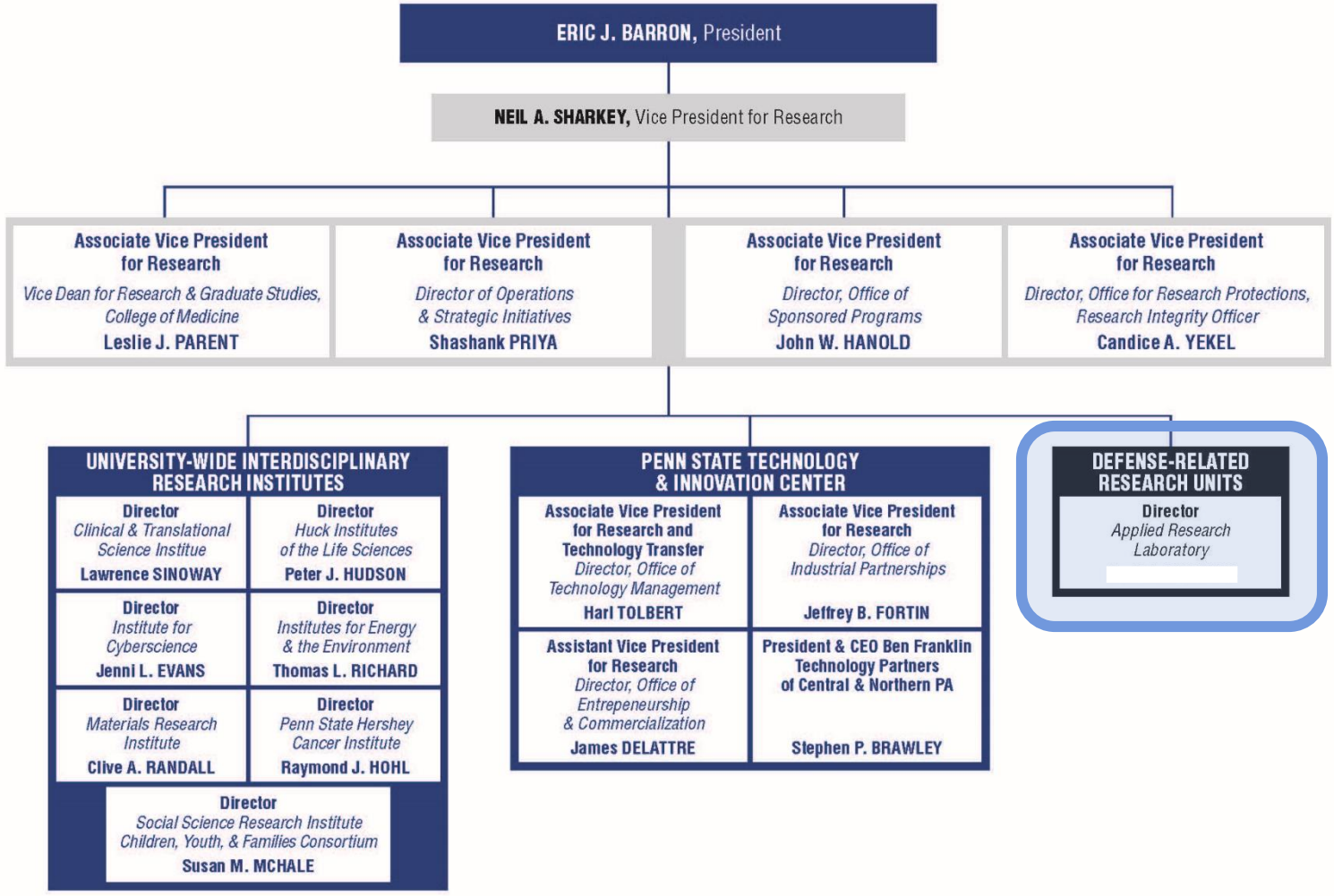
Applied Research Laboratory at Penn State
Who We Are



- Designated by DoD as a University-Affiliated Research Center (UARC)
- Maintain a strategic long-term relationship with DoD
- All U.S. Citizens (including students)
- Government Contractor within a University
- Regularly audited (financials, security, purchasing, contracts)
- Maintain timecards and detailed cost/schedule records on all projects
- Advised by Board comprising a mix of PSU and outside senior officials

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AM In-situ sensing—hype vs reality?

Interest in sensing and control of PBFAM has grown nearly exponentially over past decade. However, is difficult to differentiate between hype and reality…

2016

Concept Laser's QMmeltpool 3D: In-situ quality assurance with real-time monitoring down to the micron level

Concept Laser, based in Lichtenfels, Ge
for metal Additive Manufacturing using
the company reports on the developme
monitoring system, QMmeltpool 3D, wh
from 2016. The system, states Concept
detecting process defects at an early s
optimisation. [First published in Metal A
Issuu | Download PDF]

Share this Article

Meltpool emission

AM Monitoring: EOS Completes Pilot Testing for EOS MeltPool Solution

August 29, 2016 • by Bridget O'Neal • 3D

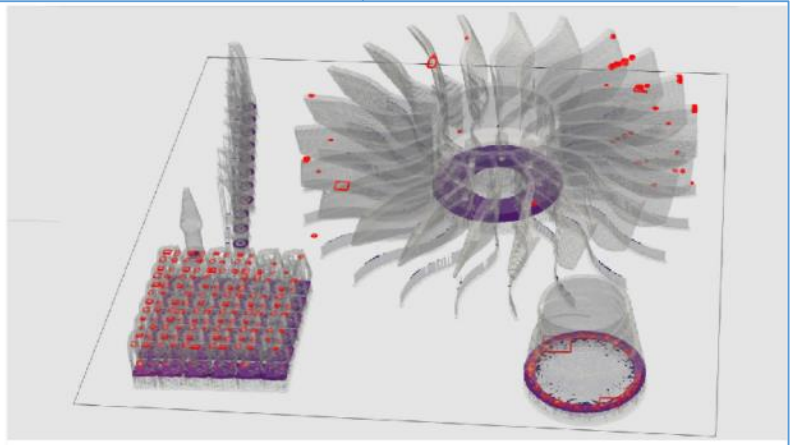
INTAMSYS
Ideal solution for printing PEI, PEEK,

Open Additive and Addiguru sign MoU for integrated industrial AM process control

April 14, 2021

ADDIGURU

Integration of Addiguru AI-
AMSENSE software architec

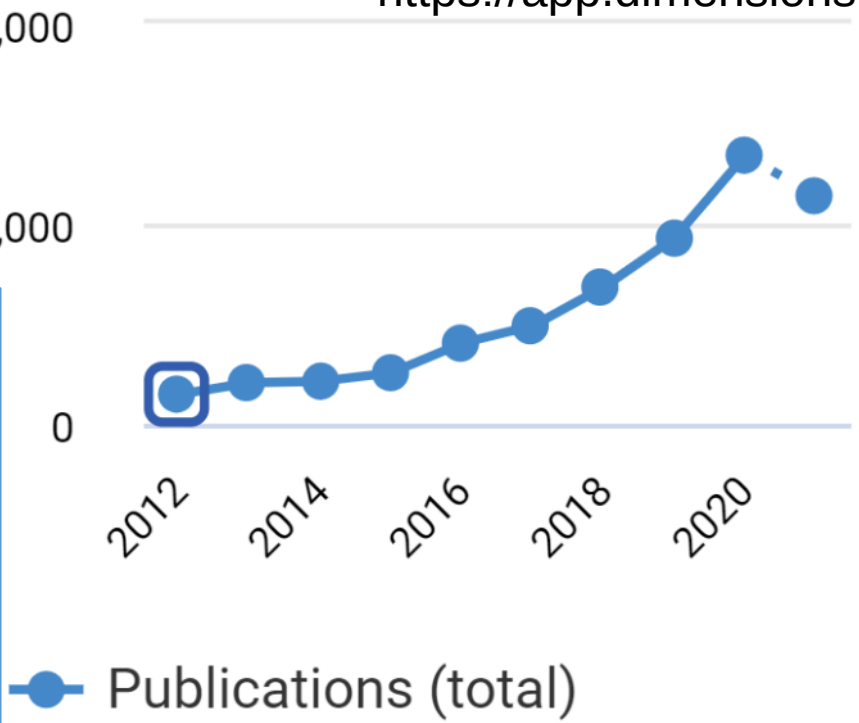


Enhanced Quality Assurance Software for 3D Metal Printing

May 3, 2021

Sigma Labs, a leading developer of quality assurance software to the commercial 3D metal printing industry, has released Version 7.0 of its industry-leading system for in-process quality assurance for industrial 3D manufacturers. The new release was developed after extensive input from existing customers, 3D metal printing manufacturers, universities and standards organizations. Next generation PrintRite3D 7.0 contains upgrades to existing features, as well

https://app.dimensions.a



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Is in-situ sensing really necessary?

- Traditional process performance qualification requires a repetitive manufacturing process to achieve products that exhibit equivalent performance.
  - For example, a Welding Procedure Specification (WPS) for a specific weld type and alloy. *(AWS C7.4, ASME Sec IX)*
    - A Procedure Qualification Record (PQR or WPQR) is used to document the performed weld and record any required tests.

- Works only if all manufacturing functions, may be well defined….AM's greatest assets is also its greatest liability: Complexity is not so free…

- In-situ sensing offers the potential to
  - verify part quality,
  - accelerate process and part qualification, and
  - enable process control.

Roles of sensing

Subsystem Status

- Laser power
- Scanner error
- Optics temperature
- Oxygen level
- Gas flow speed

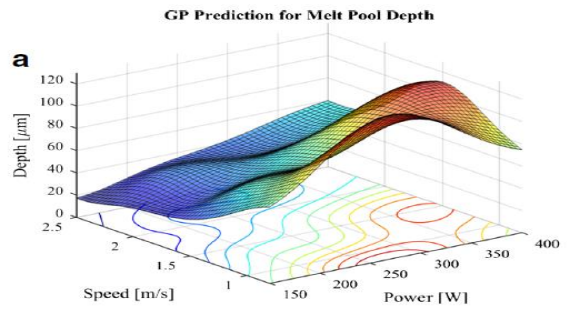
ISO/ASTM 52941, ISO/ASTM 52942

Process Monitoring (for quality & control)

- Photodiodes
- Pyrometers
- Spectrometers
- Acoustic sensors
- Layer imaging

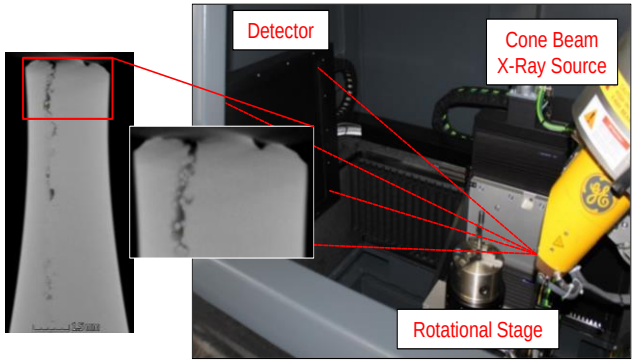
ASTM WK62181

Process Mapping

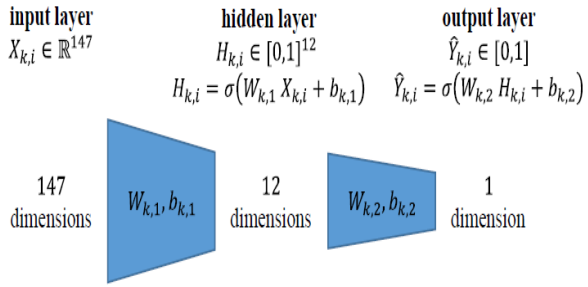


G. Tapia, et al. Int J Adv Manuf Technol, vol. 94, Feb. 2018

Post-Process Inspection

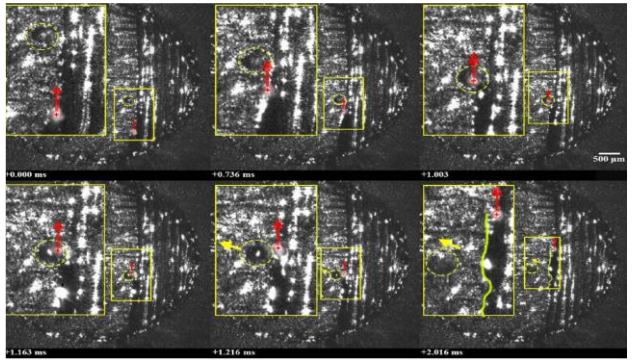


Black-Box Machine Learning



J. Petrich, et al., Solid Freeform Fabrication Symposium, Austin, TX, 2017, pp. 1363–1381.

High-Fidelity Sensing



A. R. Nassar, et al, Scientific Reports, vol. 9, p. 5038, 2019

Process Monitoring (to elucidate physics)

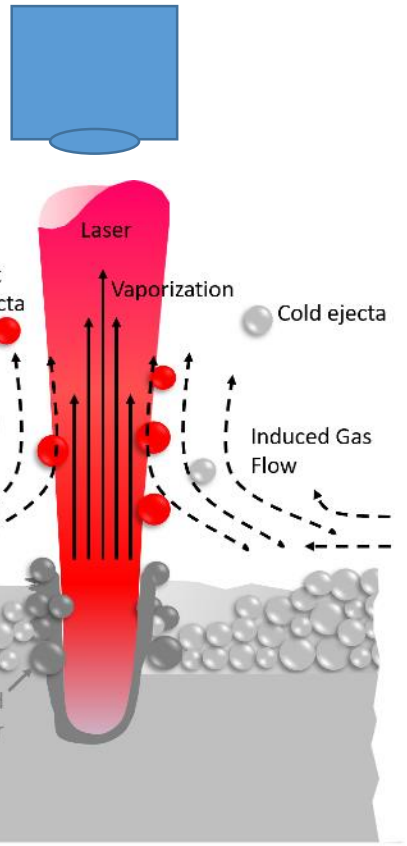
- High-speed VIS imaging
- High-speed IR imaging
- X-ray imaging
- High-resolution topography

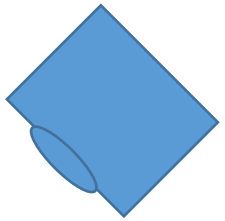
ASTM WK62181

Some definitions

Sensor configuration

Co-axial Configuration integrated within laser's optical path





Staring Configuration (i.e., off-axis) ISO/ASTM 52921-13.

Detector Type

Single-point detector: Integrates captured signal over it's total field of view.

- e.g., Photodiode, microphone

Array detector: Captures signal using a 1D or 2D array such that signal is discretized in space.

*note: by this definition a spectrometer (which uses a 1-d array of pixels is a single-point detector.

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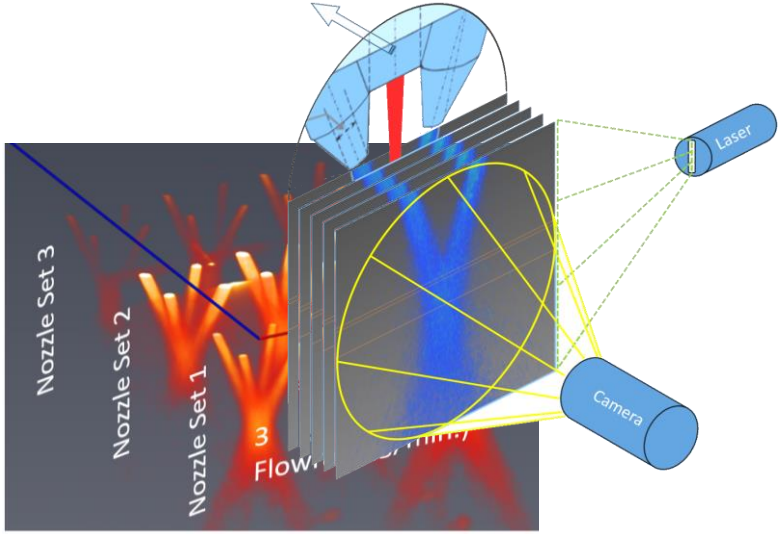
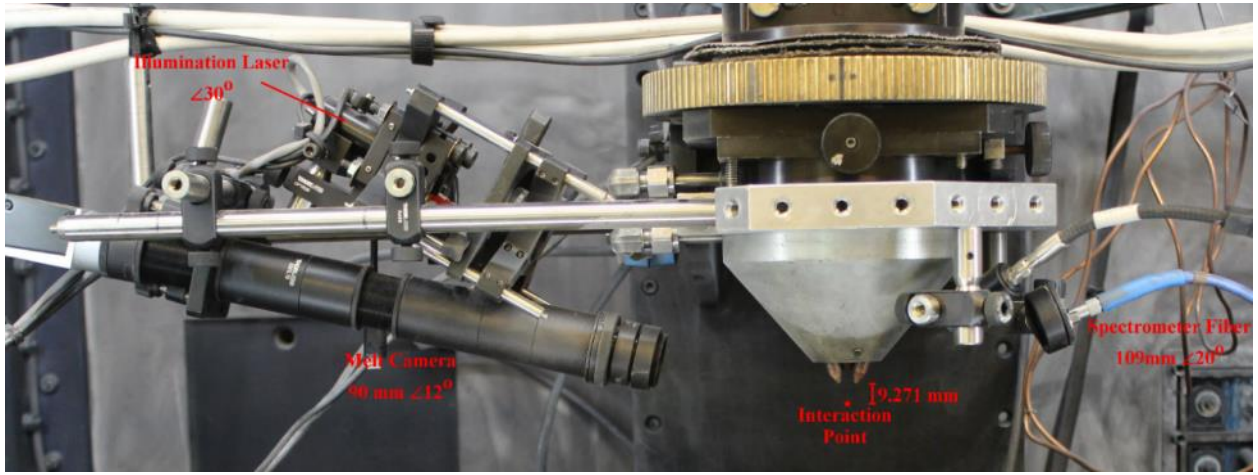
Heterogeneous monitoring of DED

Coaxial Vis & IR Imaging

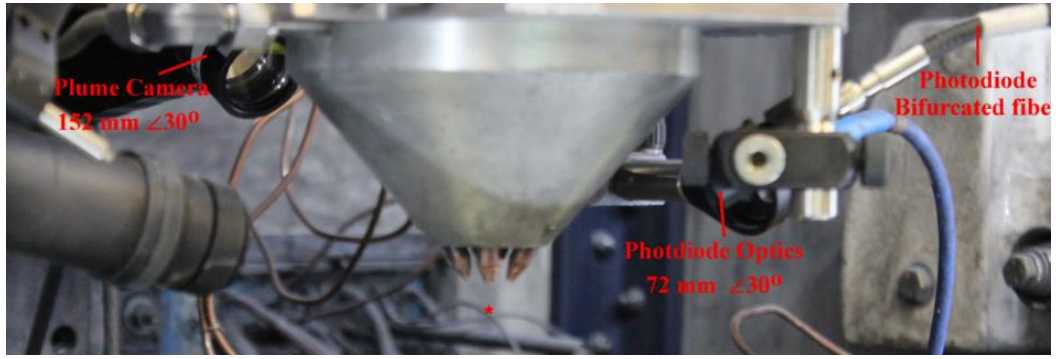


Powder Flow Monitoring

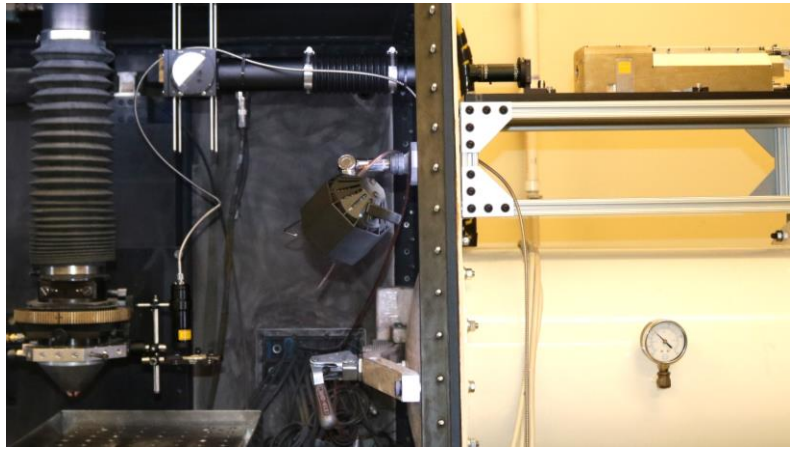
Illuminated Pool Imaging



Plume Imaging



Optical Emission Spectroscopy



Laser Ultransonics

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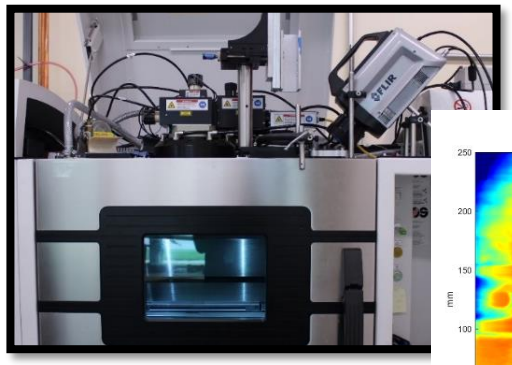
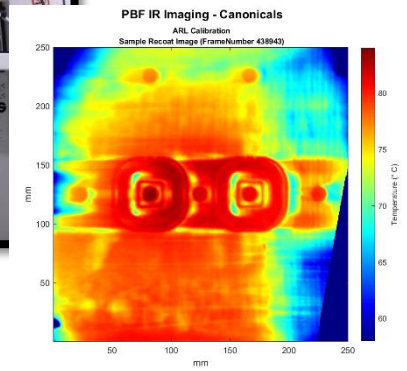
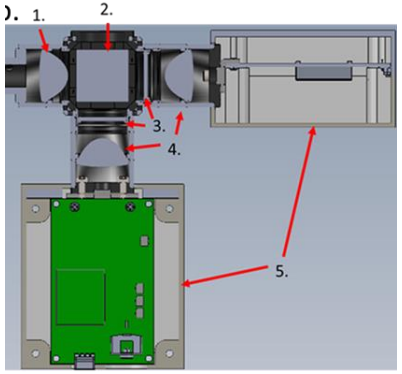
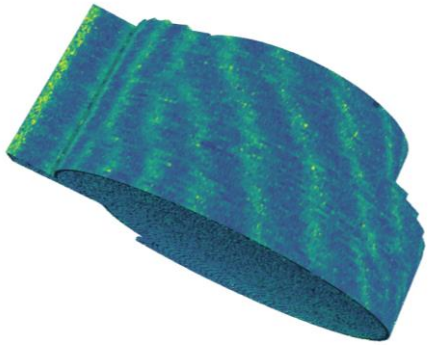
Heterogeneous monitoring of PBF





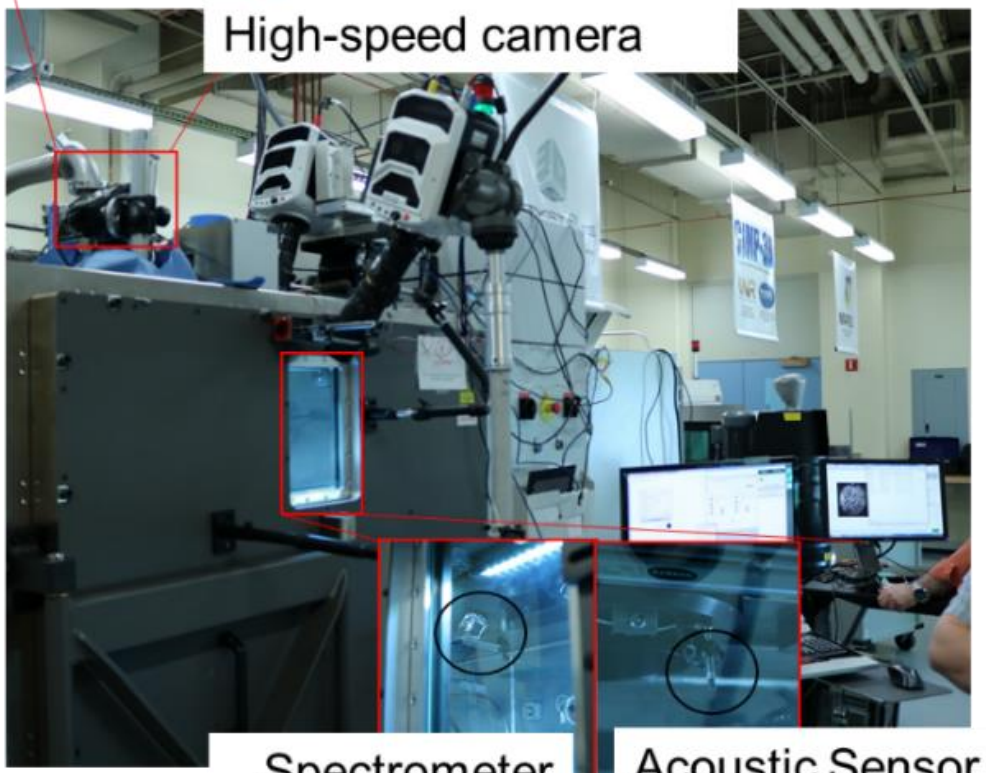
IR Imaging

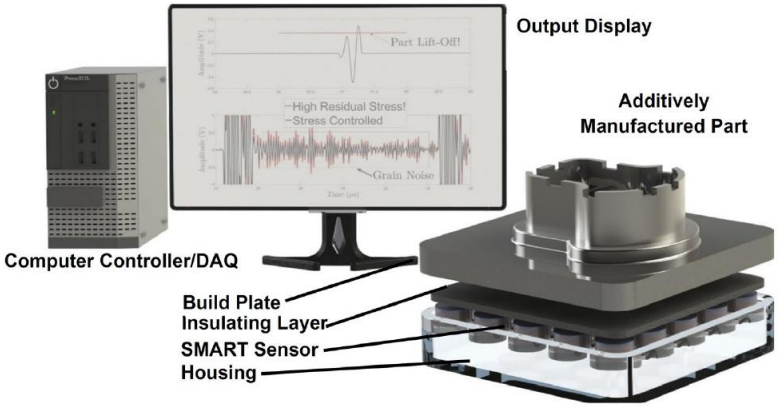




Coaxial multi-spectral

Layerwise Camera & Multi-spectral sensor





Diffuse Field Ultrasonics

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What are the fundamental challenges?

Fundamental challenges are

- Wide range of time and length scales
- System interfacing & data acquisition
- Replication crisis (too many variables)
- Volume of data being generated
- Alignment/Registration uncertainty

Getty Images

Can standardization meet each of these challenges???

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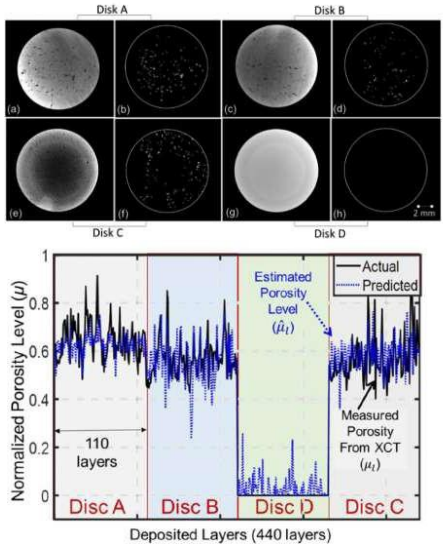
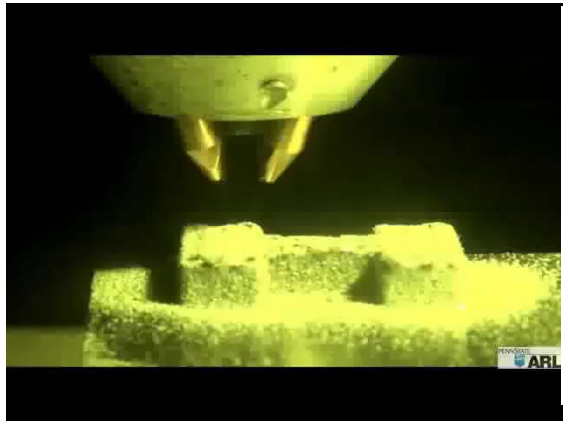
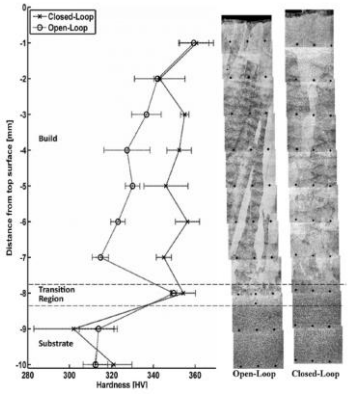
What to do after (AND ONLY AFTER) Alignment/Registration is figured out



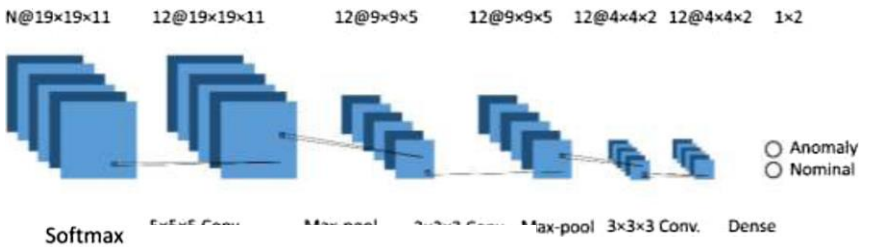
Montazeri, M., Nassar, A.R., Dunbar, A.J., Rao, P., 2020. In-Process Monitoring of Porosity in Additive Manufacturing using Optical Emission Spectroscopy. IISE Transactions 52, 500–515. https://doi.org/10.1080/24725854.2019.1659525

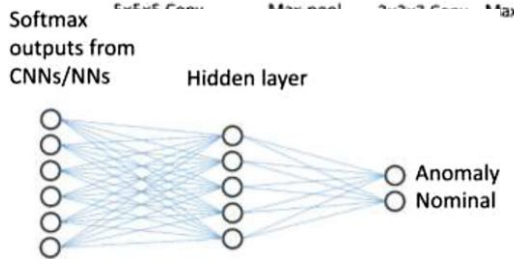




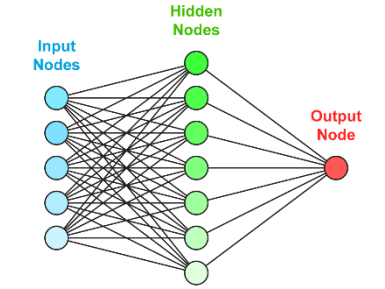
1.

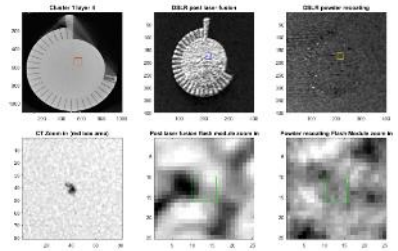
Nassar, A. R. *et al.* Intra-layer closed-loop control of build plan during directed energy additive manufacturing of Ti–6Al–4V. *Additive Manufacturing* **6**, 39–52 (2015).

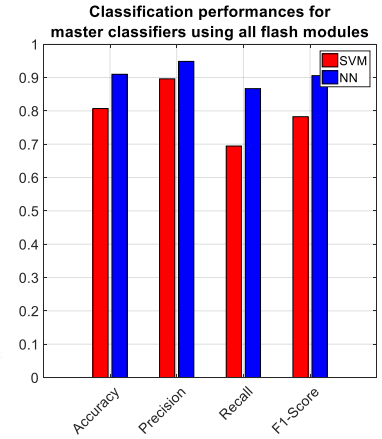




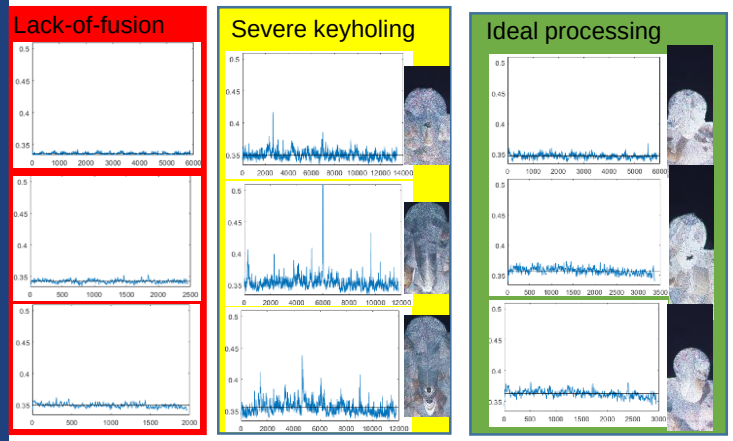
Z. Snow, B. Diehl, E. Reutzel, and A. Nassar, "Toward in-situ flaw detection in laser powder bed fusion additive manufacturing through layerwise imagery and machine learning," *Journal of Manufacturing Systems*, vol. 59, pp. 12–26, 2021, doi: https://doi.org/10.1016/j.jmsy.2021.01.008.



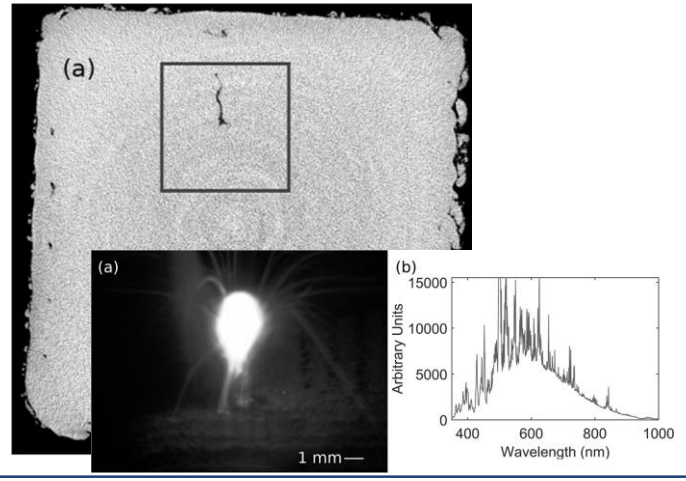




C. Gobert, E. W. Reutzel, J. Petrich, A. R. Nassar, and S. Phoha, "Application of supervised machine learning for defect detection during metallic powder bed fusion additive manufacturing using high resolution imaging.," *Additive Manufacturing*, vol. 21, pp. 517–528, May 2018, doi: 10.1016/j.addma.2018.04.005.



Stutzman, C.B., Nassar, A.R. 2021. Investigations on Optical Emissions and Their Relation to Processing Parameters and Processing Regimes in the Laser Powder Bed Fusion Process



C. B. Stutzman, A. R. Nassar, and E. W. Reutzel, "Multi-sensor investigations of optical emissions and their relations to directed energy deposition processes and quality," *Additive Manufacturing*, vol. 21, pp. 333–339, May 2018, doi:

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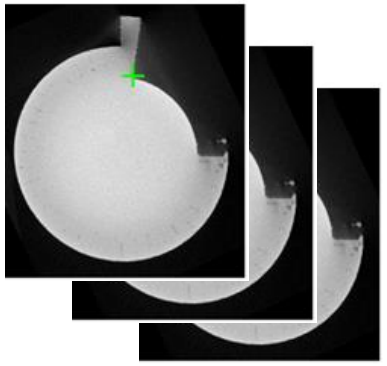
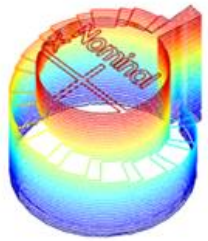
Example:
Alignment/registration for data analysis

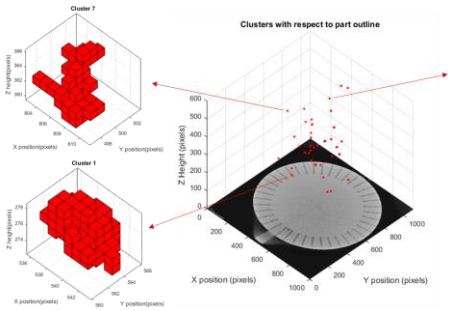


Computed Tomography (XCT) Data



Build Plan or STL

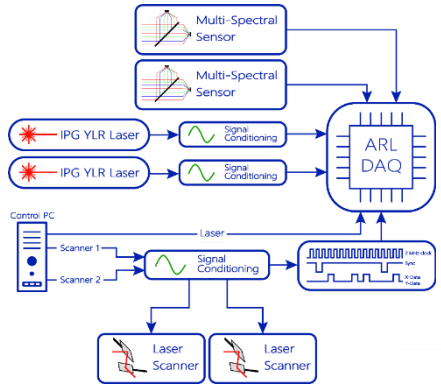
Register XCT Data



Identify Flaws/Features

Confirm Flaws/Features

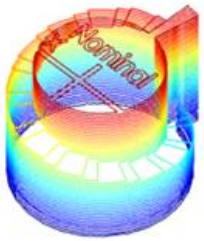
Time-series Data **Synched to X,Y,Z**



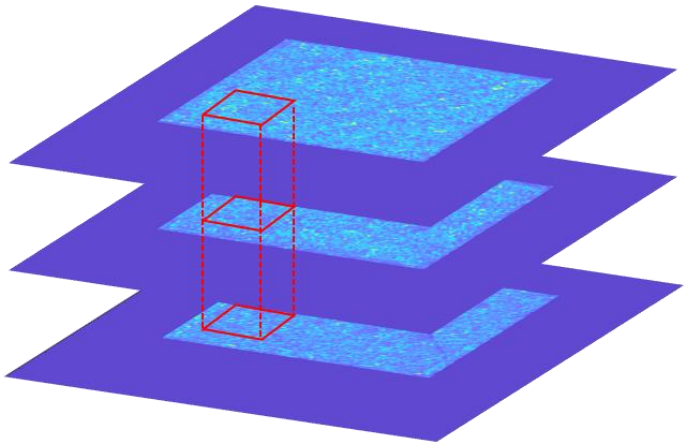
Register Data

Split Data into Parts

Build Plan or STL

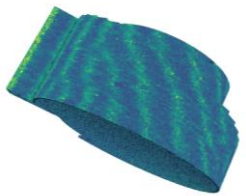


Rasterize Data



Extract Neighborhood

Run Analysis



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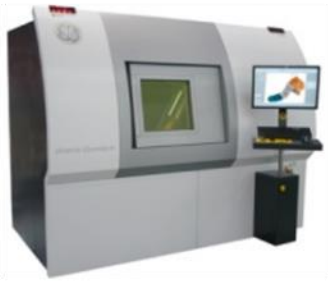
Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D)

Our Capabilities

DMG Mori Lasertec 65

GE Vtomex-M CT



FARO ScanArm HD

ExOne MLab

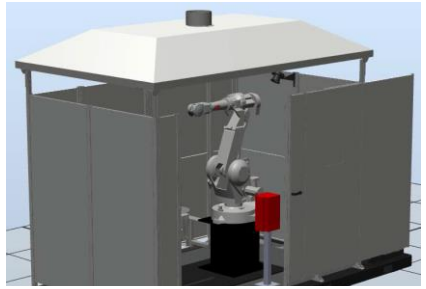
3D System DMP Factory 500

- 500 x 500 x 500 mm work envelop

Large Format–High Deposition

Stratasys Fortus 400 mc

Wire Arc Additive Manufacturing (WAAM)



Foot Print ~ 10 feet x 16 ft

HPHD

Optomec LENS

EOS M280

3D Systems ProX320

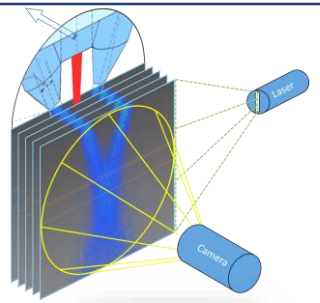
3D Systems ProX 200

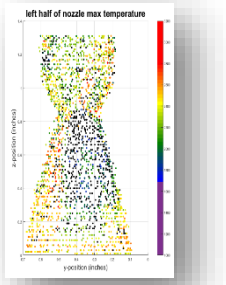
Abdalla Nassar – arn5000@psu.edu

CIMP-3D

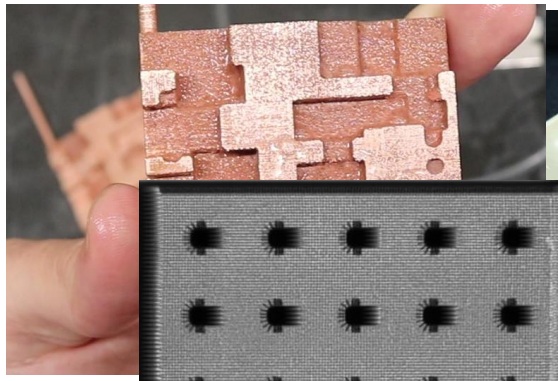
Thank You!
Questions?

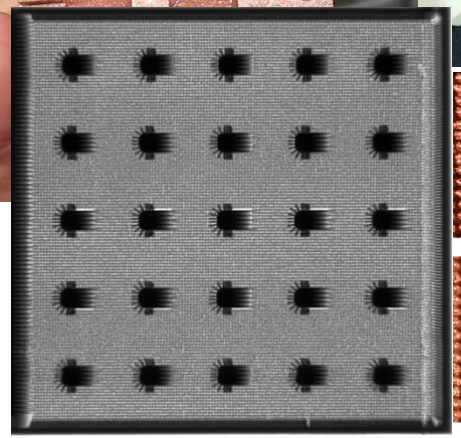
Large-Scale DED

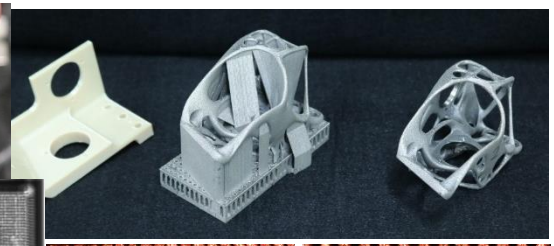


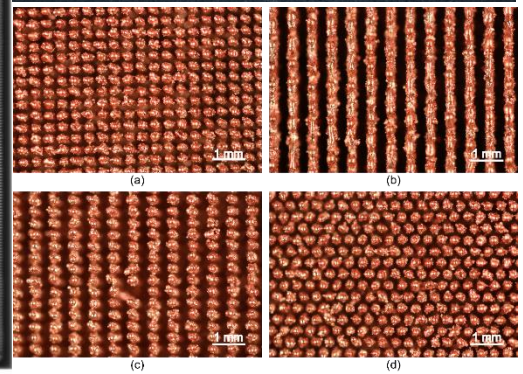


DED Sensing

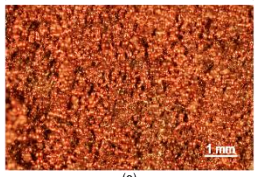


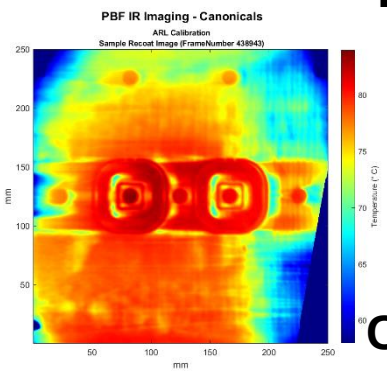


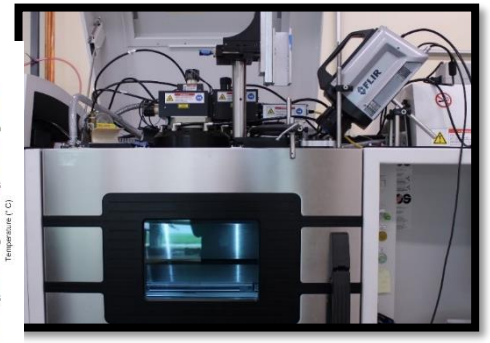




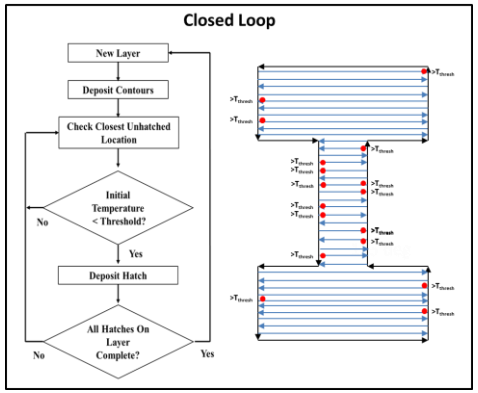
Optimized & Functional Designs



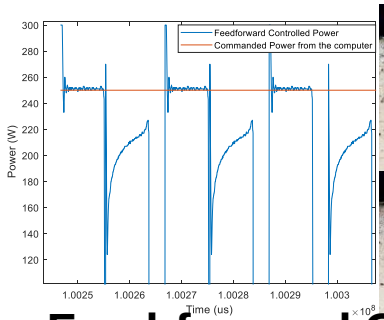


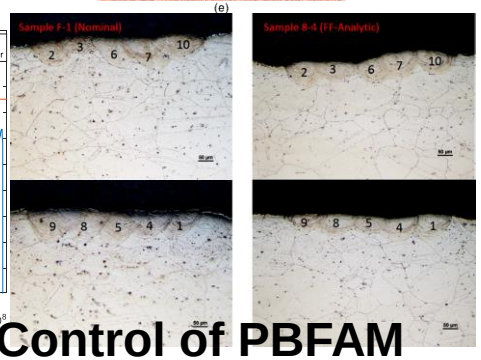


Calibrated IR Imaging



DED Feedback Control





Feed-forward Control of PBFAM

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CIMP-3D