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Title: E-1 Additive Manufacturing (AM) Existing Infrastructure and Recent Developments in Materials, Processes, and Capabilities

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E-1 Additive Manufacturing (AM) Existing Infrastructure and Recent Developments in Materials, Processes, and Capabilities

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January 10, 2022

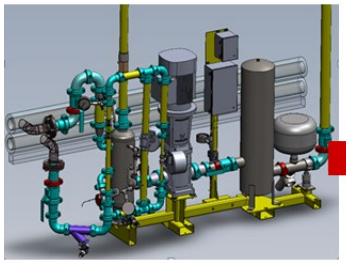
Presentation Outline

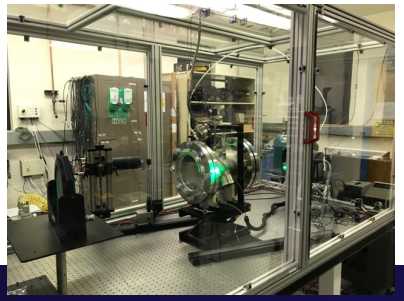
- Introduction
- E-1 AM Infrastructure, Capabilities & Partnerships
- Current AM R&D
- Various Project Examples

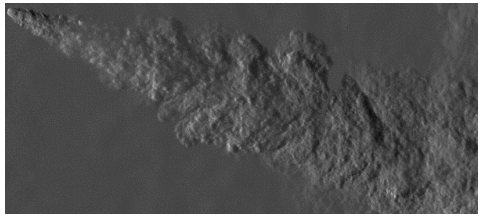
Introduction

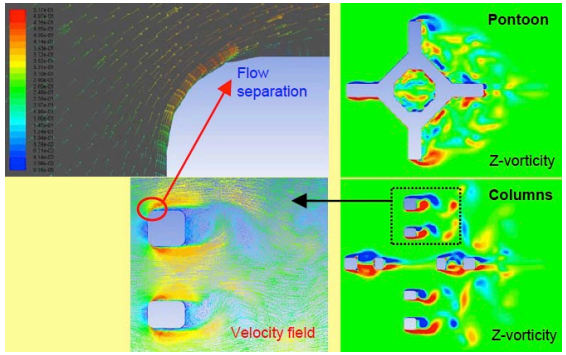
E-1: Mechanical Engineering & Technologies

- Mechanical Engineering, Design, Fabrication & Assembly
  - Structural systems
  - Electromagnetic/pulsed power
  - Spacecraft mechanical hardware
  - Accelerator systems/components
  - Fluid & gas handling systems
  - Energy harvesting devices
  - High temperature heat pipes
  - Nuclear facility infrastructure; glove box, process loops, containers, transport systems
  - Pressure vessels
  - Heat transfer systems
  - Dynamic Systems
- Analysis
  - Structural (static & dynamic)
  - CFD and Thermal
  - Acoustic
  - Electromagnetic
  - Non-Linear
- Experiment Design and Execution





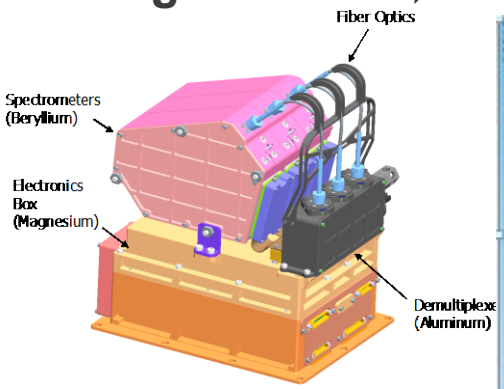


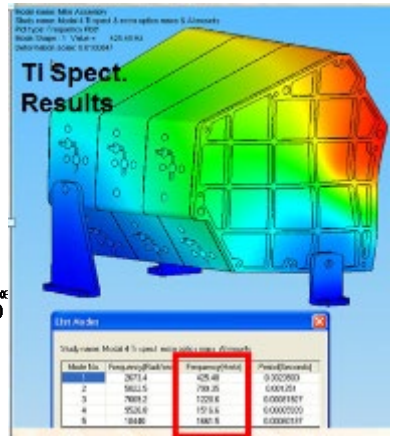


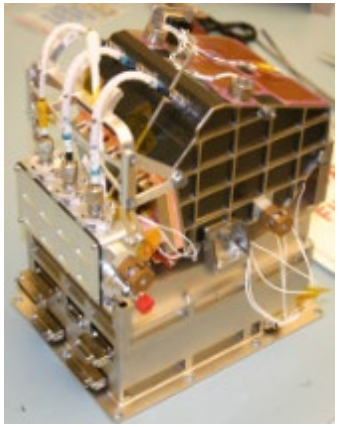
E-1's Need for AM

TRADITIONAL ENGINEERING APPROACH

Design → **Analyze** → **Fabrication** → **Assemble/Test**

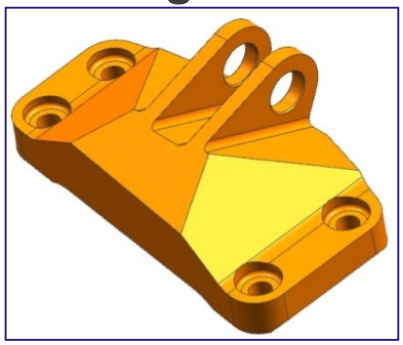


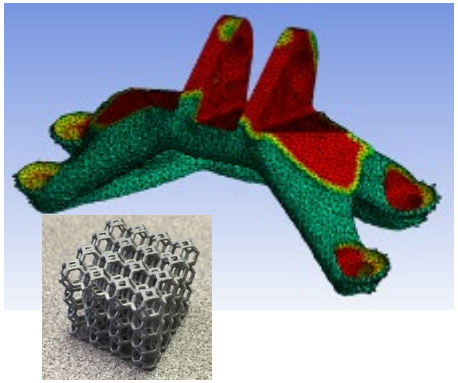


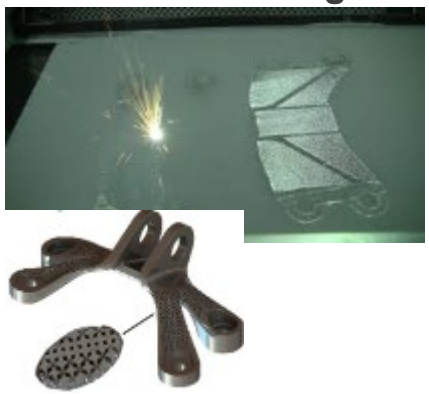


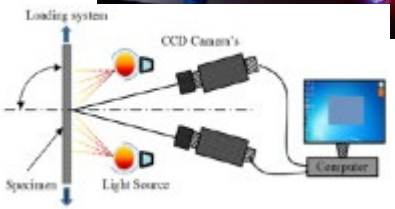
ADVANCED ENGINEERING APPROACH

Design → **Topology Optimization** → **Additive Manufacturing** → **DIC & Laser Scan**





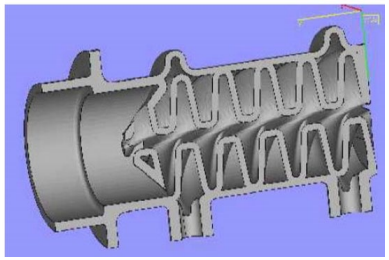




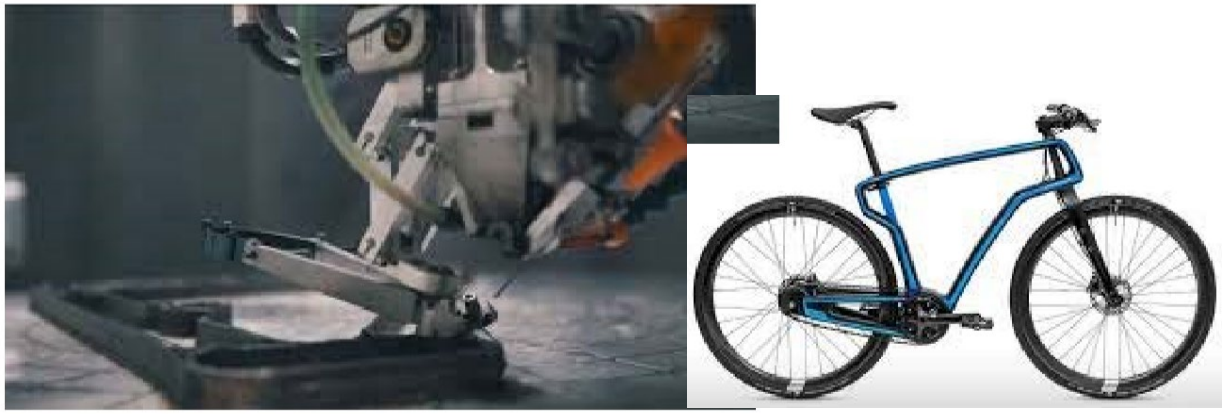
What is Industry doing with Additive Manufacturing (AM)?

Compact & Highly Efficient Heat Exchangers

Ceramic Heat Exchanger

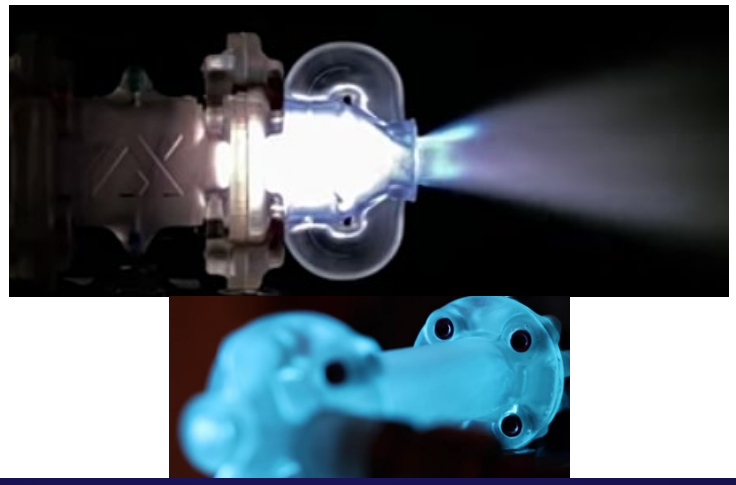


3D Printed Carbon Fiber Bike Frame (Arevo Bikes)



https://3dprinting.com/aerospace/prototyping-a-vortex-rocket-engine-with-a-desktop-3d-printer/

Vortex Cooled Polymer Rocket Engine Igniter



https://amfg.ai/2019/07/24/7-complex-designs-achieved-with-3d-printing/

TO Titanium Brake Caliper

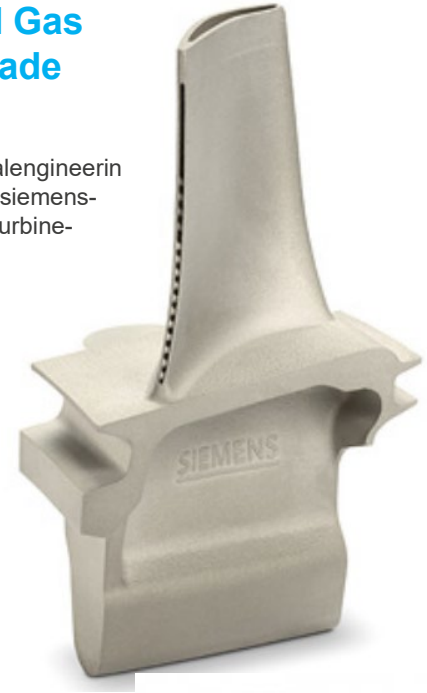
What is Industry doing with Additive Manufacturing (AM)?

Parts Reduction Example

Using generative design and additive manufacturing, GM was able to consolidate the eight different components of a small but important part—a seat bracket, where seat belts are fastened—into one 3D-printed part.

3D Printed Gas Turbine Blade (Siemens)

https://www.digitalengineering247.com/article/siemens-3d-prints-power-turbine-blades/

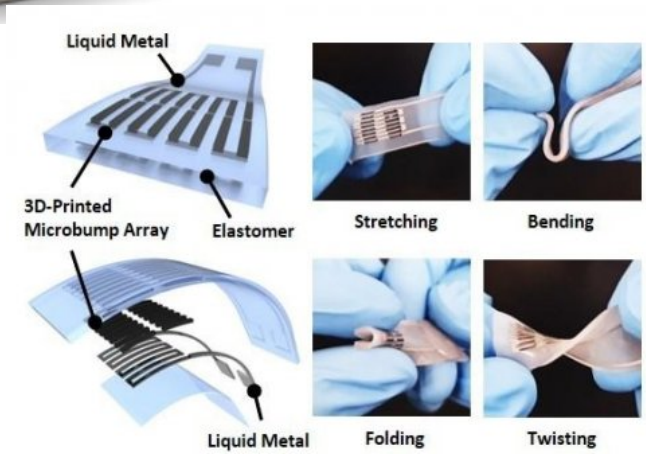


Medical Implants

https://www.mtaa.org.au/news/3d-printing-implantable-medical-devices

Flexible Pressure Sensor

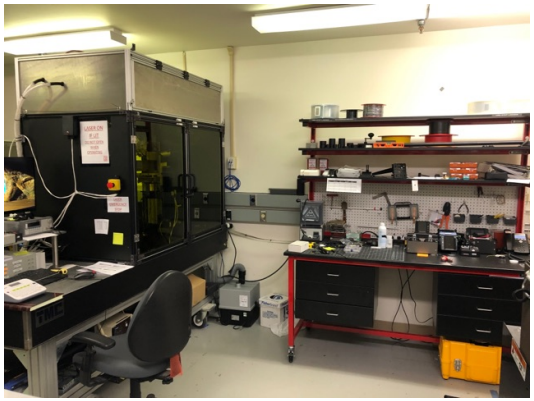
https://tectales.com/wearables-sensors/3d-printing-helps-form-wearable-sensor.html



E-1 AM Infrastructure & Partnerships

E-1 AM Capabilities & Partnerships

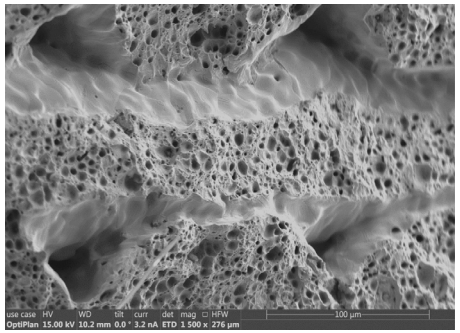
- **E-1 Laboratories**
  - **3 AM Unclassified/OUO Laboratories**
  - **2 Prototype & Testing Laboratories**
  - **1 VTR (FDM, Composites, Aerosol Jet)**

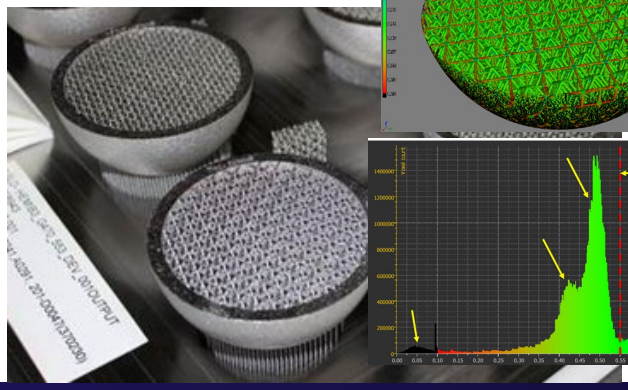


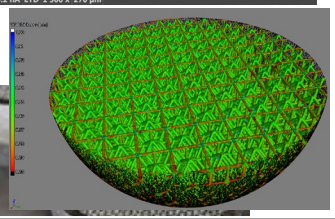
E-1 AM Capabilities & Partnerships

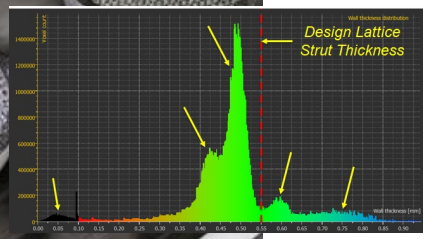
- **LANL AM Collaborations**
  - **MPA-11 & MST-7 (materials synthesis and formulation of polymers, composites, & ceramics**
  - **Sigma (metal AM)**
  - **MST-8 (material property characterization)**
- **National Laboratories**
  - **KCNSC (metal lattices)**
  - **ORNL (embedded sensing)**
- **Industrial AM Partnerships (metal AM)**
  - **Stratasys, Elementum, Protolabs, Wofmet**

Material Property	Testing Machine
Young's Modulus	Tensile Testing
Yield Strength	Tensile Testing
Ultimate tensile Strength	Tensile Testing
Poisson ratio	Tensile Testing
Young's Modulus	Compression Testing
Yield Strength	Compression Testing
Shear Modulus	Estimate from Young's modulus or measure using RUS
Bulk Modulus	Estimate from Young's modulus or measure using RUS
Impact Energy	
Density	Archimedes, pycnometer, or geometric
Specific Heat	TPS
Thermal Conductivity	TPS
CTE	Dilatometer
Speed of sound	Ultrasound waves



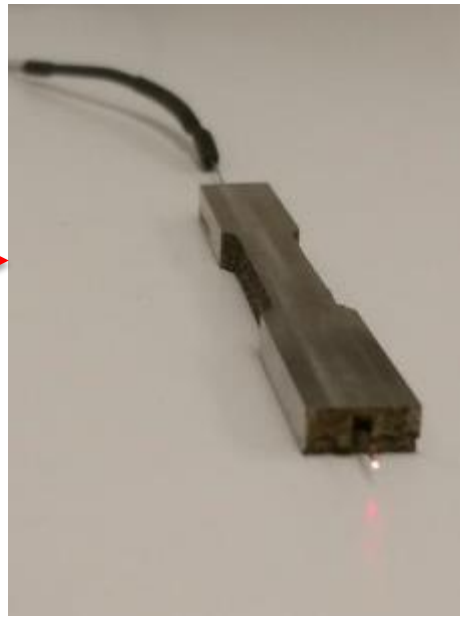


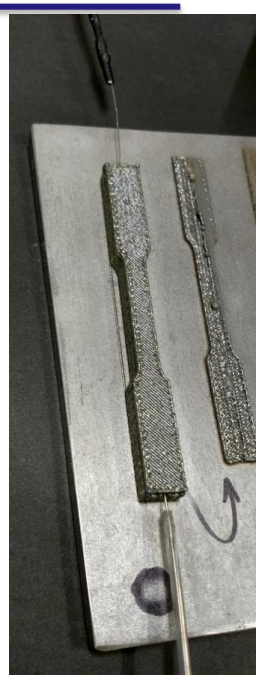


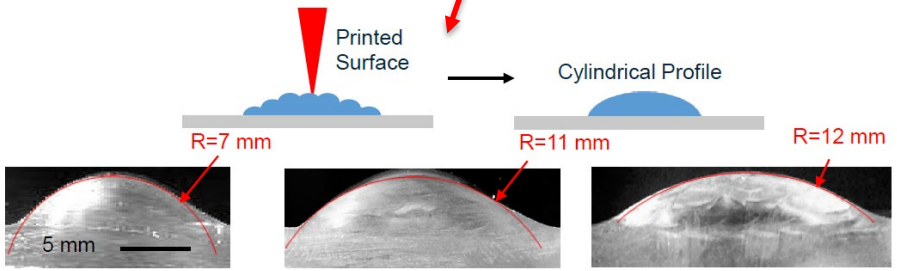


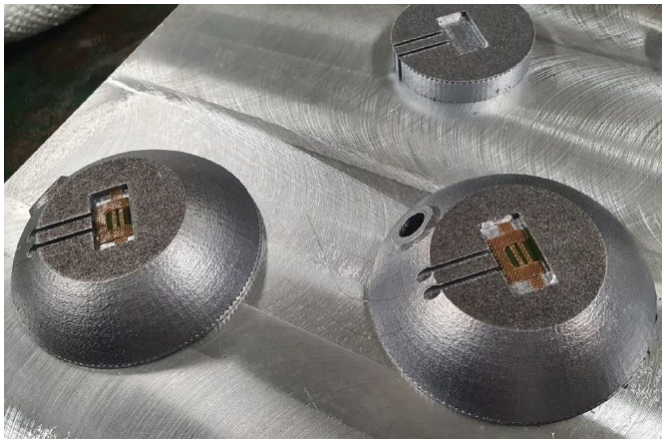
E-1 AM Capabilities & Partnerships

- **University AM Partnerships**
  - **NM Tech (materials testing & characterization)**
  - **Missouri Univ. of Science & Tech. (Embedded fiber optics)**
  - **UTEP Keck Center (Embedded COTS sensors)**
  - **Univ. Notre Dame – Glass AM**
  - **Univ. of Wisconsin – Refractory Metal AM**









AM Processes

ASTM F-42 Classification of AM Processes

Atomic Diffusion

Metal Powder

- **Powder Bed Fusion** (Powder Bed)
  - *Laser Processes*
    - *Selective Laser Melting (SLM)*
    - *Selective Laser Sintering (SLS)**
    - *Selective Mask Sintering (SMS)*
  - *Electron Beam Melting (EBM)*
- **Powder Bed Binder Jetting**** (Powder Bed)
  - *3DPrinting*
- **Directed Energy Deposition**
  - *Coaxial Powder Feed*
  - *Coaxial Wire Feed*

Polymer

- **Vat Polymerization**
  - *Stereolithography (SLA)*
  - *Flash Curing*
  - *Film Transfer Imaging (FTI)*
- **Extrusion**
  - *Fused Deposition Modeling (FDM)*
- **Material Jetting**
  - *Drop-on-Demand (DoD)*
  - *Multijet Modeling*

Lamination

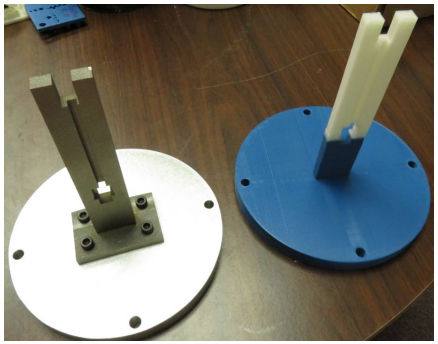
- *Ultrasonic Consolidation (UC)*
- *Adhesive Bonding*

*also polymers

** also ceramics

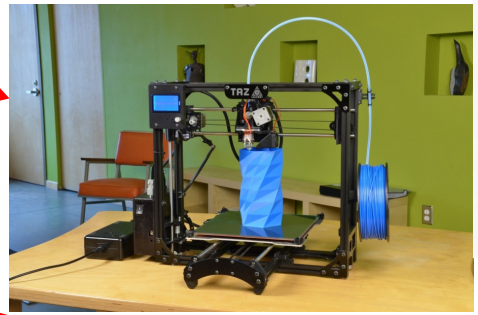
Polymers

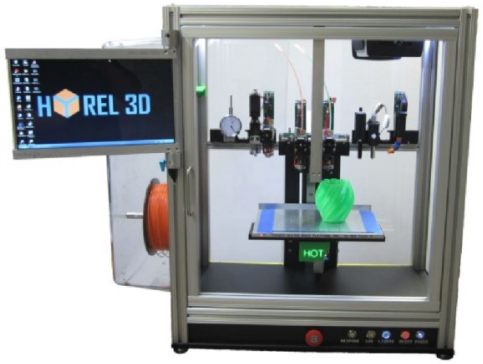
- **Thermoplastic Printers (FDM)**
  - ✓ Closed Source Machines
    - ✓ Dimension 1200ES: ABS
    - ✓ Stratasys F370: ABS, PLA
    - ✓ WASP 3MT: ABS, PLA, ASA, PETG, TPU, Flex (36” diameter by 30” tall print volume!)



Polymers, Ceramics, Soft Materials

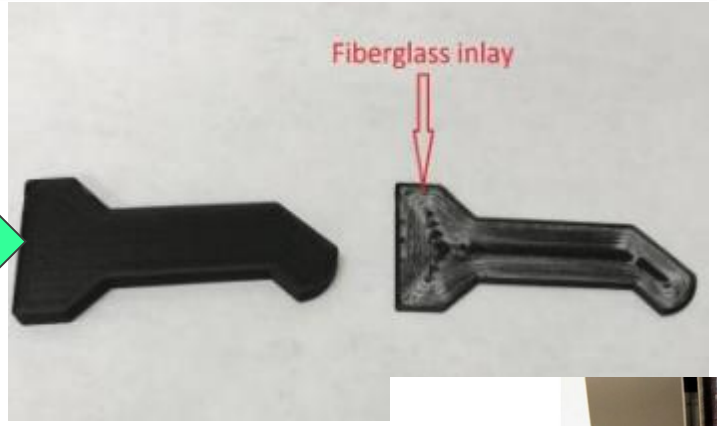
- **Plastic, Ceramics, Silicones, Photopolymerizaton, etc, Printers**
  - Open Source Machines
    - Six Ultimaker S5s: Various Materials
    - Four Lulzbot Taz's (16 polymer types, hard and soft, conductive plastics and metalized plastics)
    - Hyrel 3D and Hyrel 640 (ABS, PLA, Nylon, PEEK, Ultem, Soft flex materials, UV curable materials, conductive plastics, T-Glase, RTV Silicone, Clay, Gels, etc)
    - Deltamaker (ABS, PLA)





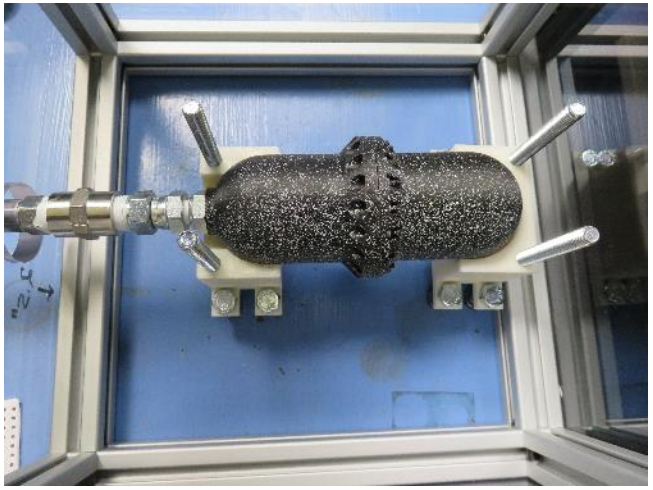
Composites

Markforged Mark 2 & 7

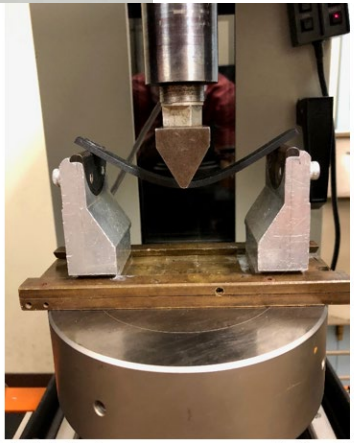


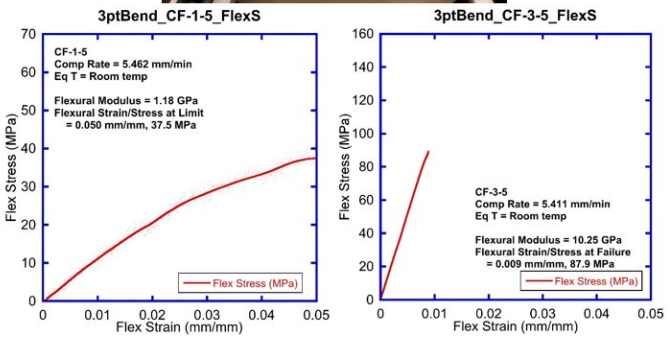
Materials
Onyx
Carbon Fiber
Glass Fiber
Kevlar Fiber

Composite Pressure Vessel



Material Testing
@ NM Tech

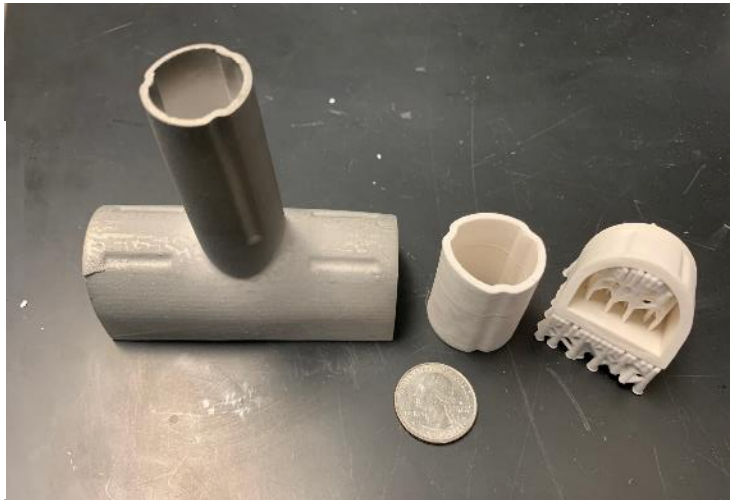


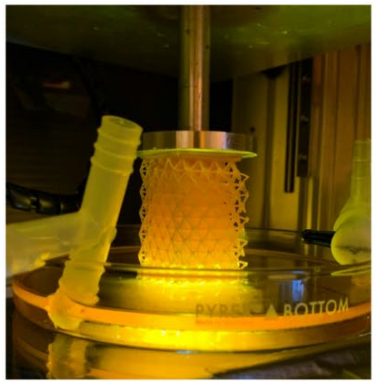


UV Curable Polymers, Ceramics (MPA-11& MST-7)

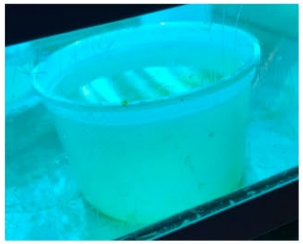
- **SLA**: Asiga Freeform Pro2 & Formlabs Form 2 (many materials and additives)
- **DLP**: GIZMO, Prodways

Doping Materials: Heat Shields, Radiation Shields, Internal Passages

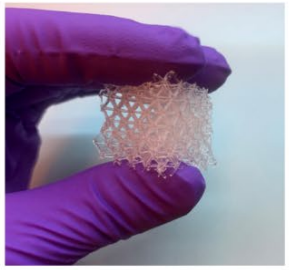


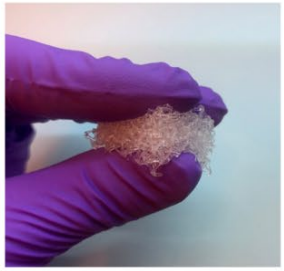


1: DLP printing of ridged polymer part



2: Post-processing of polymer part

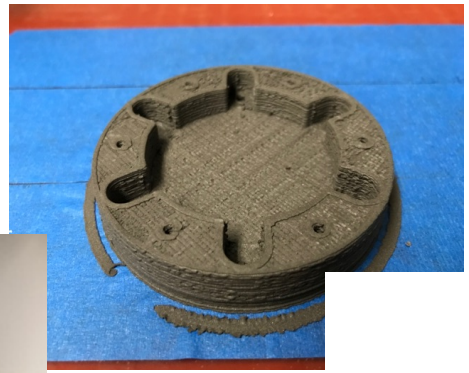


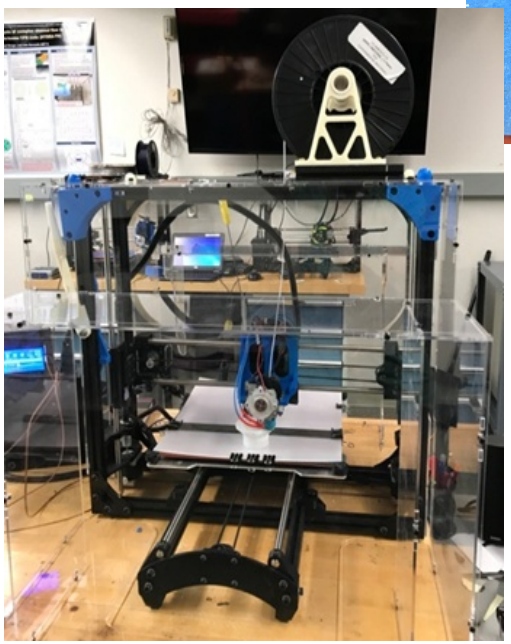


3: Resulting pure silicone lattice exhibiting excellent compliance

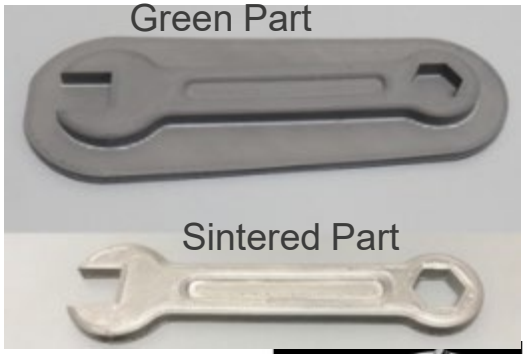
Metal Atomic Diffusion (metal particles in polymer filament)

FDM – Tungsten, steel, brass, copper in PLA (many other metals coming soon)

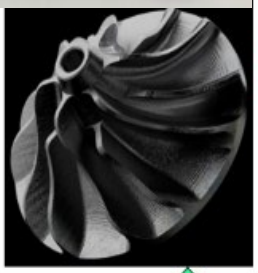




Markforged Metal X



Metals
SS316
SS17-4
IN 625
Ti-6Al-4V
Copper
Tool Steels

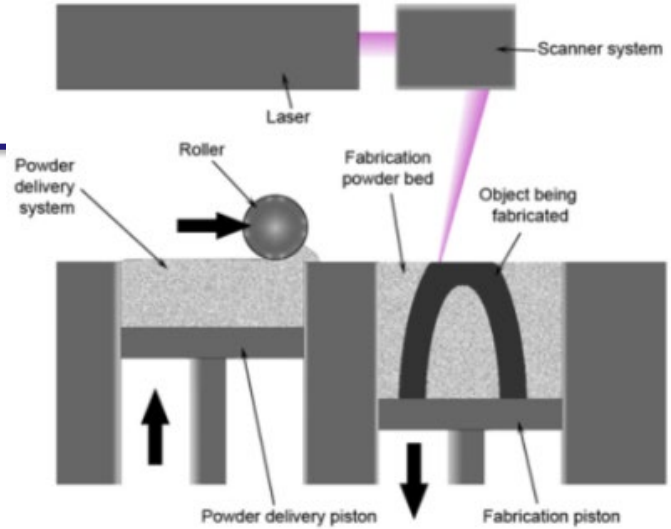


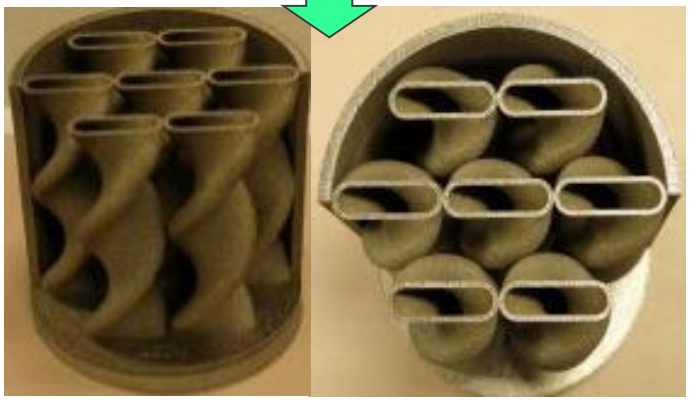
Finished Part

FDM Print Wash Furnace Sinter

Metals

- **Direct Metal Laser Sintering**
  - Laser melting metal powder bed (partner with Sigma, KCNSC, MU S&T, Keck Center, Stratasys, Elementum)
  - Materials: Stainless Steel (PH1), Inconel (IN625), Aluminum (AlSi10Mg, 6061-T6), Titanium (Ti64, 5333), Refractories
- **Powder Feed**
  - Partner with MU S&T



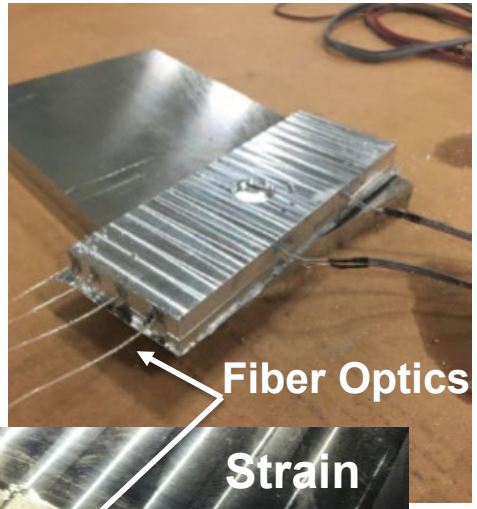


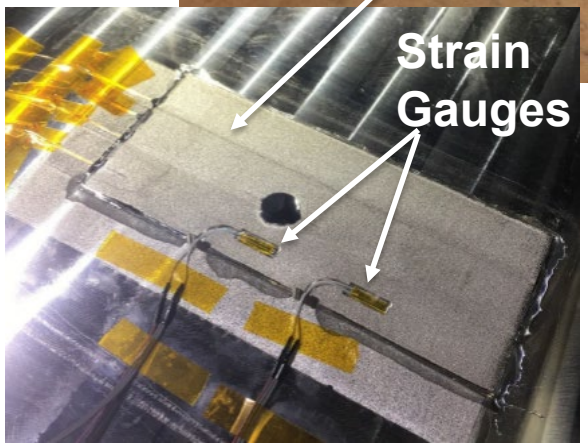
Metals

- **Ultrasonic Welding Metals (foils joined in low temperature process)**
  - Partnered with Fabrisonic and ORNL.
  - Avoids large heating in more traditional metal AM
  - Materials: almost every sort of metal foil and in many combinations

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo Alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

● Material pair proven for ultrasonic welding

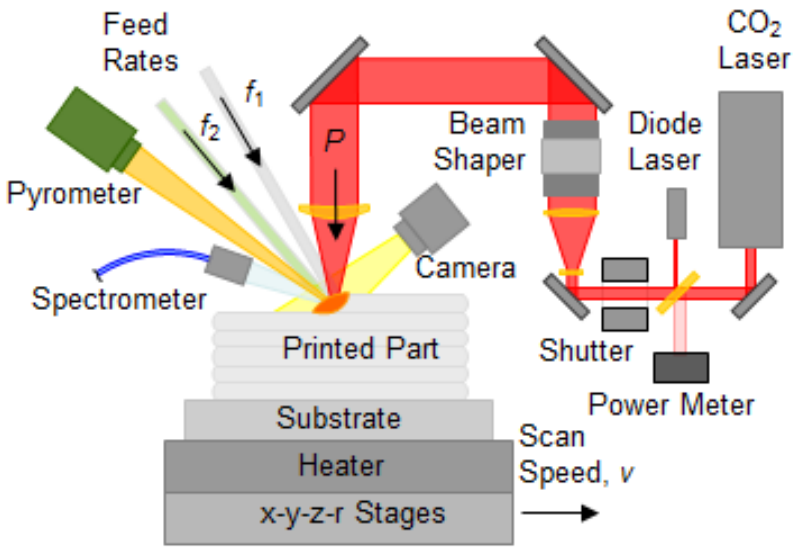


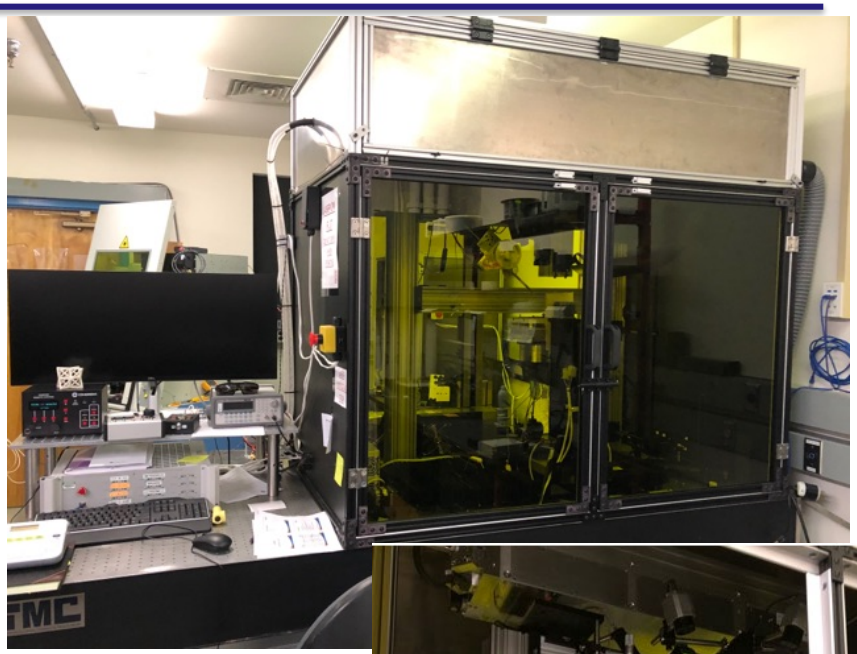


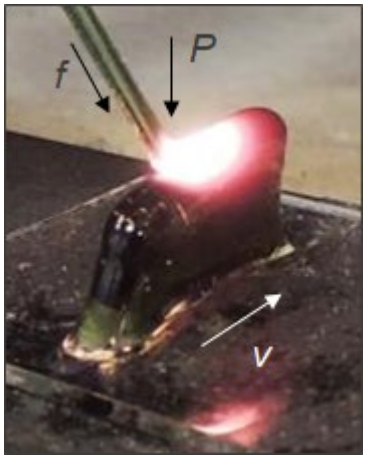
https://fabrisonic.com/gradient-material-solutions/

Glasses and Ceramics

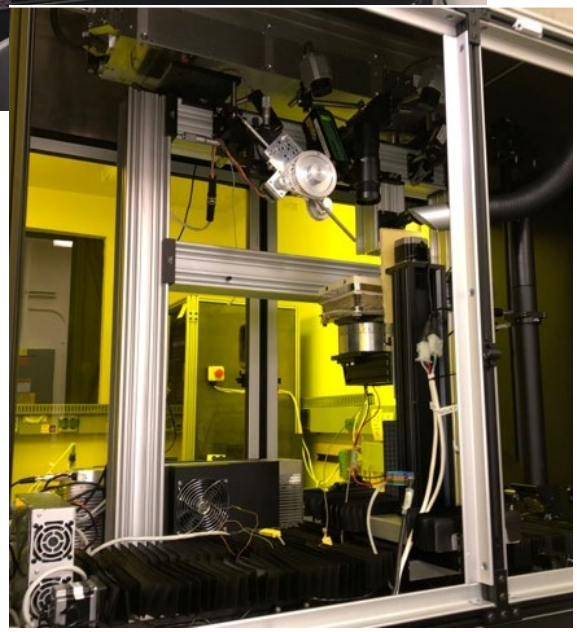
Laser Melting







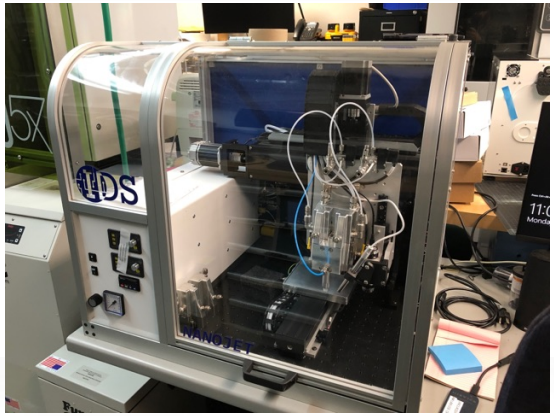
- Manipulating Fiber Optics
- 3D Printing Optical Elements
- Embedding FOCs in Metal Parts
- 3D Printing Glassware

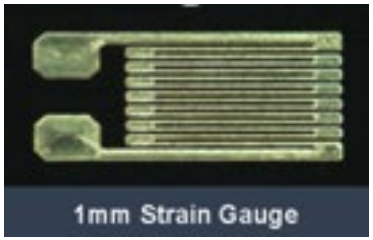


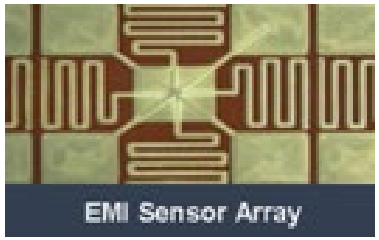
Aerosol Jet

Two Machines (IDS {3x} & Optomec unit):

- Dielectric Components
- Integrated Conductive Traces







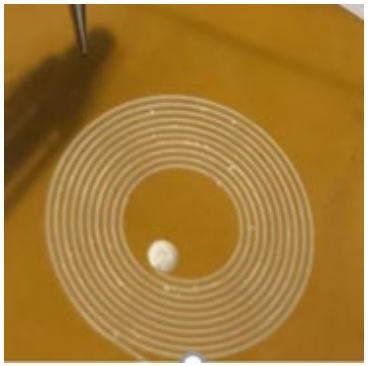
- Feature sizes from 10 microns to millimeters
- Print thickness from 100 nanometers to 10's of microns
- Conformal printing on non-planar and 3D surfaces
- Print interconnects and active/passive components
- Print using commercially-available materials
- Print on plastic, ceramic, and metallic substrates
- Scalable to support high-volume production requirements

Hybrid AM Machine

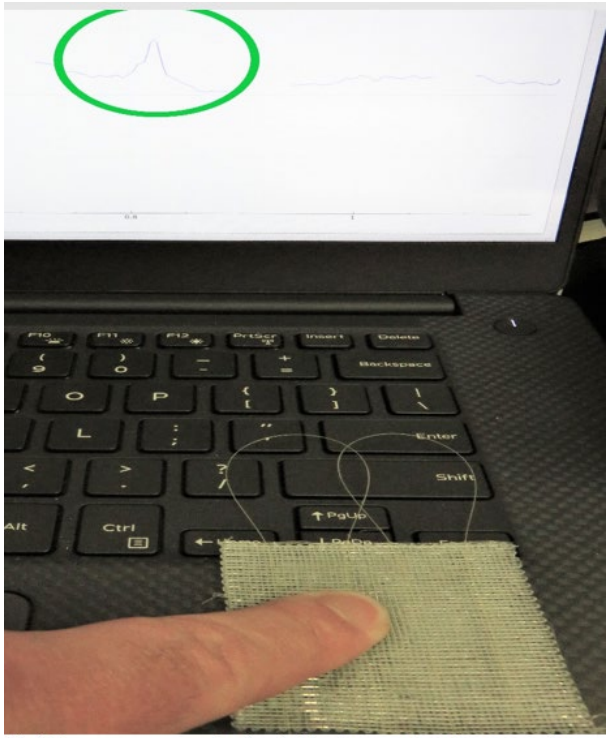
ShopBot CNC Machine Modified:

- 5 axis 3D printing (print on curved surfaces)
- 3D print lattices from composites
- Aerosol printing of electrical traces
- 3D printing soft materials
- Embedding sensors in 3D prints

AM Antenna Wire



Fiber Strain Gauge in AM Flex Pad



Current AM R&D

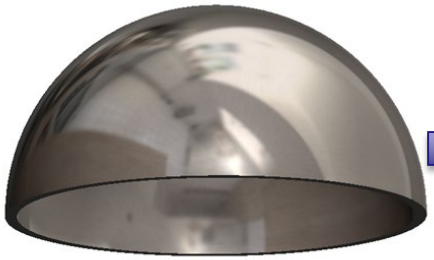
Additive Manufacturing R&D Efforts

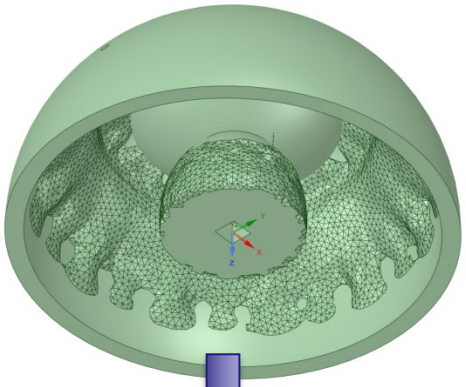
- Tunable, Instrumented, Mechanical Structures
- Shock Absorbing Structures
- Glass Structures
  - Chemical Processing Equipment
  - Optical Components
- Embedding Sensors in 3D prints
  - Fiber Optics
  - COTS Sensors
- Tamper Evident Containers
- AM Machine Development

Tunable, Instrumented, Mechanical Structures

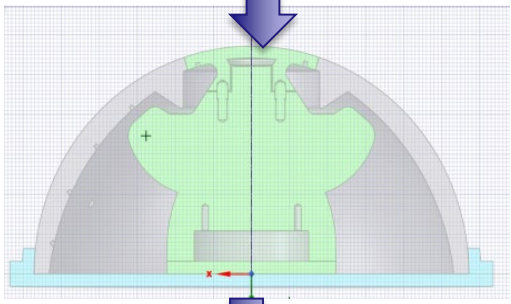
- **Design and build mechanical structures with targeted mass properties as well as mechanical response characteristics (modal frequency and shape, stiffness, temperature distribution).**

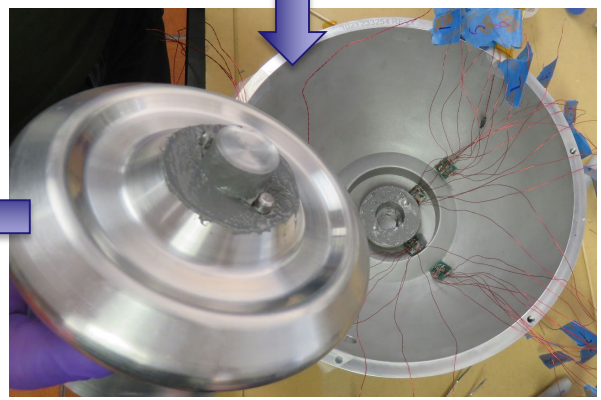
Steel Hemisphere

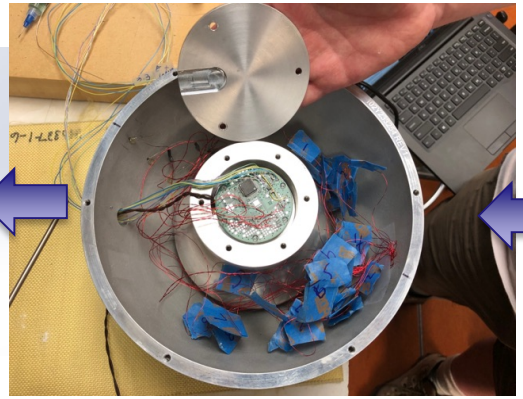




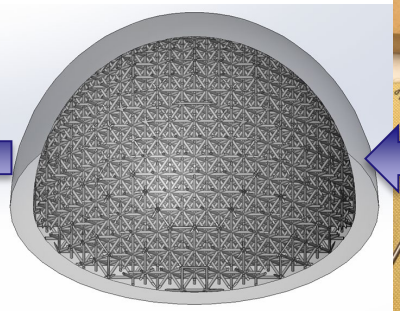
Aluminum Solid Mechanical Mock

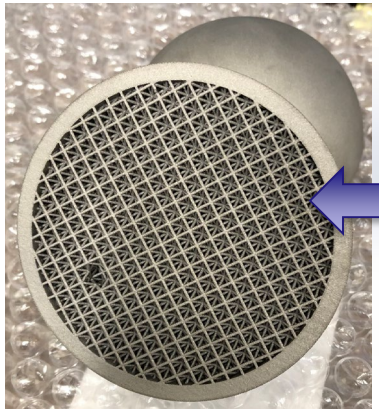






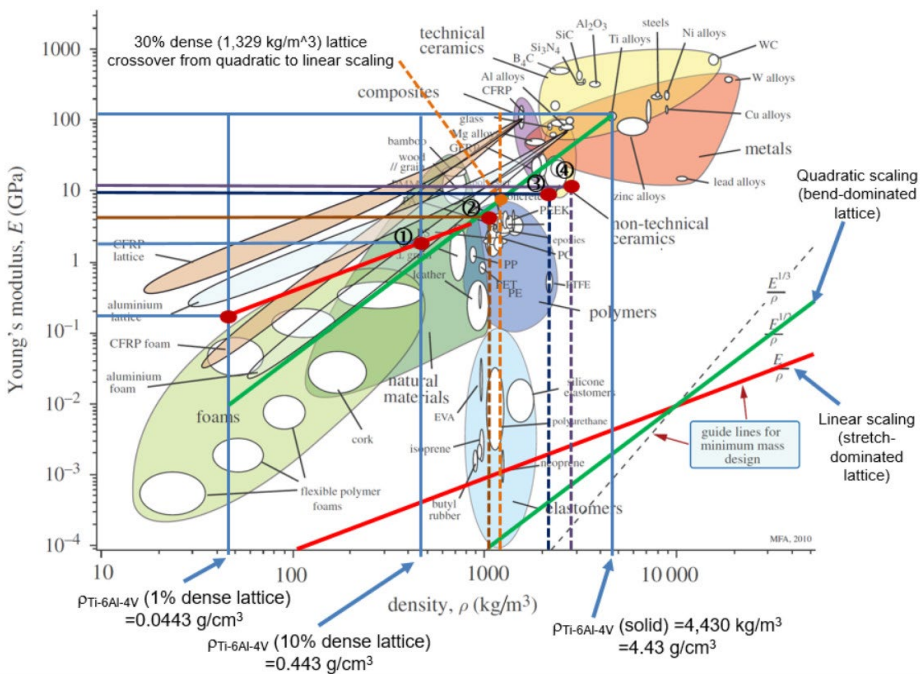
Aluminum Lattice Filled Mechanical Mock





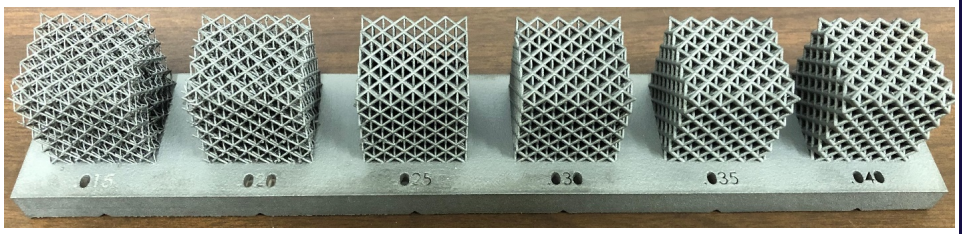
Tunable, Instrumented, Mechanical Structures

- **Lattices provide great flexibility in obtaining apparent mechanical properties while maintaining control of mass properties**

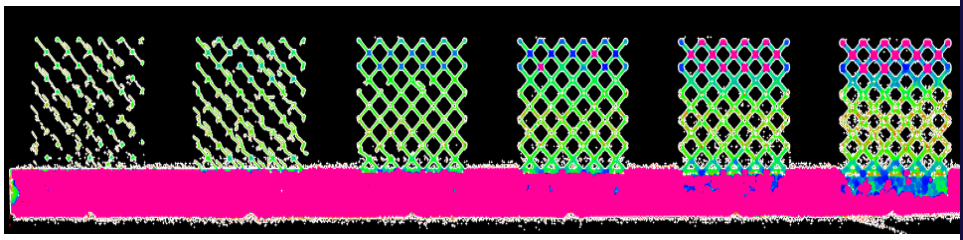


Move about on Ashbe chart with lattices

Replace 4 material components with 1 material conformal lattice



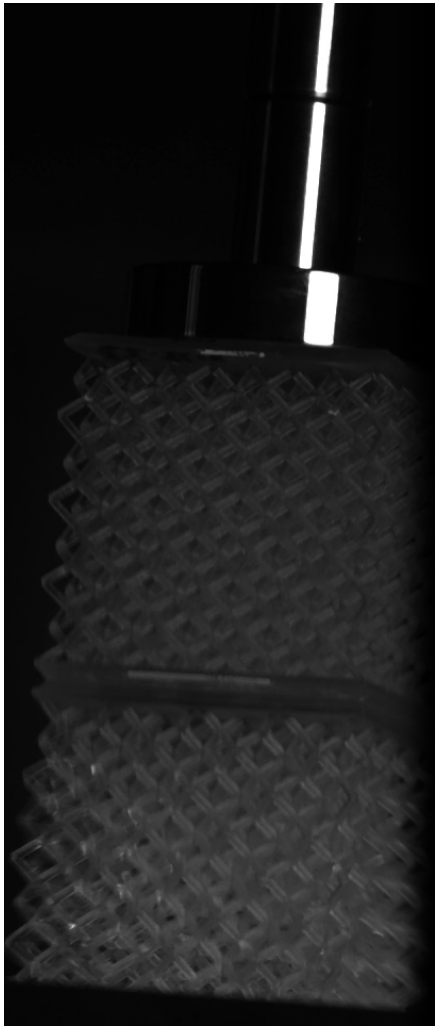
3D Printed titanium octet lattice cubes ranging in strut diameter from 0.015" to 0.040" in 0.005" increments

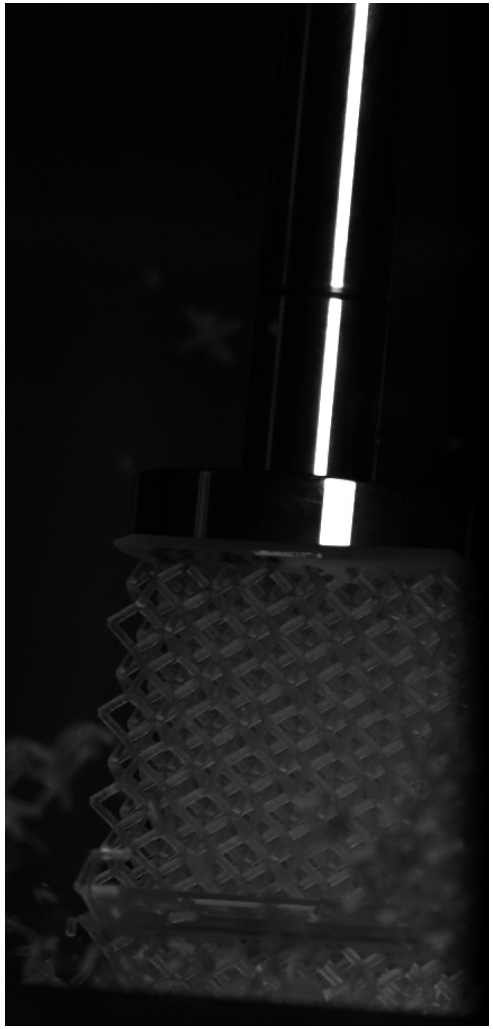


CT Scan of central plane in lattice cubes, minimal viable strut diameter = 0.025”

Shock Absorbing Structures

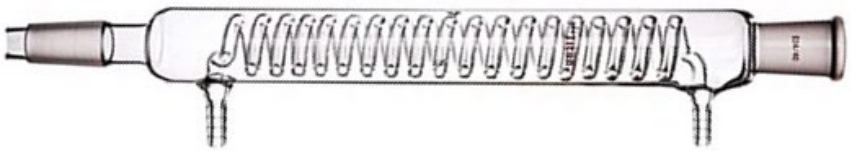
Drop Tower



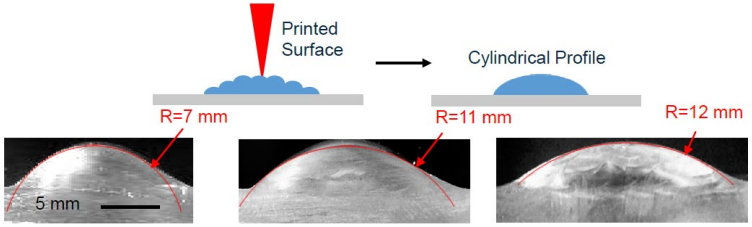


Glass Structures

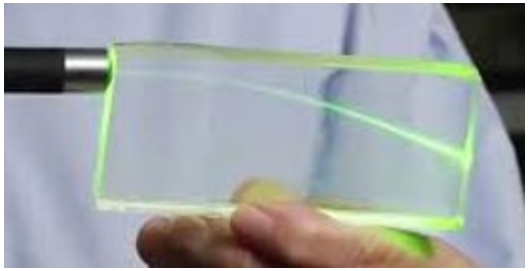
- **3D Print chemical processing hardware to replace expensive glass blowing and custom manufacturing methods.**



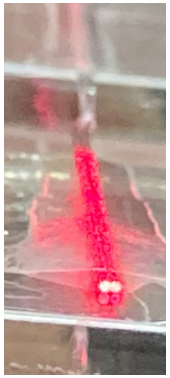
- **3D print optical elements**
  - **Lenses with constant index of refraction**



  - **Lenses with gradient index of refraction**



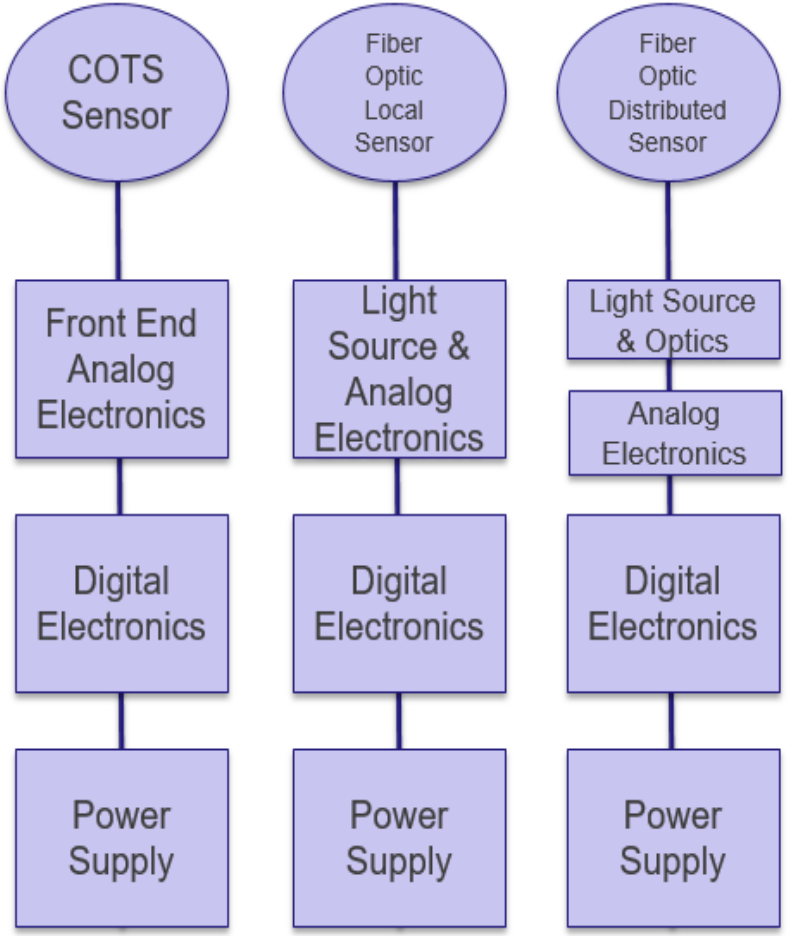
  - **Fiber optics for sensing, data, and power transmission**



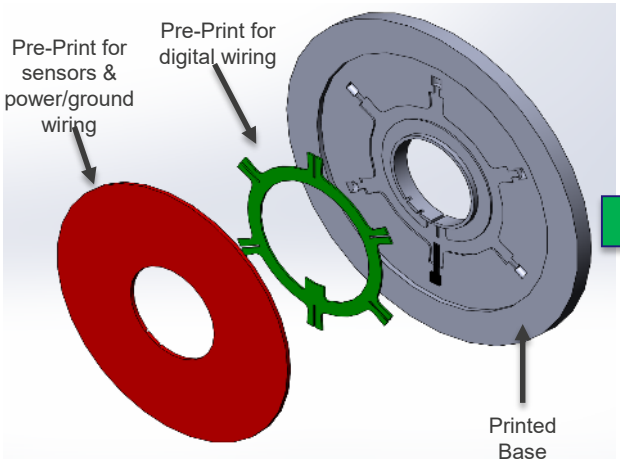
  - **Requires:**
    - **Setting up GLAMS**
    - **Thermal model of AM process**
    - **Optical design**
    - **Developing diagnostics and feedback control system**
    - **Glass synthesis, feed-stock production research**
    - **Developing optical characterization station**

Embedded Sensing in AM Parts

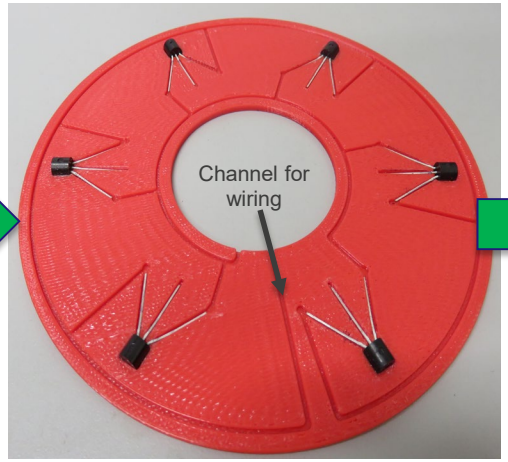
- Develop common electrical architectures for embedded sensors
- Share efforts with Delivery Environments
  - SRP – few sensors, low power, SOH, long duration
  - DE – many sensors, mid power, env. Testing, short duration
- Need to identify sensors, ranges, data frequency, etc (see next slide)
- Three paths for Additive Manufactured Embedded Sensing being investigated
  1. Commercial off the shelf (COTS) sensors
  2. Fiber optic local sensor
  3. Fiber optic distributed sensor
     - Rayleigh Backscatter
     - Fiber Bragg -Grating
- Build and test functional demonstration articles for a subset of these sensors and electronics



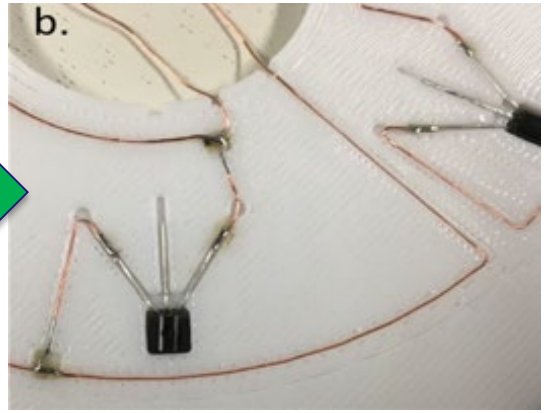
Embedded Sensing – COTS in Plastics



Exploded View of temperature array assembly

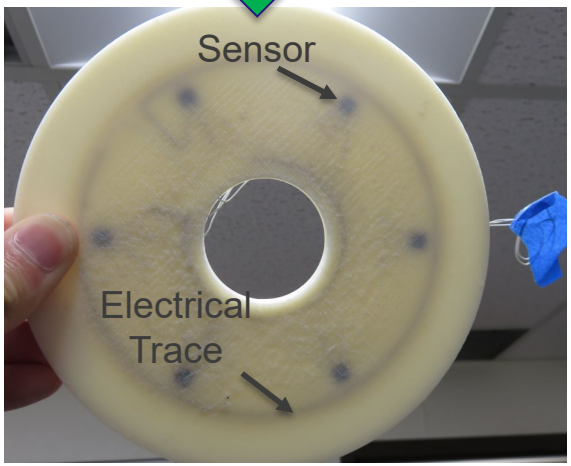


Pre-Print for sensors & power and ground



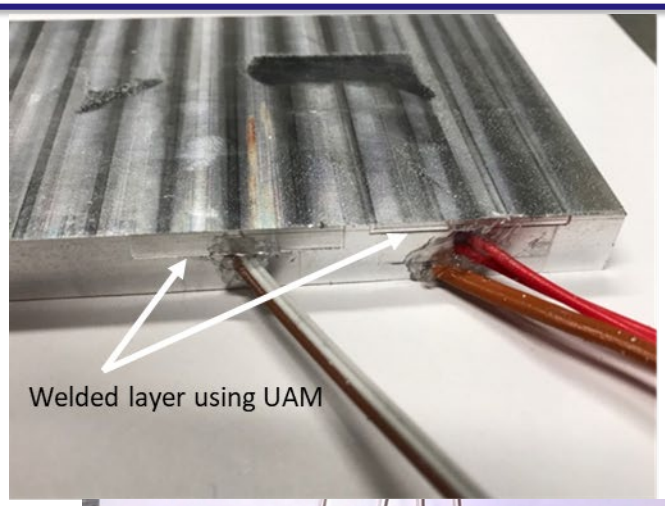
3D Printed Electrical Traces

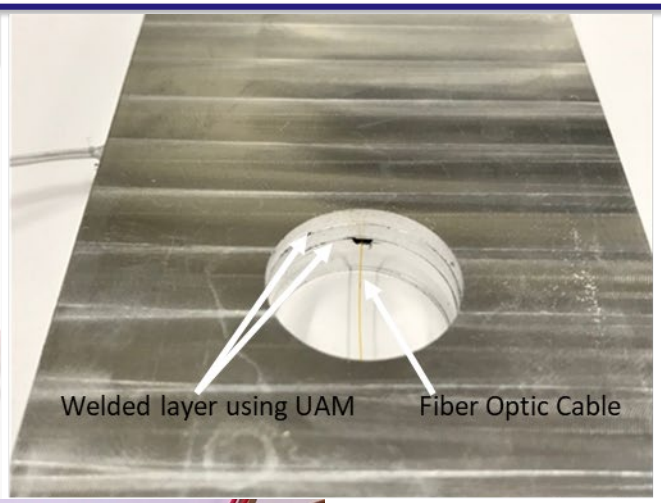
3D Printing Wire in Plastics @ Keck Center



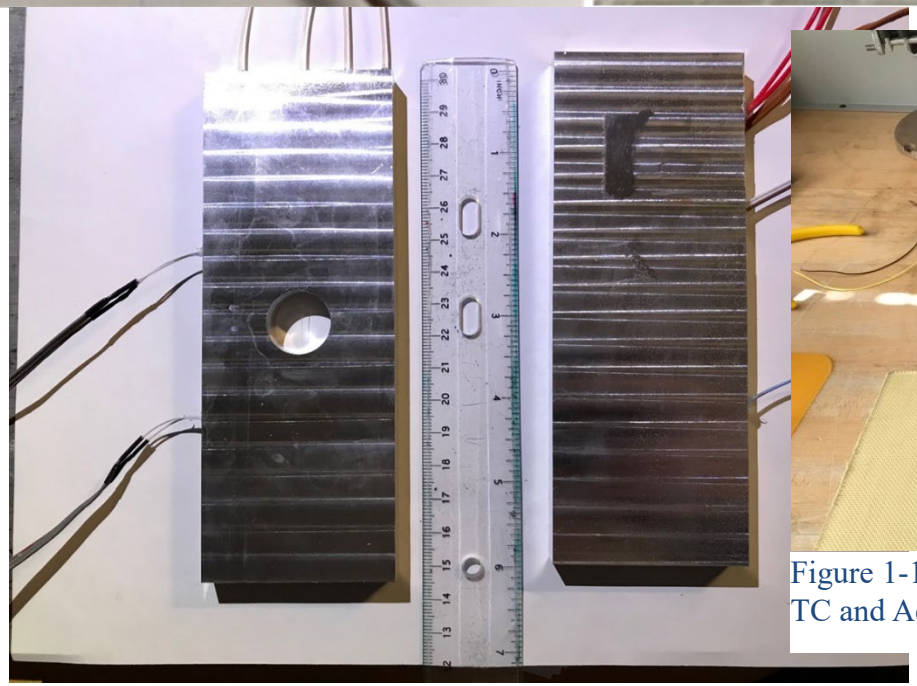
Complete Assembly

Embedded Sensing – COTS & FOCs in Metals





Sensors Embedded in AM Ultrasonically Welded Aluminum Part



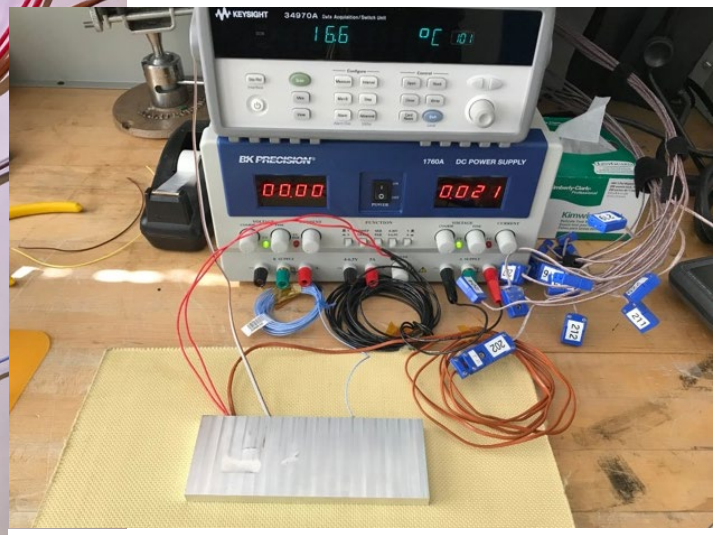
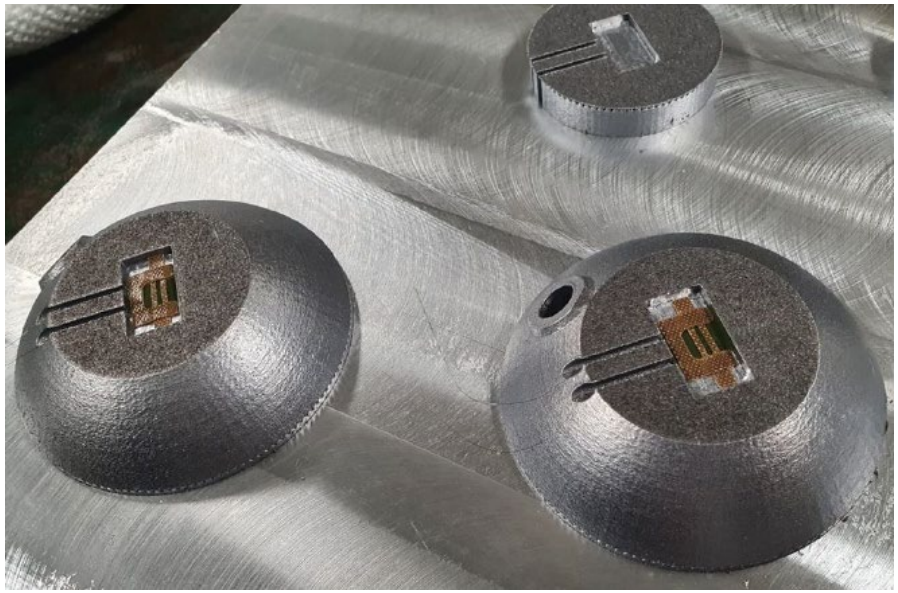


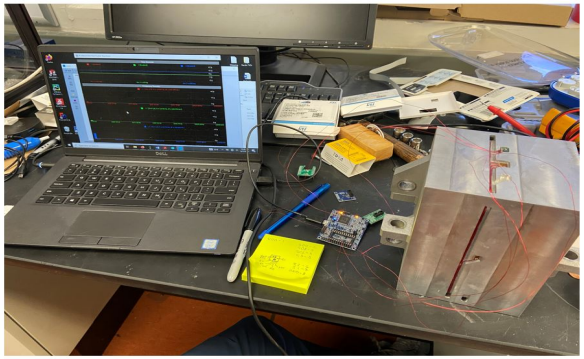
Figure 1-1: Test setup of FABRISONIC part containing RTD, TC and Accelerometer.

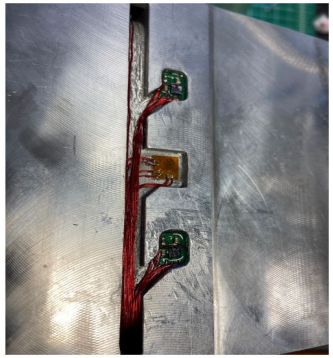
Embedded Sensing – COTS in Metals

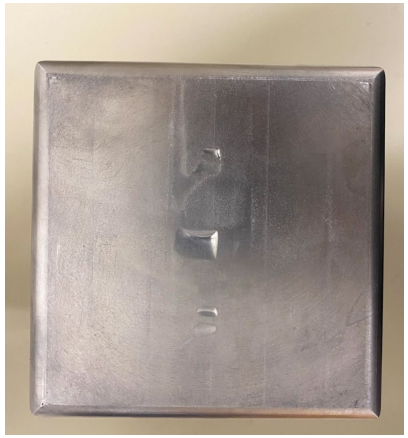
Strain Gauges In DMLS Parts

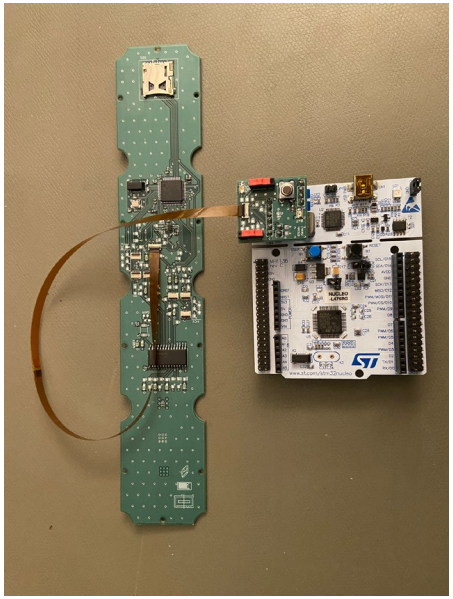


Strain Gauges & Accelerometers In UAM Parts



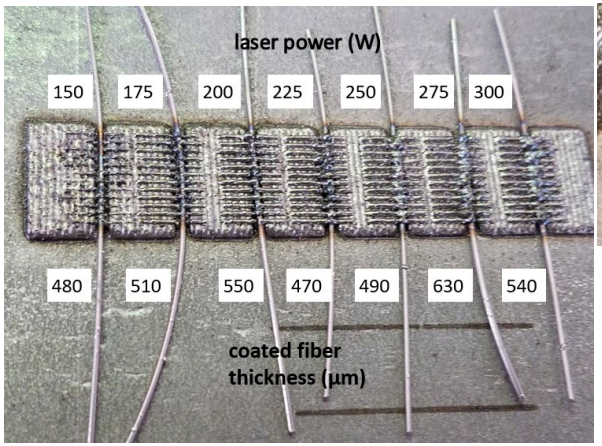


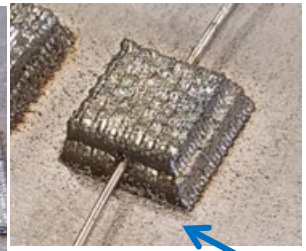




Embedded Sensing – Fiber Optics in Metals

Embedded FOC: AM Metal & Plastic





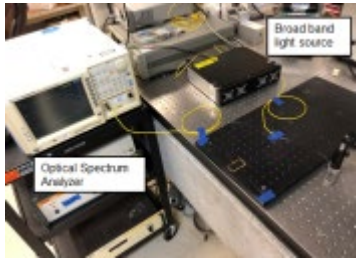
Contracts with MU S&T

Sensor Development

Partner with W-2

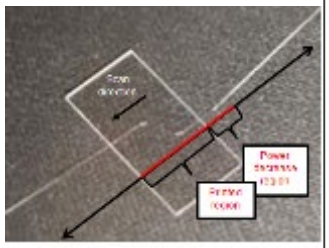
- Strain, Temperature,
- Acoustics, Load, Pressure
- Chemical
- Power Transmission

Fiber Splicing, Connectorizing, Characterizing



GLAMS (Laser AM of FOCs)

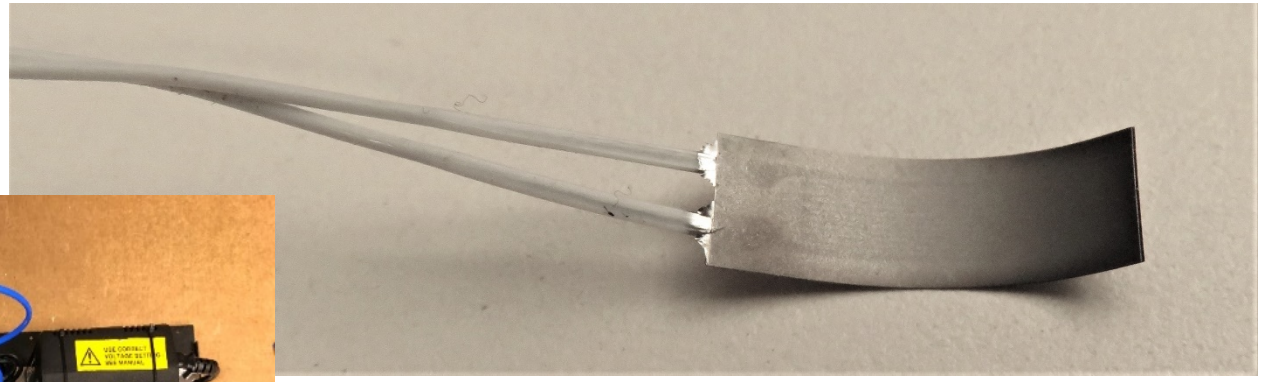
Partner with Q6 & MU S&T



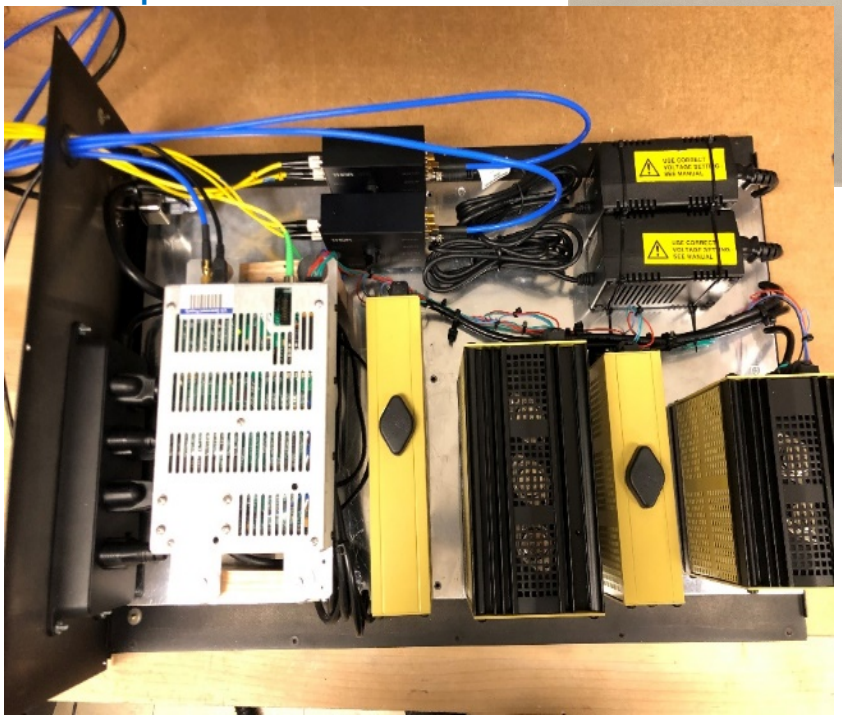
Measurement Systems (Developing Custom machine)

Embedded Sensing – Sensor Development

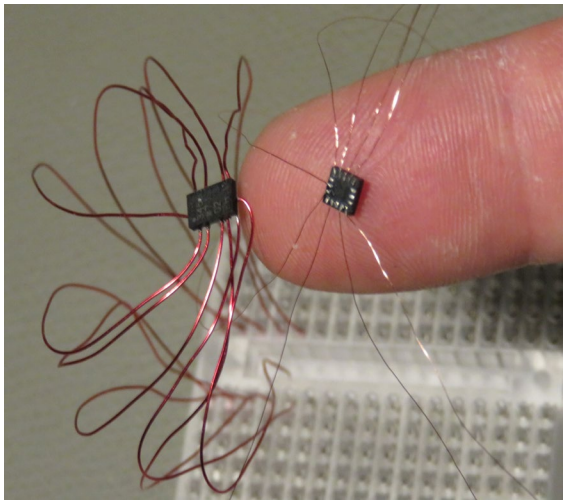
Resistive strain sensor ion sputter coated in palladium/gold alloy for hydrogen gas detection. Can also be done with optical fibers.



Flexible FOC Optical Detection System Developed with MU S&T

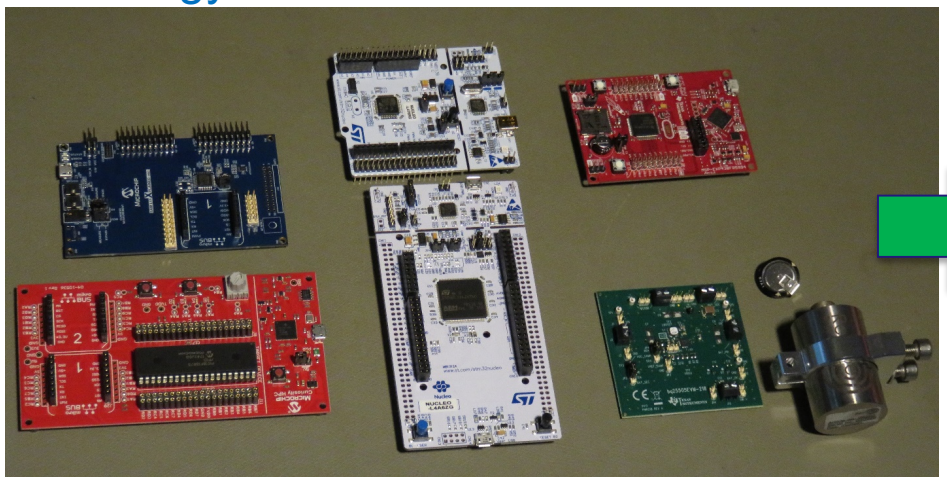


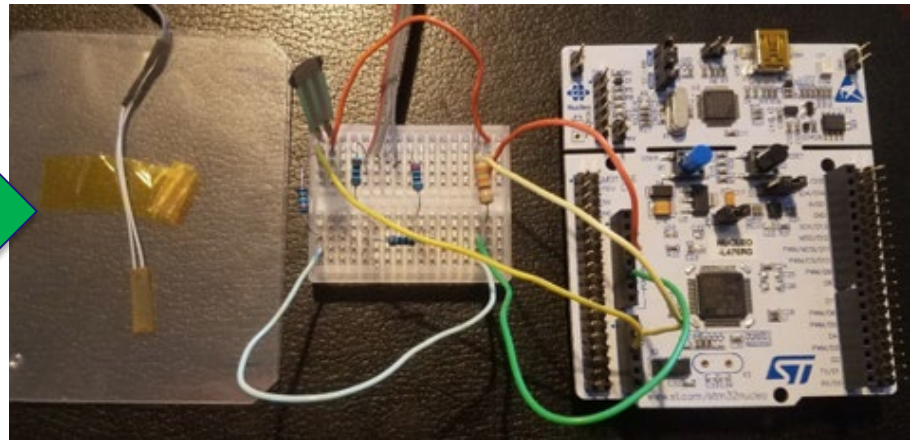
Miniature Processors & Sensors



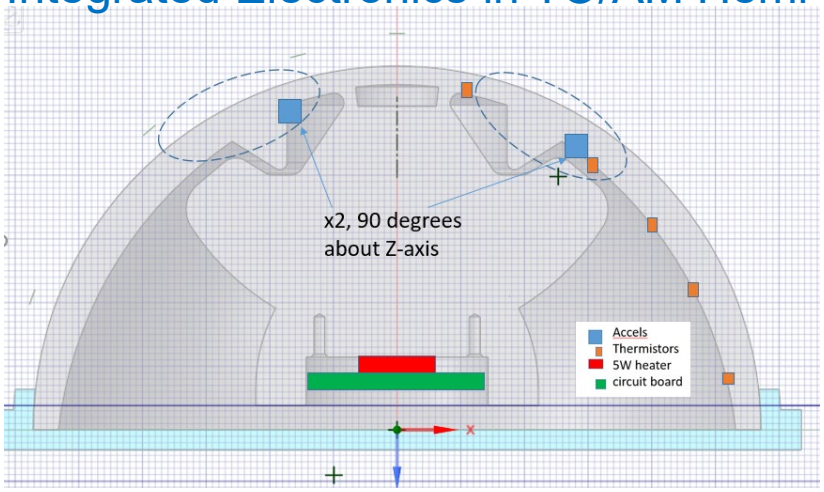
Embedded Sensing – Miniaturize Data Acquisition

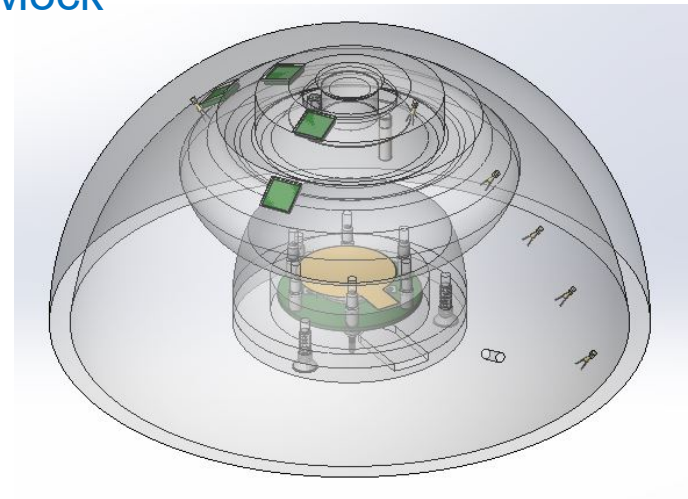
Micro-electronics Integration with Batteries & Energy Harvester



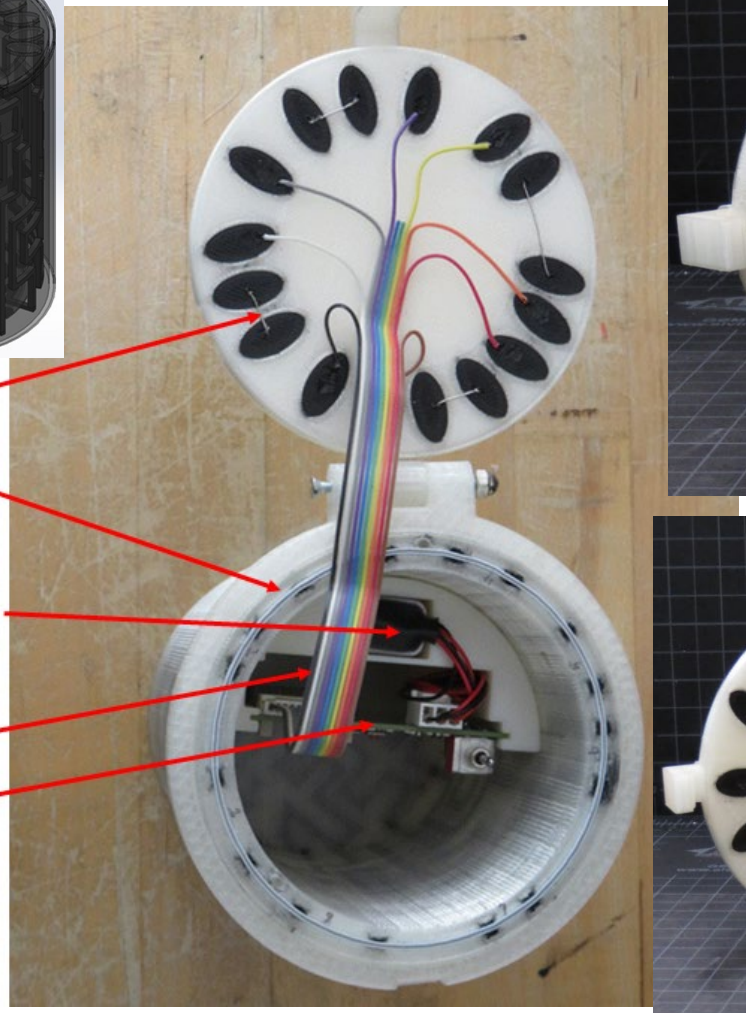


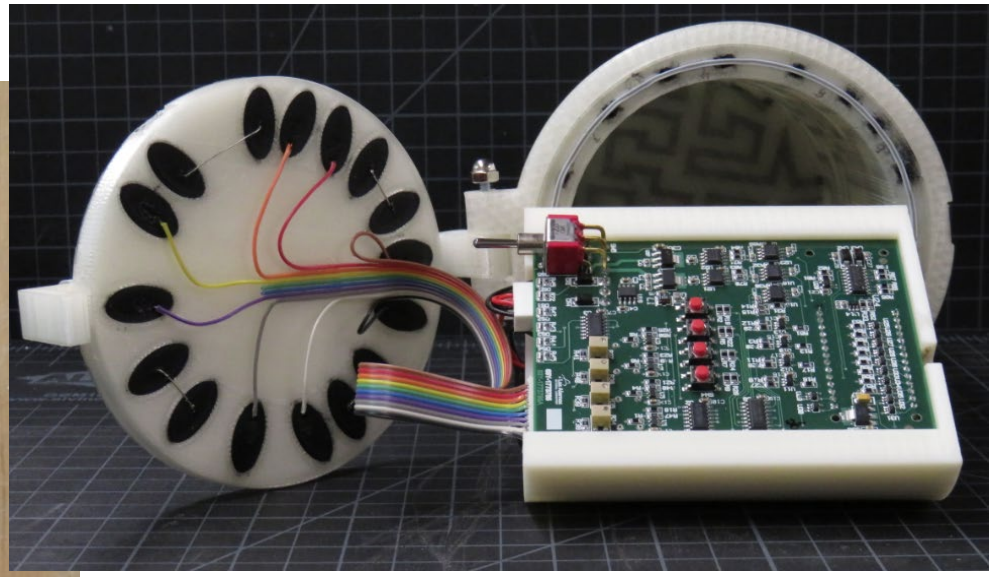
Integrated Electronics in TO/AM Hemi Mock

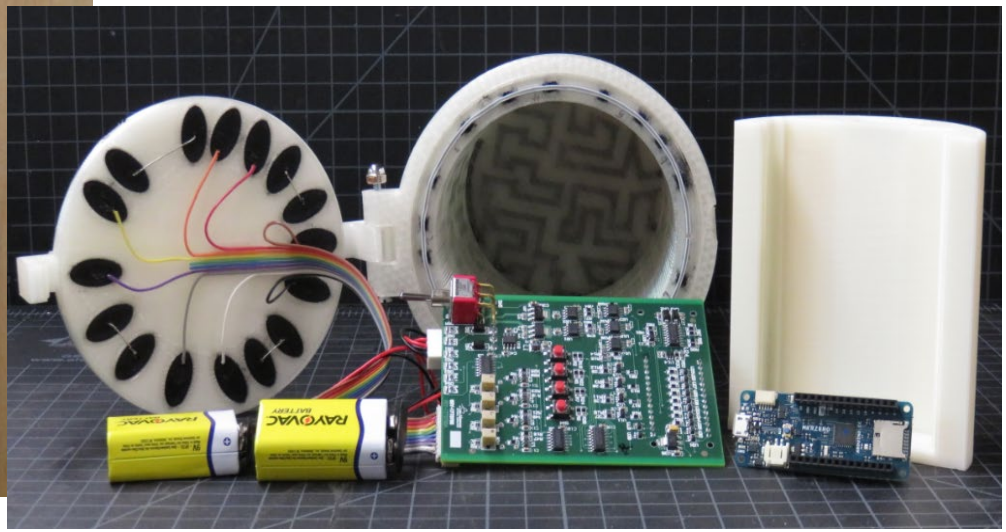




AM Tamper Evident Container – Conductive PLA Traces in Non-conductive PLA

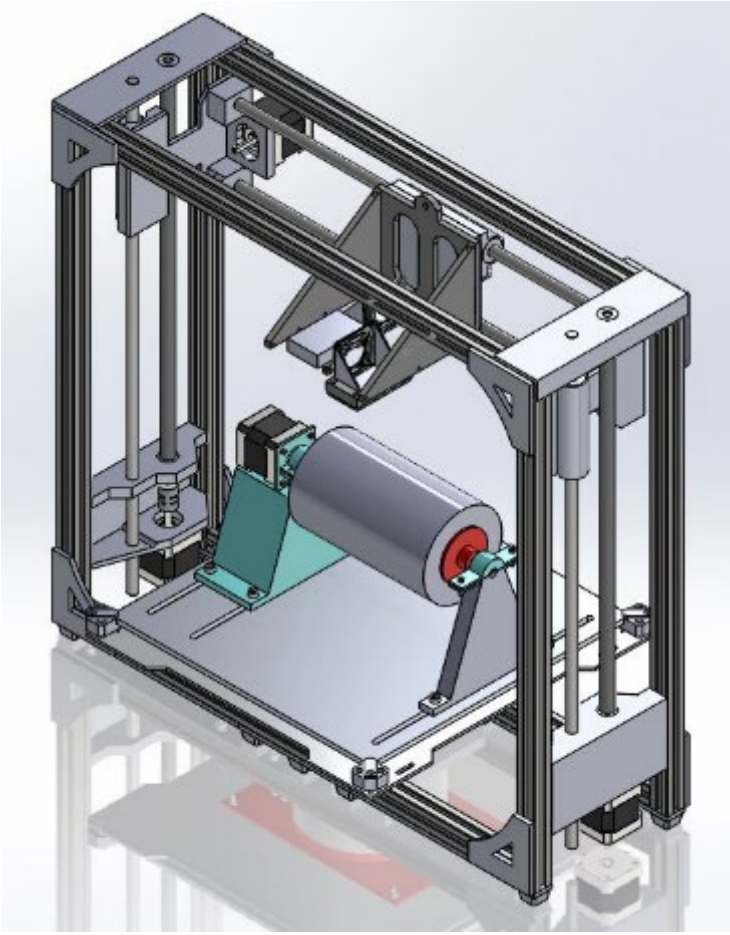


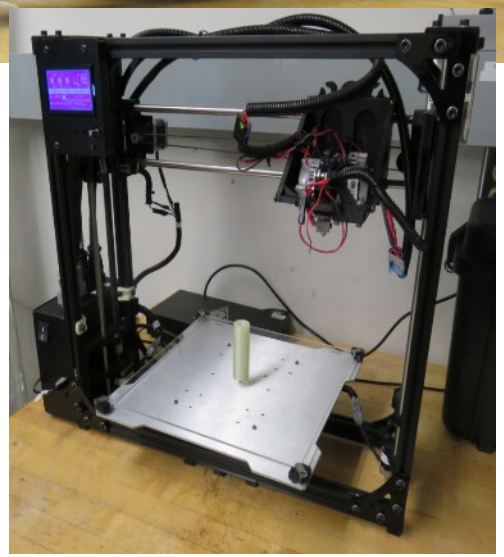




AM Machine Modifications for Advanced Printing

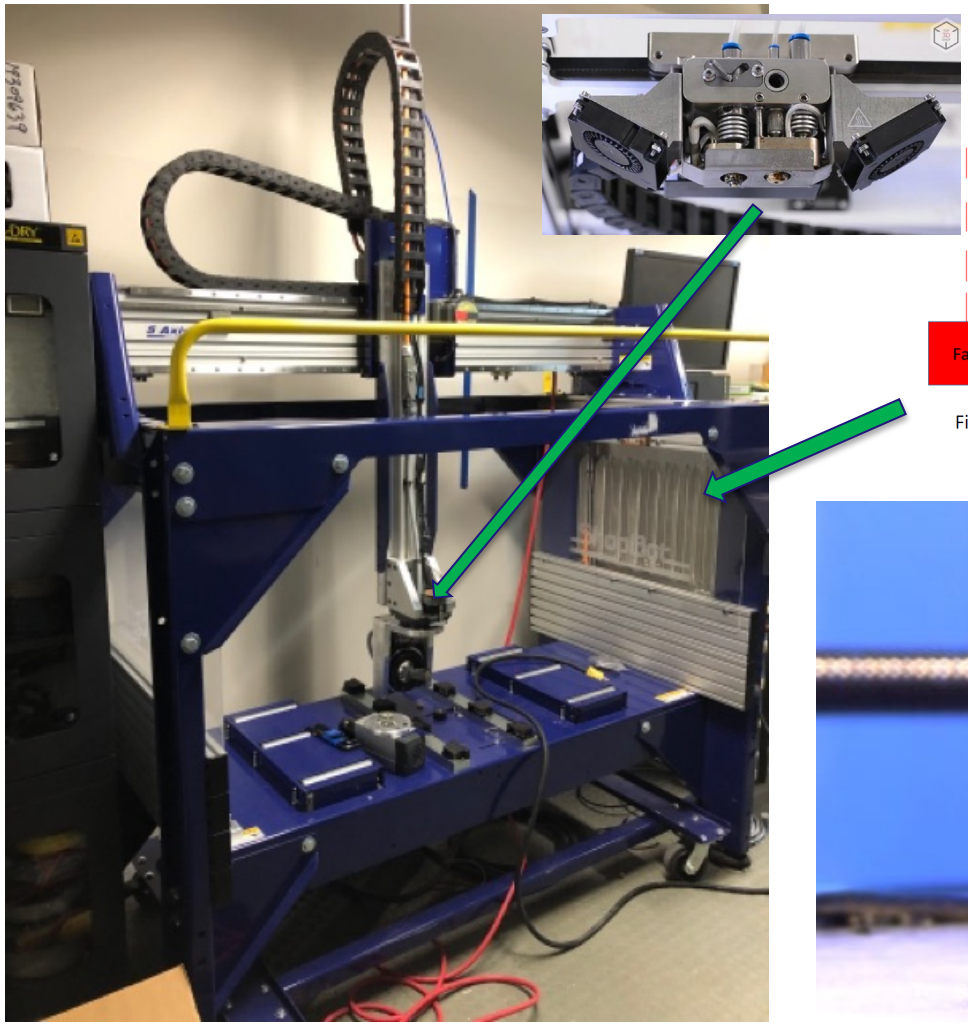
Horizontal and Vertical Rotational Stages





AM Machine Modifications for Advanced Printing

Modifying 5 Axis CNC Machine for Continuous Composite True 3D Printer



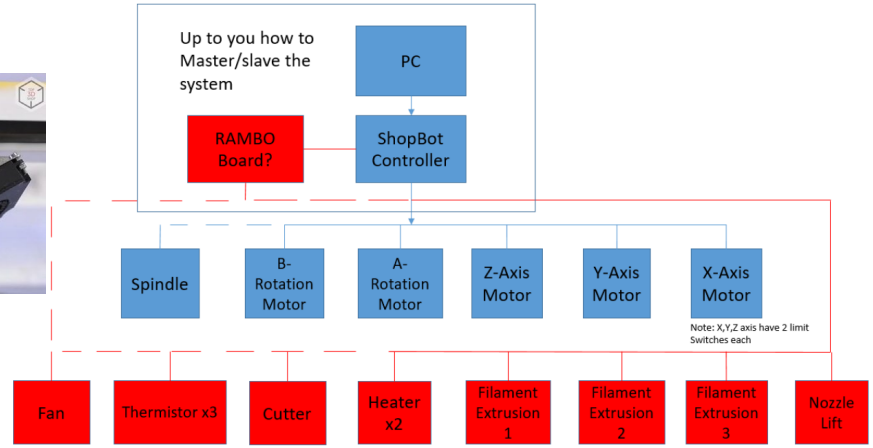
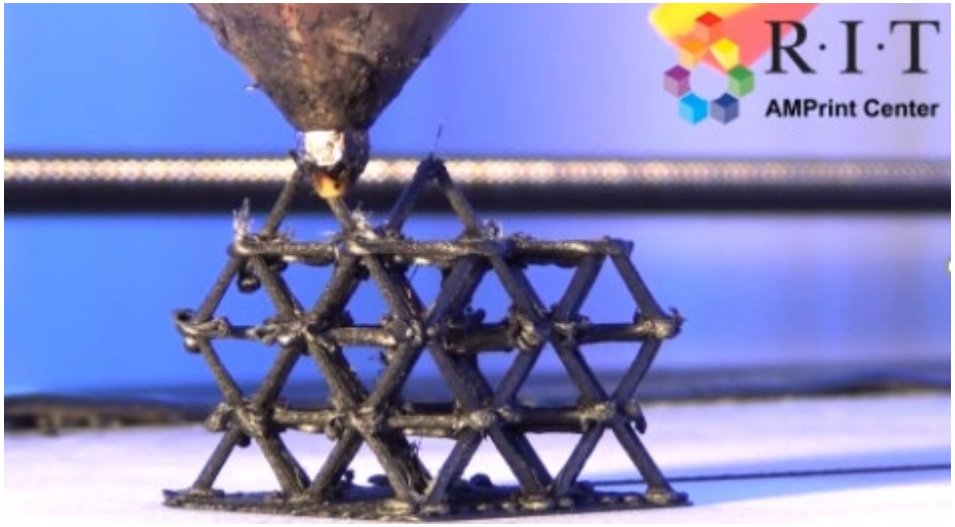


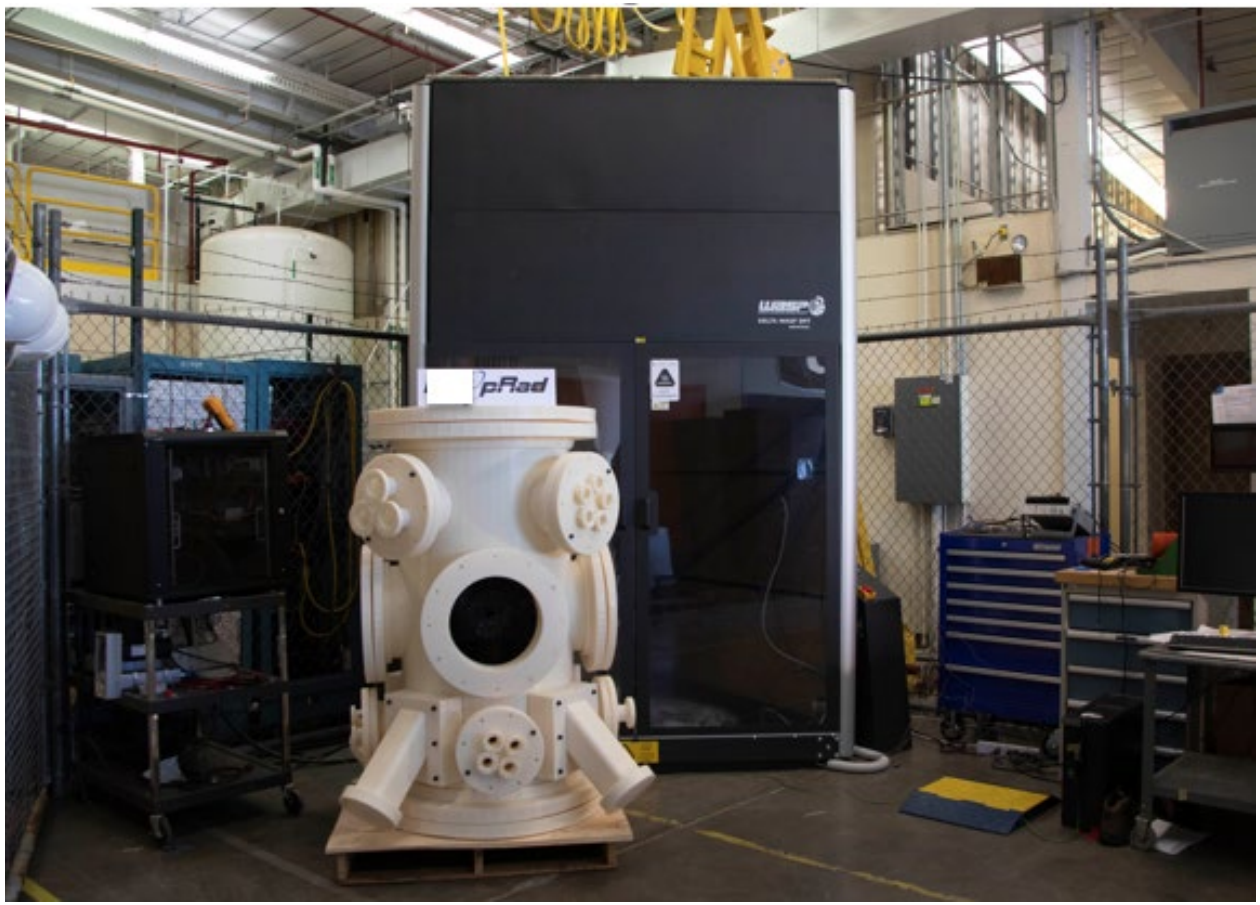
Figure 2: Box diagram of components of the system. Blue corresponds to the components of the ShopBot system and red corresponds to the components of the extrusion head.

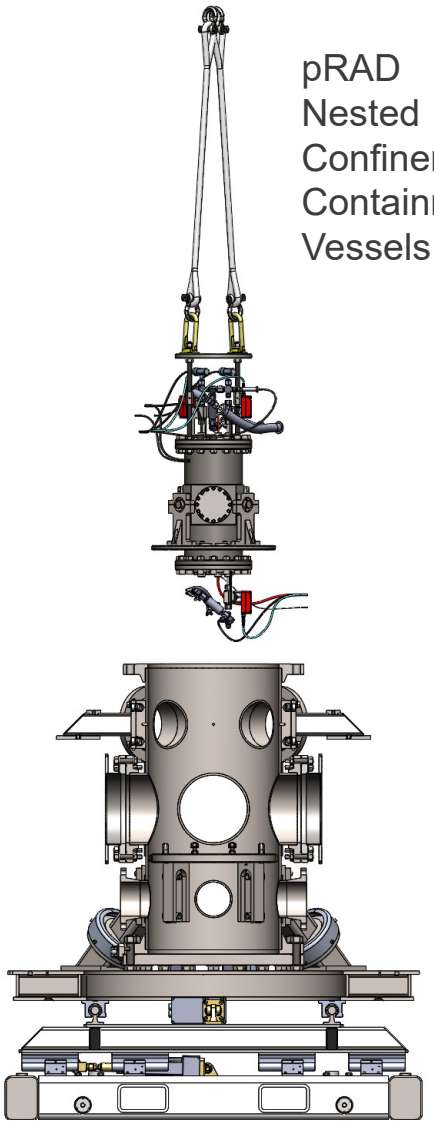


Various Project Examples

Large Scale FDM

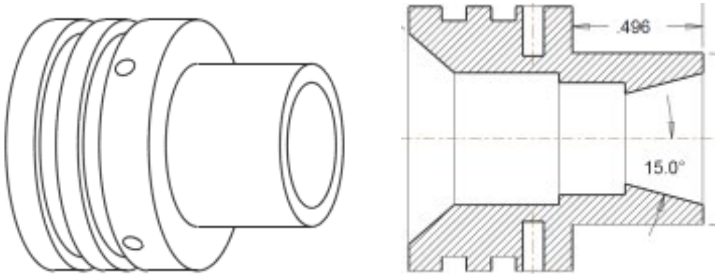
WASP Delta FDM Machine Print Volume 36” OD and 30” T



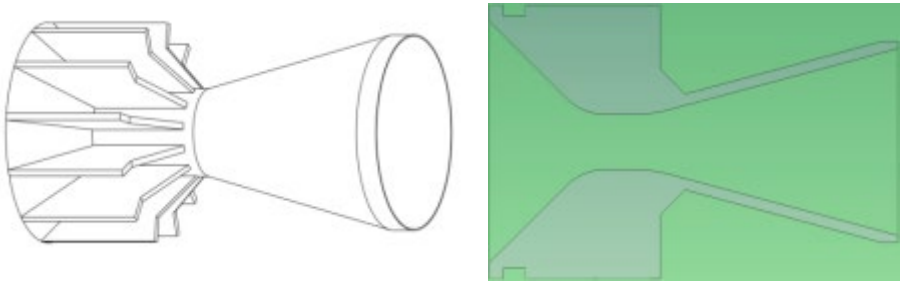


pRAD
Nested
Confinement &
Containment
Vessels

Design for AM – An Example



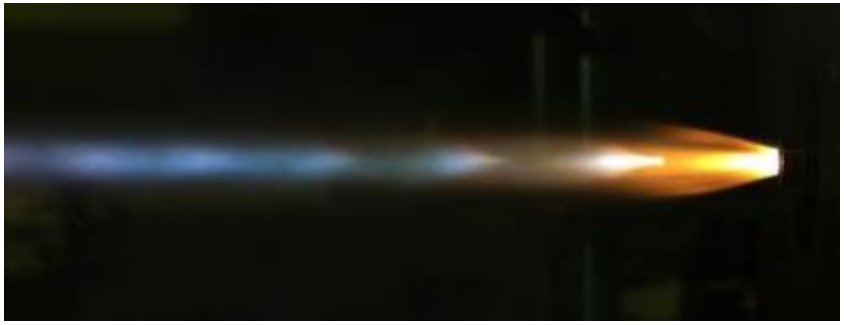
Original Nozzle Design for
Standard Subtractive Manufacturing



Modified Nozzle Design for
Additive Manufacturing

Rocket Nozzle
Prior to Firing Test

Firing Test Conducted at LANL

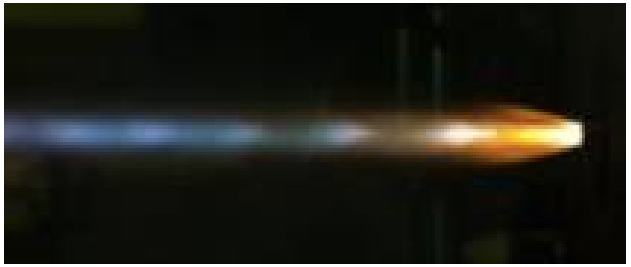


Rocket Nozzle
After Firing Test

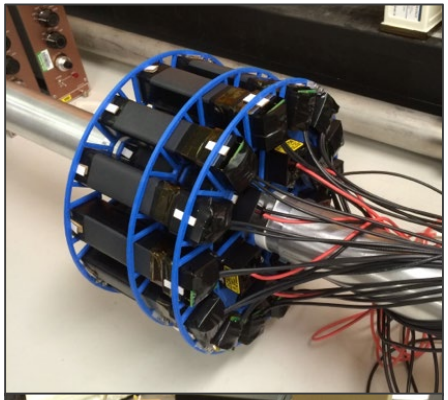
Additive Manufacturing Technique Greatly Influences the Design

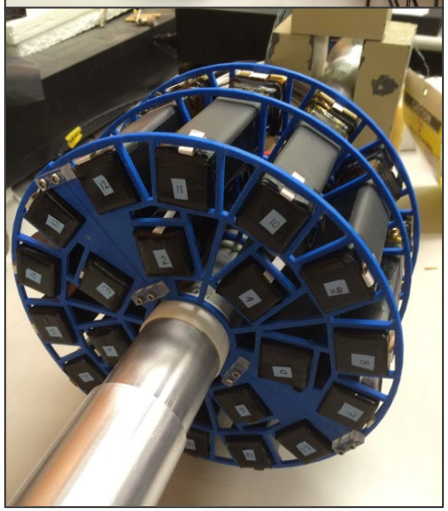
Functional Parts

Rocket Nozzle



Scintillator Holder



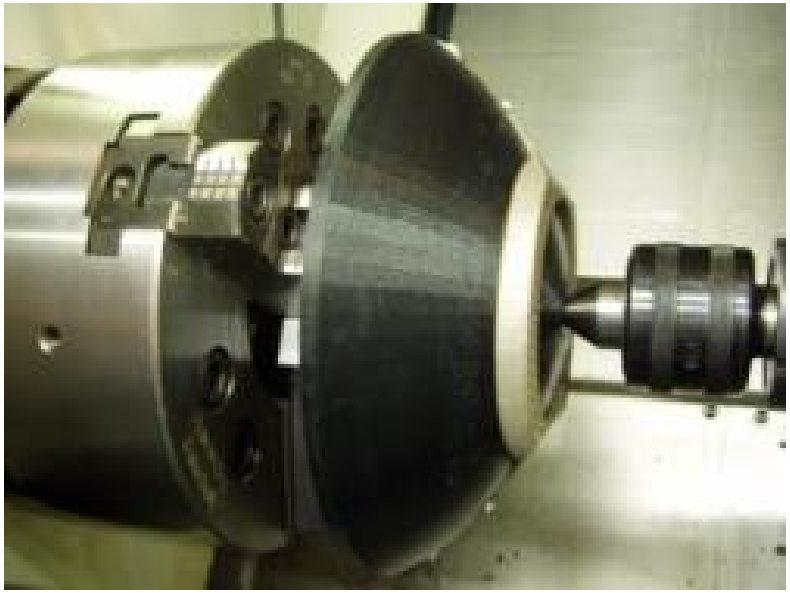


Shell-n-Tube Heat Exchanger

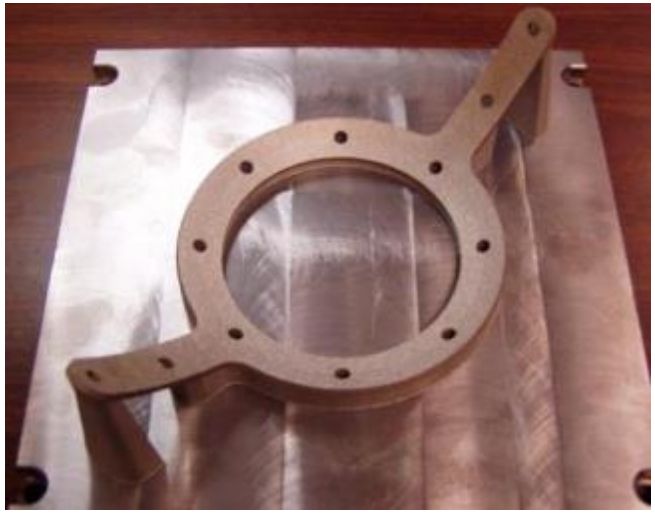
Spectrometer

Tooling & Fixtures

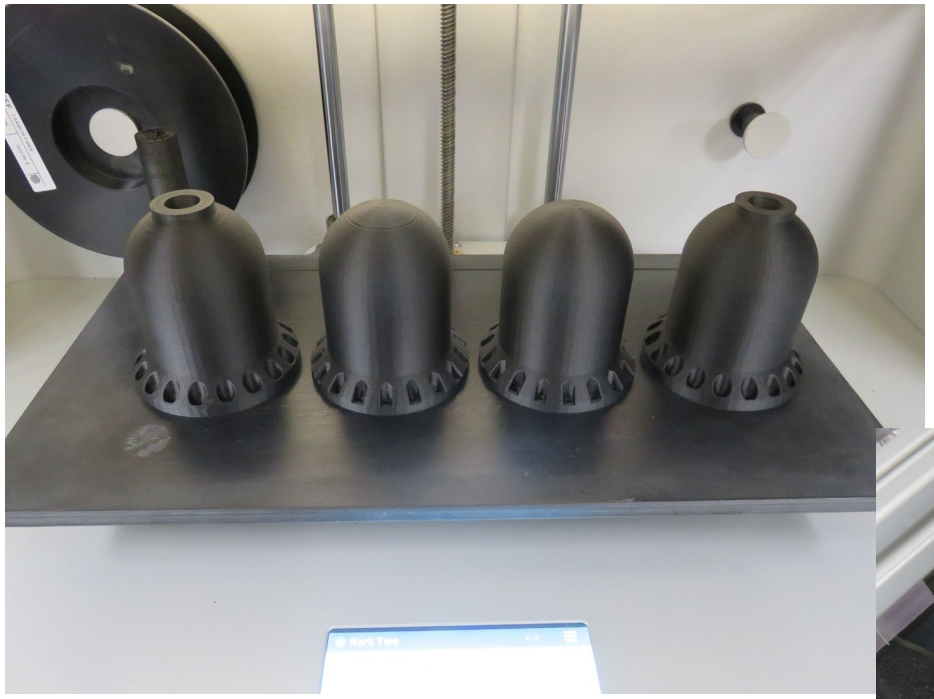
Lathe Fixture

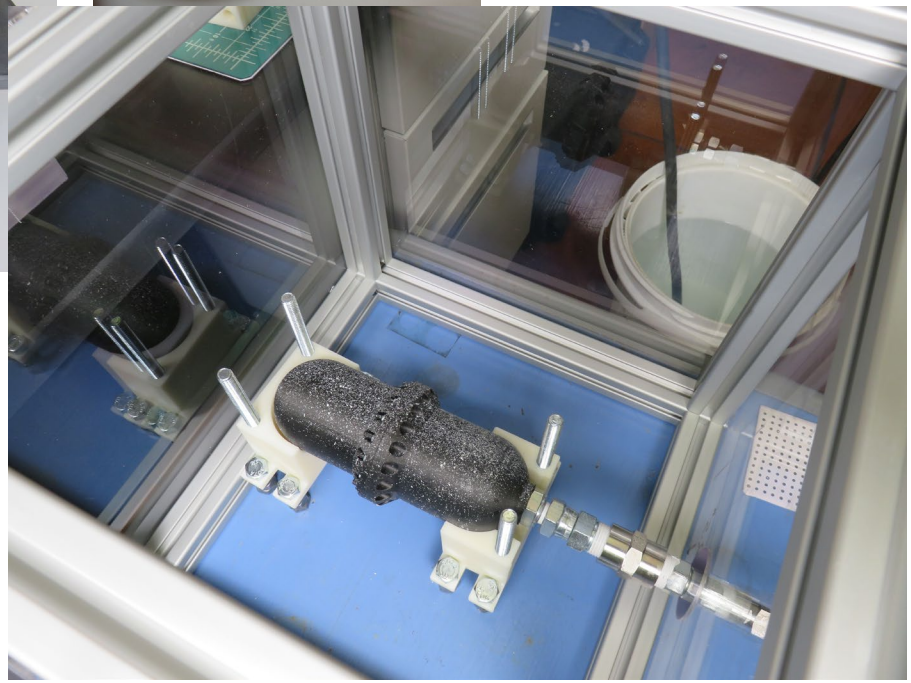


Diagnostic Holders



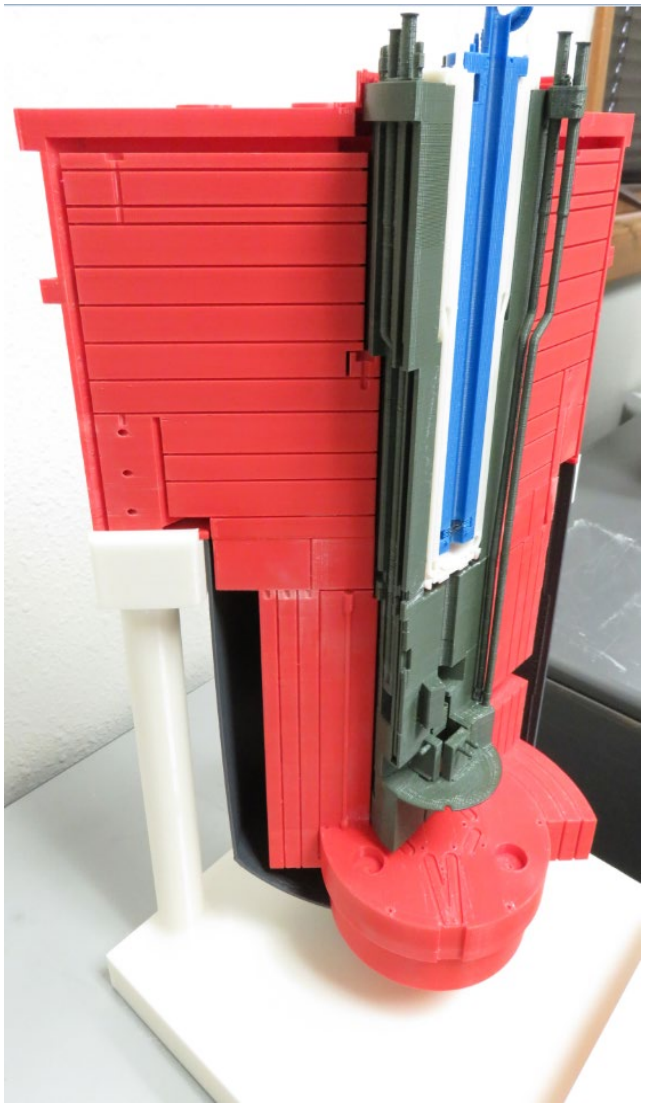
Continuous Fiber Composite Pressure Vessels

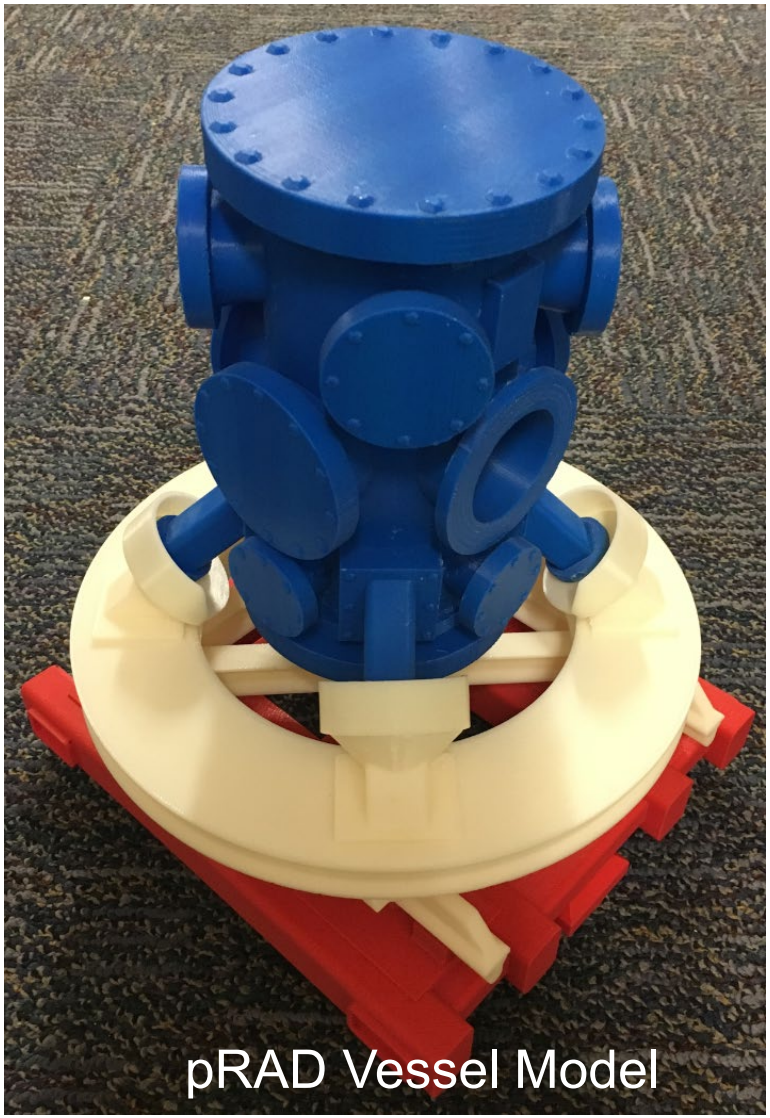




Prototype Models

LANSCE MKIII Neutron Target Assembly



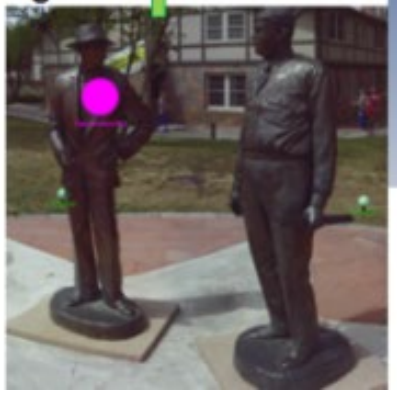


Reverse Engineering

Optical Scanning to 3D Printing

3D Printed Part

Laser Scan data & Color Photos Integrated (4 scans)



Meshed Surfaces Generated In Geomagic Design X (STL file can now be created)