TUTORIAL:
Additive Manufacturing

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The DREAMS Lab at Virginia Tech

Design for Additive Manufacturing
- DFAM decision support methodologies
- Cellular material topology design & optimization

Process and Materials Research
- 3D Printing of novel photopolymers
- 3D Printing of metals and ceramics
- 3D Printing with nanocomposites
- Embedded electrical and actuation systems

Education
- K-12 STEM Outreach
- Undergraduate and graduate courses
- Informal learning environments
- AM Workforce Development
- Continuing education
DREAMS Lab: Facilities

- Material Extrusion
- Metal/Ceramic/Sand Binder Jetting
- Multi-Material Jetting
- Polymer Powder Bed Fusion
- Mask Projection Vat Photopolymerization
- Multi-Modality Printing

Macromolecules Innovation Institute
A virtual, university-wide materials program

- 60 faculty and 200 graduate students from Chemistry, Engineering, Physics, and Sustainable Biomaterials.
- Sponsored by over 20 industrial partners.
- M.S. and Ph.D. Degrees in Internationally Ranked and Interdisciplinary Macromolecular Science and Engineering (MACR) Program
- Please visit: www.mii.vt.edu
Tutorial Objectives

➤ Overview of Additive Manufacturing Processes & Materials
  ➤ Material Extrusion
  ➤ Vat Photopolymerization
  ➤ Powder Bed Fusion
  ➤ Binder Jetting
  ➤ Material Jetting
  ➤ Directed Energy Deposition
  ➤ Sheet Lamination

➤ Additive Manufacturing Examples
  ➤ Design for Additive Manufacturing

➤ Future of Additive Manufacturing
  ➤ Potential applications to Power Electronics domain
Additive Manufacturing (AM) is the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.

Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication"

AM enables a designer to specify material location and material properties on a voxel-by-voxel basis.

Additive Manufacturing

- CAD Model
- STL File
- Slicing Software
- Layer Slices & Tool Path
- 3D Printer
- 3D Object
The power of an additive approach

"If you can draw it, we can print it."

DREAMS

ADDITIVE MANUFACTURING TECHNOLOGIES

https://www.3dhub.com/what-is-3d-printing/additive-manufacturing-infographic

DREAMS
Material Extrusion

- A heated thermoplastic filament is extruded from a capillary die
- Thin layers are formed between the die face and previous layer(s)
- Parts chamber is heated to minimize stresses and deformation
- Required support structures
- Cleanup required
- No post processing

Material Extrusion Processes
Printed Polymers in Aerospace

Material Extrusion: PEEK-based material (Arter) for Orion Spacecraft

Material Extrusion: ULTEM air duct
http://blog.stratasys.com/2015/03/14/printed-air-duct-flying-eye-hospital/

PBF: PEEK air mixer & Nylon 12 gimbal
Solid Concepts: Inside 3D Printing Conference & Expo

Extrusion-based Processes

Fused-Deposition Modeling (Stratasys)

**PROS:**
- Cheap
- Robust, strong parts
  - 85% strength of conventional ABS
- Easy post-processing
- Office-friendly
- Sandable, paintable, tapable
- Little material waste
- Easy material change

**CONS:**
- Slow
  - Viscosity of plastics
  - Fill cross-section
- Poor surface finish
- Anisotropic parts
- Poor resolution
- Porous
- Can’t make point-like depositions
Vat Photopolymerization

**Stereolithography** (3D Systems)

- Laser Source
- Scanning Mirrors
- Laser Beam
- Resin Surface
- Platform
- Photopolymer Resin
- Vat

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+ UV laser solidifies liquid photopolymer in layers using a scanning system
+ Liquid is replenished and leveled between layers
+ Parts require support structures
+ Completed parts require cleaning and UV or Thermal post curing
Photopolymerization

**PROS:**
- Great surface finish
- Excellent resolution
- High detail and thin walls
- Very accurate

**CONS:**
- Post-curing needed
- Manual removal of support structures
- Odd (expensive) material
  - Brittle
  - Sensitivity to heat, humidity and sunlight (warping)
  - Yellow appearance
  - Toxic material when uncured
    (not office friendly)

Vat Photopolymerization

**Mask Projection Stereolithography**

- Selective UV light exposure via DMD
  - White areas are exposed to UV light and cured
  - Black areas remain uncured liquid resin

http://www.youtube.com/watch?v=snOfE
http://www.youtube.com/watch?v=0Re7RQp
CLIP - Carbon3D
Continuous Liquid Interface Production

https://www.youtube.com/watch?v=VTJo9Z5q4Jk

Two-Photon Vat Photo

http://asdn.net/asdn/nanotools/images/lg2.jpg
http://www.3dprintersworld.com/article/3d-print-a-3d-printer-and-make-it-tiny-two-photon
**Binder Jetting**

**PROS:**
- Fast (wide print head)
- Can create color models
- Cheap
- Can print sand casting molds and patterns
- Unused powder is 100% recyclable
- Material options

**CONS:**
- Parts are weak
- Parts need infiltration for strength
- Powder-like finish
- Powder process can be messy

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**ExOne Metal 3D Printing**

1. Binder printed into metal bed
2. Cure binder in low temperature furnace
3. Burn off binder in furnace at low temperature
4. Sinter the metal powder in furnace at high temperature
5. Infiltrate with second metal (copper or bronze)
Printed Copper Components via BJ

Material Jetting

DREAMS
**Stratasys PolyJet**

- **Print Block Travel direction (X)**
- **Print Block**
- **UV Lamp**
- **Inkjet heads**
- **Leveling Roller**
- **Model Materials**
- **Support Material**
- **Build Tray**
- **Build Tray Travel Direction (Z)**

**Material Jetting**

- Direct jetting beads of wax or photopolymer.
- Material is "printed" out layer by layer.
- Wax solidifies; Photopolymer cured by UV lamps
- Fast and inexpensive.
- Extensive support structures needed.
- Able to process multiple materials

**DREAMS**
### Material Jetting

**PROS:**
- Fast (wide print head)
- Graded materials!
- Excellent feature detail
- Excellent surface finish
- Cheaper (no laser)
- No powder/resin vat

**CONS:**
- Slow (thin layers)
- Photopolymers
- Parts warp easily in heat
- Support material can be difficult to remove (waterjet)

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### Material Jetted Ceramics & Metals

- Zirconia
- "metal part"

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Xjet3d.com
Polymer Powder Bed Fusion

+ CO₂ laser fuses thermoplastics powders in layers using a computer controller scanning system
+ Powder is replenished and the next layer is scanned
+ Powder temperature is maintained near melting point to aid fusion and minimize distortions
+ Supports provided by surrounding loose powder

Polymer Powder Bed Fusion Processes

**PROS:**
- Strong, robust parts
- No support structures
- Limited stair-stepping (sand-cast finish)
- Minimal post-processing
- No post-curing
- Wide range of materials (nylon, polycarbonates, metals, ceramics)
- Stackable builds

**CONS:**
- Not office friendly (loose powder)
- Slow: long warm-up time; slow scan-speed
- Arduous breakout & powder recycling process
- Surface finish and accuracy limited by particle size
- Limited powder reusability
- Thermal process difficulties (extra fusing, curling, etc.)
Metal Powder Bed Fusion

Selective Laser Melting (MTT Technologies)

- Fully dense parts in steel, stainless steel (316 L), titanium, gold.
### Powder Bed Metals

Commercially available:
- Ti6Al4V
- (stainless) Steel
- Inconel 625/718
- Cobalt Chrome
- AlSi10Mg
- Maraging Steel

[Periodic Table of 3D printable metals]

http://coolestblog.stratisys.com/2015/06/materials-additive-manufacturing-metals/
In the literature...

- Pure metals
  - Gold, copper, niobium, tantalum, titanium

- Alloy systems
  - Al-40Ti-10Si, Al-Si-10Mg, Al-15Cu
  - Co-29Cr-6Mo, Co26Cr-6Mo-0.2C
  - CuCr1Zr; Cu-30Ni
  - Stainless steels, tool steels, alloy steels
  - IN625, IN718; Waspalloy, MAR-247, CM2427LC, Rene 142, CMSX-4
  - Ti-6Al-4V, Ti-24Nb-4Zr-8Sn, Ti-6Al-7Nb, Ti-6.5Al-3.5Mo-1.5Zr-0.3Si, Ti-Aluminides
Ultrasonic Consolidation

- **Process Characteristics**
  - Uses sonic welding to fuse aluminum strips to one another to add a layer.
  - Machines contours of layers (3 axis machine tool).
  - Titanium alloys also.
  - Can embed components - fiber optics for sensing.

Friction at interface break up oxides
Atoms diffuse across clean interface
Ultrasonic Consolidation

Most common:
Al/Cu, Al/Fe and Al/Ti

Directed Energy Deposition
Laser Engineered Net Shaping
Directed Energy Deposition

Laser Engineered Net Shaping (Optomec)

- Optomec, developed at Sandia
- Process Characteristics
  - Direct metal fabrication using laser cladding process.
- Materials: 316 and 304 stainless steels, H13 tool steel, nickel-based superalloys such as Inconel 625, 690, and 718, 2024 aluminum, and Ti-6Al-4V titanium alloy.
- 5-axis deposition head available.
- Related Technologies
  - POM Group, AeroMet

Directed Energy Deposition

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium</th>
<th>Nickel</th>
<th>Tool Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Ti, Ti 6-4, Ti 62-2-4-2, Ti 6-2-+*</td>
<td>In625, IN718, IN690*, Hastelloy N*, Inconel 718, Maxalloy, Rene 412*</td>
<td>NH3, S7, A-2*</td>
<td></td>
</tr>
<tr>
<td>Scrolling Steel, Polycrystals, Composites</td>
<td>Aluminum</td>
<td>Copper</td>
<td></td>
</tr>
<tr>
<td>Stellite 21, 4047</td>
<td>GRCsp-84*, Cu-Ni*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Materials used in R&D

https://www.optomec.com/3d-printed-metal/fab-materials/
Advantages and Disadvantages

Advantages

- Fully dense metal parts, good material properties, OK speed
- Fabricates complex shapes and functionally gradient materials (e.g., add high strength material in areas of high stress, low corrosion or lighter materials elsewhere; add materials that can be tapped in certain regions)
- Useful for repairing high value parts (e.g., turbine blades, molds, dies) with small heat-affected zones

Disadvantages

- Limits on overhang (30 degrees from vertical, typically)
- Surface finish requires subsequent machining
- Further refinement needed for microstructure control, etc.
- Large power and space requirements
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Additive Manufacturing: By Use

Applications: From RP to AM

Rapid Prototyping
Rapid Tooling
Additive Manufacturing

When to pursue AM?
Take advantage of what differentiates AM!

- Complex Geometries
  - Weight reduction
  - Added functionality
- Functional customization
  - Personalization
- Assembly Reduction
  - Part consolidation
- Low-volume Production
AM Industry Example: Invisalign

http://www.themditondentalhospital.com/dental-treatments/orthodontics/invisalign

AM Industry Examples

http://www.ccm.com/2014/02/30/technology/additive-manufacturing
http://times-echs.com/2014/02/30/0013460e_d.jpg
AM Industry Examples

Applications: Industrial Use

<table>
<thead>
<tr>
<th>Composite Interface Fitting (JWST)</th>
<th>Hot Air Mixer (UCAS-D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Manufacturing</td>
<td>Traditional Manufacturing</td>
</tr>
<tr>
<td>~500 CNC machining hours</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>~16 – 26 week lead time</td>
<td>Buy-to-Fly ratio 10 – 20:1</td>
</tr>
<tr>
<td>Nominal</td>
<td>Buy-to-Fly ratio ~2:1</td>
</tr>
<tr>
<td></td>
<td>Min. 4-pieces w/ 2 welds</td>
</tr>
<tr>
<td></td>
<td>1 piece w/ no welding</td>
</tr>
<tr>
<td></td>
<td>Nominal</td>
</tr>
<tr>
<td></td>
<td>35% - 45% cost savings</td>
</tr>
</tbody>
</table>

~10" (25.4cm)

Courtesy of Northrop Grumman Corp. and CalRam Inc.
**Printed Rocket Engine Components**

Fuel injector made via printed Nickel-Chromium
1,400 psi @ 6,000F
http://www.wired.com/2013/08/nasa-3d-printed-rocket-engine/

SuperDraco inconel rocket chamber with regen cooling jacket built on EOS M280
(Courtesy of EOS)

**Cellular Structures & Functional Joints**

https://www.youtube.com/watch?v=68D24U89A8e

Courtesy: AVD, LLC, Innovative Structures & Structures Tech
Shape Optimization

- Diesel front plate by Delphi Diesel Systems
- Original design constrained by conventional manufacturing
- Optimized for AM:
  - Flow channels constructed around flow lines
  - Minimal weight

**Rapid Manufacturing text (p. 11) &
http://www.stining-project.com/download/files/Shape%20ability%20study.pdf

LEAP 56 Next Generation Fuel Nozzles

- 40K+ Annual Production
- 5x more durable
- 25% less weight
- 20 pieces to 1

https://www.youtube.com/watch?v=MrVShNebFGZ
Light weighting via Topology Optimization & AM

Airbus A320 Nacelle Bracket
- DMLS Titanium
- 10 kg weight reduction per plane
- Reduction of CO₂ emission over product lifecycle
- 25% reduction in material waste compared to casting
- 40% reduction in CO₂ emissions over part lifetime

More Industry Examples
- Engine part, formula 1 racecar – 24 hours
- Rocket engine impeller – 36 hours
- Landing gear component – 36 hours
- Environmental Control System ducts for F-18 military jet
- Air plenum parts for corporate helicopter
- Gas turbine engine compressor support case – 30 hours

Courtesy: J. Barkley, MITRE
A Manufacturing Revolution!

- Digital design and manufacture
- Reduced delay between design iterations
- Complexity is “free”

DREAMS

A Manufacturing Revolution!

- Digital design and manufacture
- Reduced delay between design iterations
- Complexity is “free”
- Multiple unique parts per “batch”
- Low-level operator expertise
- Unmonitored (overnight) builds
- Single tool
- Assembly reduction (part integration)

DREAMS
**A Manufacturing Revolution!**

**Subtractive Machining:**
- 5000 lb. forged billet
- 4750 lb. chips
- 250 lb. finish machined part

**Additive Manufacturing via EBF³:**
- 200 lb. rolled sheet
- 75 lb. wire
- 25 lb. chips
- 250 lb. finish machined part

EBF³ saves significant resources over current methods: raw materials, energy, fewer chemicals (cutting fluids), lead time = cost

Courtesy: Karen Taminger, NASA Langley

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**A Manufacturing Revolution?**


**Figure 9.4** Cut-off volumes for the 3.6 g part by different processes
A Manufacturing Revolution?

- Not built for economies of scale
  - “Rapid” is relative (~1.5 vertical inch per hour)
  - Physical bottlenecks of processes

- Materials and Standards need to be improved
  - Process repeatability & part certification
  - Standards for processes & parts
  - Material selection
  - Material properties
  - Part design

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Expanding Materials Catalog

Programmable Matter

> Selective deposition of material that can
has response to external input (force,
heat, water, electricity, etc.)

https://www.youtube.com/watch?v=w88tWWMupVw

http://www.nature.com/scientificamerican/materials/55/scientificamerican114-40.html#TNT-etc._id=SCIENTIFICAMERICAN-201411
Multi-Material Vat Photopolymerization

Hierarchical Order (n)

Effective Volumetric CTE (β_{pc})

- High CTE
- Low CTE

Tunable positive-zero-negative thermal expansions achieved from multi-material hierarchical metamaterials

Rayne Zheng (VaTech MechEng)

Expanding the Polymeric Materials Toolbox for Additive Manufacturing

- Extrusion: Water-soluble material for tailored dissolution
- Vat Photopolymerization: Polyimide
- Vat Photopolymerization: Polybutadiene Elastomers
- Material Jetting: Quantum dot inks
- Powder Bed Fusion: Polyphenylene Sulfide
- Vat Photopolymerization: Phosphonium Ionic Liquid

With Tim Long (VaTech Chemistry)
Expanding Material Selection: Polyimides

- Operating temp. up to 600 °C
- Elastic modulus 2+ GPa
- Thermal, electrical, radiation resistance
- Chemically inert

All-Aromatic Polyimides: very difficult materials to process

- No Tg – 'pseudothermoplastics'
- No melt flow → can't be melt processed
- Resistant to all organic solvents

Poly(4,4’-oxydiphenylene-pyromellitimide) (PMDA-ODA) known commercially as Kapton® by DuPont

- Some are only produced as films (e.g., Kapton®)
- Complex shapes are often impossible
AM of Fully Aromatic Polyimide (Kapton)

- Operating temp. up to 600 °C
- Elastic modulus 2.2 GPa
- Thermal, electrical, radiation resistance
- Chemically inert

Ceramics via Vat Photopolymerization

- Alumina
- Zirconia
- Fused Silica
- Barium Titanate
- PZT
- Hydroxapatite
- Calcium Phosphate

DREAMS
RF Materials & Structures

Electromagnetic Structures

Embedded Microstrip Line

Ceramic Waveguide

Average Relative Permittivity (εr) vs Latice Density
Electromagnetic Structures

Graded electrical and magnetic materials
http://rsta.royalsocietypublishing.org/content/373/2049/20140353

Printed Luneberg Lens

Embedding
“A fundamental advantage of SFF over conventional manufacturing techniques is the capability to access the entire volume of work-piece at some stage of the process (as opposed to only the external surfaces in conventional manufacturing).”

V. Kumar, S. Rajagopalan, M. Cutkosky, D. Dutta, “Representation and processing of heterogeneous objects for solid freeform fabrication.”

Embedding: FDM

Example: Embedded RFID tag into "Hokie Bird" bust

Functioning Embedded RFID tag (horizontal cavity)
**Embedding: UOC**

- **Em**: Pneumatic cylinder applies damping force (130-241kPa)
- **Embed**: Transducer
- **Direct**: Oscillation
- **Amplitude**: 6.5-4.5μm

Embed SMA's into Aluminum
(Kong et. al. 2004)

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**Ultrasonic Consolidation**

- 6061 aluminum + Copper
- aluminum + embedded tantalum and europium for radiation shielding
- embedded sensors
- Aluminum 6061 + ceramic fibers
Embedding: UOC

http://dx.doi.org/10.1016/j.composit.2004.04.064

(Sigurd et al. 2005)

http://dx.doi.org/10.1016/j.jmatprotc.2008.01.014

(DREAMS)

http://dx.doi.org/10.1108/135525407107765179

(DREAMS)
Embedded: UOC

http://digitalcommons.usu.edu/jeq/viewcontent.cgi?article=210&context=etd
http://csse.usu.edu/0cum/0index.html

DREAMS

Printed Electronics
(Direct Ink Write; Aerosol Jetting)
Direct-Write: Printed Circuits

Multi-Material Micro-Extrusion AM

3D Printer capable of printing 4 materials simultaneously (including conductive materials). Resolution = 100 μm

B. Johnson
Quantum Dot LED - Optoelectronics

Printed Materials
(electronic inks: electronic conductors, hole-transport layers, optical emission layers, insulators)

Ink 1: Eutectic mixture (cathode)
Ink 2: Solvent + NPs (EL)
Ink 3: Poly-TPD (HTL)
Ink 4: PEDOT:PSS (HTL)
Ink 5: Silver NPs (anode)
Ink 6: Silicone

B. Johnson

Conformal DIW Antenna

Figure 1. A) Schematic illustration of an electrochemically cast antenna with labeled geometric parameters. B) Optical image of an antenna during the printing process. C) Optical image of a completed antenna (ELA), in side and top (front) views. D) Optical profilometry scan of representative mean diameters on DIW with the background surface subtracted and scanning electron microscopy image of these features (front).

https://doi.org/10.1002/adma.201003764

DREAMS
Direct-Write: Printed Circuits

3-axis linear translation stages with direct print micro-dispensing system

Visual feedback from DP camera

nScrypt DP dispensing pump

DPSS solid-state laser system

SLA 250/50 stereolithography machine

http://dx.doi.org/10.1108/13552541211232113
Overall Vision

To directly fabricate *mechatronic* devices without post-process assembly.
**Direct Printing of Mechatronic Devices**

**Goal:** Create printed segment of wing with actuated control surface
- Flexible material used for control surface "living hinge"
- Embedded SMA fibers provide actuation
- Embedded, printed strain gauge provides deflection feedback

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**Design of a DW Machine for PolyJet**

- Designed to fit on PolyJet Build Tray
- Extrusion-based pneumatic dispenser
- Metal-loaded silver ink
- Stepper motor driven lead screws
- .gcode interpreted by Arduino
Creation of Integrated Sensing and Actuating Wing via PolyJet 3D Printing

Virginia Tech DREAMS Lab

Wing segment featuring control surface with integrated actuation & sensing
- Flexible material used for control surface "living hinge"
- Embedded Shape Memory Alloy wires provide actuation
- Embedded thermistors provide temperature feedback
- Embedded flex sensors provide deflection feedback
- Embedded antennas provide communication

https://vimeo.com/185066184
Multi-Modality Printing: DREAM Machine

- Multi-modality, Multi-material AM system
  - extrusion,
  - binder jetting,
  - material jetting,
  - vat photopolymerization

DREAM Machine: Early Printing Results

**Multi-Modality Prints**

- Conductive paste (DW) embedded in stiff, transparent resin (VP):

- Stiff, acrylate resin (VP) interior with flexible, silicone (DW) border:

- Stiff thermoplastic (FE) embedded in flexible silicone (DW):
Robotics Integration

Large-Scale Robotic Extrusion

https://www.youtube.com/watch?v=NRkGBk1ETdQ
https://www.youtube.com/watch?v=4s7E6F3g3Q
Robotic Integration & Assembly

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TUTORIAL:
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Thank you.

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