3D Printing: Technology and Research

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Definition

Adding material (often in sequential layers) under computer control to create a 3D object.
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✓ Adding material (often in sequential layers) under computer control to create a 3D object.
✓ An Additive Manufacturing (AM) technology.
Definition

- Adding material (often in sequential layers) under computer control to create a 3D object.
- Opposite Subtractive Manufacturing (SM): remove material from stock.
History

- Despite the recent interest, 3D printing technology dates back to 1981.
- Became a hot topic since 2009 when FDM patents (Stratasys) expired.
  - Paves the way to innovation in FDM 3D printers.
  - Drops desktop 3D printer prices.
  - Initiates online 3D printing services (Sculpteo).
  - Increases visibility.
- FDM not the only AM technique. The first one ('81) was SLA, not FDM.
**History**

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✓ Resin was polymerized by UV light where UV exposure is controlled by a mask.
History

- Despite the recent interest, 3D printing technology dates back to 1981.
- Resin was polymerized by UV light where UV exposure is controlled by a mask.
- Polymerization: binding monomers (one part) form a polymer (many parts).
- Spider silk is the strongest natural polymer. String confetti is a synthetic one.
Some recent cool 3D printing activities are:

- First 3D printed prototype car by Urbee, 2010
- First 3D food printer by Cornell, 2011
- First 3D printed and implanted prosthetic jaw by Hasselt, 2012
- First 3D printed animal bone using bio-ink by Trinitiy, 2016.
✓ Uses translational elements to fabricate a digital model.
Technology

- FDM: Fused Deposition Modeling.
- Begins by slicing 3D digital model into layers.
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- **Material deposition nozzle**, aka extrusion nozzle, pours polymeric filament in the horizontal X-Y plane to build the current layer $L_c$.
- Filament is cooled down with the fans around nozzle.
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Filament is cooled down with the fans around nozzle.
Stage, aka build plate, moves down one layer when $L_c$ is done.

Principle: Material deposition.
Technology

- SLA: Stereolithography.
- Begins by slicing 3D digital model into layers.
- Ultraviolet laser is directed (via mirrors) in the horizontal X-Y plane to harden the liquid photopolymer/resin on contact w/ the cross-section to build the current layer $L_c$. 
Technology

- **SLA**: Stereolithography.
- Begins by slicing 3D digital model into layers.
- **Ultraviolet laser** is directed (via mirrors) in the horizontal X-Y plane to harden the liquid photopolymer/resin on contact with the cross-section to build the current layer $L_c$.
- **Stage**, aka build plate, moves down one layer when $L_c$ is done.

- Principle: Material solidification.
- Cool demo: [https://youtu.be/NM55ct5KwiI](https://youtu.be/NM55ct5KwiI)
Technology

- SLS: Selective Laser Sintering.
- Begins by slicing 3D digital model into layers.
- \(\text{CO}_2\) laser is directed in the horizontal X-Y plane to fuse the polymer powder on contact with the cross-section to build the current layer \(L_c\).
Technology

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- Principle: Material solidification.
- Cool demo: https://youtu.be/9E5MfBAV_tA
Technology

- SLA/DLP: Direct Light Processing based SLA.
- Begins by slicing 3D digital model into layers.
- Instead of a continuous path a deposition (FDM) or laser (SLA, SLS), you project a set of contour/cross-section images via DLP projector onto the liquid photopolymer/resin to build the current layer.

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- Cool demo: https://youtu.be/hQ21gbeYFYQ
Technology

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- SLA/DLP is raster-based, all other techs are vector-based.
Technology Wrap-Up

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- Go with FDM for fully closed *empty* voids (non-solidified material gets trapped there in the other technologies).
Technology Wrap-Up

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✓ Go with FDM for multi-material/color (deposition).
✓ Go with FDM for fully closed empty voids (non-solidified traps there).
✓ Go with SLS, SLA, SLA/DLP for complex geometries (creation and removal of support structures are problematic and inevitable in FDM).

Without support, overhangs fall ➔ Sacrificial external support structure, and

3D input model ➔ model after its removal.
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- New techs can print out-of-plane (doable with FDM if you manage to avoid head hitting an already printed part): youtu.be/NWBa8OWgApM
Technology Wrap-Up

- **FDM**: Fused Deposition Modeling. //polymeric filament, nozzle.
- **SLA**: Stereolithography. //photopolymer: resin, UV laser.
- **SLS**: Selective Laser Sintering. //polymer powder, CO₂ laser.
- **SLA/DLP**: DLP-based SLA. //photopolymer: resin, image.

- Go with FDM for multi-material/color (deposition).
- Go with FDM for fully closed empty voids (non-solidified traps there).
- Go with SLS, SLA, SLA/DLP for complex geometries (creation and removal of support structures are problematic and inevitable in FDM).

- New techs can print out-of-plane (FDM logic; a biological fabrication technique via silkworms):
  
  https://youtu.be/0ePriBJKYt8
Technology Wrap-Up

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- New techs can print out-of-plane (doable with FDM if you manage to avoid head hitting an already printed part): youtu.be/NWBa8OWgApM
- Print time depends on part volume in FDM, part height in others (‘cos constant sweeptime requird per layer); they’re bad for single small obj.
Product Development Pipeline

Figure from: Livesu et al., 2017, From 3D models to 3D prints: an overview of the processing pipeline.
We assume that product concept, e.g., Armadillo, is already designed, e.g., by a CAD expert, without knowing whether it’ll be printed or not.

We will go through each single step in Process Planning (PP) pipeline (dashed boxes optional) that prepares the 3D model for fabrication.

PP: After design and before actual manufacturing.
Process Planning Pipeline in a Nutshell

✓ Update the mesh to comply with the input representation requirements.
  ✓ Tessellated geometry must be watertight: enclose a solid: no water leakage.
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- Orient optimally to minimize print time, support need, .. or fit chamber.

Should have been upside-down T.

Sagged result without support.
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Sagged result without support.

- Create support structures (if FDM in use).
- Slice the model uniformly or adaptively.
- Convert each slice to a toolpath (vector) or grid of solid pixels (raster).
Audience

- People who contribute to the PP pipeline in the context of AM:
  - Computer graphics experts.
  - Mechanical engineers.
  - Material scientists.
  - Mathematicians.
AM vs. SM

- PP in traditional SM, such as CNC machining, is complex, e.g., experienced skilled manufacturer needed.
- PP in AM is mostly algorithmic.
- Also notice the significantly less material waste in AM.
AM vs. SM

✓ AM enables fabrication of shapes that cannot be done with SM.
  ✓ Shapes that were interesting from a theoretical point can now be printed and their functionality can now be exploited.

✓ Made possible because 2D toolpaths are generated (within each slice) instead of complex 3D paths.
AM vs. SM

✓ AM enables fabrication of shapes that cannot be done with SM.
  ✓ Shapes that were interesting from a theoretical point can now be printed and their functionality can now be exploited.

A mathematician, like a painter or poet, is a maker of patterns. If his patterns are more permanent than theirs, it is because they are made with ideas. //G. Hardy
AM vs. SM

✓ AM is excellent for customization.
  ✓ 3D scan yourself or any other thing, manipulate digitally (optional), fabricate.

✓ See my rigid registration slides that teach how to convert 3D raw scans into printable watertight meshes that enclose a solid:
  http://ceng.metu.edu.tr/~ys/ceng789-dgp/08-rigid.ppt
AM vs. SM

✓ AM is practical for multi-color and multi-material prototypes thanks to the slice-by-slice approach.
AM vs. SM

✓ Drawbacks of AM also exist
  ✓ Limited part sizes, fabrication speed, materials.
  ✓ Poor surface finish.
  ✓ High cost.
  ✓ Gravity effective during manufacturing (overhangs/islands must be supported).

✓ So go with SM if you need many (speed) precise (surface finish) items.
✓ Or go with AM if you need highly complex and intricate items, e.g., those that require a hollow interior (to save weight or material).
AM vs. SM

✓ Drawbacks of AM also exist
  ✓ Limited part sizes, fabrication speed, materials.
  ✓ Poor surface finish.
  ✓ High cost.
  ✓ Gravity effective during manufacturing (overhangs/islands must be supported).

✓ Better yet, go with a hybrid solution: AM and SM together.

Surface finish achieved by AM (left) is improved with SM (right, milling).
Tuning PP Pipeline - Cost

✓ Minimize Pre-build Cost + Build Cost + Post-processing Cost.
Tuning PP Pipeline

✓ PP can be tuned to optimize for one or a combination of objectives.
  ✓ Cost.
  ✓ Fidelity.
  ✓ Functionality.
Tuning PP Pipeline - Cost

✓ Minimize Pre-build Cost + Build Cost + Post-processing Cost.

✓ Cost to turn a design into a set of printer instructions.
  ✓ Efficient algorithms, e.g., slicing:
  ✓ Reduced user interaction.

✓ Labor cost.
  ✓ Load print material, e.g., powder.
  ✓ Clean and warm up printer.
  ✓ Deal with printer software, e.g., Cura.
Tuning PP Pipeline - Cost

- Minimize Pre-build Cost + Build Cost + Post-processing Cost.

- Printing time.
  - Efficient algorithms, e.g., orientation.
  - Reduced user interaction.

- Material cost.
  - Reduce material waste.
  - Structural strength may degrade to use less mat: bad for industrial production.

- Support structure amount affects both printing time and material cost.

- Can be computed by the sum of the volumes of the prisms generated by extruding the down-facing triangles up to the building plate.
Tuning PP Pipeline - Cost

- Minimize Pre-build Cost + Build Cost + Post-processing Cost.

- Printing time.
  - Efficient algorithms, e.g., orientation.
  - Reduced user interaction.

- Material cost.
  - Reduce material waste.
  - Structural strength may degrade to use less mat: bad for industrial production.

- Support structure amount affects both printing time and material cost.
- Can be reduced by employing tree- or scaffold-based structures.
Tuning PP Pipeline - Cost

✓ Minimize Pre-build Cost + Build Cost + Post-processing Cost.

✓ Polishing time.
  ✓ Detach supports.
  ✓ Chemical, mechanical or manual surface finishing.
Tuning PP Pipeline - Fidelity

✓ How perfect the replica is?
✓ Form fidelity: difference in shape b/w design and production.

✓ Layers piled along building direction causes staircase effect $\Rightarrow$ fidelity $\downarrow$
✓ Cusp-height error measures form fidelity.

\[
h = \begin{cases} 
  l|\cos \theta| & \text{for } |\cos \theta| \neq 1 \\
  0 & \text{for } |\cos \theta| = 1 
\end{cases}
\]

✓ $|\cos \Theta|$ grows as $\Theta$ decreases (see nearly horizontal part above).
How perfect the replica is?
Form fidelity: difference in shape b/w design and production.

Layers piled along building direction causes staircase effect ⇒ fidelity ↓
Cusp-height error measures form fidelity.

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Integral of cusp-height before printing (build direction \(b\)): for each face w/ normal \(n\), \(|\cos \Theta| = |b \cdot n|\). Add these errors (more for horizontal).
Tuning PP Pipeline - Fidelity

- How perfect the replica is?
- Form fidelity: difference in shape b/w design and production.

- Layers piled along building direction causes staircase effect → fidelity ↓
- Volumetric loss measures form fidelity.
- Red area above.
- Similar to cusp-height, compute before printing.
Tuning PP Pipeline - Fidelity

✓ How perfect the replica is?
✓ Texture fidelity: tiny local variations over the printed surface.
✓ Unlike form fidelity, computed after printing (using sampling schemes).
✓ Aka surface finish.
✓ To obtain better fidelity, meniscus smoothing or support hiding popular.
Tuning PP Pipeline - Fidelity

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- Lift the solidified layer above the upper surface of the resin tank to stretch a meniscus of liquid b/w each layer ➔ smoother transition.
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✓ Place supports at the least salient parts so that removal artifacts are hidden.
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To find building direction: i) consider a small # of candid orientations (predefined or computed on convex hull), ii) shortlist from a regular sampling of orientations.

Perceptual models of preference in 3d printing direction, 2015; Improved Surface Quality in 3D Printing by Optimizing the Printing Direction, 2016.
Tuning PP Pipeline - Fidelity

✓ How perfect the replica is?
✓ Texture fidelity: tiny local variations over the printed surface.
✓ Unlike form fidelity, computed after printing (using sampling schemes).
✓ Aka surface finish.
✓ To obtain better fidelity, meniscus, support hiding, or self-supports.
✓ Split model into approximately pyramidal parts that support themselves.

Approximate Pyramidal Shape Decomposition, 2014.
Tuning PP Pipeline - Functionality

✓ Optimize shape to comply with some functional requirements.
  ✓ Robustness: insensitive to known or unknown forces.
  ✓ Mass distribution: achieve static or dynamic equilibrium.
  ✓ Light/sound propagation: guide light/sound inside the object.
Tuning PP Pipeline - Functionality

- Optimize shape to comply with some functional requirements.
  - Robustness: insensitive to known or unknown forces.

Input:

Output: probability of failure/fraction & location of common point of failures.
Optimize shape to comply with some functional requirements.

- Robustness: insensitive to known or unknown forces.

Optimal orientation that will result in an as-strong-as-possible 3D print. Weak sections are identified and up direction for printing is determined accordingly.
Tuning PP Pipeline - Functionality

- Optimize shape to comply with some functional requirements.
  - Robustness: insensitive to known or unknown forces.

Elastic objs deform under gravity after printing. Take this into account beforehand.

![Diagram](image.png)

Tuning PP Pipeline - Functionality

- Optimize shape to comply with some functional requirements.
  - Mass distribution: achieve static or dynamic equilibrium.

Make an object stand, spin, or float after fabrication by distributing cavities inside.

Tuning PP Pipeline - Functionality

- Optimize shape to comply with some functional requirements.
  - Mass distribution: achieve static or dynamic equilibrium.

  Topology optimization to get low weight to strength ratios, e.g., for aerospace.

**Original Part**
Volume: 263,346 cubic mm
Mass: 2.06 kg

**Topology Optimized Part**
Volume: 97,884 cubic mm
Mass: 0.766 kg
Optimize shape to comply with some functional requirements.
  - Light/sound propagation: guide light/sound inside the object.

Multi-material printing to fabricate curved displays w/ embedded optical fibers.
Tuning PP Pipeline - Functionality

✓ Optimize shape to comply with some functional requirements.
  ✓ Light/sound propagation: guide light/sound inside the object.

Natural frequency optimization to make object sound in a controlled manner.
Input Requirements

- Printing technology is for solid objects: tessellation.
- A raw point cloud, e.g. 3D scan result, must be tessellated into a mesh.
- There exist books on the subject.
Input Requirements

✓ Printing technology is for solid objects: tessellation.
✓ A raw point cloud, e.g. 3D scan result, must be tessellated into a mesh.
✓ There exist books on the subject but here is a simple algorithm:

✓ Find local neighborhood $L_i$ of each point $p_i$ in the 3D point cloud input.
  ✓ Closest $k$ points (using a k-d tree).
✓ For each $L_i$ compute tangent plane using PCA.
✓ Project all points in $L_i$ to the tangent plane and compute their 2D Delaunay triangulation $D_i$. 
Input Requirements

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- \( D_i \) is a set of edges: \( D_i = \{ e_i^1, e_i^2, ..., e_i^{\text{noe}(i)} \} \) where \( \text{noe}(i) \) where is the number of edges of the \( i^{\text{th}} \) Delaunay triangulation.

- Final triangulation is the composition of all \( N \) local triangulations:

\[
D = \bigcup_{i=1}^{N} \{ e_i^1, e_i^2, ..., e_i^{\text{noe}(i)} \}.
\]

- Note that global \( D \) not necessarily a 2-manifold. Set \( k = 0.02n \) and restrict value to \([8, 12]\).
Input Requirements

- Printing technology is for solid objects: tessellation.
- A raw point cloud, e.g., 3D scan result, must be tessellated into a mesh.
- There exist books on the subject but here is another simple algorithm:

  - Previous algorithm performed an explicit reconstruction.
  - Marching cubes is an implicit method that extracts the zero-set of a scalar function, commonly a signed distance function $F(x) = (x - o_i) \cdot n_i$. 

Input Requirements

- Printing technology is for solid objects: watertight meshes.
- No holes, voids, or non-conforming/non-manifold polygon structures.
- Closed mesh (no boundary edges).
- Imagine filling the inside of the mesh with water, would anything leak out? If not, then chances are the mesh is watertight.
Input Requirements

- Printing technology is for solid objects: watertight meshes.
- Thicken sheet-like structures to make them printable: surface-to-solid.
Input Requirements

- Printing technology is for solid objects: watertight meshes.
- Fill holes to ensure that the resulting mesh encloses a solid.

MeshLab software: Filters → Fill Holes.
Shape Requirements

✓ Printing technology is for moderate-size shapes that fits into chamber.
✓ Split big model into parts that can be printed separately & assembled.
Shape Requirements

- Printing technology is for moderate-size shapes that fits into chamber.
- A related issue is to compute the tight arrangement of the parts within a container to be shipped for reassembly in the destination.
Shape Interior

- Is a key factor regarding material use, print time, mechanical props.
- Inner volume grows to the cube of scaling factor, e.g., doubling object size multiplies its volume by $2^3 = 8$.
  - This explains interior’s impact on material use and print time.
  - Varying elasticity can be achieved, e.g., by using different interior microstructs.
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Shape Interior

- Is a key factor regarding material use, print time, mechanical props.
- Aka interior support, infill.
- Raster device: produce an image of the filled layer contour; project it.
- Vector device: trickier. Nozzle/laser must follow a space filling curve when depositing/solidifying material.

- Fermat spiral: Reduce # of sharp turns to enable faster motions and remove vibrations (beats the most common Dir parallel and Hilbert). Continuous to prevent stops and restarts (beats Con parallel).

Connected Fermat spirals for layered fabrication, 2016.
Shape Interior

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An important open question: can we design shapes with AM in mind?

3D printing algorithms work on a 3D shape that is designed without AM in mind and aim to find the best way to print it to match one or some of the criteria: Cost, Fidelity, Functionality (Slide 40).

It’d be better if we consider these issues during 3D design, not after.
Future Work

- An important open question: can we design shapes with AM in mind?
- 3D printing algorithms work on a 3D shape that is designed without AM in mind and aim to find the best way to print it to match one or some of the criteria: Cost, Fidelity, Functionality (Slide 40).

Future Work

- An important open question: structures on the surface.
- For esthetic, stability, fast prototyping.
- Current work: manual, labor-intensive, skill-based, curve primitives.
- Future work: extract patterns directly from the existing mesh facets?
Future Work

✓ An important open question: 4D printing?
✓ Metamaterials that are able to morph into a target shape after being printed (4th dimension: time).

Biomimetic 4D Printing, 2016.
Thanks

Yusuf, Assoc. Prof.