Additive Manufacturing – Module 7

Spring 2015

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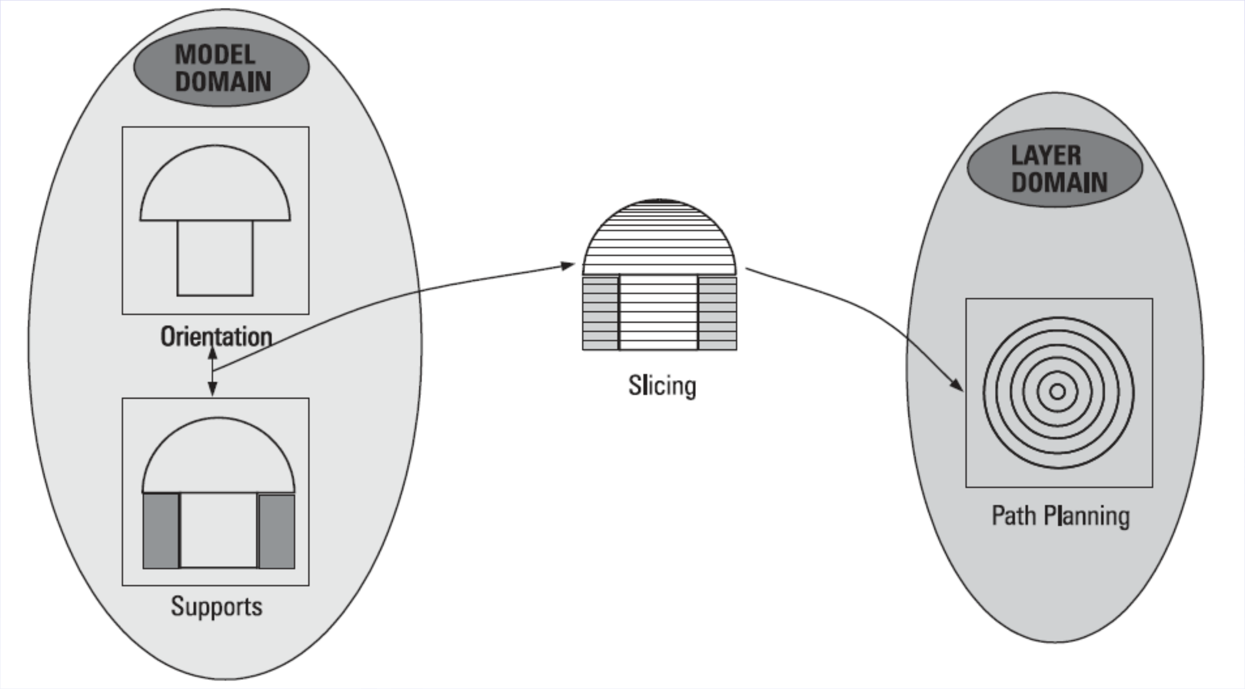
University of Arkansas, Fayetteville

Design for AM

Process planning



- **Orientation**
- **Supports**
- **Slicing**
- **Path planning (& Process parameters): choosing path layout, determining path coordinates, determining path spacing, accounting for physics of the process in the planning**

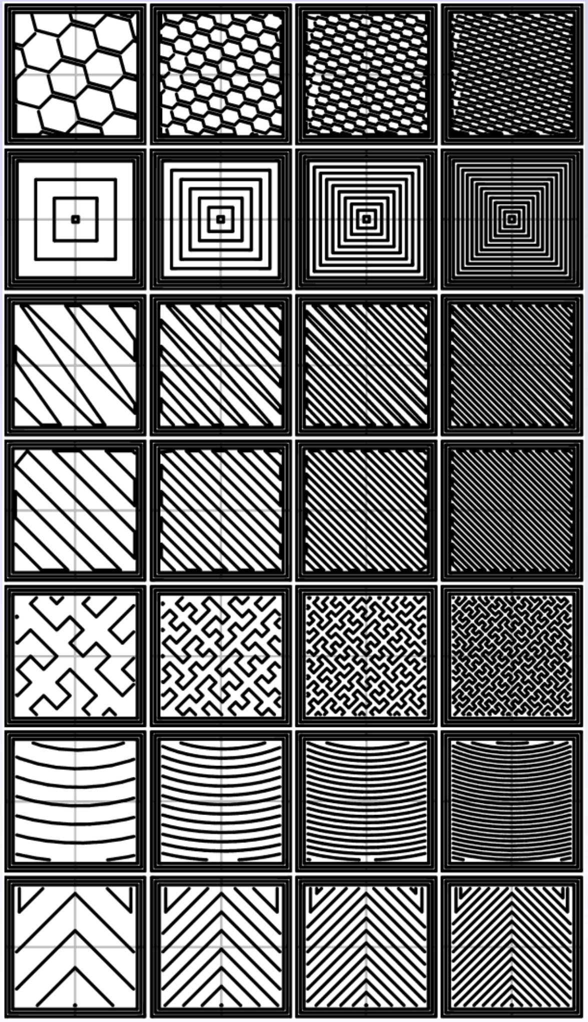
Source: Kulkarni, Prashant, Anne Marsan, and Debasish Dutta. "A review of process planning techniques in layered manufacturing." *Rapid Prototyping Journal* 6.1 (2000): 18-35.

Design for AM

Design
Process
Functionality

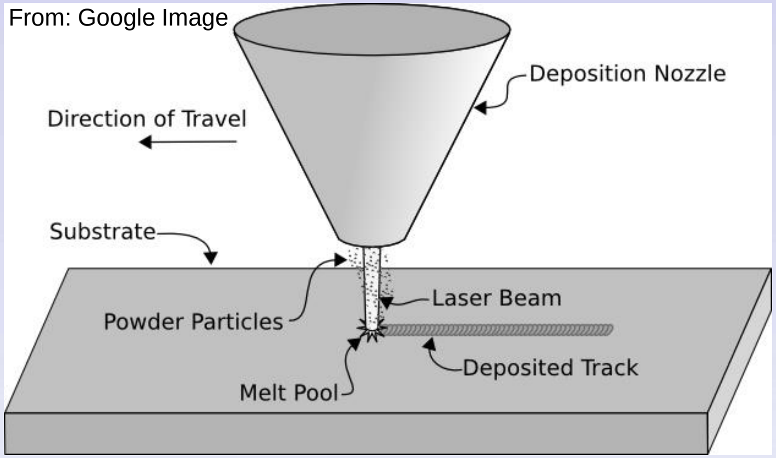
Process planning

From: slic3r.org

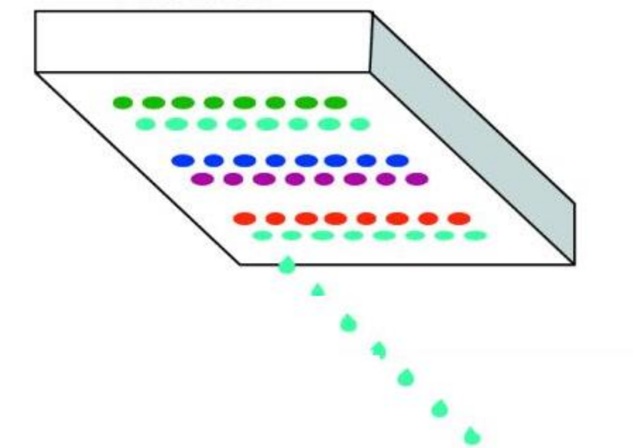


Infill pattern & density

From: Google Image



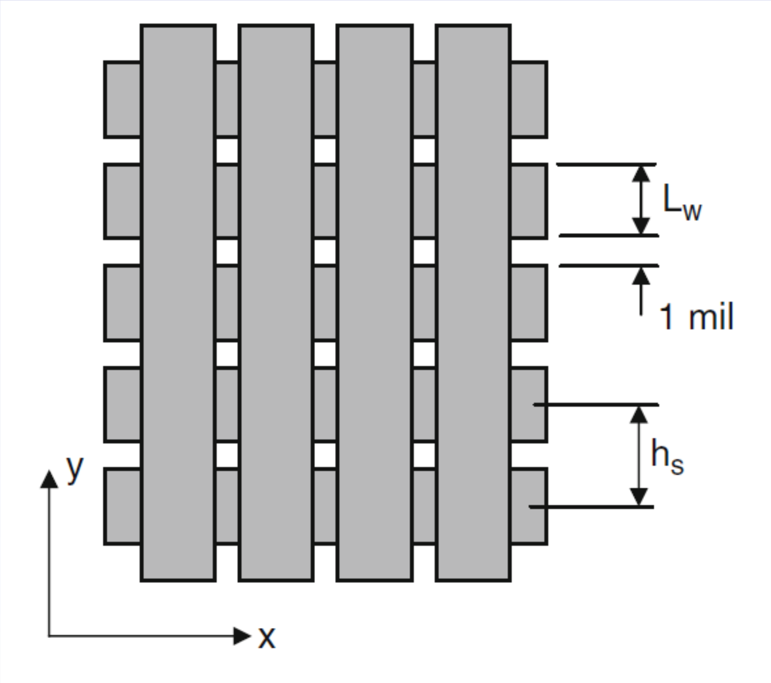
- **Scanning speed (function of time & location)**
- **Laser power (function of time & location)**



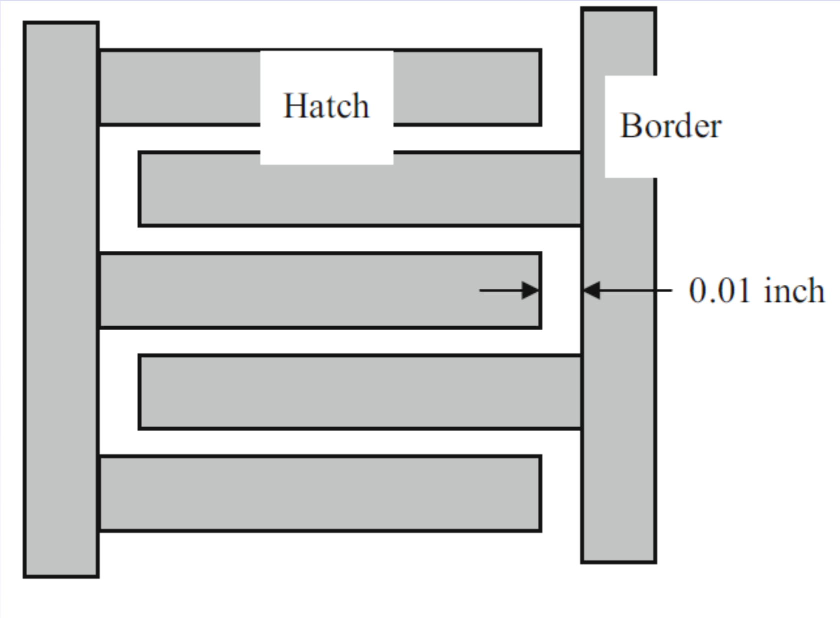
Inkjet control voltage for each nozzle

Process planning

Influence of path layout on the part properties: Reduce internal stress and improve accuracy



WEAVE Pattern



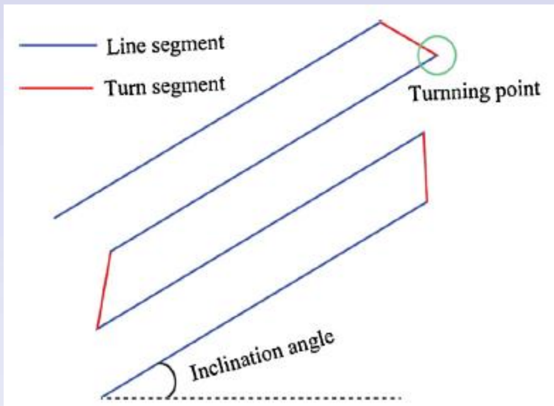
STAR-WEAVE Pattern

Gibson, Ian, David W. Rosen, and Brent Stucker. *Additive manufacturing technologies*. New York: Springer, 2010.

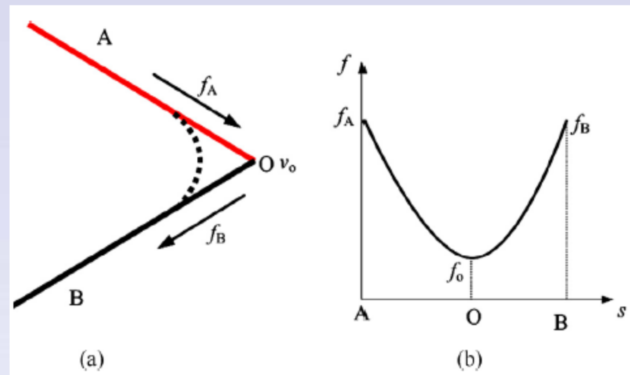
Design for AM

Process planning

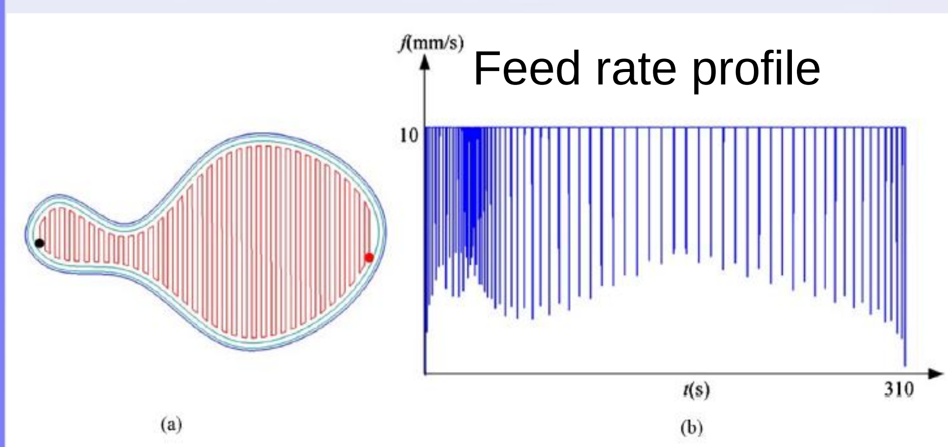
Reduce fabrication time and improve quality



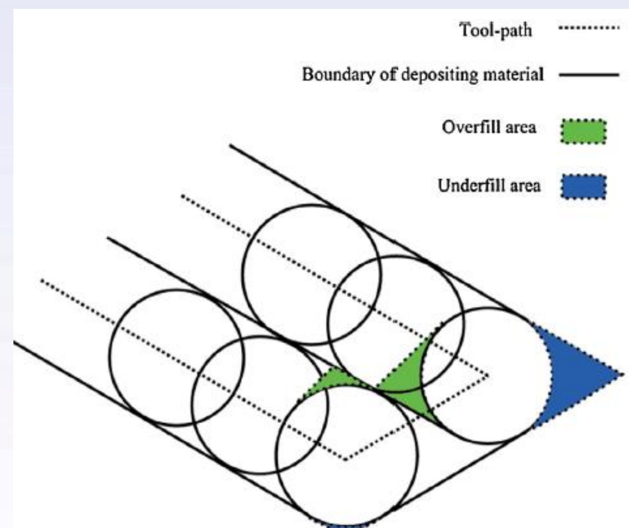
Scan path



Feed rate change at corners



Feed rate profile



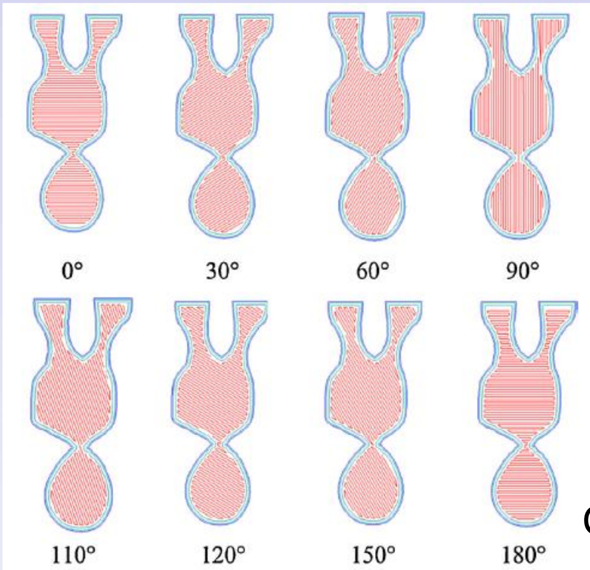
Overfill and underfill

Jin, Yu-an, et al. "Optimization of tool-path generation for material extrusion-based additive manufacturing technology." *Additive Manufacturing* 1 (2014): 32-47.

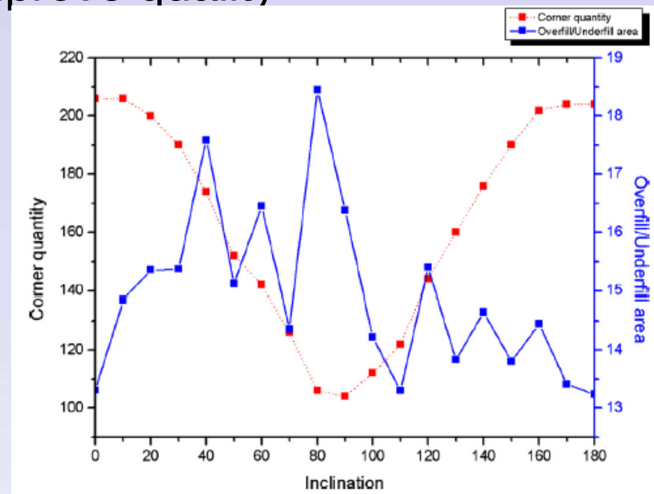
Design for AM

Process planning

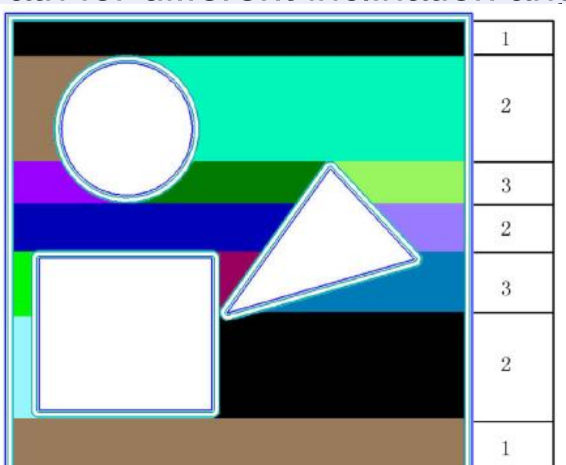
Reduce fabrication time and improve quality



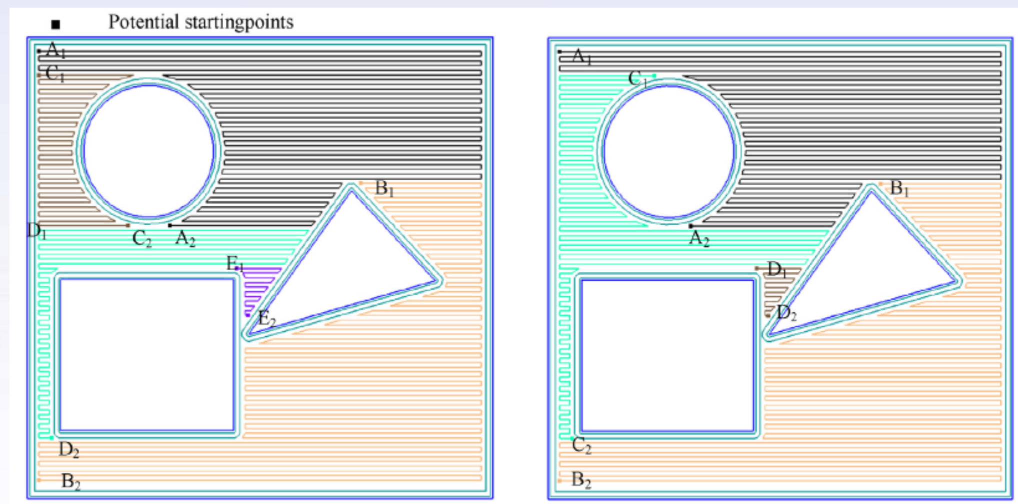
Path for different inclination angle



Corner quantity and over/under fill area change with angle



Identify sub-paths



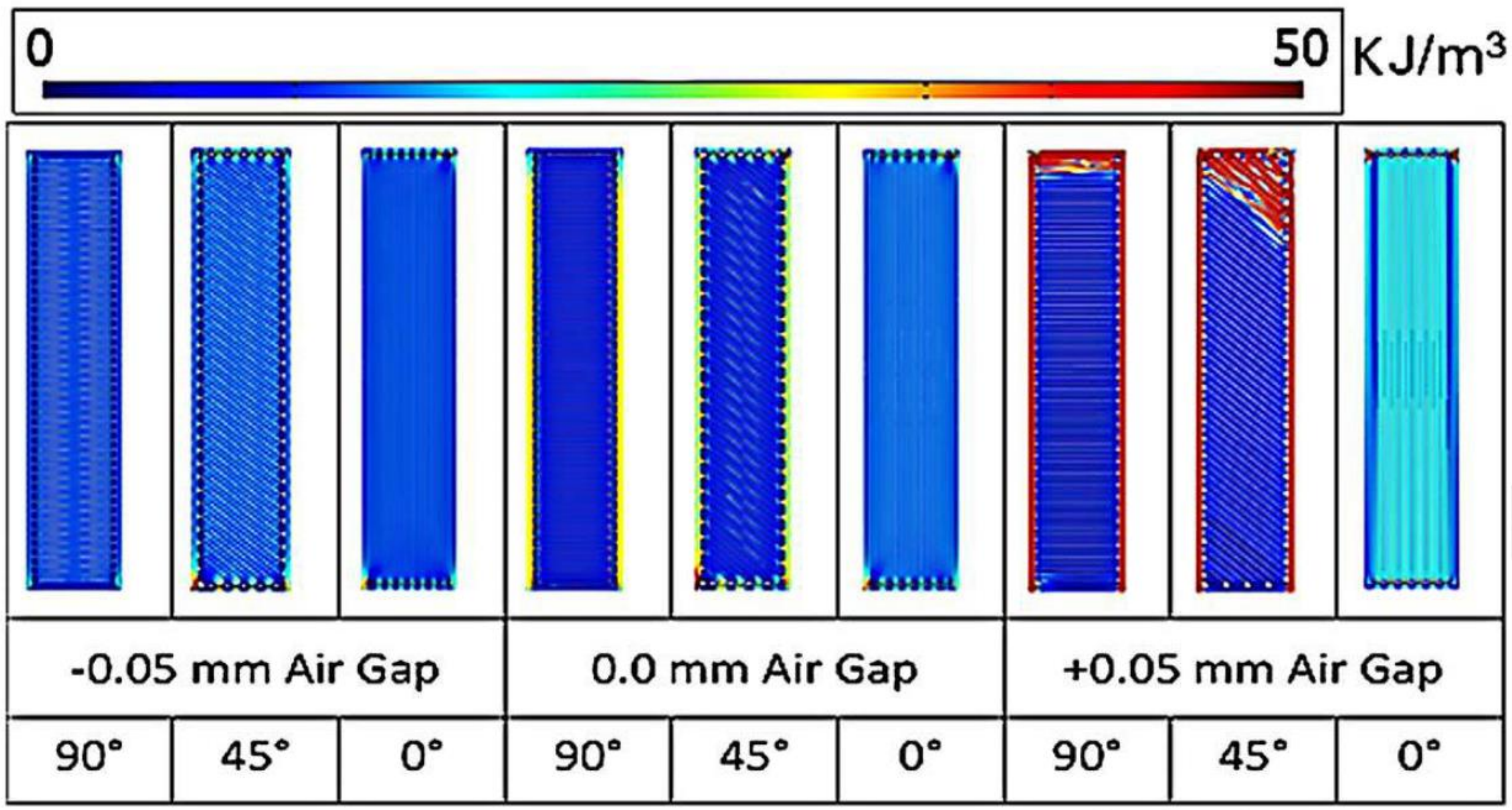
Link sub-paths

Jin, Yu-an, et al. "Optimization of tool-path generation for material extrusion-based additive manufacturing technology." *Additive Manufacturing* 1 (2014): 32-47.

Design for AM

Process planning

Tool path on structure properties



4 Strain energy density distribution in FDM part for different raster angles and air gaps

Rezayat, H., Zhou, W., Siriruk, A., Penumadu, D., & Babu, S. S. (2015). Structure-mechanical property relationship in fused deposition modelling. Materials Science and Technology.

Design for AM

Process planning – Dynamic optimization

$$\text{Minimize} \quad f(\mathbf{x})$$
$$\textit{Subject to} \quad g(\mathbf{x}) \le 0$$
$$h(\mathbf{x}) = 0$$

- $f(\mathbf{x})$: Objective function to be minimized
- $g(\mathbf{x})$: Inequality constraints
- $h(\mathbf{x})$: Equality constraints
- $\mathbf{x}$: Design variables

Static optimization: x in Euclidean space

$$\min \psi(z(t), y(t), u(t), p, t_f)$$

$$s.t. \quad \frac{dz(t)}{dt} = F(z(t), y(t), u(t), t, p)$$
$$G(z(t), y(t), u(t), t, p) = 0$$
$$z^o = z(0)$$
$$z^l \le z(t) \le z^u$$
$$y^l \le y(t) \le y^u$$
$$u^l \le u(t) \le u^u$$
$$p^l \le p \le p^u$$

Credit: Dr. L. T. Biegler@CMU

- t, time
- z, differential variables
- y, algebraic variables
- t_f, final time
- u, control variables
- p, time independent parameters

Dynamic optimization: u in functional space

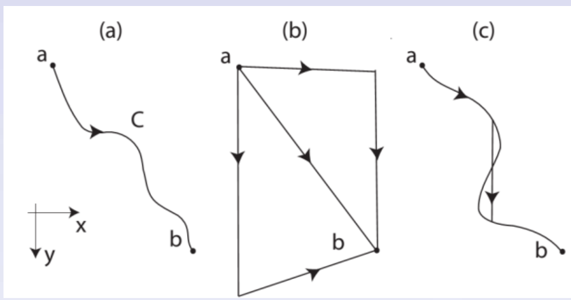
Design for AM

Design
Process
Functionality

- **Process planning – Dynamic optimization – Calculus of Variation**

Functional: function of function: example F(x(t)) or $\int_{t_0}^{t_1} x(t)$

Brachistochrone curve (curve of fastest descent): over 3 centuries



$$v(y) = \sqrt{2gy}.$$

$$ds = \sqrt{(dx)^2 + (dy)^2} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx.$$

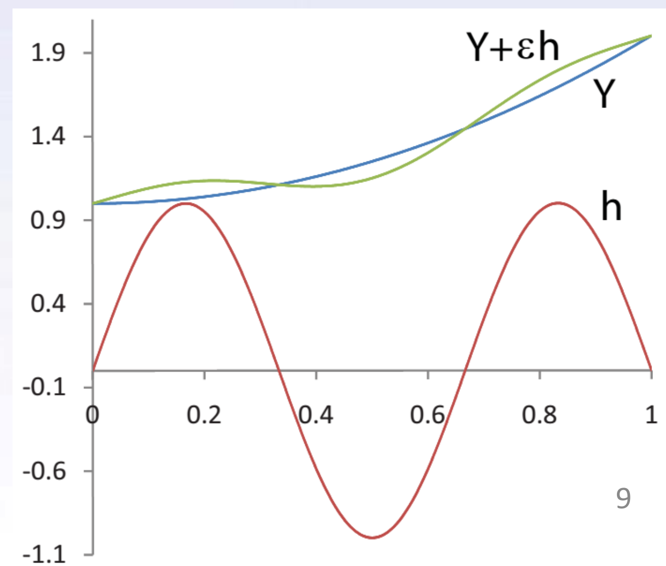
$$dt = \frac{ds}{v} = \frac{\sqrt{1 + \left(\frac{dy}{dx}\right)^2}}{\sqrt{2gy}} dx,$$

$$\min\ T = \int_0^{x_b} \frac{\sqrt{1 + \left(\frac{dy}{dx}\right)^2}}{\sqrt{2gy}} dx.$$

$$\min\ I(y) = \int_{x_0}^{x_1} F(y, y', x)\, dx$$

$$\begin{aligned} y(x) &= Y(x) + \epsilon h(x), \\ y'(x) &= Y'(x) + \epsilon h'(x). \end{aligned}$$

Euler–Lagrange equation: $\frac{\partial F}{\partial y} - \frac{d}{dx}\left(\frac{\partial F}{\partial y'}\right) = 0$



Design for AM

- **Process planning – Dynamic optimization – Optimal Control**

An extension of calculus of variations for deriving control policy

A dynamic system is described by state equation:

$$\dot{x}(t) = f(x(t), u(t), t), \quad x(0) = x_0,$$

where x(t) is state variable, u(t) is control variable.
The control aim is to maximize the objective function:

$$J = \int_0^T F(x(t), u(t), t)dt + S[x(T), T].$$

Constraints:

Inequality: $g(x(t), u(t), t) \geq 0, \ t \in [0, T],$

Constraints on state variables: $h(x, t) \geq 0, \ t \in [0, T]$

Boundary conditions: $\phi[\mathbf{x}(t_0), t_0, \mathbf{x}(t_f), t_f] = 0$

Solution: typically nonlinear and no analytical solution, need numerical methods to solve

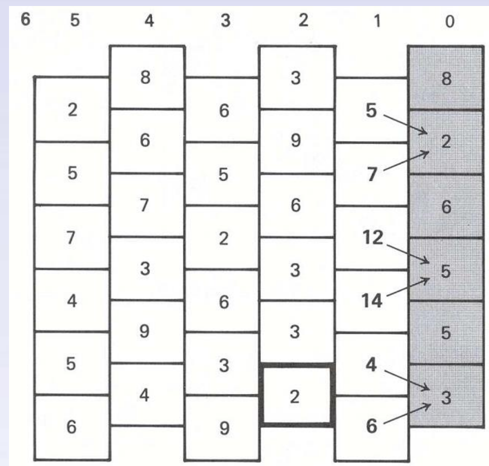
Design for AM

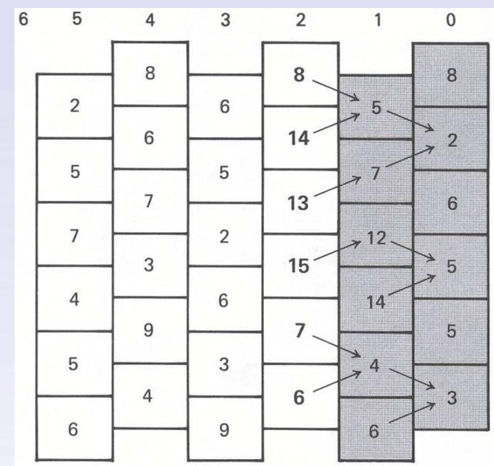
- **Process planning – Dynamic optimization – Dynamic programming**

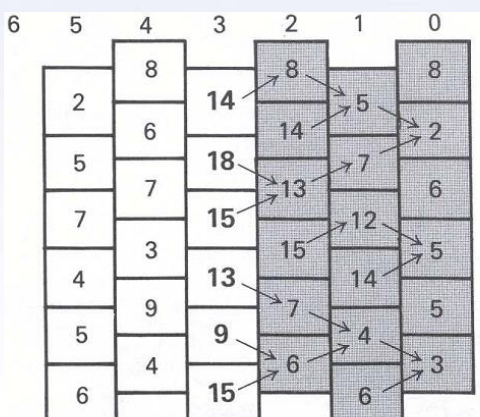
Bellman's Principle of Optimality: An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

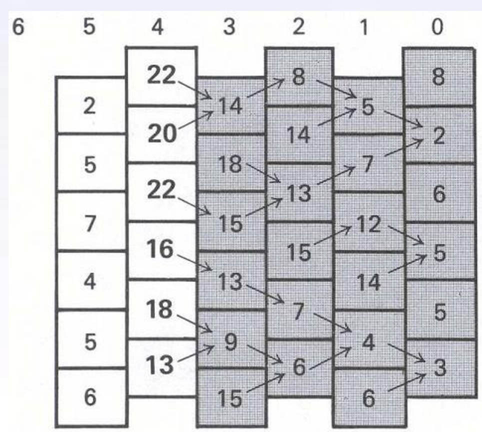
- **Backward induction to solve a sequence of smaller decisions**

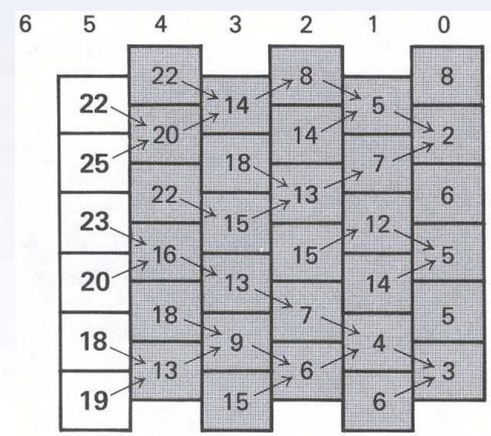
Travel from left to right, numbers are delays at each intersection,
minimize delay
Use recursion











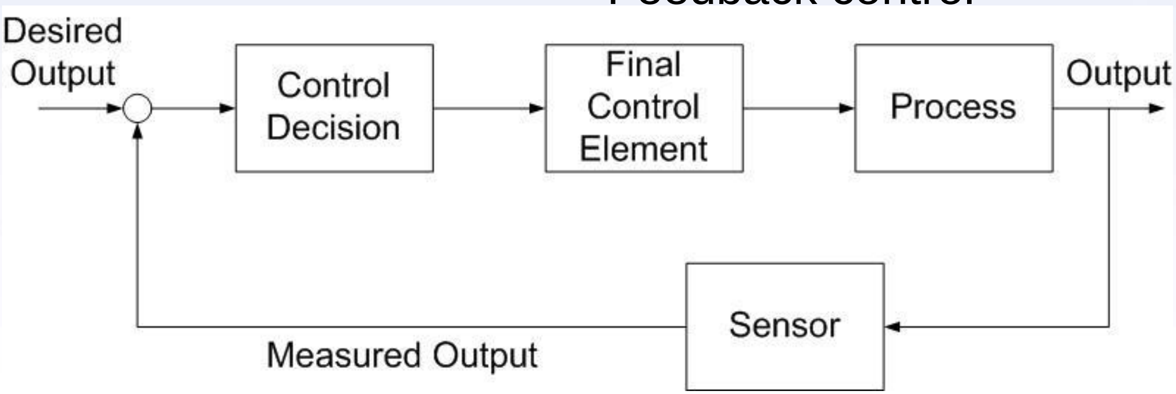
Design for AM

- **Process planning – Other methods**

Machine Learning

- **Decision tree learning**
- **Association rule learning**
- **Artificial neural networks**
- **Inductive logic programming**
- **Support vector machines**
- **Clustering**
- **Bayesian networks**
- **Reinforcement learning**
- **Representation learning**
- **Similarity and metric learning**
- **Sparse dictionary learning**
- **Genetic algorithms**

Feedback control



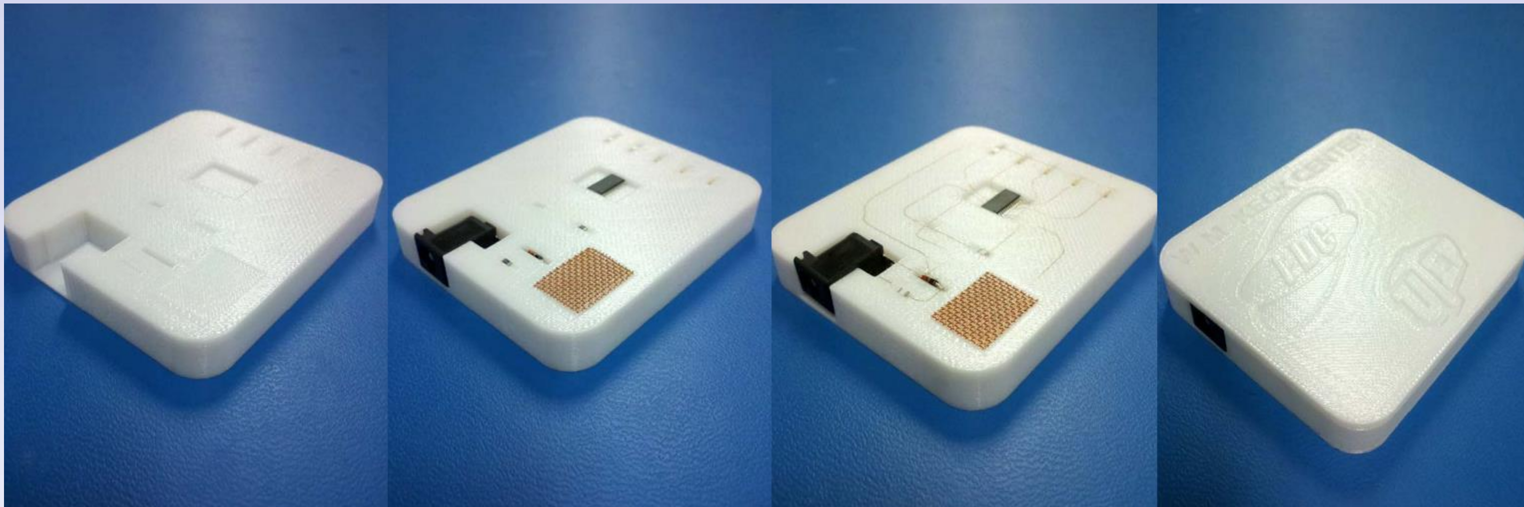
Design for AM

- Functionality
  - Mechanical
    - Geometry
    - Carry load
  - Electrical
    - Conduct electricity
    - Transmit or receive electrical signal
  - Optical
    - Lens
    - Display

  - Sensor
  - Actuator
  - Communication
  - Energy source
  - Display

Design for AM

Functionality – Sensor



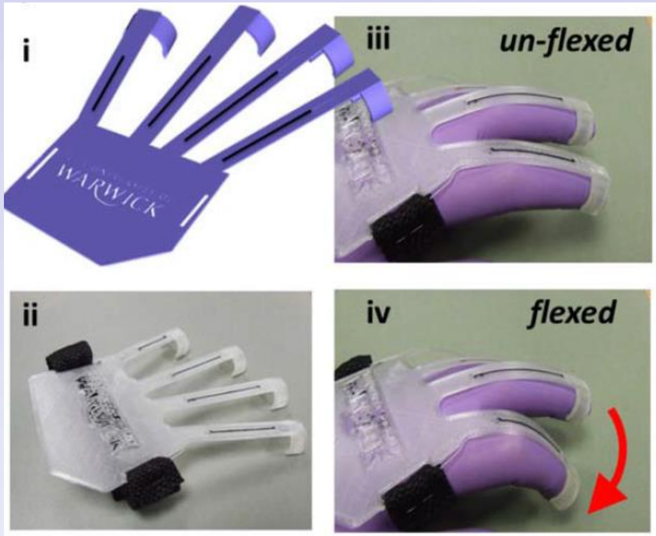
Embedded capacitive sensor in FDM part
UTEP Keck center

Shemelya, C., et al. "3D printed capacitive sensors." *SENSORS, 2013 IEEE*. IEEE, 2013.

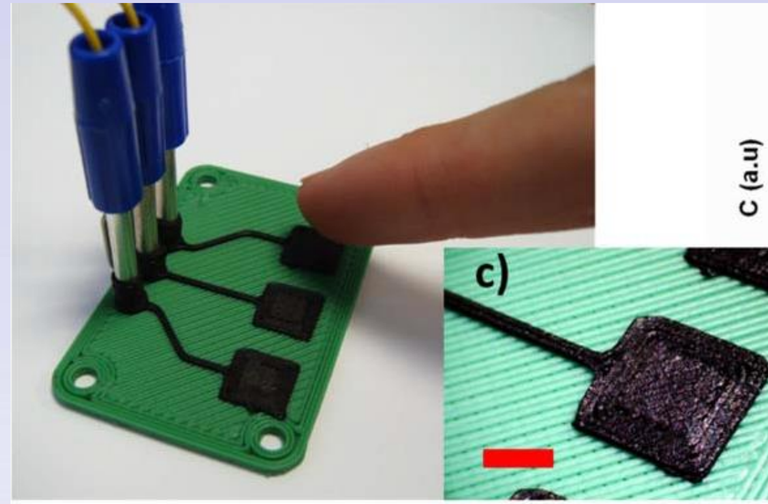
- **Process: FDM**
- **Materials: polyphenylsulfone, polycarbonate, copper wire**

Design for AM

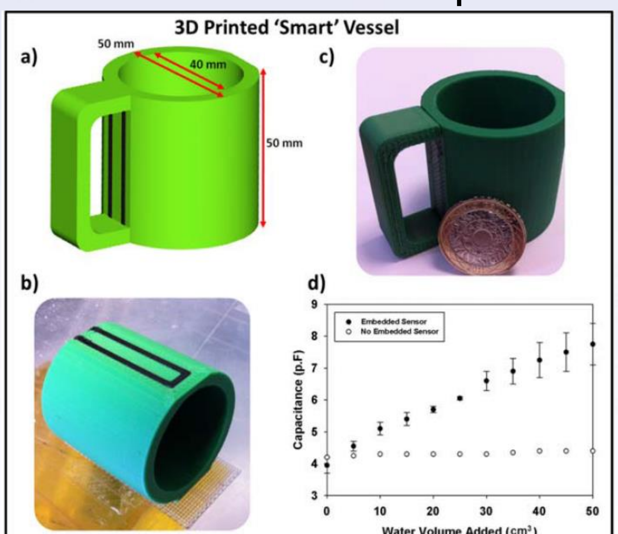
Functionality – Sensor



Flex sensor based on piezoresistivity



Capacitive buttons



Smart cup

FDM Printed sensors

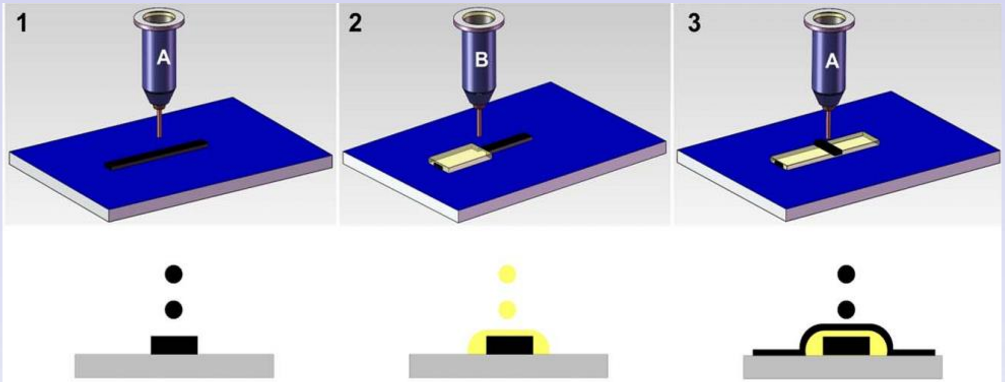
- **Process: FDM**
- **Materials: ABS and conductive filament** (carbomorph)

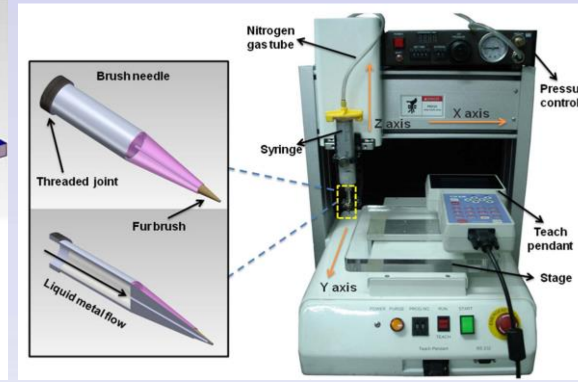
Leigh, Simon J., et al. "A simple, low-cost conductive composite material for 3D printing of electronic sensors." *PloS one* 7.11 (2012): e49365.

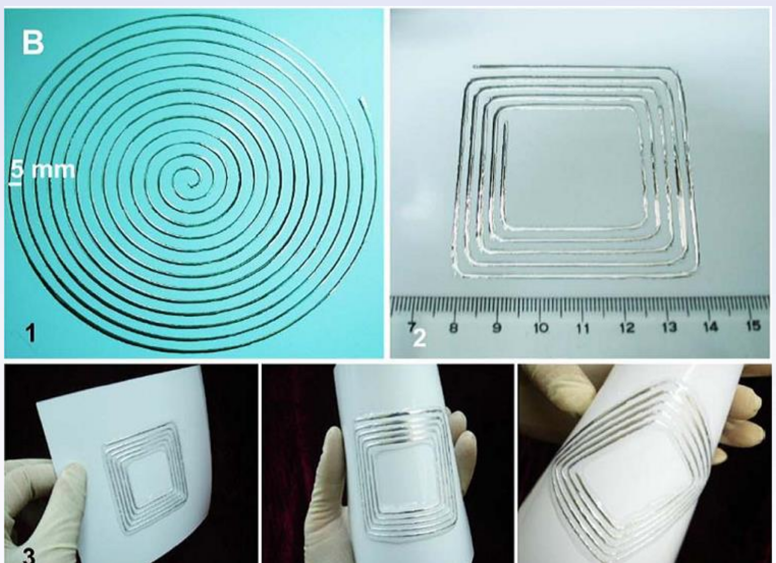
Design for AM

Design
Process
Functionality

Functionality – Circuits







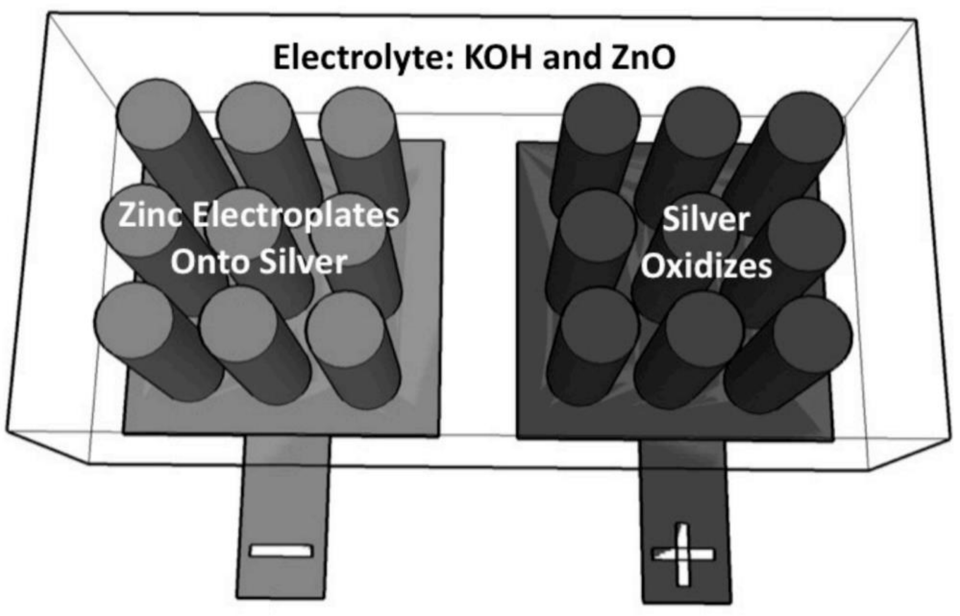
Direct Desktop Printing Circuits on Paper

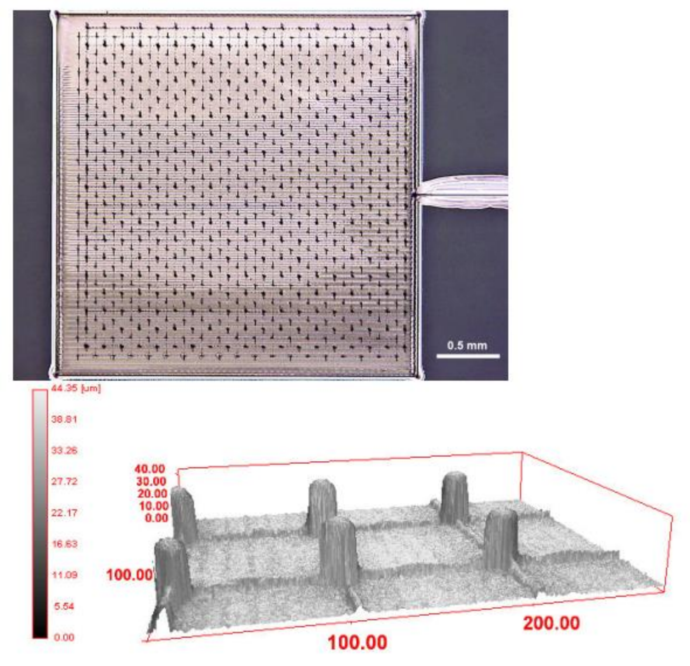
Zheng, Yi, et al. "Direct desktop printed-circuits-on-paper flexible electronics."*Scientific reports* 3 (2013).

- **Process: Syringe based direct write**
- **Materials: Liquid metal $GaIn_{24.5}$ alloy as conductive ink, vulcanizing (RTV) silicone rubber for isolating**
- **Metal remains liquid after printing**

Design for AM

Functionality – Microbattery





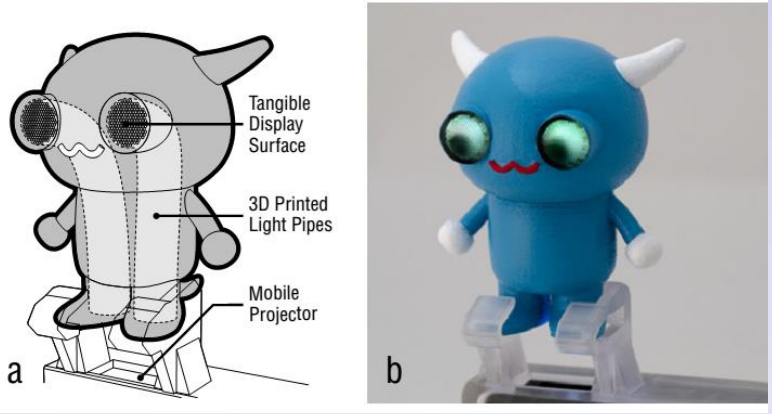
Inkjet Printed Microbattery

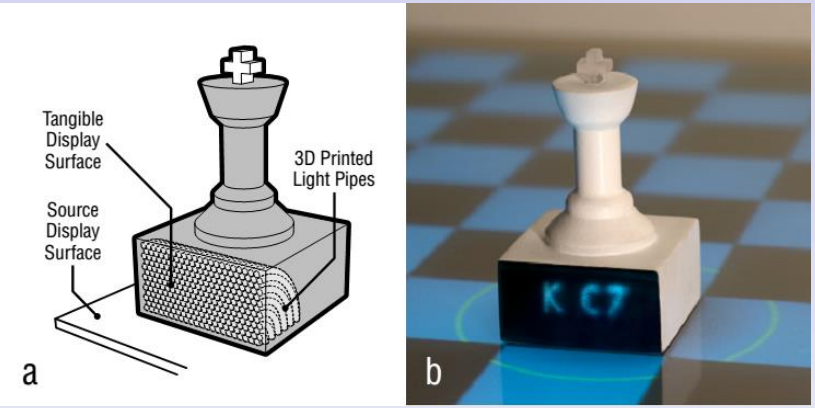
Ho, Christine C., et al. "A super ink jet printed zinc–silver 3D microbattery."*Journal of Micromechanics and Microengineering* 19.9 (2009): 094013.

- **Process: Super inkjet (electrostatic inkjet)**
- **Materials: Silver nanopaste** (Harima Chemicals) **and KOH electrolyte** (Sigma Aldrich) **with dissolved ZnO powder**
- **Zinc self-assembles on printed silver pillars during first charge**

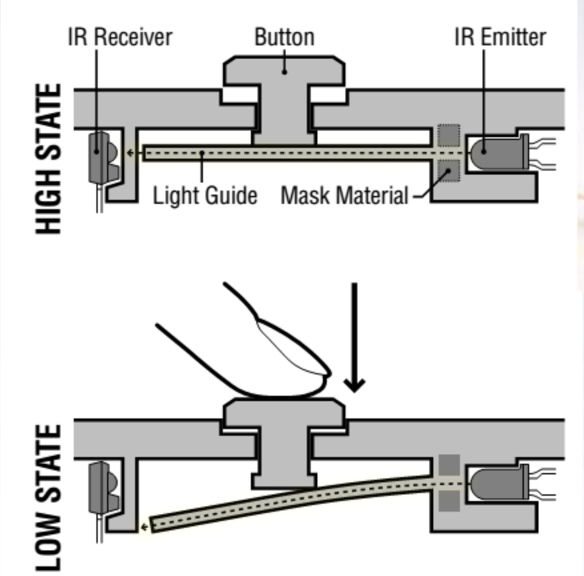
Design for AM

Functionality – Printed Optics

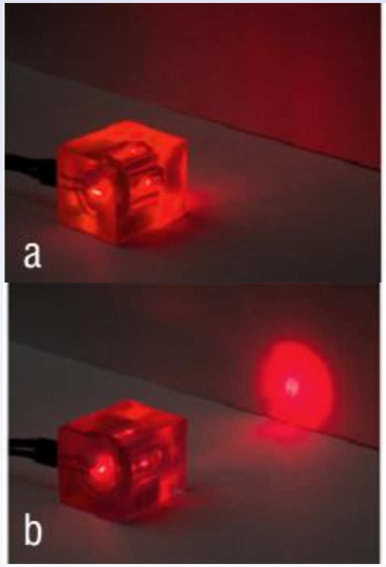




Light pipes (guide light)



Sensing movement



Printed lens

Inkjet Printed Optics

- **Process: Objet Eden260V**
- **Material: VeroClear**

Willis, Karl, et al. "Printed optics: 3d printing of embedded optical elements for interactive devices." *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 2012.

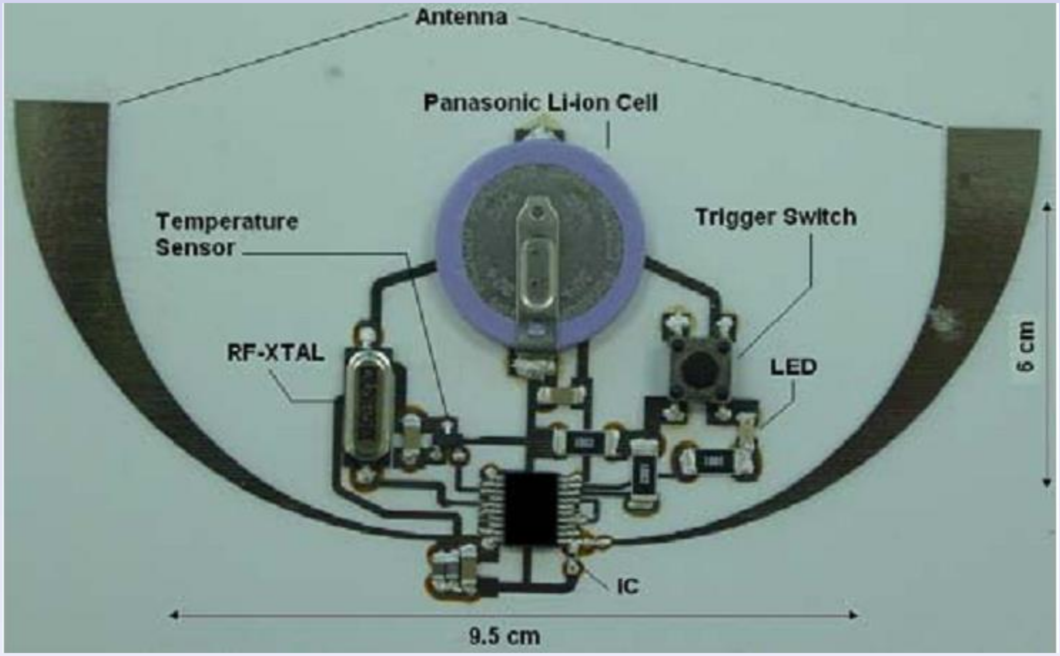
Design for AM

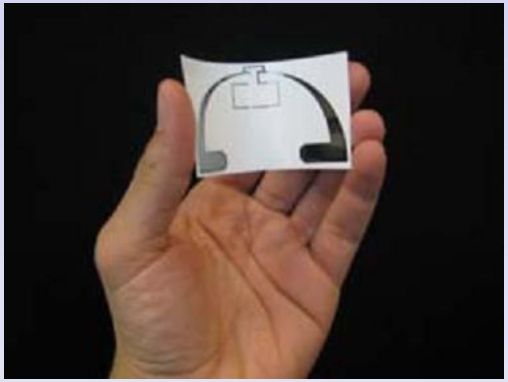
Design

Process

Functionality

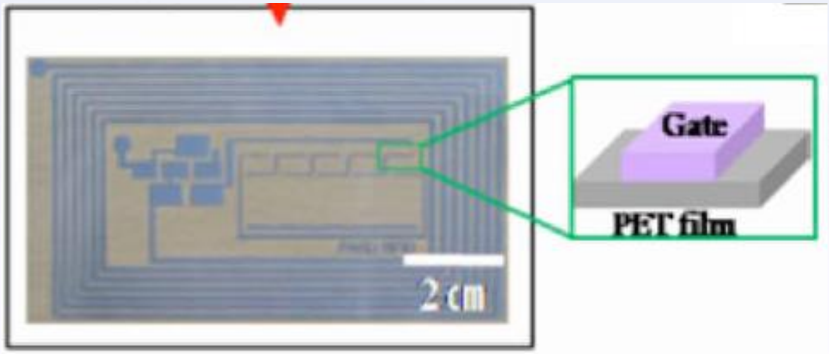
Functionality – Printed Antenna





Antenna

Fully-integrated wireless sensor modules on paper



RFID tags

Inkjet Printed Wireless Sensor Networks and Antenna

- **Process: Fuji DMP Inkjet**
- **Material: Silver nanoparticle ink**

Tentzeris, M. M. "Novel paper-based inkjet-printed antennas and wireless sensor modules." *Microwaves, Communications, Antennas and Electronic Systems, 2008. COMCAS 2008. IEEE International Conference on*. IEEE, 2008.

Design for AM

Functionality – 4D printing

4D Printing = **3D Printing** + **Smart Materials**

From wiki: Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

- **Piezoelectric materials**
- **Shape-memory alloys and shape-memory polymers**
- **Temperature-responsive polymers**
- **Dielectric elastomers**
- **Thermoelectric materials**
- **Self-healing materials**
- **Magnetic shape memory**
- **pH-sensitive polymers**

Functionality – 4D printing

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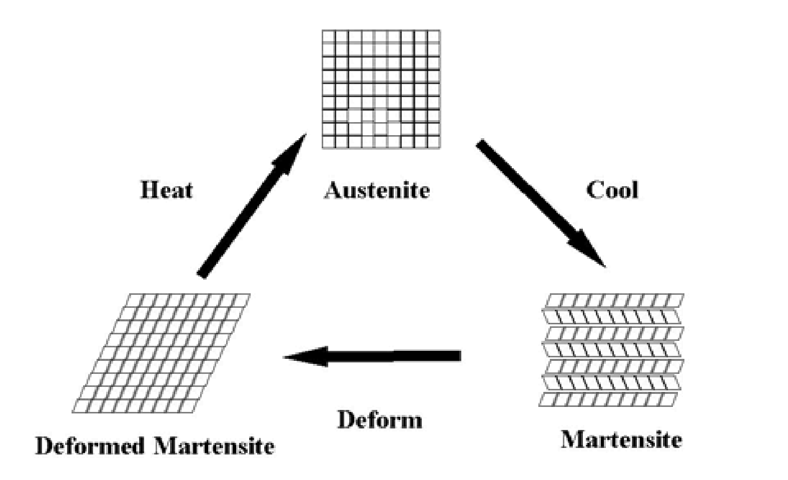
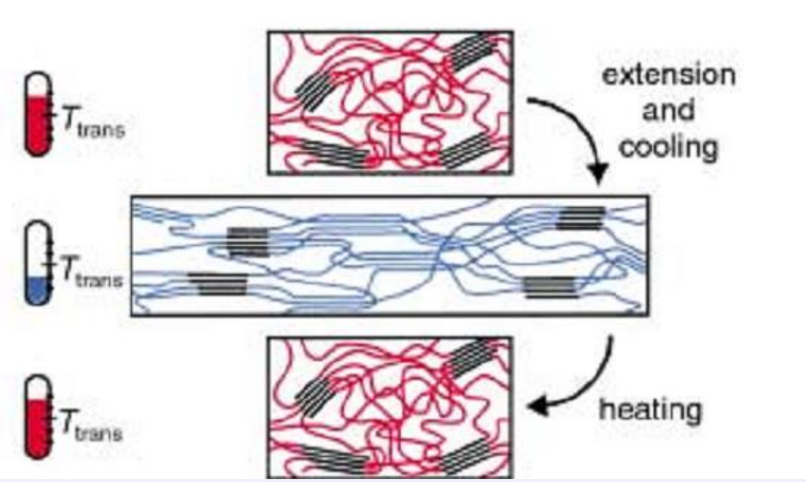
Functionality – Shape memory

Shape Memory Alloys (SMAs) are a class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature.

Design
Process
Functionality



Shape memory alloys

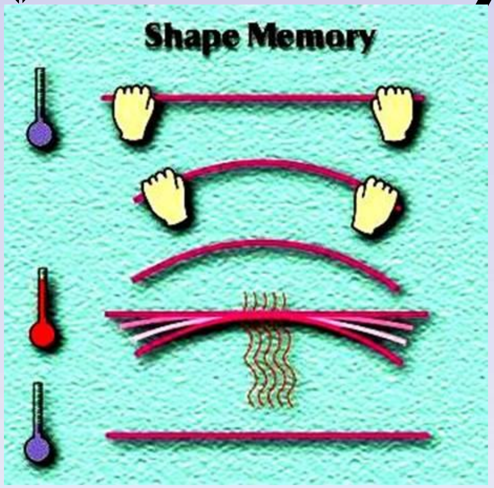


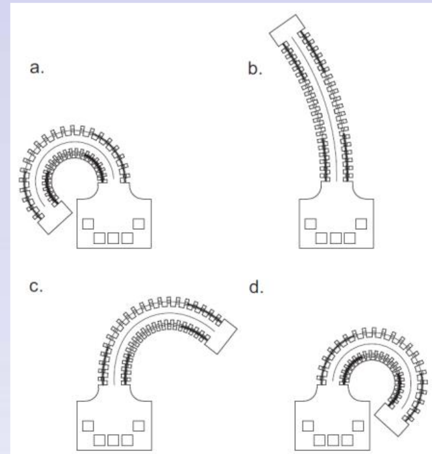
Shape memory polymers

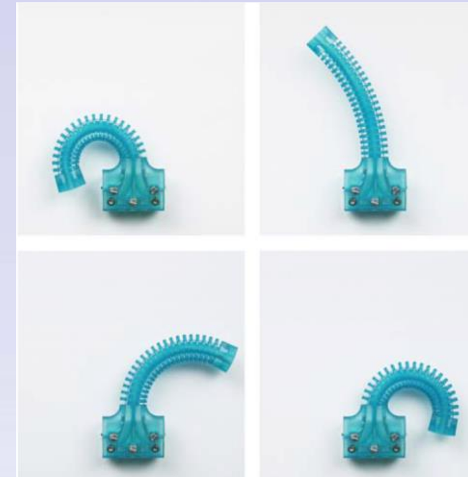
Shape-memory polymers (SMPs) are polymeric smart materials that have the ability to return from a deformed state (temporary shape) to their original (permanent) shape induced by an external stimulus (trigger), such as temperature change.

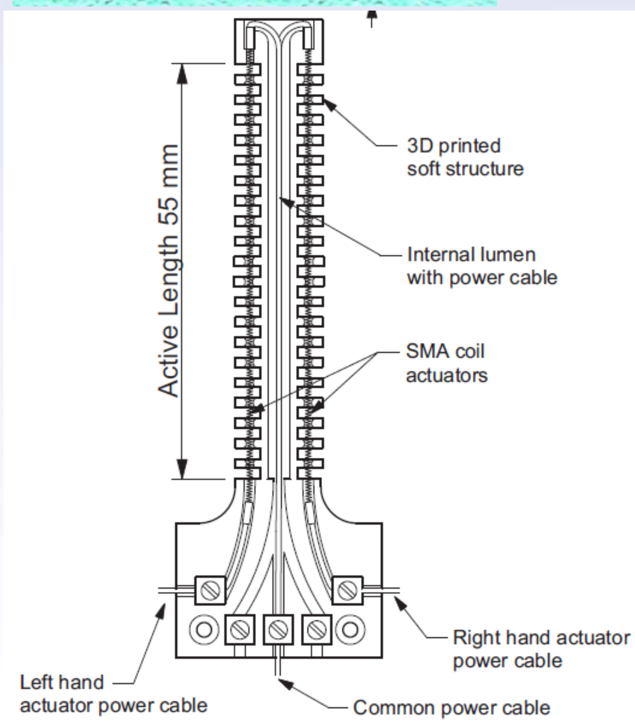
Design
Process
Functionality

Functionality – Smart structures (robots)









Inkjet Printed Soft Robot (a tentacle)

- **Process: Objet**
- **Material: Fullcure 930 material**
- **Shape memory alloy coil (NiTi) mounted on the printed tentacle**

Walters, Peter, and David McGoran. "Digital fabrication of “smart” structures and mechanisms-creative applications in art and design." *NIP & Digital Fabrication Conference*. Vol. 2011. No. 1. Society for Imaging Science and Technology, 2011.

Design for AM

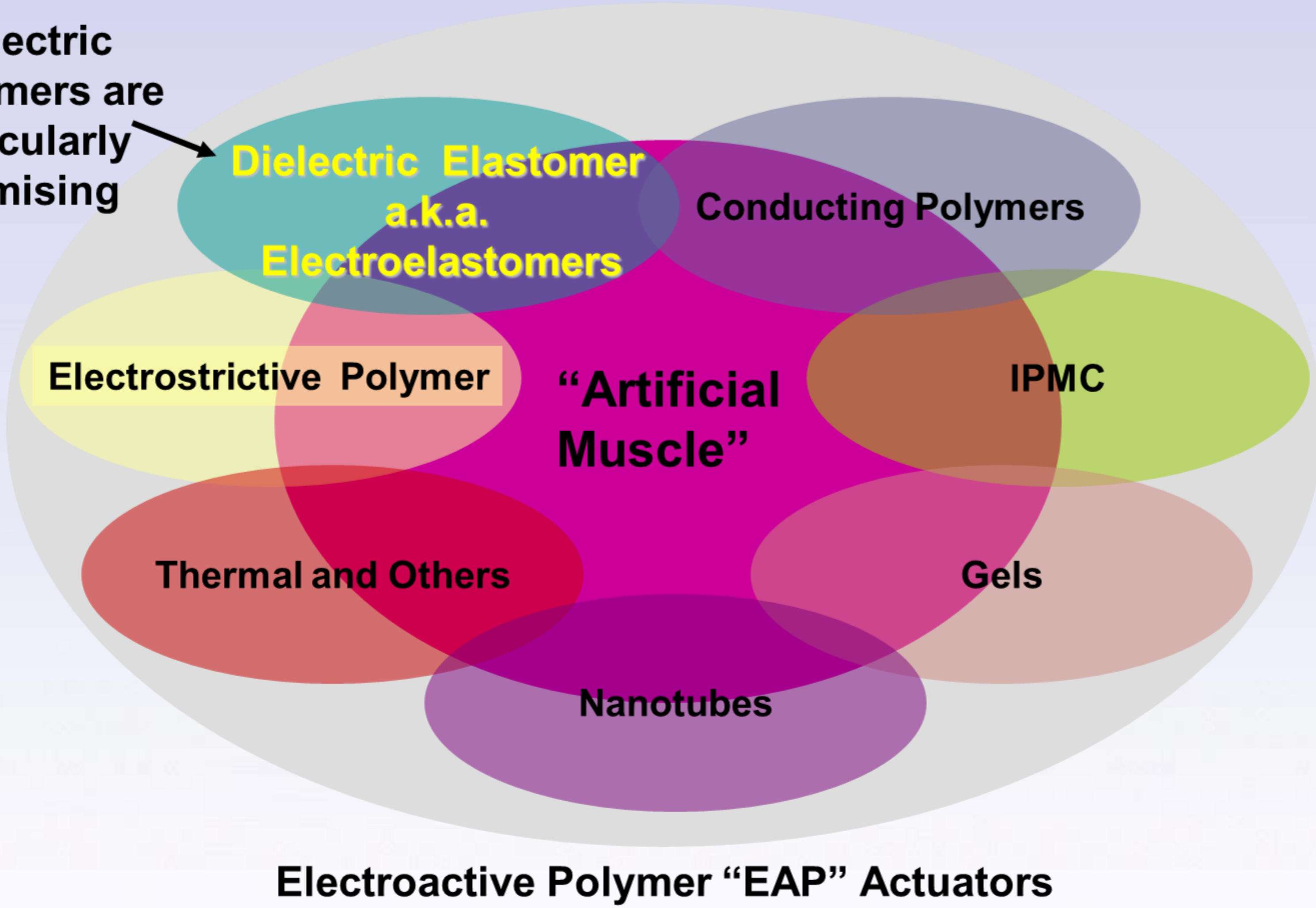
Design

Process

Functionality

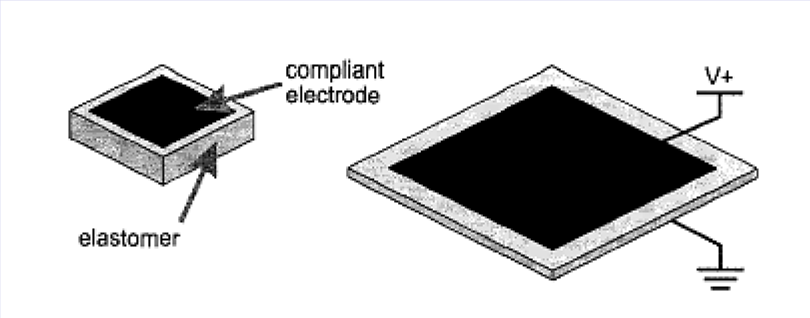
Functionality – DEA actuator

Dielectric elastomers are particularly promising



Design for AM

Functionality – DEA actuator

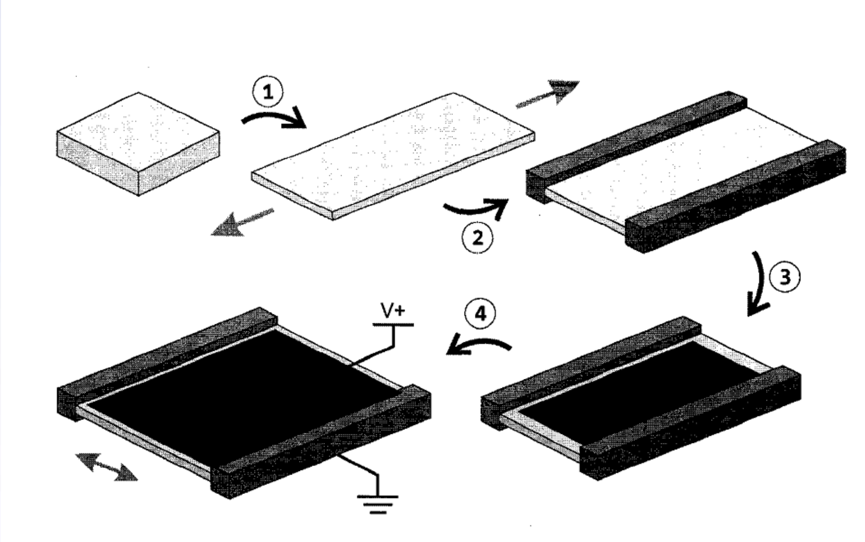


Working Principle

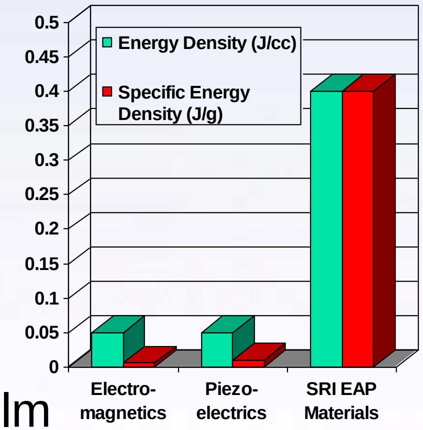
Maxwell pressure

$$P = \epsilon\epsilon_0 E^2$$

- **Require high voltage**
- **Material can break down under high voltage**
- **Can potential achieve 120% strain compared to 10% for shape memory materials**
- **High strain rate**
- **High energy density**



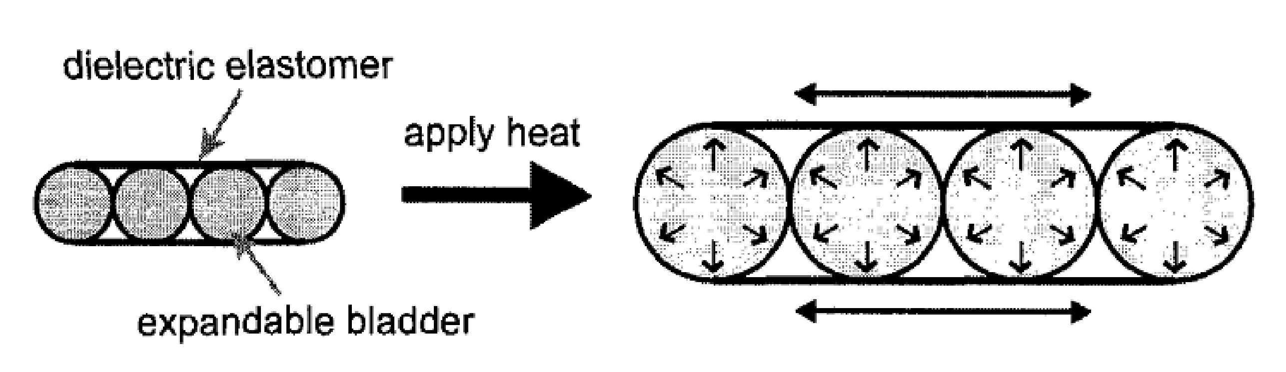
Process of generating pre-strained elastomer film



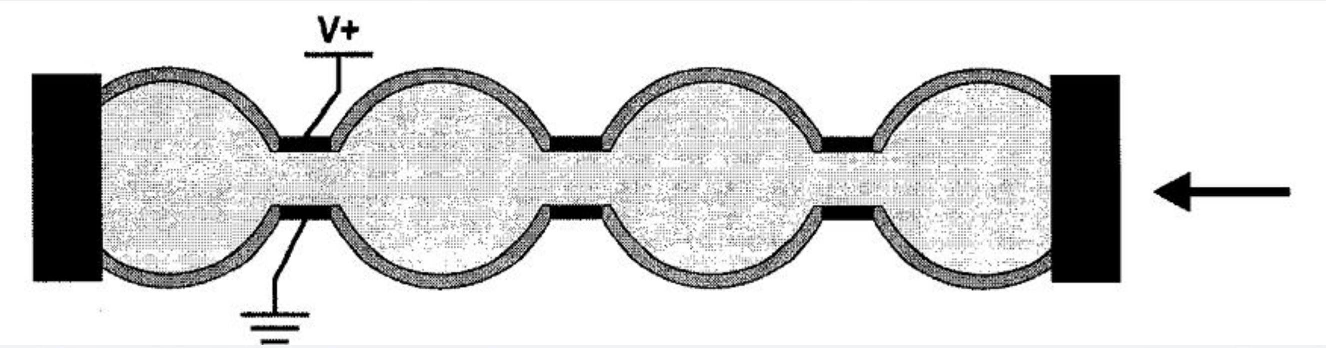
Risner, Jeremy. *Investigation of Dielectric Elastomer Actuation for Printable Mechatronics*. ProQuest, 2008.

Design for AM

Functionality – DEA actuator



Inflatable structure to generate pre-strain



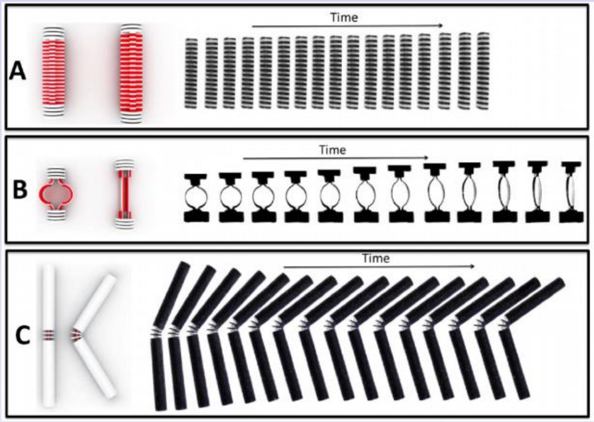
Wrinkle actuator

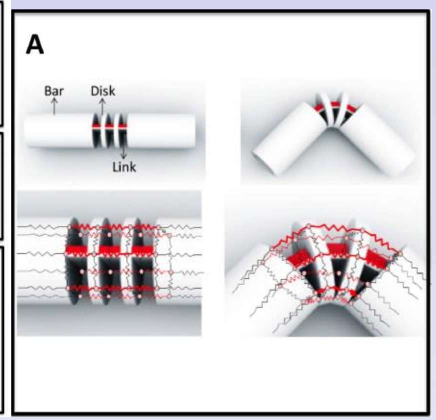
- **Process: Syringe based extrusion**
- **Material: Silicone as elastomer and carbon grease as electrode materials**

Risner, Jeremy. *Investigation of Dielectric Elastomer Actuation for Printable Mechatronics*. ProQuest, 2008.

Design for AM

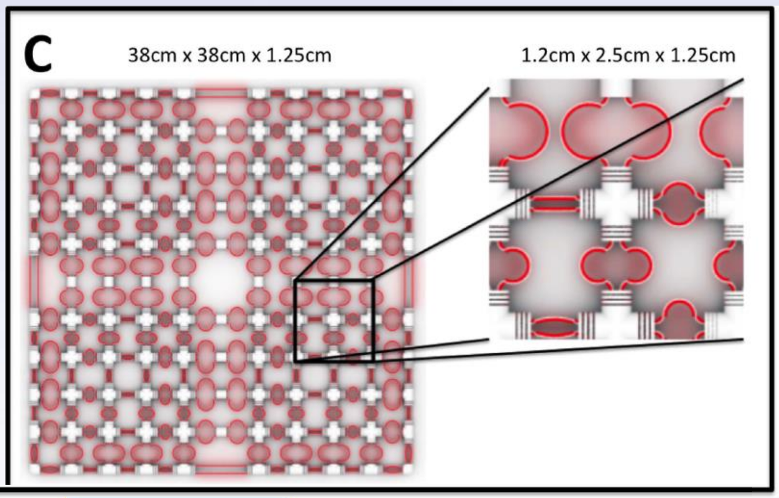
Functionality – Self-evolving structure

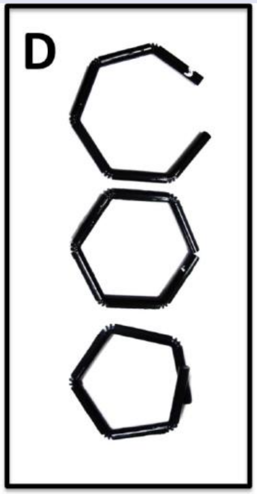


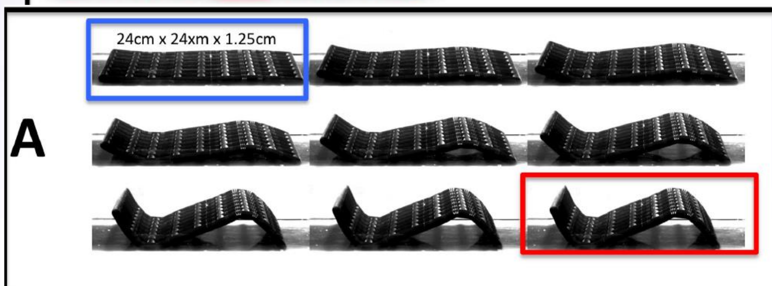


- **Process: Objet Connex**
- **Material: Multi-material UV curable polymers – rigid, and hydrophilic materials**
- **Actuation by swelling in water**

Raviv, Dan, et al. "Active Printed Materials for Complex Self-Evolving Deformations." *Scientific reports* 4 (2014).







Design

Process

Functionality