GAMES Webinar
Topics on CAD/CAE/CAM

# Robot-assisted Multi-Axis Additive Manufacturing (MAAM):

## *Curved Layer Slicing and 3D Toolpath Generation*

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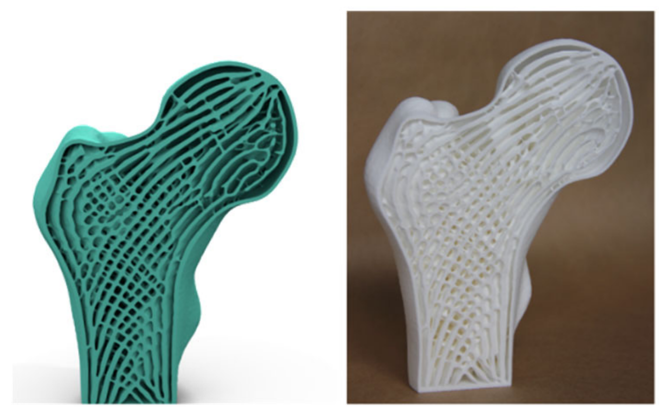
# Additive Manufacturing (3D Printing)

- Defined by ASTM as:

  Process of building 3D objects by adding **layer-upon-layer** of material.

- Different Types of AM:
  - Stereolithography Apparatus **(SLA),** Selective Laser Sintering **(SLS)**
  - Direct Energy Deposition (**DED**), two-photon polymerization (**TPP**)
  - Fused Deposition Modeling **(FDM)** …


Rapid Prototyping & 'Mass'-customization Production [1]



Fabricate model with complex geometry [Wu et al,. IEEE TVCG, 2018]



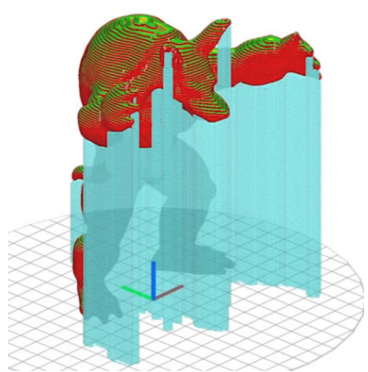
[1] X. Zhang, **G. Fang**, C. Dai, J. Verlinden, J. Wu, E. Whiting, and C. C.L. Wang, "Thermal-comfort design of personalized casts", ACM Symposium on User Interface Software and Technology (UIST), pp.243-254, 22-25, 2017.

# 2.5D / 3D Printing ? Pros. and Cons.

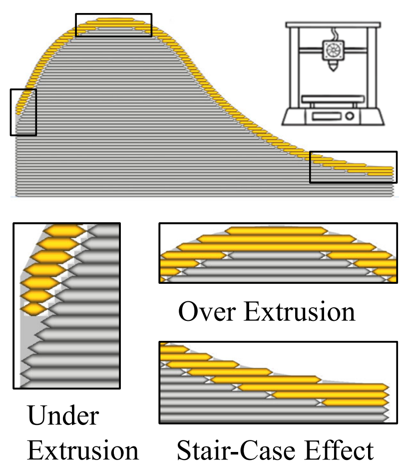
**Conventional**
Planar-based 3D printer

**Planar-layer-based material accumulation**

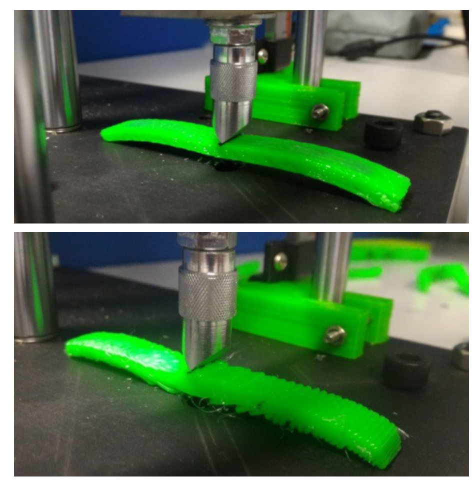
- Simplify the algorithms of motion-planning
- Limited shape of models that can be support-free fabricated – i.e., support-structures in many cases
- Relatively weak mechanical property between layer delamination between layers / small fragments



Heavy support structure

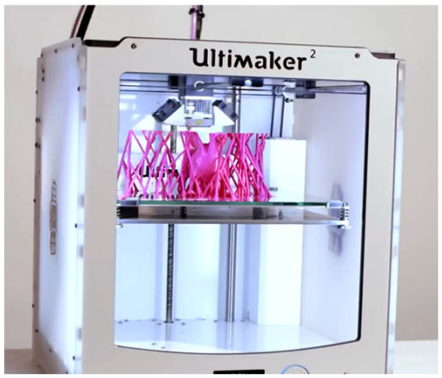



Discontinuous Toolpath & Stair-Case Effect



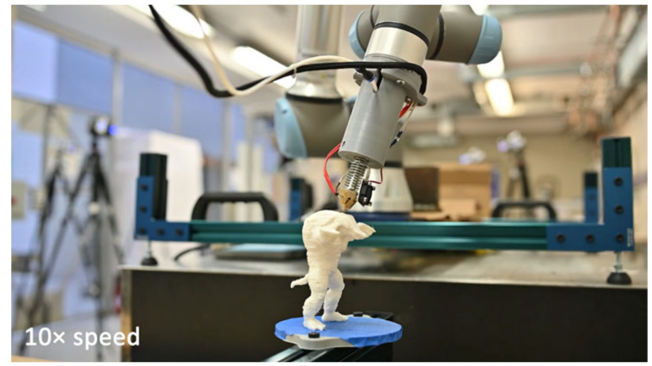
Weak mechanical property between layers

# Planar-based 3DP v.s. Multi-axis 3DP with Curved Layers

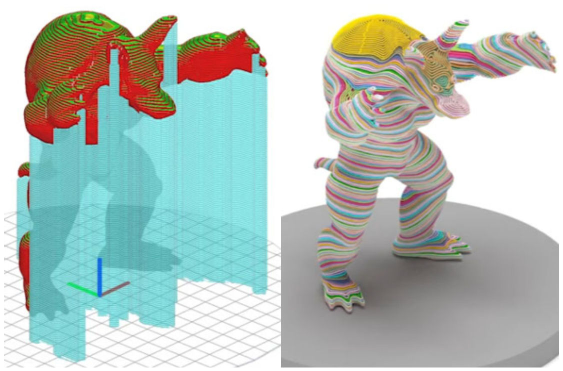



Planar-based 3D printing

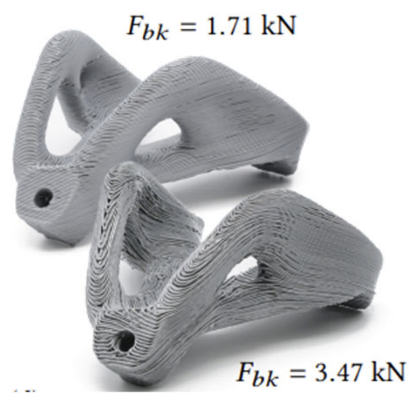
*V.S.*



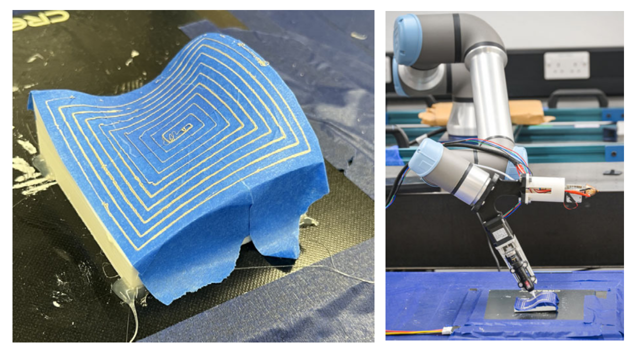

**Multi-axis 3D printing:** Accumulation of materials occurs in space and is not constrained to planar layers.



Support-free Printing

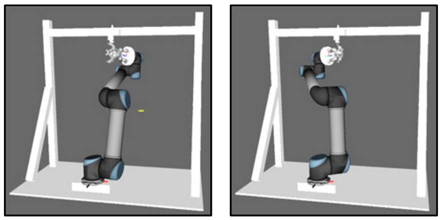


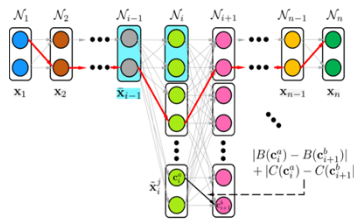

Stress Reinforcement

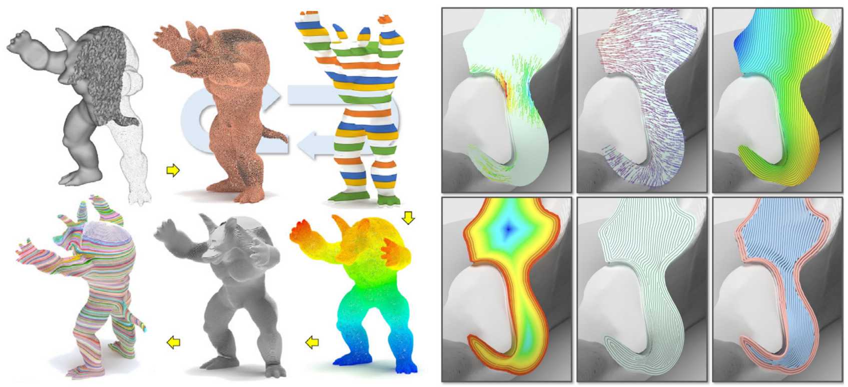


Conformal Material Alignment

# Multi-Axis AM: Research Directions

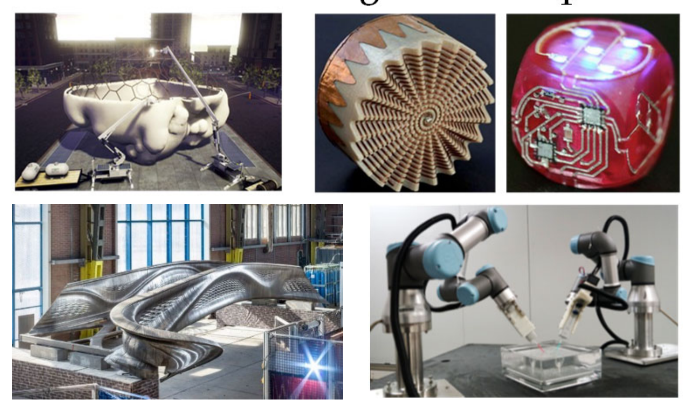






**Software (Slicer & Machine Control):**
- Curved-layer slicer and Toolpath generator
- Motion planner with extrusion control.

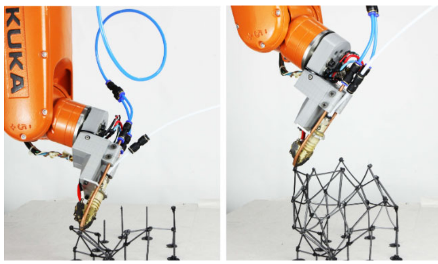
**Hardware: Robot arm/CNC machine** enables materials alignment in space.



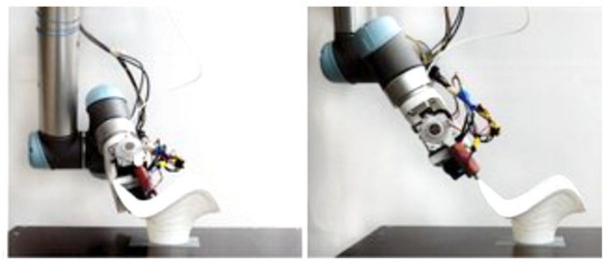
**Materials & Applications:**
Metal [1]; Conformal electronics printing [2]; Large-scale construction [3]; Bio-printing [4].

[1] Image credit @MX3D
[2] Z. Zhang et al. Bio. Mat., vol.18, pp.138-150, 2022.
[3] C. Gosselin et al., Materials & Design, 100, 102-109. 2016
[4] E. MacDonald et al., IEEE Access 2, 234–242 (2014)

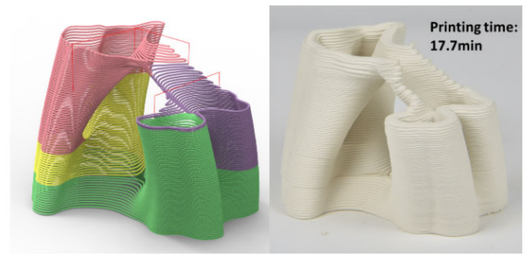
# MAAM/Non-planar AM Research in Graphics Community



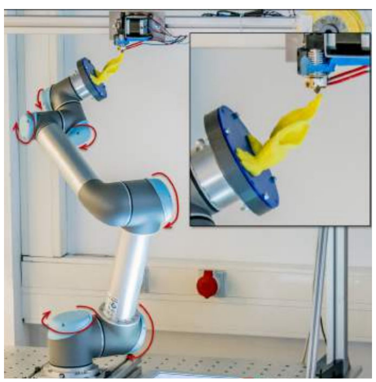
[Huang et al, SIG Asia 16]



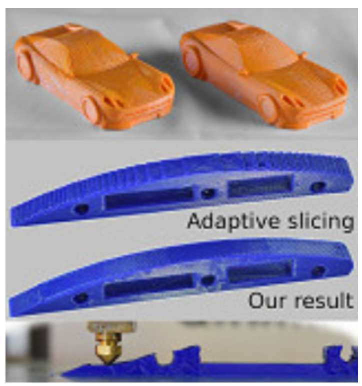
[Mitropoulou et al, SCF 20]



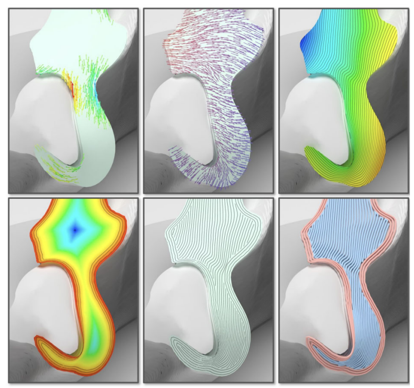

[Zhong et al, TOG 22]



[Dai et al, SIG 18]




[Etienne et al, SIG 19]

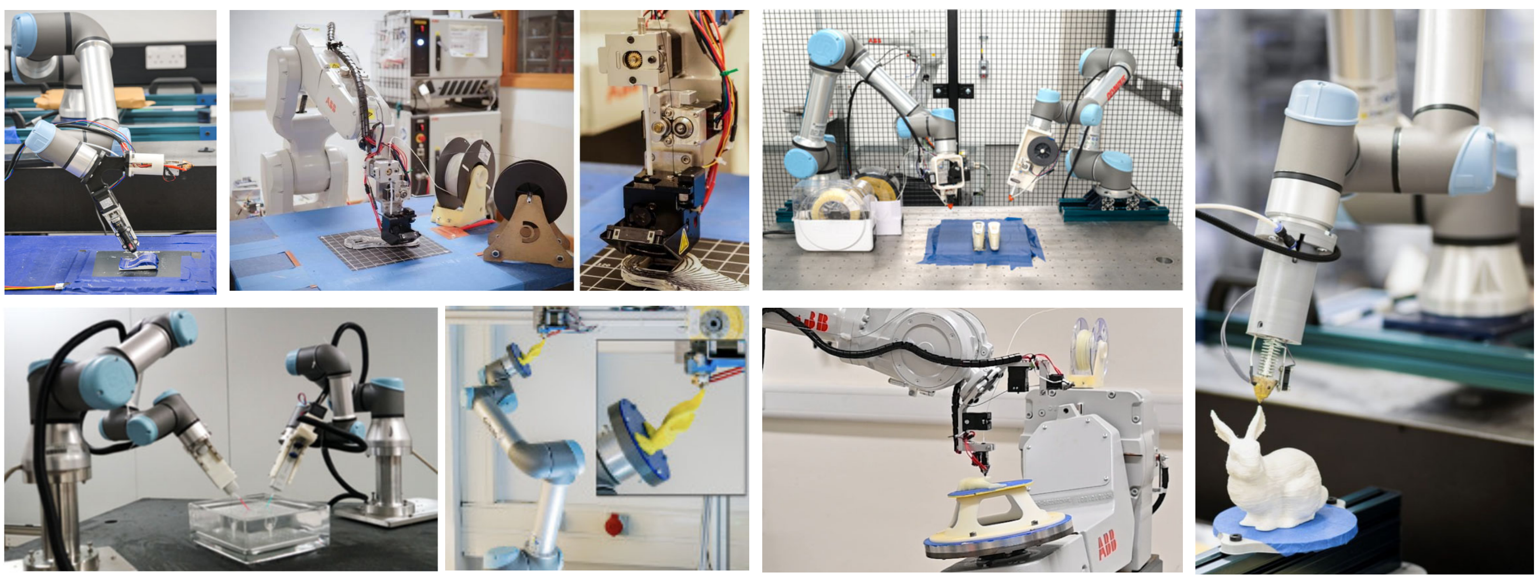


[Fang et al, SIG Asia 20]

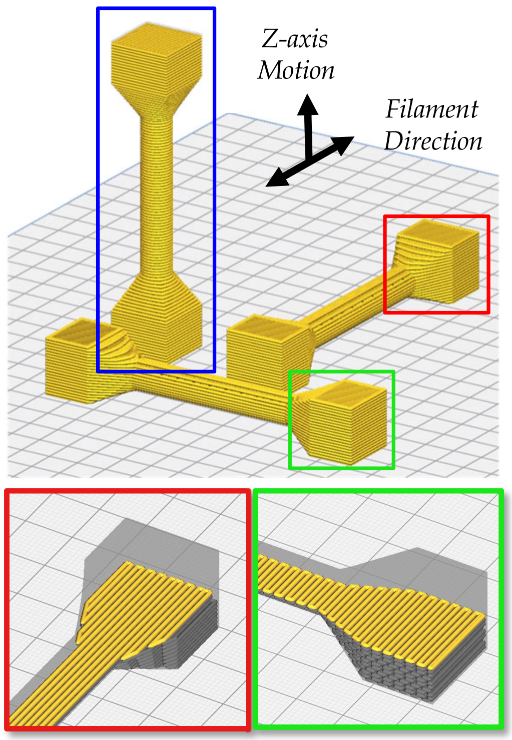
[Zhang et al, SIG Asia 22]

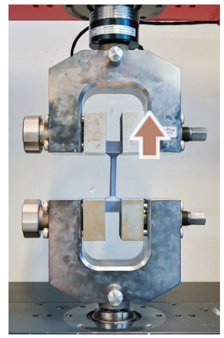
# Outline

- MAAM with controlled anisotropic strength [SIG Asia 2020]
- MAAM with functional material CFRPTCs: toolpath design [ADDMA 21,22]
- $S^3$-Slicer: a general curved layer slicer for MAAM [SIG Asia 2022, best paper award]



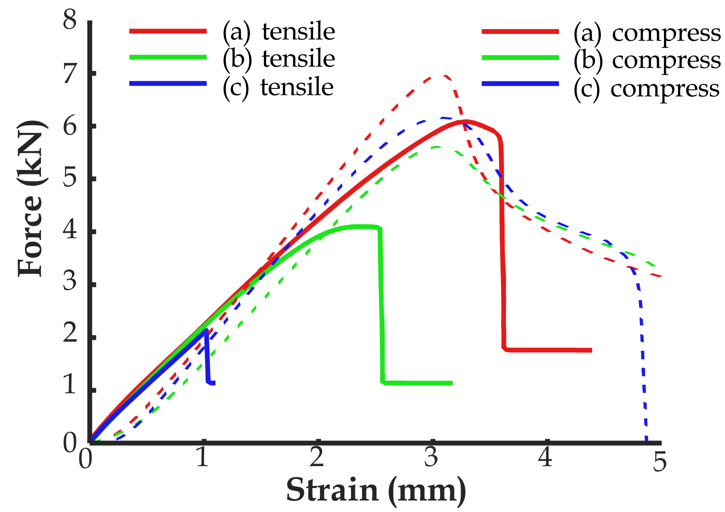
# Anisotropy of Mechanical Property in 3D Printing



Tensil
e

Compres
s




***176% enhance in tensile test***
***27% enhance in compress test***

[*Ahn et al, J. Rapid Prototyping.* 2002;
*Tam and Muller, 3DP&AM.* 2017]

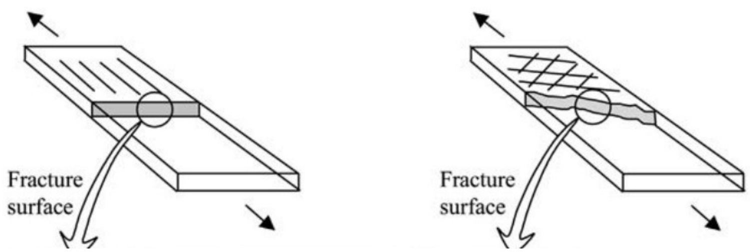
- Transversal direction is weaker than axial direction
- Analyze the stress tensor distribution by finite element analysis (FEA)

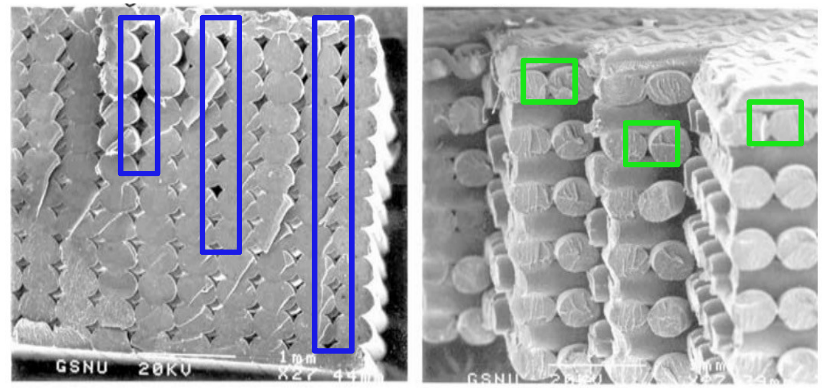


**G.Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

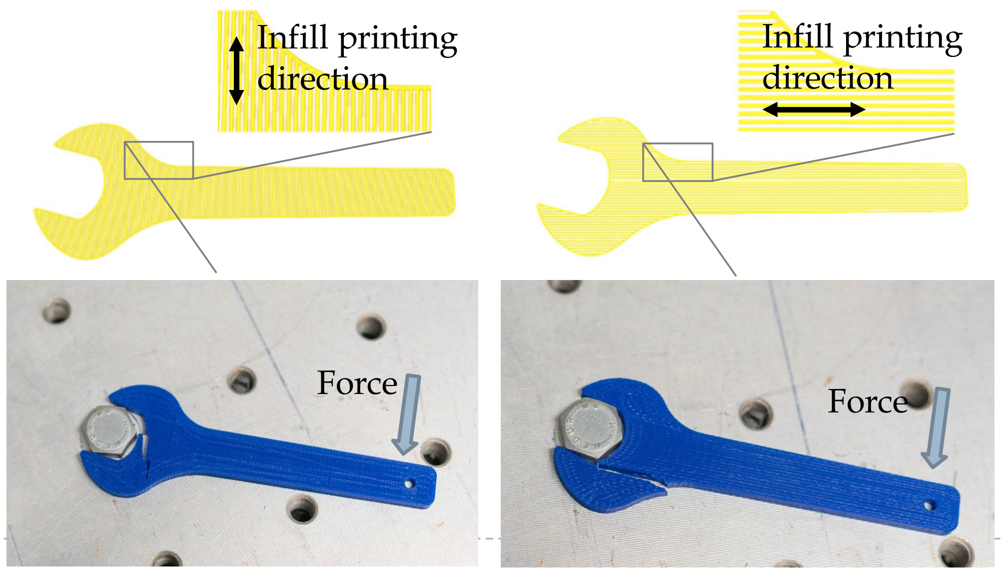
# Delamination: Major Source of Fracture

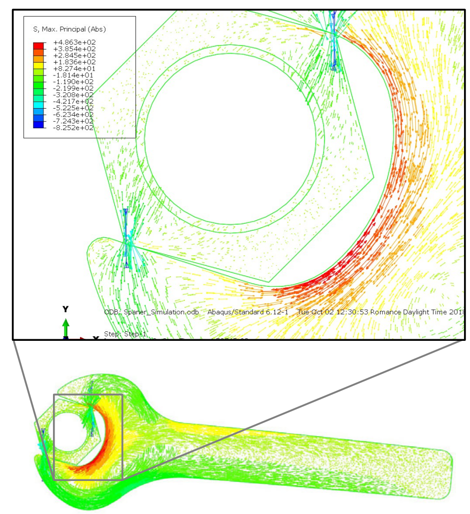
*[Ahn et al, J. Rapid Prototyping. 2002]*



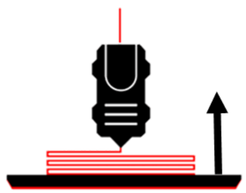

Anisotropic strength caused by the weak adhesion at incompletely filled area

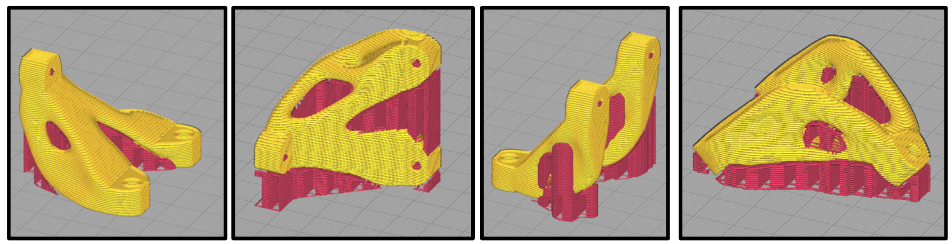


# Reinforcement by Filament Alignment

**Our Solution:** aligning filaments along the directions of *principal stresses*





Planar-layer slicing have limited design space on controlling material alignment, therefore cannot compute an optimum solution in strengthening [Umetani and Schmidt, SIG Asia 2013]

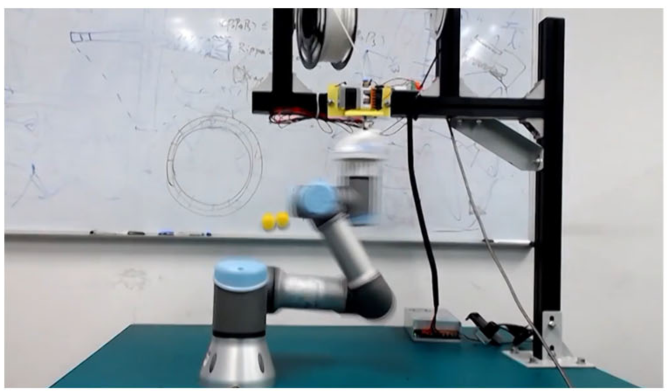
 **G.Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

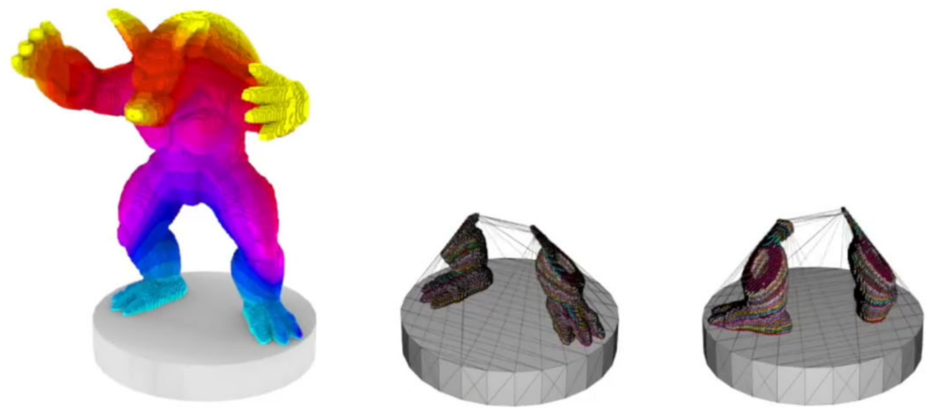
# Curved Support-Free Volume Printing

Methodology: decompose a solid into a sequence of collision-free working surface layers (iso-surfaces of a scalar field) and then generate toolpaths on each layer

Two levels of decomposition (constraints):

- **Volume-to-Surface** – uniform, accessible & self-supported
- **Surface-to-Curve** – uniform and continuous in position, orientation & pose

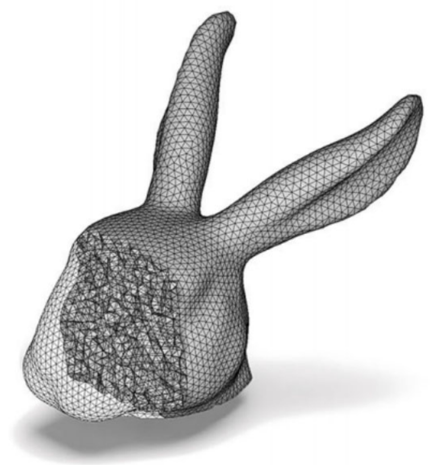




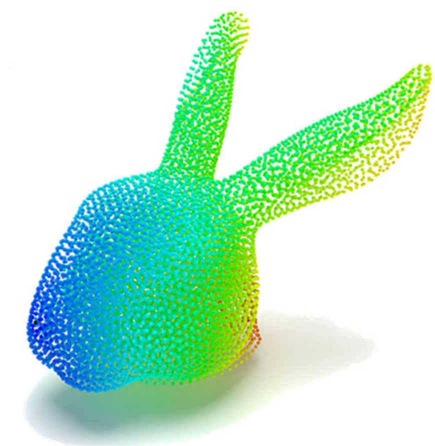
Volume Segmentation [1] ➡ Volume Decomposition: by voxel representation [2]

[1] C. Wu, C. Dai, **G. Fang**, Y. Liu, and C. C.L. Wang, "RoboFDM: a robotic system for support-free fabrication using FDM", IEEE International Conference on Robotics and Automation (ICRA 2017), May 29 - June 3, 2017, pp.1175-1180.
[2] C. Dai, C.C.L.Wang, C.Wu, S. Lefebvre, **G. Fang**, and Y.J. Liu, “Support-free Volume Printing by Multi-Axis Motion", ACM Transactions on Graphics (SIGGRAPH 2018), vol.37, no.4, article no.134 (13 pages), July 2018.

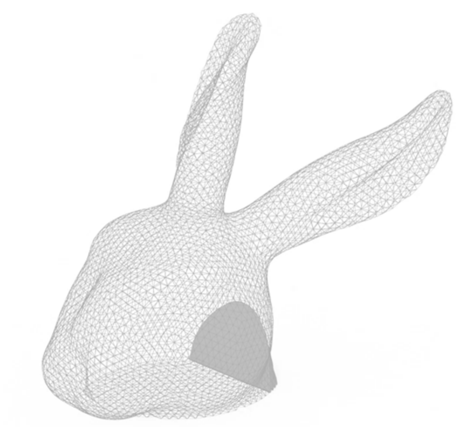
# Field-based Slicing



Model with volumetric mesh representation



Optimized Scalar Field (on mesh vertex)



Curved layers as iso-surfaces

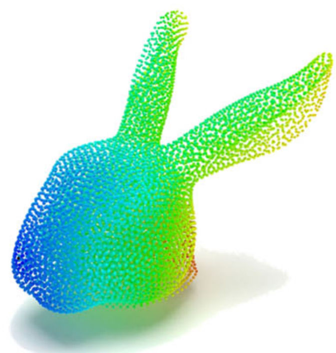
**Computation is conducted on volumetric mesh:**

- Continuous representation (scalar field)
- Effectively in integrating design & manufacturing objectives
  - *Reinforcement (following the direction of principal stresses)*
  - *Fabrication constraints (smoothness, layer thickness control etc.)*
- Curved layers naturally fit with mesh boundary



**G.Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

# Computational Framework: Design Objectives on Scalar Field (Gradient)



**Piece-wise Linear Func.:**

$$G^e(\mathbf{x}) = \sum_{i=1}^{4} \lambda_i(\mathbf{x}) g_i,$$

$$\nabla G^e(\mathbf{x}) = \left( \sum_{i=1}^{4} \frac{\partial \lambda_i(\mathbf{x})}{\partial x} g_i, \sum_{i=1}^{4} \frac{\partial \lambda_i(\mathbf{x})}{\partial y} g_i, \sum_{i=1}^{4} \frac{\partial \lambda_i(\mathbf{x})}{\partial z} g_i \right)$$
$$= \left( \sum_{i=1}^{4} a_i g_i, \sum_{i=1}^{4} b_i g_i, \sum_{i=1}^{4} c_i g_i \right).$$

*Control growing direction - Reinforcement*

*Direction parallel to minimum principal stress direction*

*Principal Stress direction alignment*

$$E_s = \sum_{e \in \mathcal{T}^*} V_e \|\nabla G(\mathbf{x}_e) \times \tau_{\min}(e)\|^2$$

*Control growing speed*

*Ensure uniform layer thickness*

*Layer thickness constraint*

$$E_t = \sum_{e \in \mathcal{T}} V_e (\|\nabla G(\mathbf{x}_e)\| - c)^2$$

*Smoothness in curved layers*

*Harmonic of gradients*

$$E_h = \sum_{(e_a, e_b) \in \mathcal{N}} A_{a,b} \|\nabla G(\mathbf{x}_{e_a}) - \nabla G(\mathbf{x}_{e_b})\|^2$$

**Directly minimizing** $w_s E_s + w_t E_t + w_h E_h$ ?

# Computational Framework: Optimization on Vector Field

*Apply normalization*

**Layer thickness constraint**

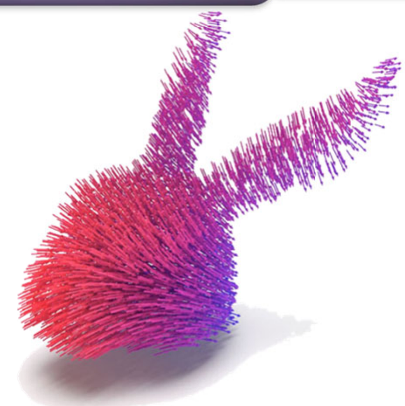
$$\hat{\mathbf{v}}_e = c\mathbf{v}_e / \|\mathbf{v}_e\|$$

$$\Rightarrow \arg\min \sum_{e \in \mathcal{T}} w_e \|\nabla G(\mathbf{x}_e) - \hat{\mathbf{v}}_e\|^2$$

$$E_s = \sum_{e \in \mathcal{T}^*} V_e \|\nabla G(\mathbf{x}_e) \times \tau_{\min}(e)\|^2$$

$$E_t = \sum_{e \in \mathcal{T}} V_e (\|\nabla G(\mathbf{x}_e)\| - c)^2$$

$$E_h = \sum_{(e_a, e_b) \in \mathcal{N}} A_{a,b} \|\nabla G(\mathbf{x}_{e_a}) - \nabla G(\mathbf{x}_{e_b})\|^2$$



**Vector Field V( · )** → **Optimized Scalar Field G( · )**

*Harmonic energy*

$$\arg\min_{\mathbf{v}_e} E_w = \sum_{(e_a, e_b) \in \mathcal{N}} A_{a,b} \|\mathbf{v}_{e_a} - \mathbf{v}_{e_b}\|^2,$$

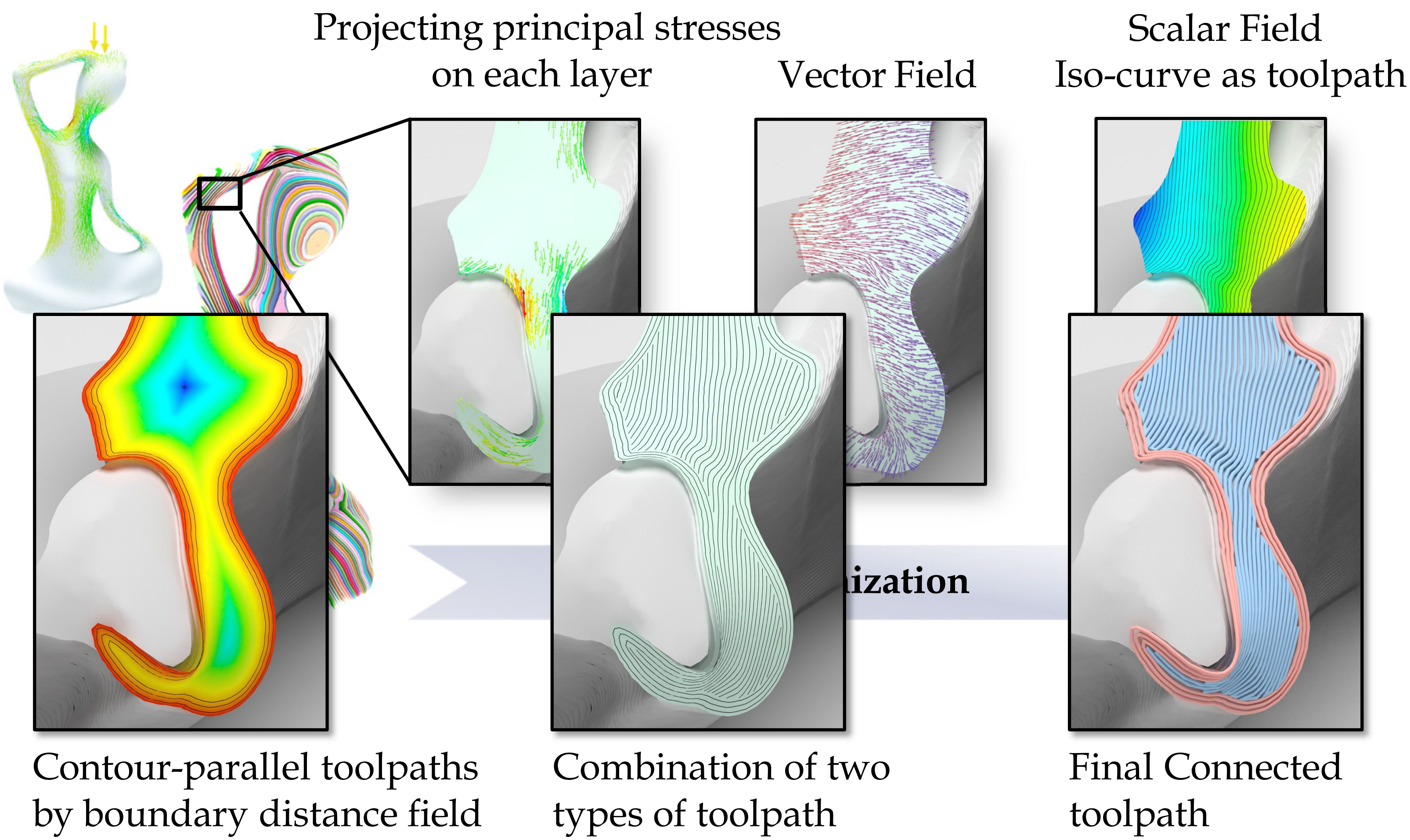
$$s.t. \quad \mathbf{v}_e = \rho_j \tau_{\min}(e) \quad (\forall e \in \mathcal{T}_j^*, j = 1, 2, \ldots m).$$

*Stress-follow constraint*

**Harmonic of Gradients**

**Principal Stress direction alignment**

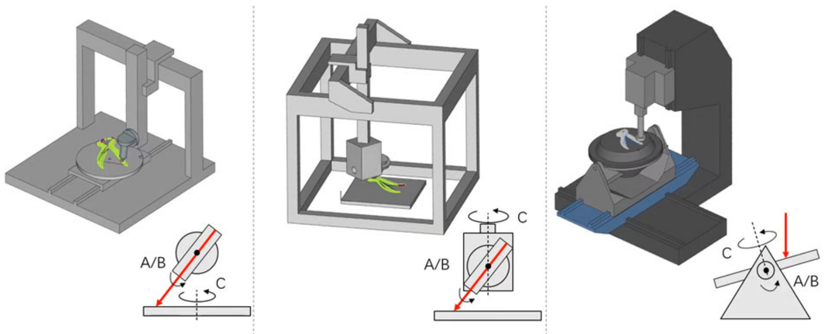
# Toolpath Generation on Curved Layers

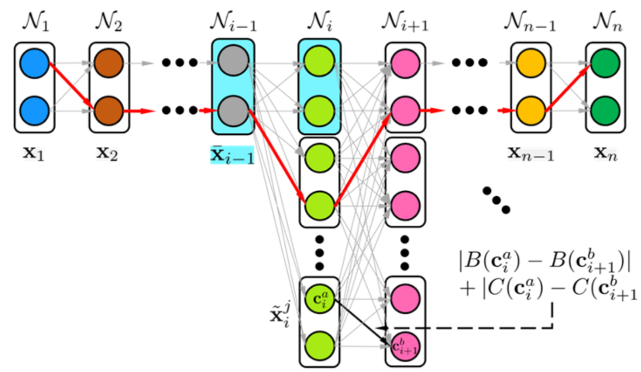




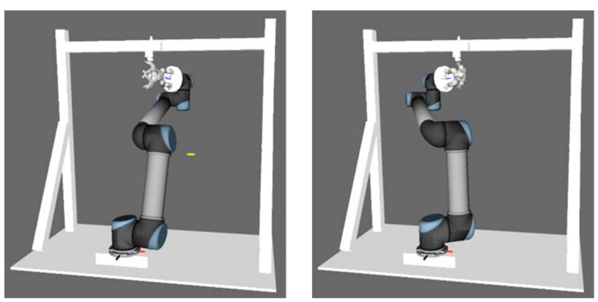
**G.Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

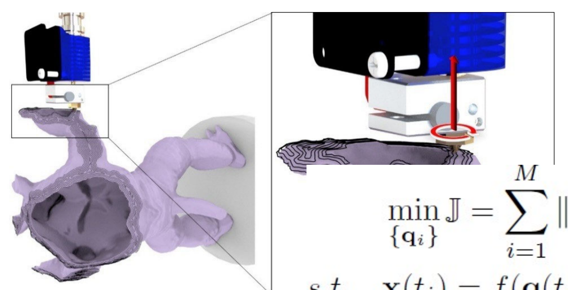
# Motion & Extrusion Control for MAAM




Graph-Based Algorithm of Motion Planning & Extrusion Control [1]





$$\min_{\{\mathbf{q}_i\}} \mathbb{J} = \sum_{i=1}^{M} \|\dddot{\mathbf{q}}(t_i)\|_W^2$$

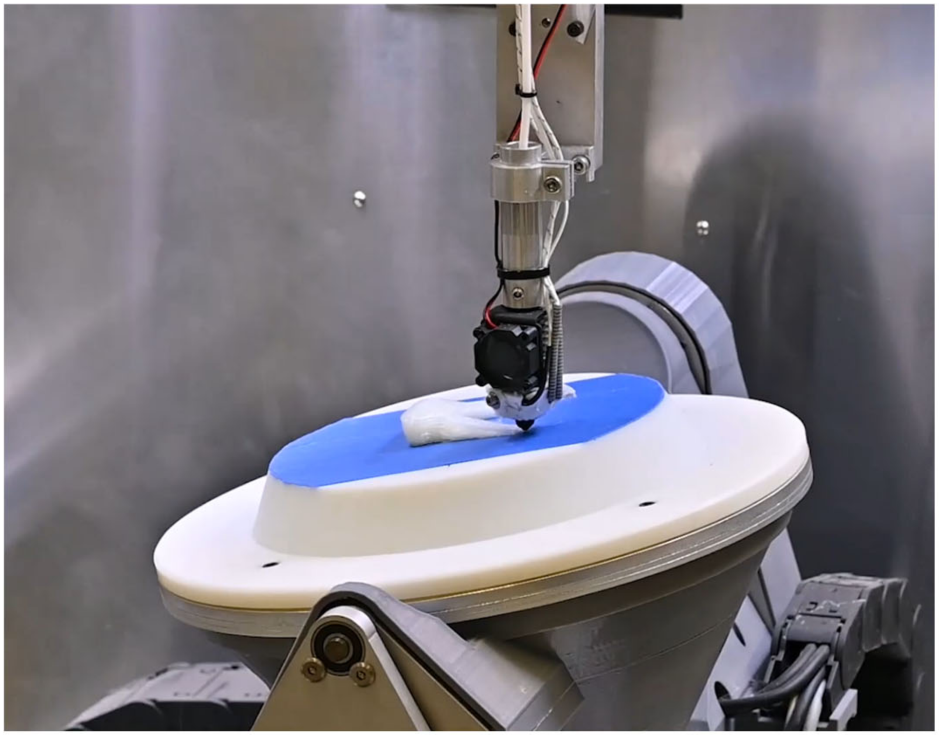
$$\begin{aligned} s.t.\quad & \mathbf{x}(t_i) = f(\mathbf{q}(t_i)) \quad (\forall i = 1, \ldots, M), \\ & \Gamma(\mathbf{q}(t_i)) < 0, \\ & \mathbf{q}_{\min} \leq \mathbf{q}(t_i) \leq \mathbf{q}_{\max}, \\ & |\dot{\mathbf{q}}(t_i)| \leq \mathbf{v}_{\max},\ |\ddot{\mathbf{q}}(t_i)| \leq \mathbf{a}_{\max},\ |\dddot{\mathbf{q}}(t_i)| \leq \mathbf{j}_{\max}. \end{aligned}$$

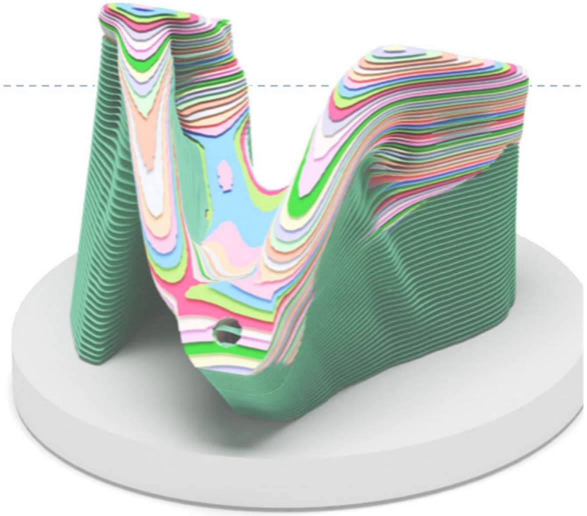
Sampling based motion planning algorithm to generate a singularity-aware, smooth and collision-free motion.
[Dai et al, IEEE T-ASE, 2020]



[1] T. Zhang, X. Chen, **G. Fang**, Y.Tian, and C.C.L.Wang, "Singularity-aware motion planning for multi-axis additive manufacturing", IEEE Robotics and Automation Letters, 6(4). (**Finalist of Best Student Paper Award – IEEE CASE 2021**)

# Multi-axis Fabrication





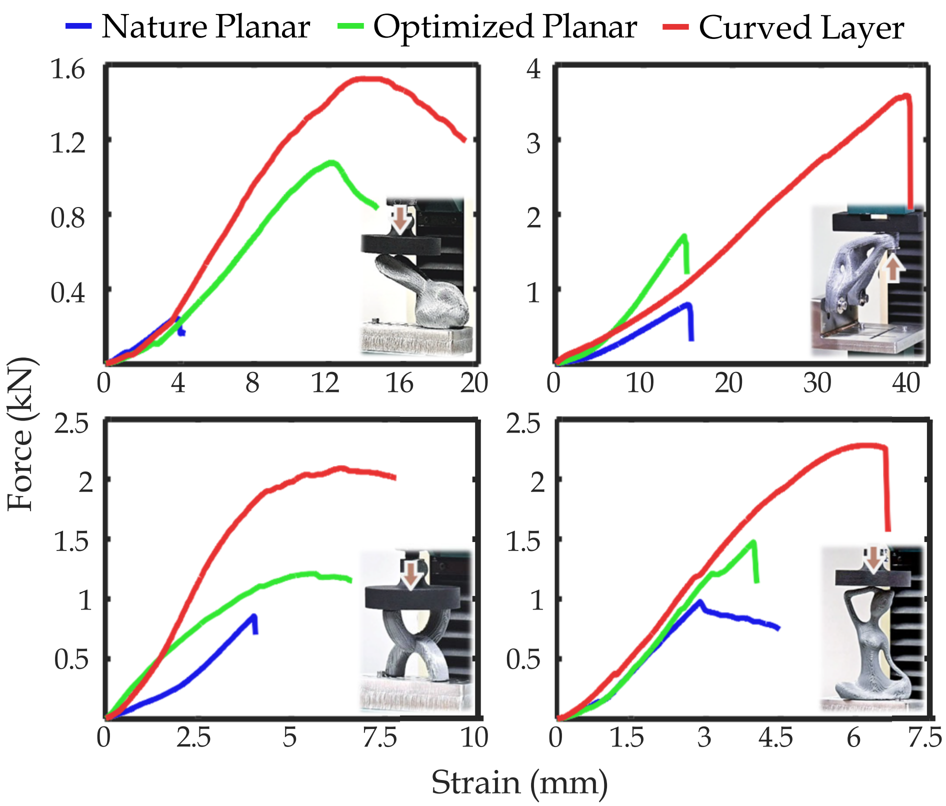
*Fabricated result*
*(After removing support structure)*

 **G.Fang**,T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

# Fabrication: Robotic Arm + Tilting Table


 **G. Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

# Validation: Physical Experiment




Bunny:
635% ↑ (natural ort.); 42% ↑ (optimized ort.)

Topo-opt：
450% ↑ (natural ort.); 103% ↑ (optimized ort.)

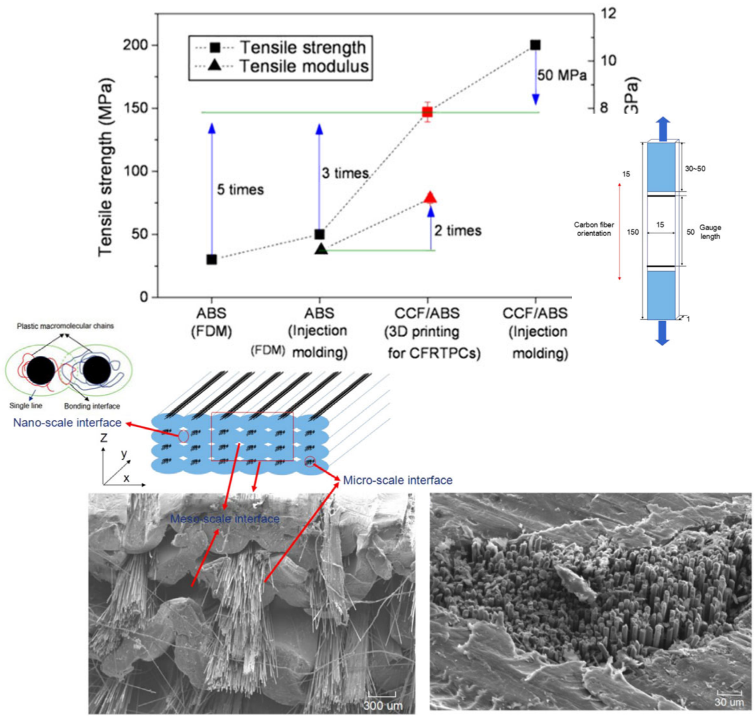
$C^2$-model:
243% ↑ (natural ort.); 73%↑ (optimized ort.)

Yoga:
132% ↑ (natural ort.); 55%↑ (optimized ort.)

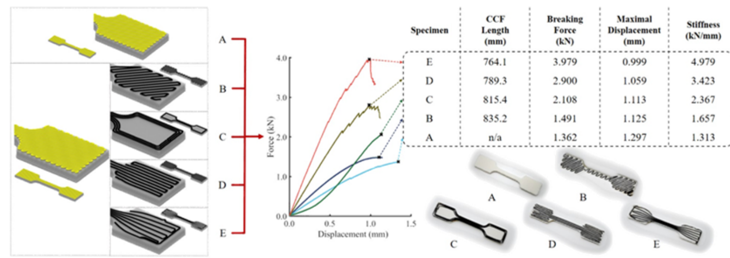

**G. Fang**, T. Zhang, S. Zhong, X. Chen, Z. Zhong, and C.C.L.Wang, "Reinforced FDM: multi-axis filament alignment with controlled anisotropic strength", *ACM Transaction on Graphics* (SIGGRAPH Asia 2020), vol.39, no.6, article no.204, 2020.

# 3D Printing for Continuous Fiber-Reinforced Thermoplastic Composites (CFRTPCs)

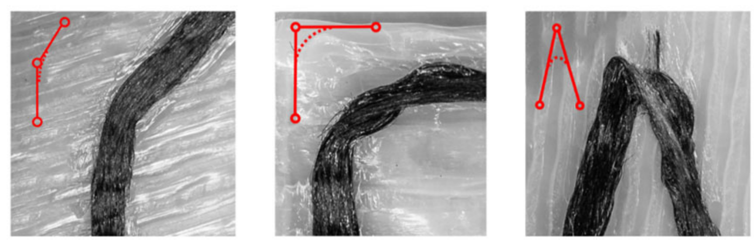
CFRTPCs enables **revolutionary strength performance**, and 3D printing allows CCF impregnation inside product with **complex geometry**.




*Cross-section for CFRTPCs and structure of internal fibres* [Yang et al. RPJ 2017]



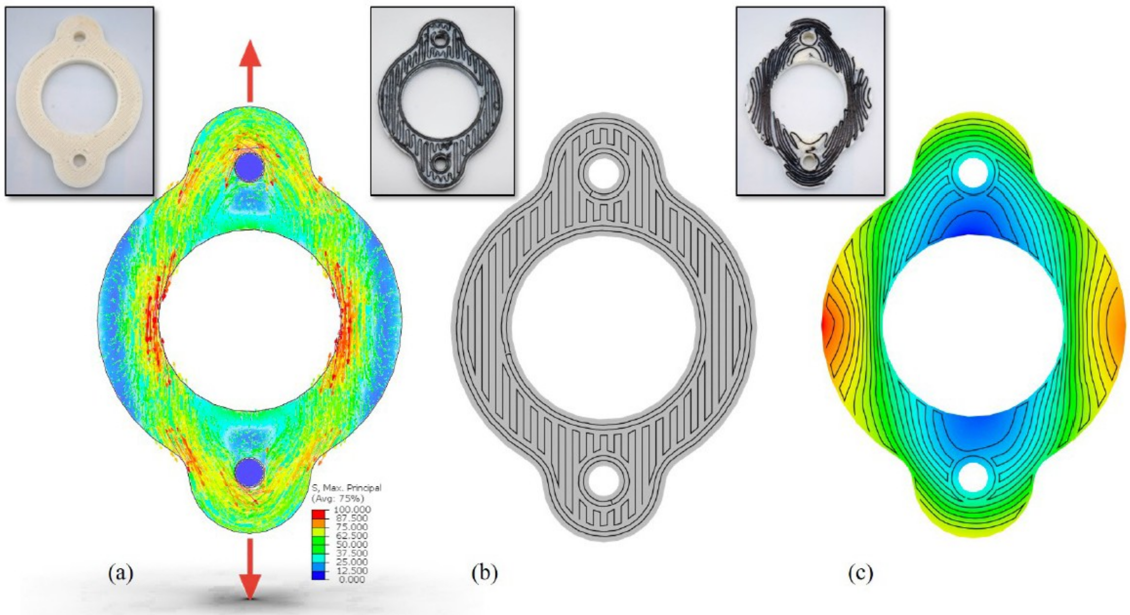

| Specimen | CCF Length (mm) | Breaking Force (kN) | Maximal Displacement (mm) | Stiffness (kN/mm) |
|---|---|---|---|---|
| E | 764.1 | 3.979 | 0.999 | 4.979 |
| D | 789.3 | 2.900 | 1.059 | 3.423 |
| C | 815.4 | 2.108 | 1.113 | 2.367 |
| B | 835.2 | 1.491 | 1.125 | 1.657 |
| A | n/a | 1.362 | 1.297 | 1.313 |



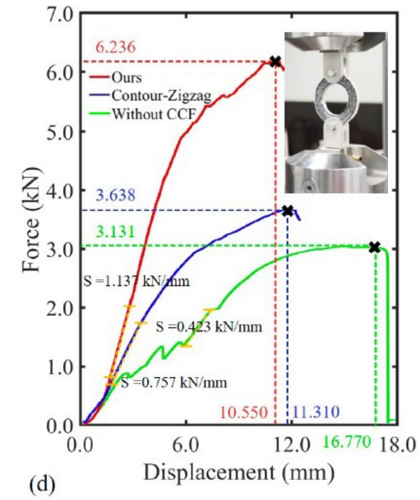
**Deign objectives** for CCF toolpath:

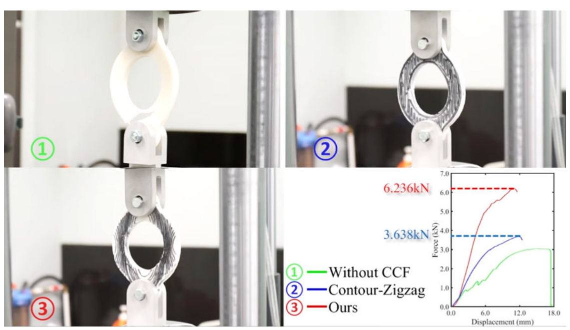
- Aligning CCF along the direction of PSD.
- Minimizing turning angle of CCF toolpath
- As continues as possible to reduce cutting.

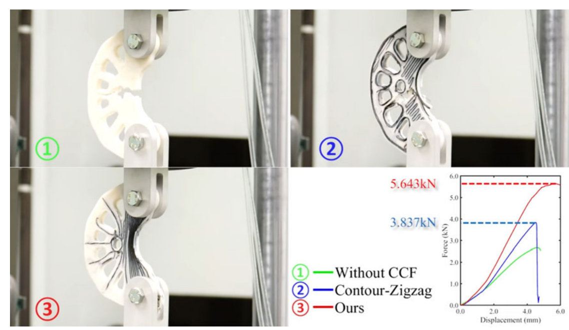
# 3D Printing of CFRTCs: Adaptive Toolpaths

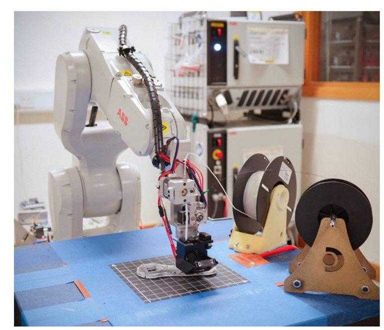



Breaking force: 171.4%
Stiffness: 150.2%



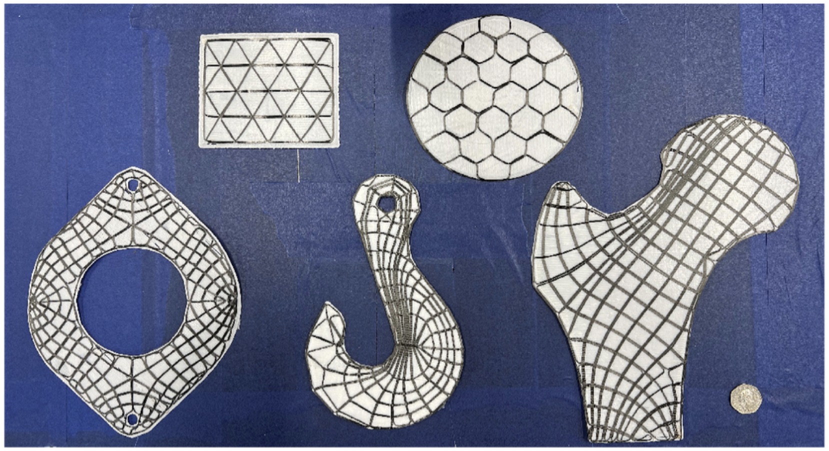



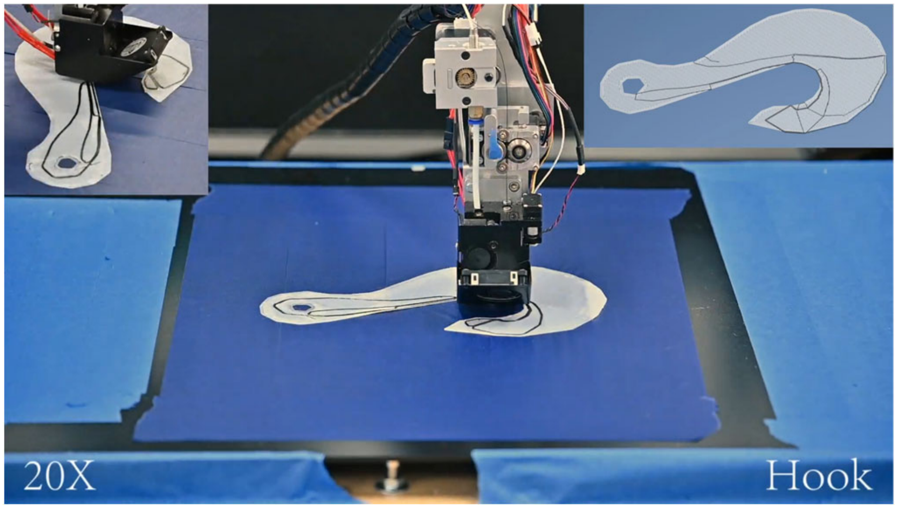



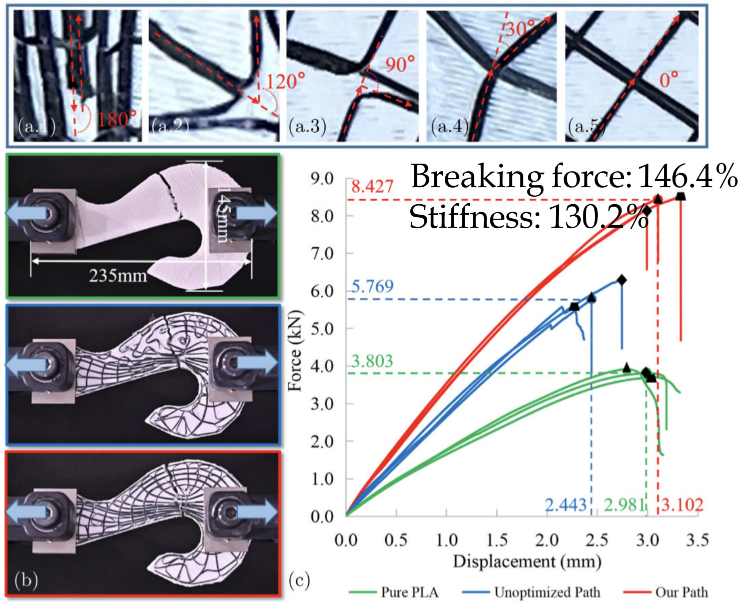


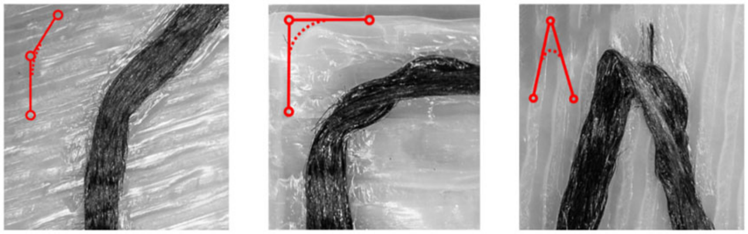
X. Chen*, **G. Fang***, W.H. Liao, and C.C.L. Wang, "Field-based toolpath generation for 3D printing continuous fibre reinforced thermoplastic composites", Additive Manufacturing, vol.49, 102470 (13 pages), January 2022.

# 3D Printing CFRTCs: Optimize Turning Angles



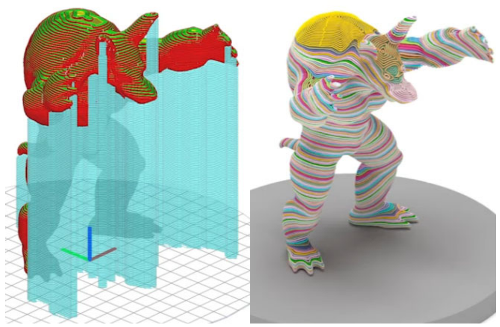


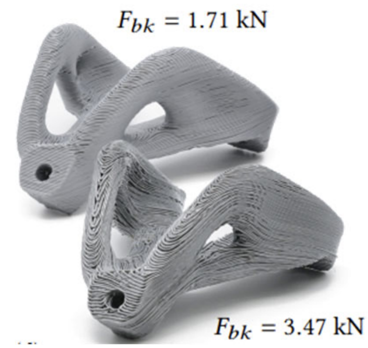



 Y. Huang*, **G. Fang***, T. Zhang, and C. C.L. Wang, "Turning-angle optimized printing path of continuous carbon fiber for cellular structures", Additive Manufacturing, vol.68, 103501 (16 pages), April 2023.

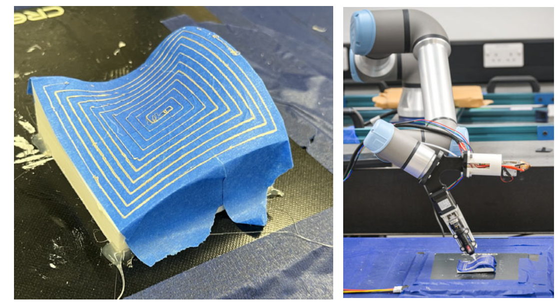
# Recall: Design objectives & Fabrication Constraints for MAAM



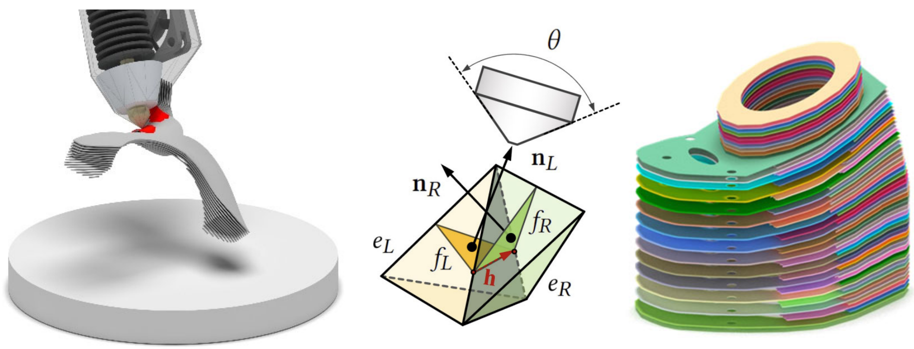
Support-free Printing



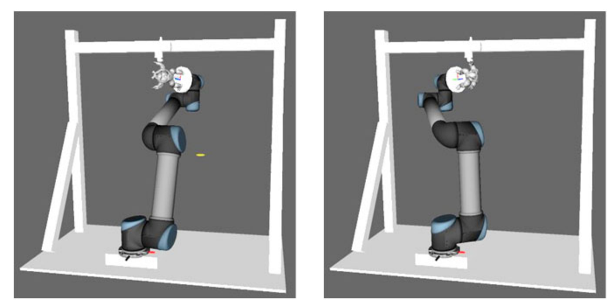

Strength Reinforcement



Conformal Material Alignment & Surface Quality Enhancement




Local collision Free & Layer Thickness Control



Motion Planning & Extrusion Control

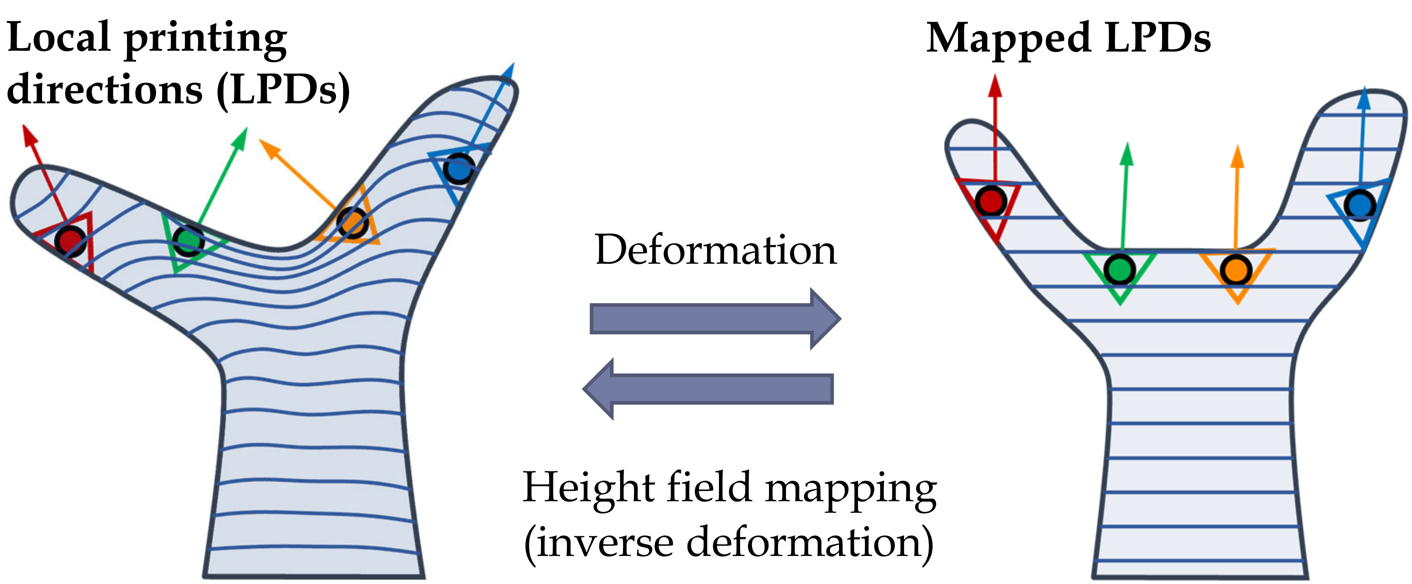
**Challenge**: How to achieve multi-objectives together?

- $S^3$-Slicer: as a general slicer for multi-axis additive manufacturing

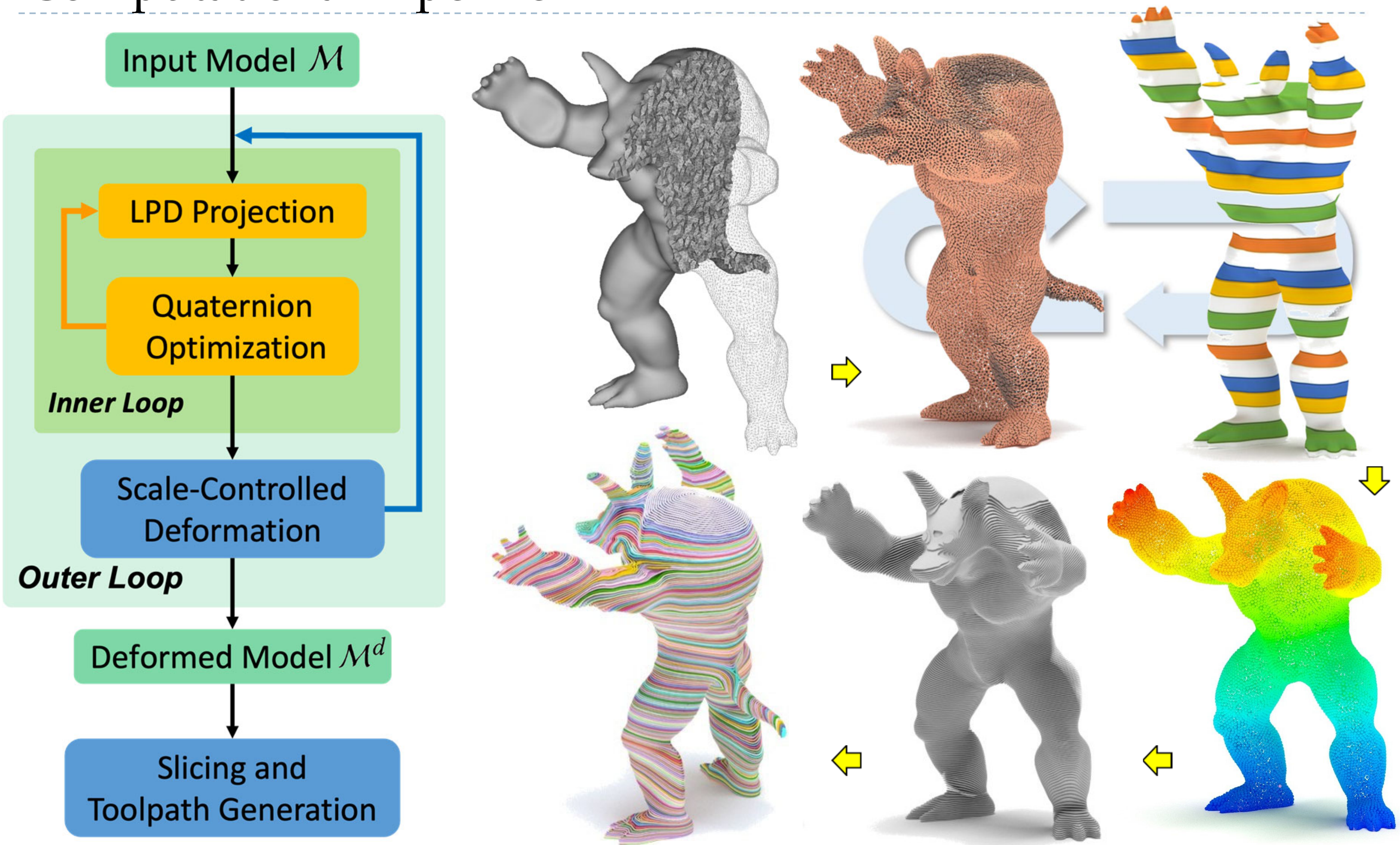
## Challenges and Insight

Optimizing the local printing directions (LPDs) in all elements according to (multiple) objectives

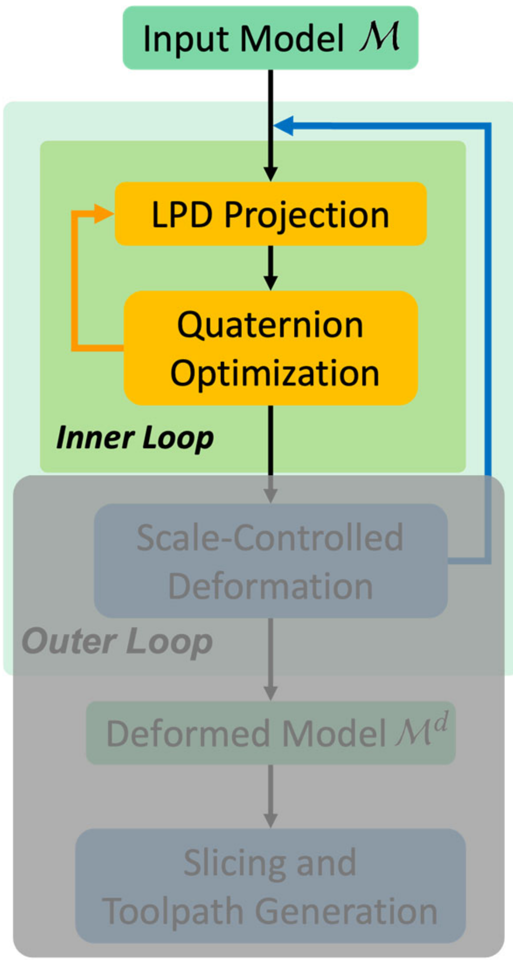
- **Challenges:** angular constraints of LPDs in neighboring elements may disagree with each other
- **Methodology:** a rotation-driven deformation framework

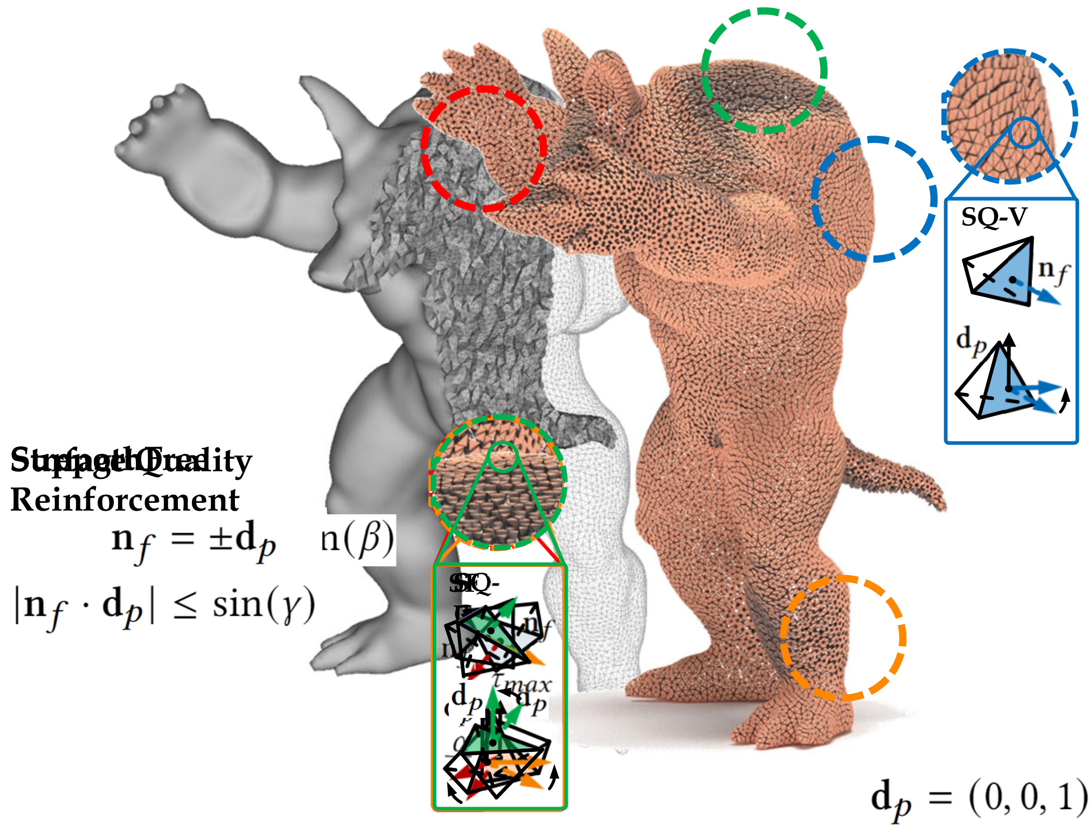


# Computational Pipeline

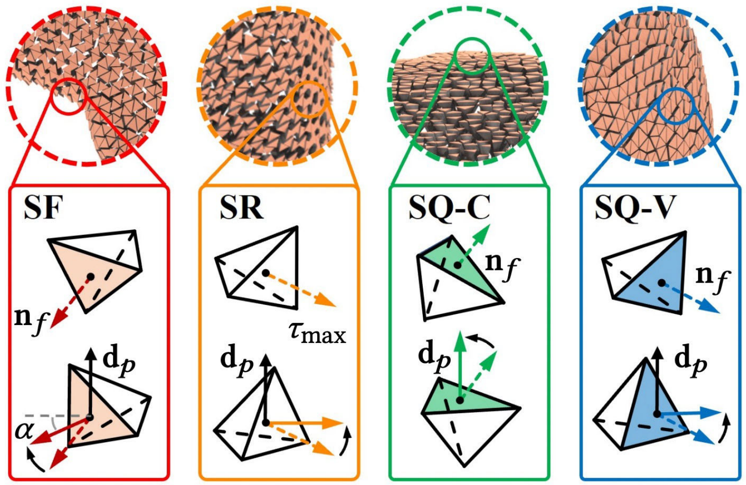


# Computational Pipeline



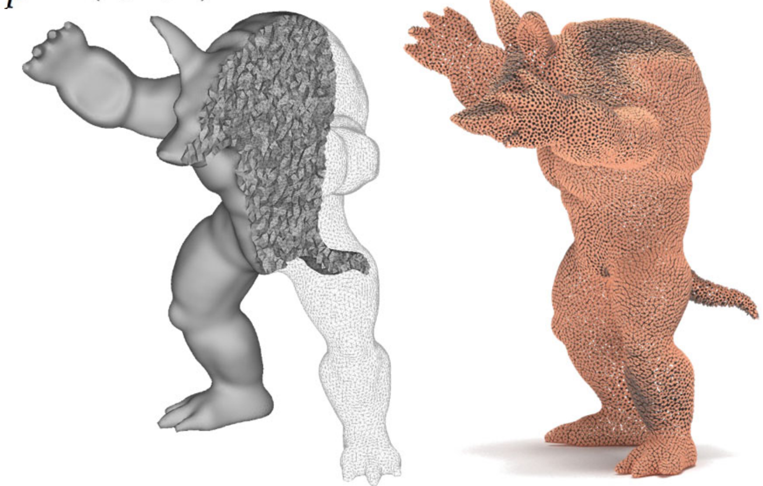



# Computational Pipeline: Inner Loop




Local Rotations of Elements Driven by Different Objectives

$\mathbf{d}_p = (0, 0, 1)$



$$\arg\min_{\{\mathbf{q}_e\}} \sum_{(e_i,e_j)\in\mathcal{N}_F} w_s(e_i, e_j)\|\mathbf{q}_{e_i} - \mathbf{q}_{e_j}\|^2$$

$$\begin{aligned} s.t.\ \ & C_{SR}(\mathbf{q}_e) && (\forall e \in \mathcal{S}) \\ & C_{SF}(\mathbf{q}_e),\ C_{SQ}(\mathbf{q}_e) && (\forall e \in \mathcal{B}) \end{aligned}$$

Quaternion-Based Formulation

# Multi-Objectives: Compatibility Analysis

- Analysis on Gauss sphere
- Objectives as half-spaces:

**S**upport **F**ree

$\mathcal{H}_{SF} = \{\mathbf{d} \mid \forall \mathbf{d} \in \mathbb{S}^2,\ \mathbf{d} \cdot \mathbf{n}_f + \sin(\alpha) \geq 0\}$

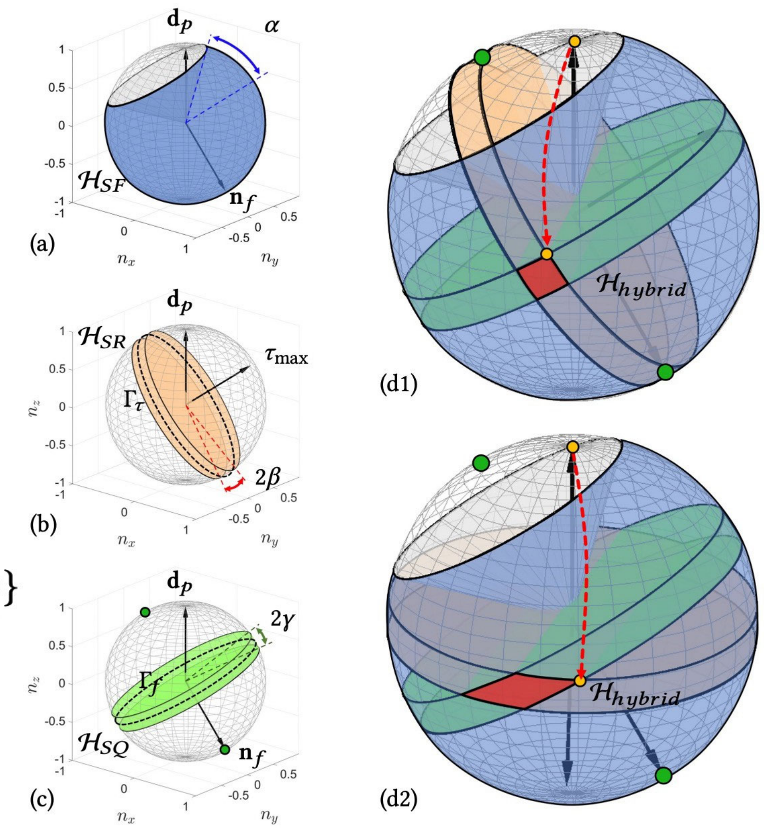
**S**trength **R**einforcement

$\mathcal{H}_{SR} = \{\mathbf{d} \mid \forall \mathbf{d} \in \mathbb{S}^2,\ |\mathbf{d} \cdot \tau_{\max}| \leq \sin(\beta)\}$

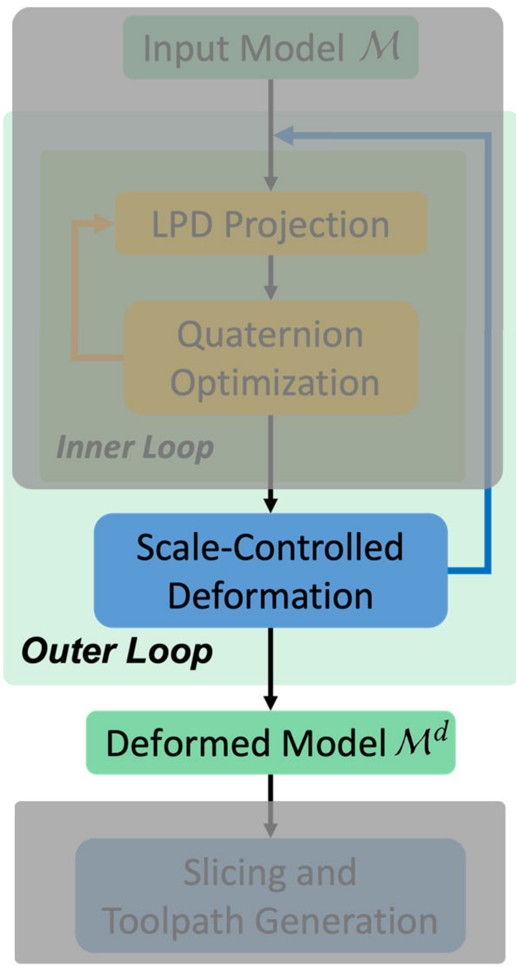
**S**urface **Q**uality

$\mathcal{H}_{SQ} = \{\mathbf{d} \mid \forall \mathbf{d} \in \mathbb{S}^2,\ \mathbf{d} = \pm\mathbf{n}_f \text{ or } |\mathbf{d} \cdot \mathbf{n}_f| \leq \sin(\gamma)\}$

- Feasible rotation: those can move $(0, 0, 1)$ into a commonly determined $\mathcal{H}_{hybrid} = \mathcal{H}_{SF} \cap \mathcal{H}_{SR} \cap \mathcal{H}_{SQ}$

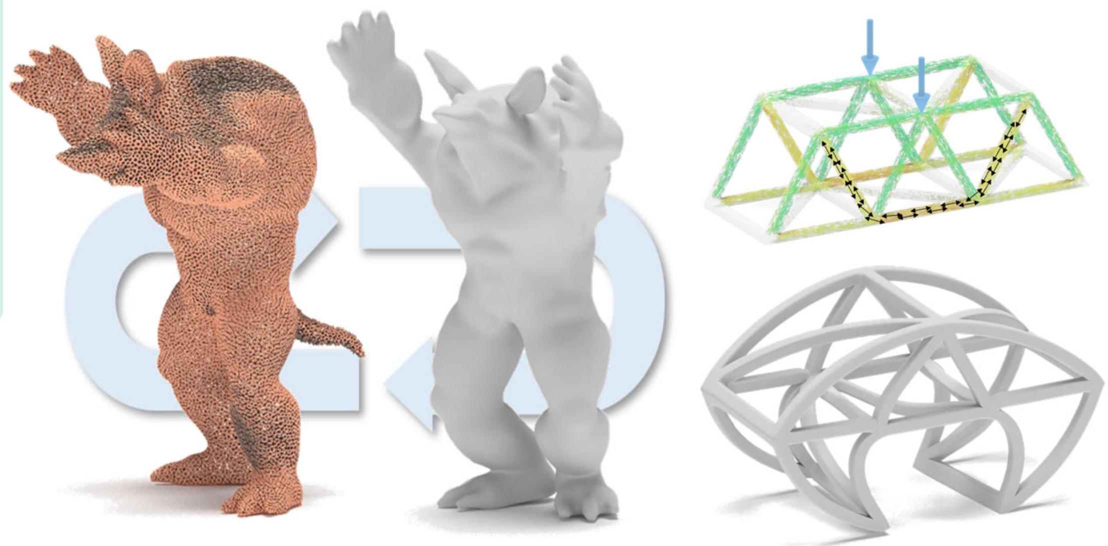


# Computational Pipeline: Outer Loop



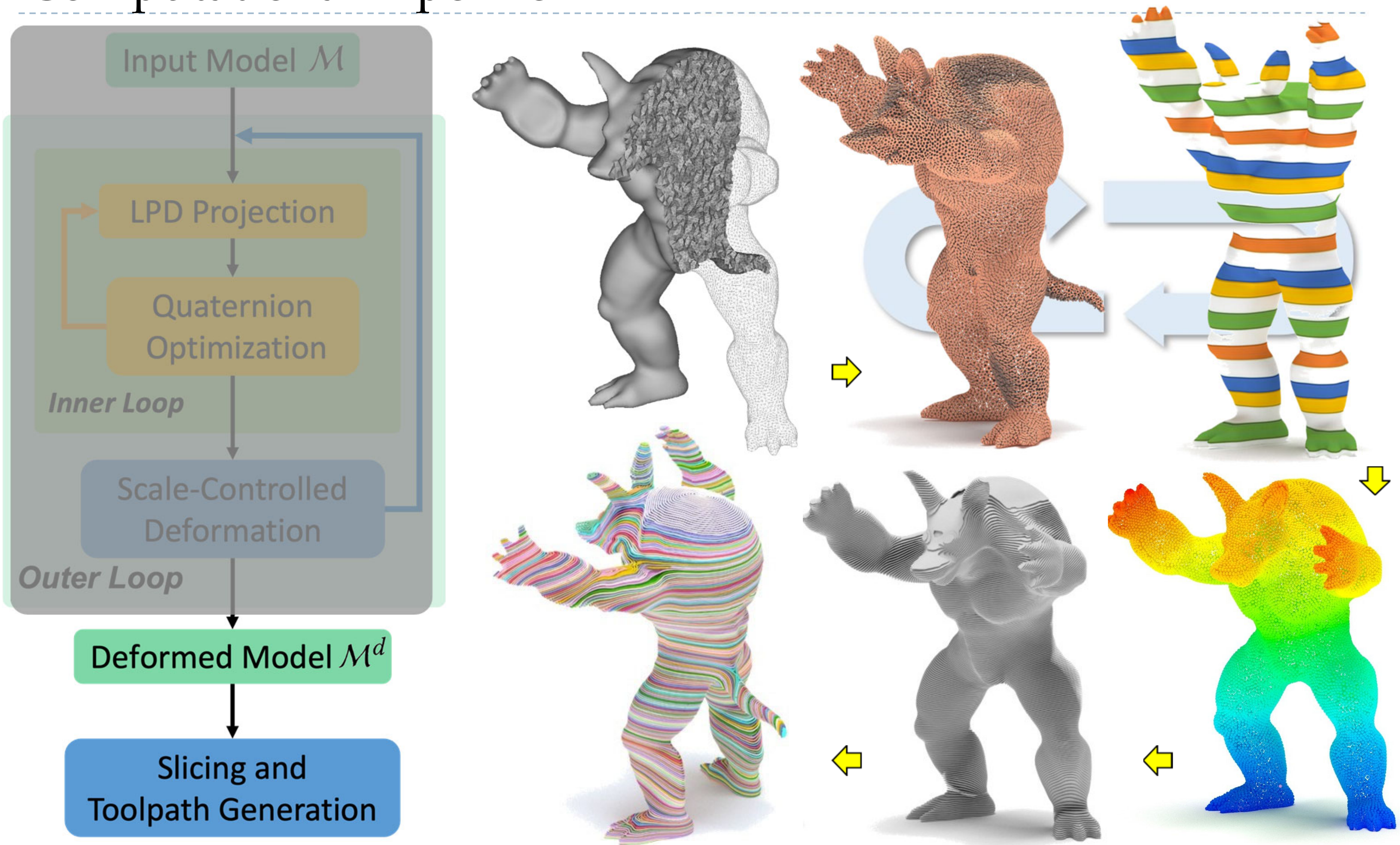

$$\arg\min_{\mathcal{M}^d} \sum_{e\in\mathcal{M}} \underbrace{\|(\mathbf{N}\mathbf{V}_e^d)^\mathrm{T} - \mathbf{R}_e\mathbf{S}_e(\mathbf{N}\mathbf{V}_e)^\mathrm{T}\|_F^2}_{\text{Position}-\text{Compatibility}} +$$

$$w_r \sum_{e\in\mathcal{M}} \underbrace{\|\mathbf{S}_e-\mathbf{I}\|_F^2}_{\text{Rigidity}} + w_c \sum_{(e_i,e_j)\in\mathcal{N}_F} \underbrace{\|\mathbf{S}_{e_i}-\mathbf{S}_{e_j}\|_F^2}_{\text{Scale}-\text{Compatibility}}$$



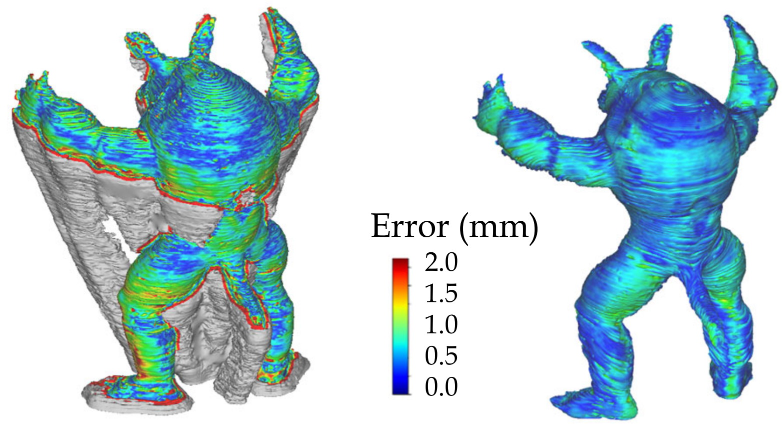
Scale-Controlled Deformation

# Computational Pipeline



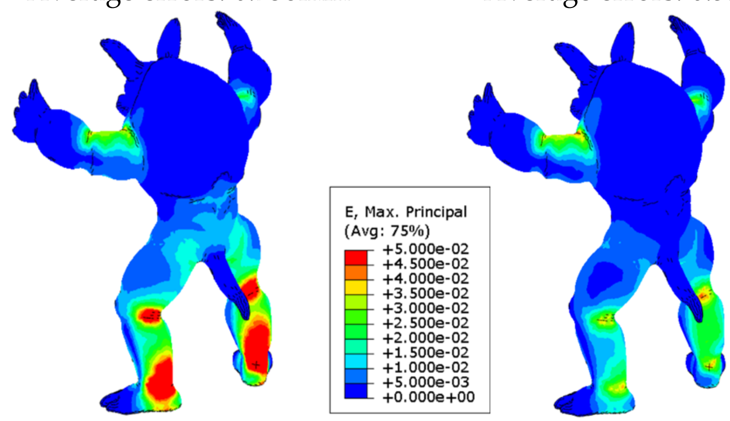
# Multi-Objectives Achieved on S³-Slicer

Support Free printing process

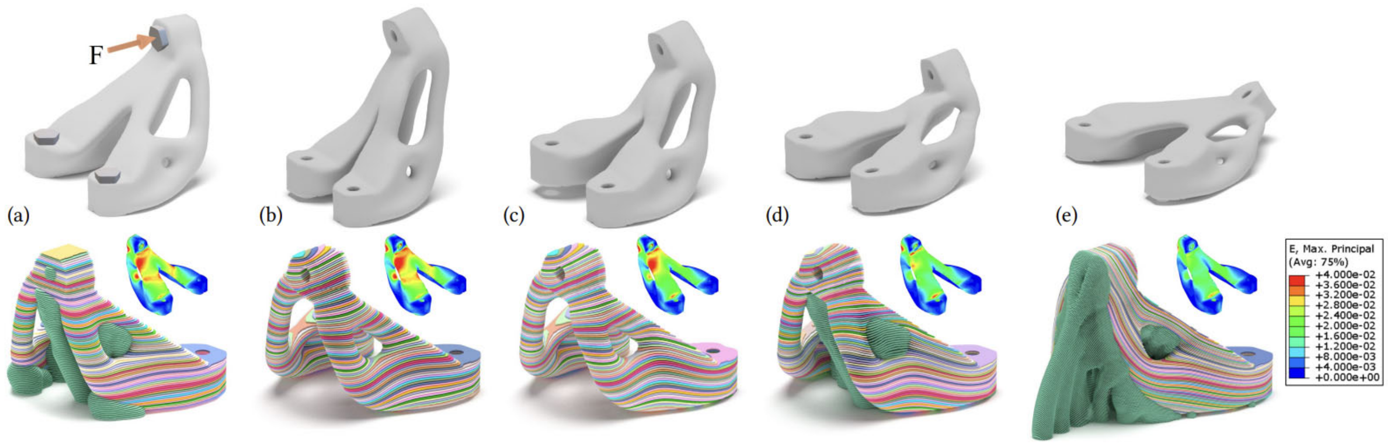



Planar Slicing
Average errors: 0.738mm

Curved Slicing
Average errors: 0.534mm



# Balance Between Multi-Objectives & Computational Statistics




| User Preference | | (a) Planar Slicing | (b) $w_{SF} : w_{SR} = 1.0 : 0.0$ | (c) $w_{SF} : w_{SR} = 0.7 : 0.3$ | (d) $w_{SF} : w_{SR} = 0.3 : 0.7$ | (e) $w_{SF} : w_{SR} = 0.0 : 1.0$ |
|---|---|---|---|---|---|---|
| Strain | Average | 3.06e-3 | 2.94e-3 | 2.53e-3 | 2.16e-3 | 2.01e-3 |
| | Maximal | 3.52e-2 | 3.76e-2 | 3.50e-2 | 3.01e-2 | 2.28e-2 |
| Support Volume (%) | | 72.4% | 0.0% (No Support) | 0.0% (No Support) | 61.6% | 173.9% |

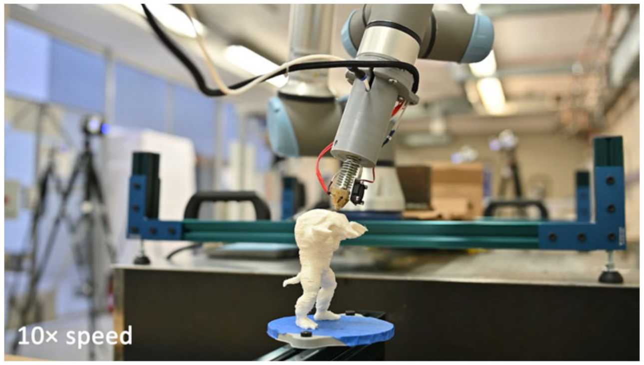
Table 1. Computational statistics for the pipeline of $S^3$-slicer.

| Model | Objective | Fig. | Solid #tets | Computing Time of $S^3$-Slicer (sec.) LDP Proj. | Quaternion Opt. | Scale-controlled Def. | Total of Def. | Slicing | Toolpath Gen. (sec.) | Total Time (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| Bunny | (SF, SR & SQ) | 1,9 | 196.8$k$ | 0.7 | 42.7 | 12.8 | 56.2 | 8.6 | 10.9 | 75.7 |
| Armadillo | (SF, SR & SQ) | 2 | 245.4$k$ | 1.0 | 44.5 | 15.4 | 60.9 | 29.9 | 9.3 | 100.1 |
| Topo-Opt | (SF & SR) | 4 | 70.5$k$ | 0.3 | 7.4 | 2.3 | 10.0 | 3.3 | 11.2 | 24.5 |
| Teapot | (SF & SQ) | 11 | 201.8$k$ | 0.8 | 51.1 | 15.2 | 67.1 | 16.6 | 31.3 | 115.0 |
| Ankle | (SF & SQ) | 8,12 | 97.8$k$ | 0.4 | 11.9 | 5.3 | 17.6 | 97.6$^\dagger$ | 2.9 | 118.1 |
| Ring | (SF) | 6,13 | 24.8$k$ | 0.1 | 2.8 | 1.5 | 4.4 | 2.4 | 1.1 | 7.9 |
| Bridge | (SR) | 7 | 100.4$k$ | 0.5 | 9.8 | 4.9 | 15.2 | 7.1 | 1.5 | 23.8 |

 T. Zhang*, **G. Fang***, Y. Huang, N. Dutta, S. Lefebvre, Z.M. Kilic, and C.C.L. Wang, "$S^3$-Slicer: A general slicing framework for multi-axis 3D printing", ACM Transactions on Graphics, 41(6):277, Dec. 2022. **(SIGGRAPH Asia Best Paper Award)**

## Conclusion Remarks

- A vector field-based computational fabrication framework – the anisotropy of fused filaments (including functional materials like **CFRPTCs**) is well controlled to reinforce the mechanical strength of 3D printed models;
- **S³-slicer** (quaternion field-based) to generate curved layers that can achieve the combined objectives of support-free (SF), strength reinforcement (SR) & enhanced surface quality (SQ);
- Development of MAAM system by robot arm and multi-axis CNC machine, motion planning and extrusion control have been studied.




Multi-axis additive manufacturing: next generation of AM system

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China Scholarship Council, China

GAMES Webinar
Topics on CAD/CAE/CAM

# Thanks for your attention!

## Guoxin Fang

**Source Code of Reinforced FDM (SIG Asia 20)**

**Source Code of S^3-Slicer (SIG Asia 22)**

MANCHESTER 1824
The University of Manchester

Digital Manufacturing Lab

July 13, 2023