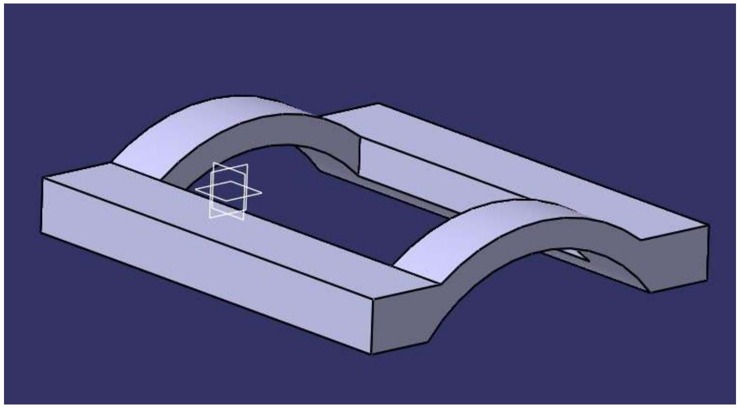
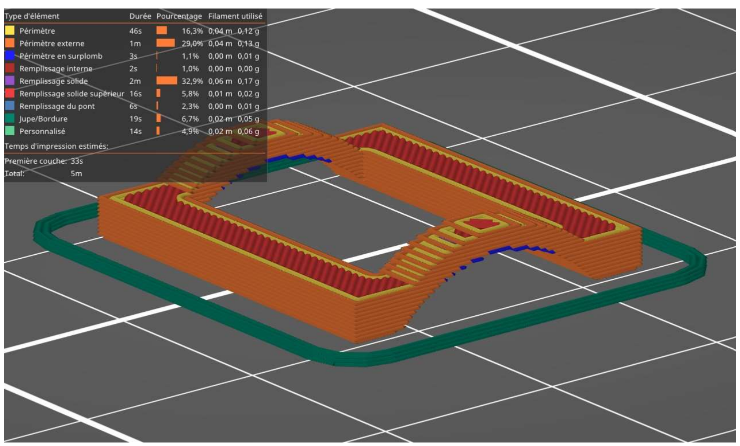
Non-planar Additive Manufacturing

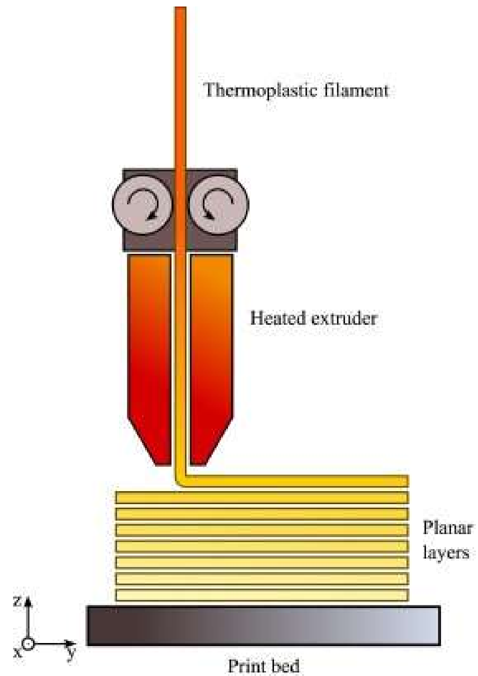
Laura Bosch Galdeano
Luciano Calcoen
Clément Chalut
Aron Dagur Beck
Manuel Fernandez Alonso

Context

What is Planar Additive Manufacturing (PAM) ?

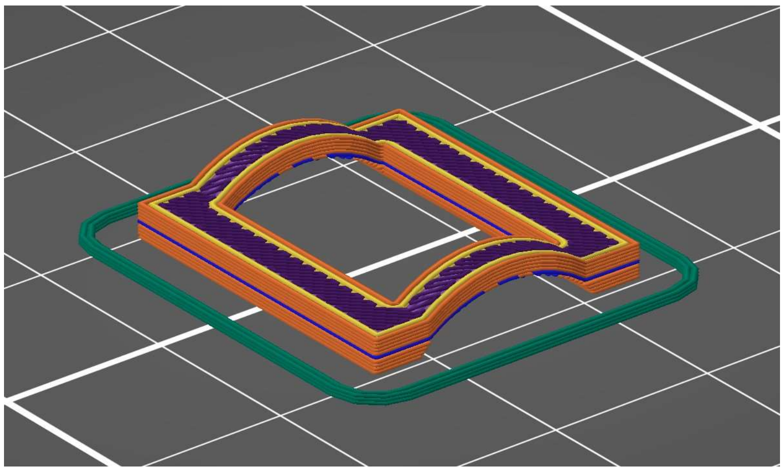


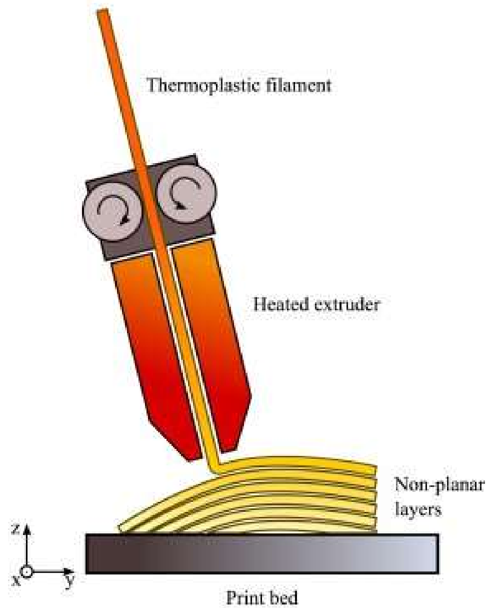




Guidetti et al, *Stress flow guided non-planar print trajectory optimization for additive manufacturing of anisotropic polymers*

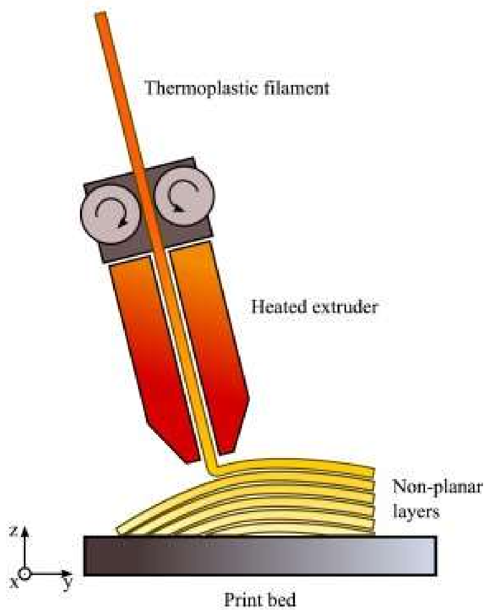
What is Non-Planar Additive Manufacturing (NPAM) ?

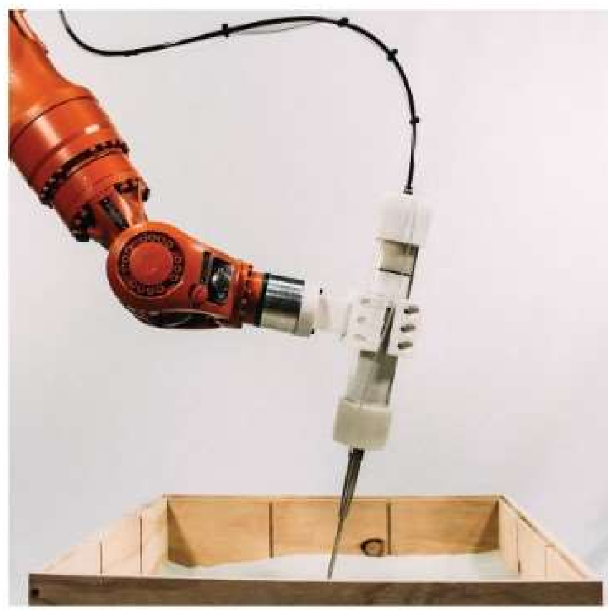




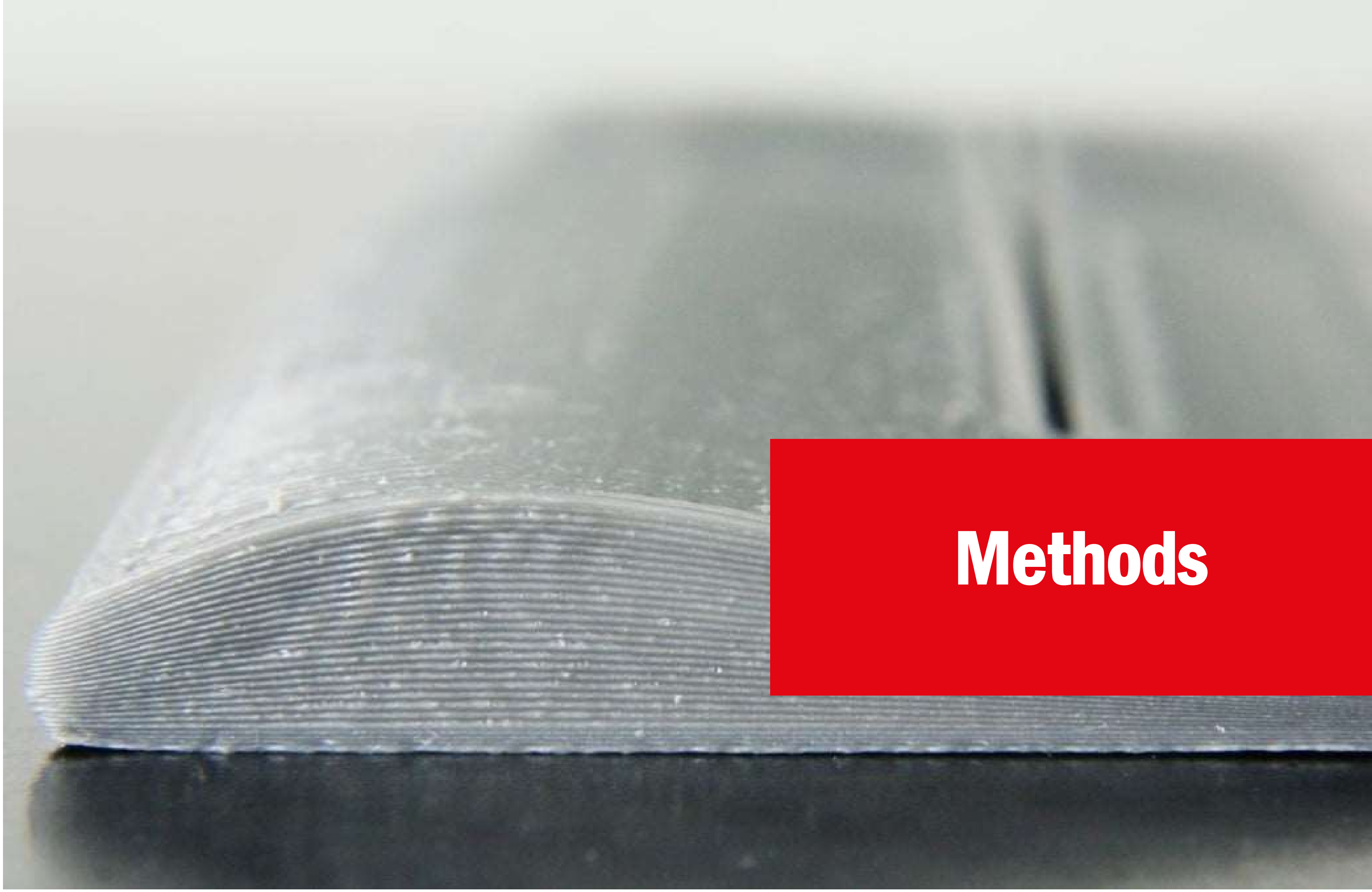
Guidetti et al, *Stress flow guided non-planar print trajectory optimization for additive manufacturing of anisotropic polymers*

Examples of NPAM





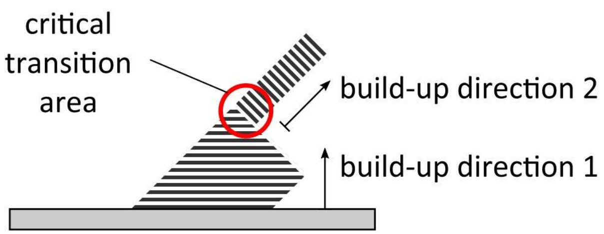
EPFL



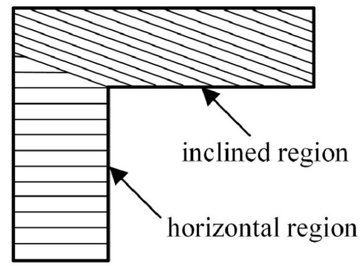
Methods

Methods

Multi-Direction Slicing

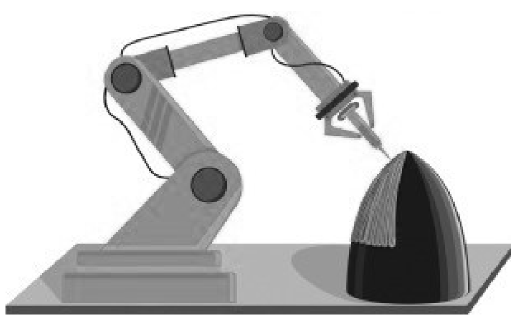


Inclined Layer Printing

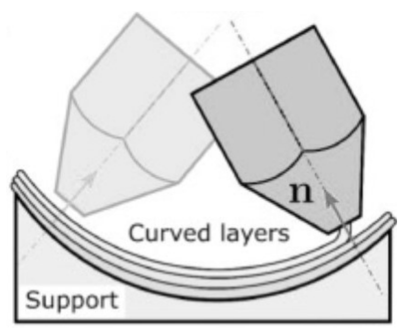


Active Z Printing

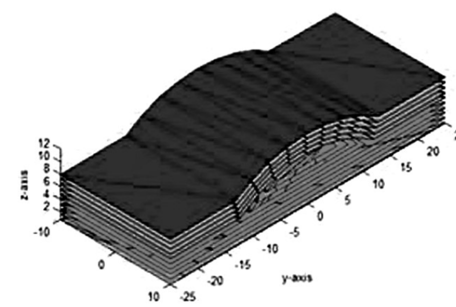
Multi-Axis Material Extrusion



Curved Layer Fused Deposition Modeling



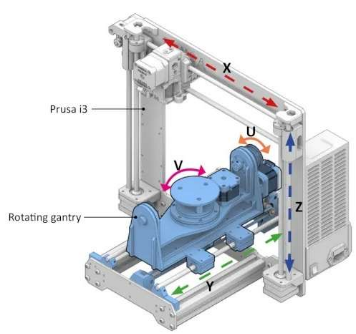
Combining Flat and Curved Layers

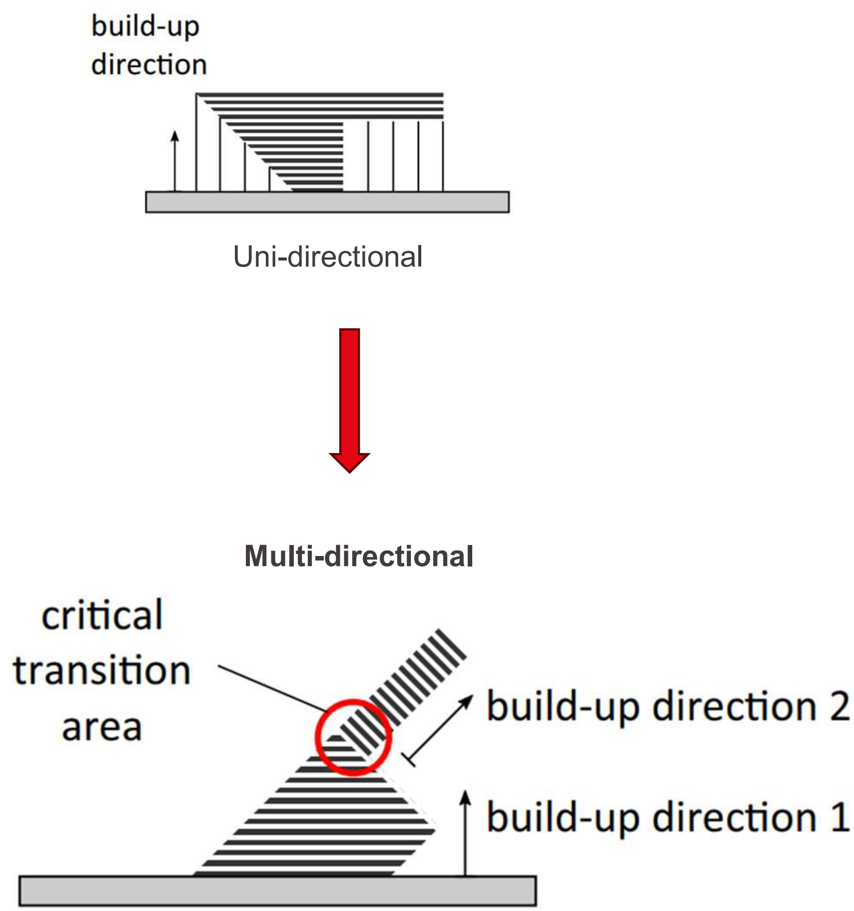


Speaker: Laura Bosch

1. Multi-Direction Slicing

- Objects with significant overhangs **without supports.**
- Creates **non-horizontal layers** to handle overhangs.
- Utilizes multi-directional toolpath planning, typically for **5-axis printers**.





Speaker: Laura Bosch

1. Multi-Direction Slicing: Modules

Volume Decomposition Module

- Identifies and groups concave loops to **form subvolumes.**
- **Fills holes** created during decomposition.
- Stores subvolume positions for **reassembly post-slicing.**

Slicing Module

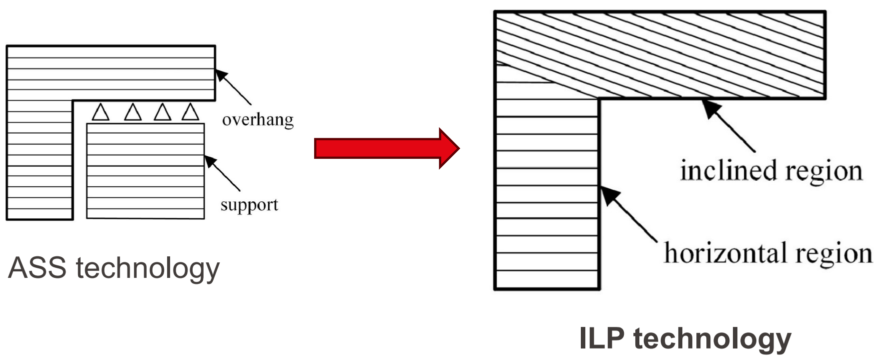
- Calculates **optimal** printing **direction** for each subvolume.
- Slices subvolumes using **planar slicing algorithm**.
- Rotates and translates toolpaths back to initial positions.

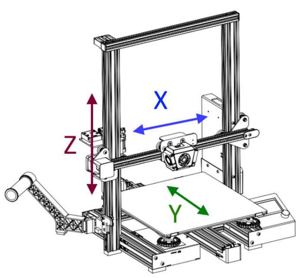
Results in efficient, high-quality prints without supports.

Speaker: Laura Bosch

2. Inclined Layer Printing

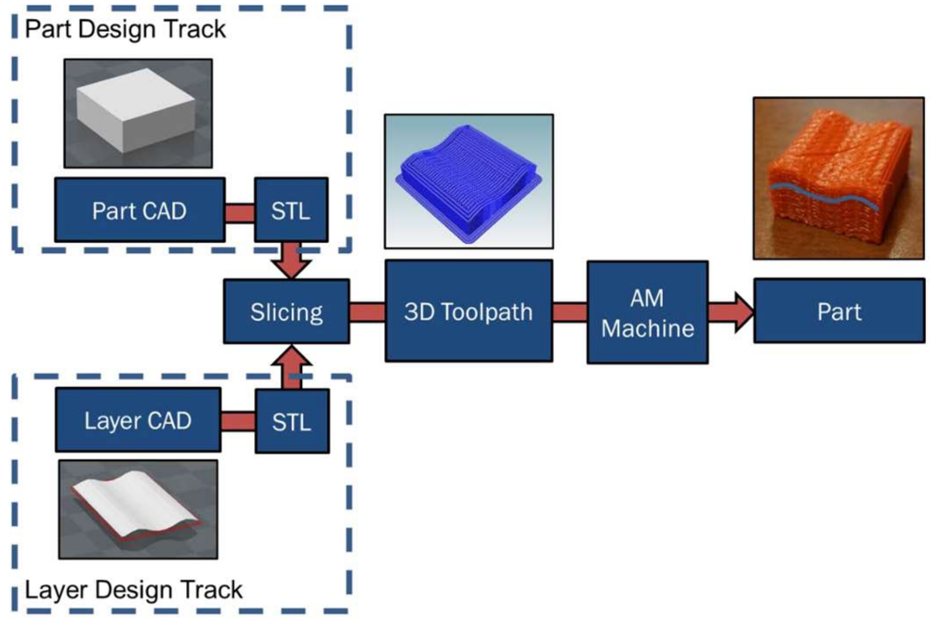
- Prints protruding regions at different angles.
- **Divides** object into regions based on **overhangs**.
- Rotates and slices regions for optimal printing.
- Multi-directional toolpath on **standard 3-axis printers**.

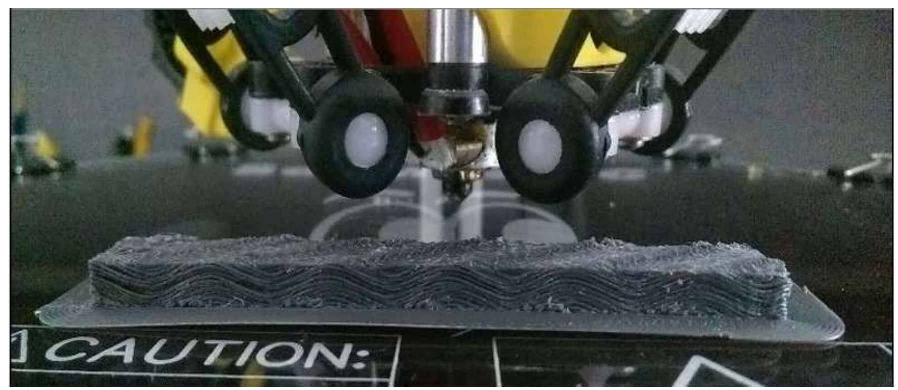




3. Active Z Printing

- Enhances strength using **curved layers.**
- Tests show nonplanar layers **improve strength** and **stiffness**.
- Employs Bread Slicer software requiring two STL files.
- Uses a **3-axis printer** to move in x, y, and z axes simultaneously.





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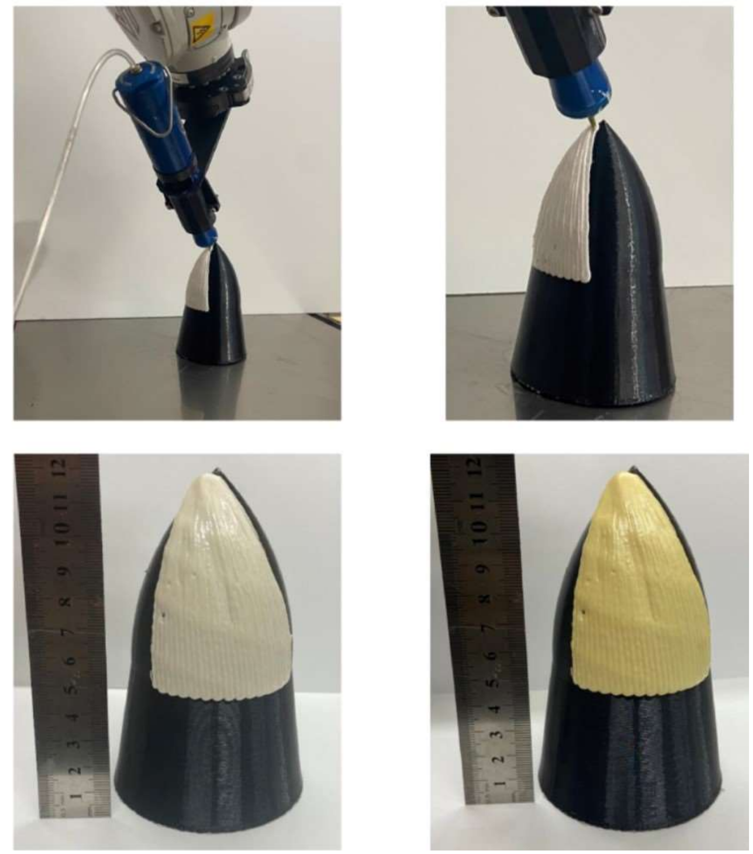
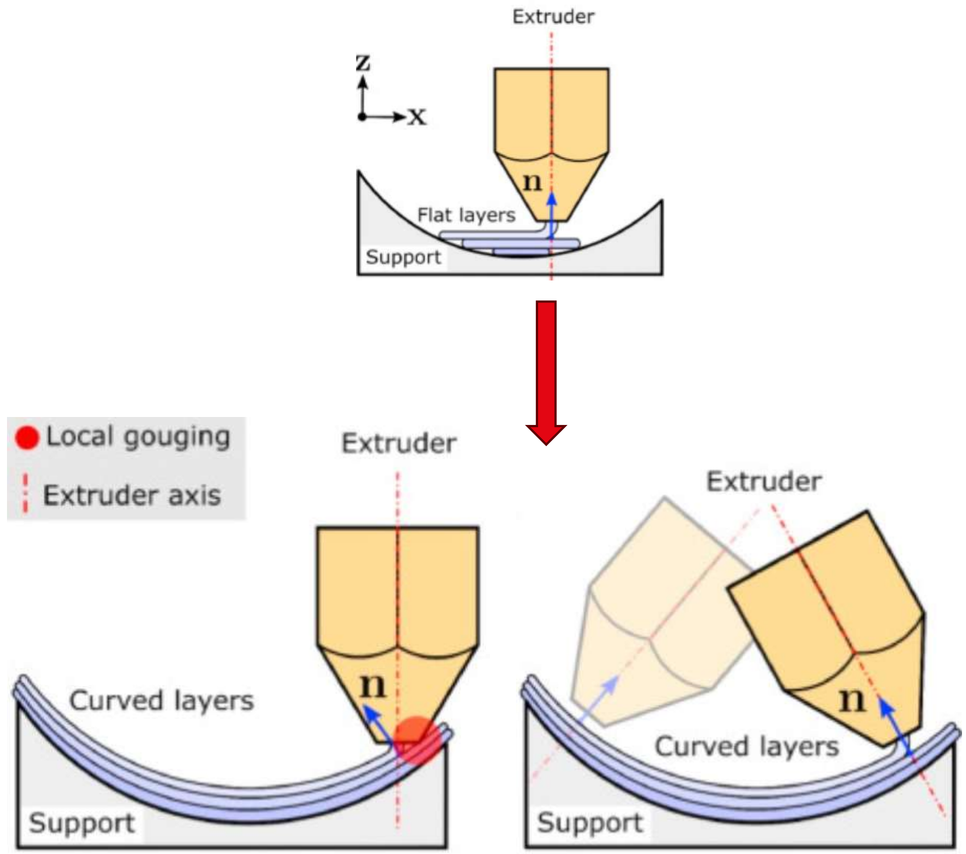
4. Multi-Axis Material Extrusion

- Prints a **reinforced shell over a core**, enhancing mechanical properties.
- Shifts **stress** from layer bonding to the object's **shell**.
- Path generation **follows specified angles** around the object.
- Uses a **six-axis robotic arm** printing system.



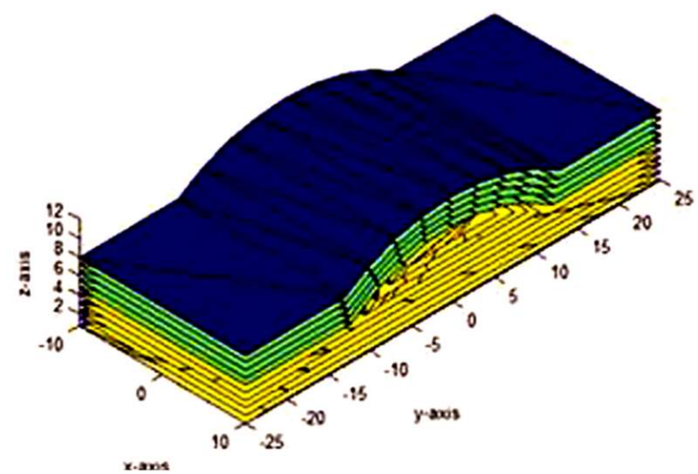
5. Extrusion Curved Layer Fused Deposition Modeling

- Prints nonplanar curved layers at **different z-heights.**
- Requires proper toolpath generation, filament orientation, and bonding.
- Assumes improved **inter-layer** bonding with **curved layers**.
- Uses **three**-axis or **five-axis** printers.



6. Combining Flat and Curved Layers

- **Eliminates stair-stepping** artifacts.
- Classifies and merges surface areas for curved printing.
- **Offsets surfaces** to create **shell layers**.
- Enhances mechanical strength, best printed in **load direction.**
- Uses **three-axis** printers.



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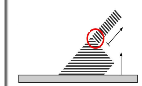
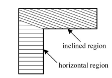
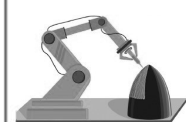
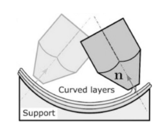
Summary

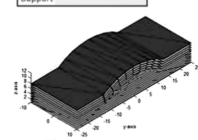
Technique	Printer Type	Key Feature
Multi-Direction Slicing	5-axis printer	Slices model in various directions to create non-horizontal layers. Prints overhangs without supports using multi-directional toolpaths.
Inclined Layer Printing	3-axis printer	Prints protruding regions at angles. Rotates regions to desired angles to avoid supports.
Active-Z Printing	3-axis printer	Prints curved layers, moving in x, y, and z axes simultaneously.
Multi-Axis Material Extrusion	6-axis robotic arm	Prints a reinforced surface on a core with the shell oriented differently to enhance mechanical properties.
Curved Layer Fused Deposition Modeling	3-axis or 5-axis	Prints nonplanar curved layers at different z-heights to improve surface quality.
Combining Flat and Curved Layers	3-axis printer	Combines flat and curved layers to eliminate stair-stepping artifacts.











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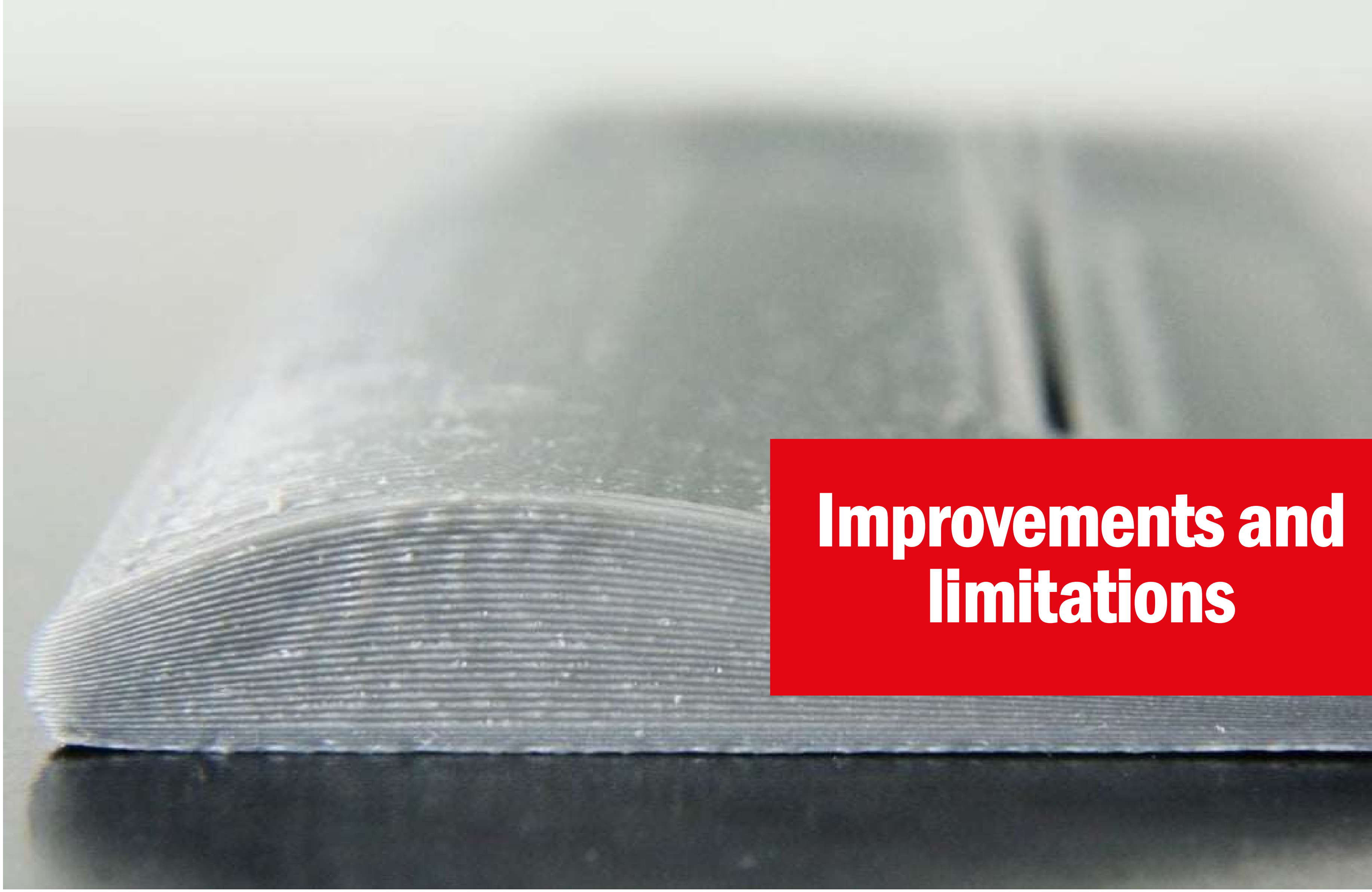
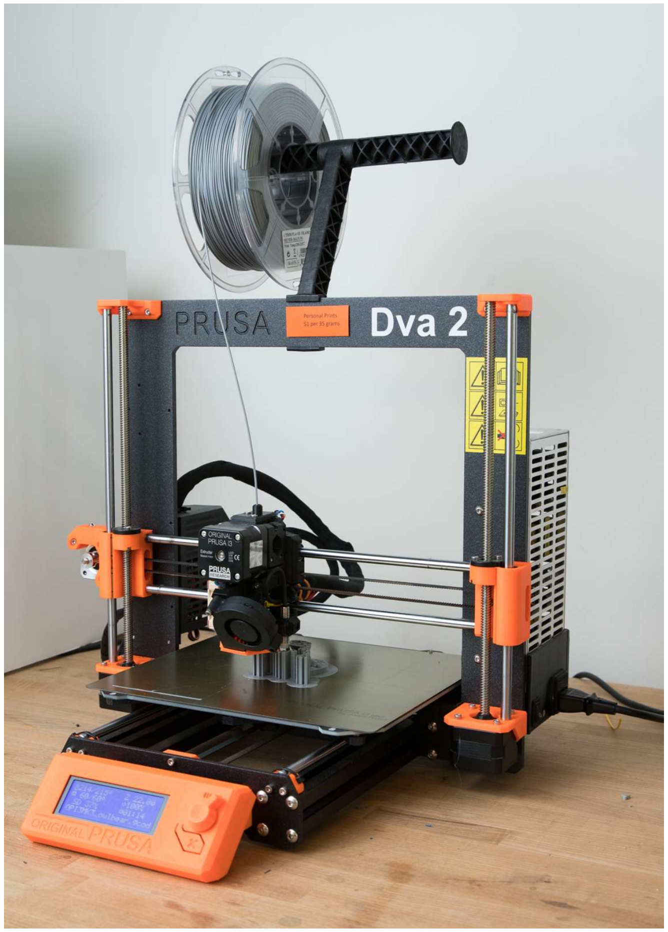


Improvements and limitations

Advances in non-planar slicing

❖ Need for further development:

- Main objective for non-planar layers is to[1]:
  - Increase surface quality
  - Eliminate support structures
  - Increase strength
- One slicing algorithm not suitable to increase all objectives
- A software capable of allowing user to specify requirements and select slicing algorithms required based on them required for robust manufacturing with non-planar layers.



FDM printer, Prusa i3 MK3S[2]

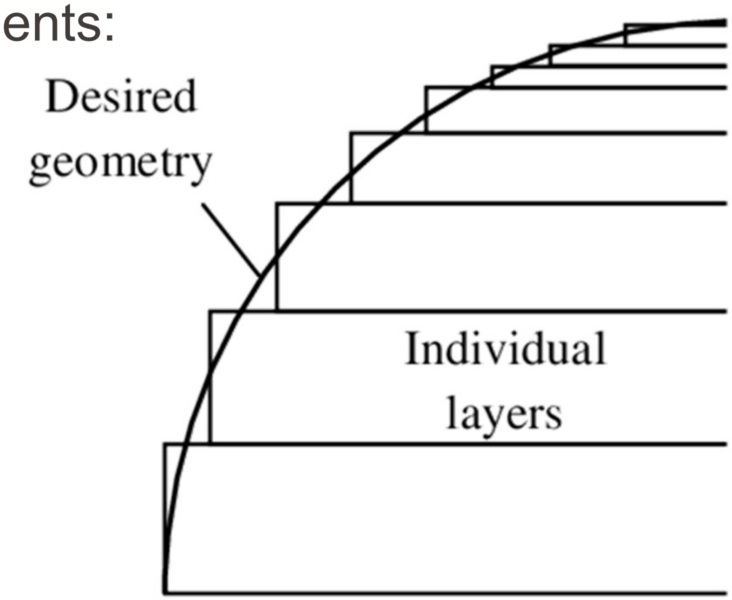
[1] Nayyeri et al, *The international Journal of Advanced Manufacturing*, 2024
[2] *Santa Clara University*

Speaker: Aron D. Beck

Surface enhancements

❖ Goal and advances with surface enhancements:

- Elimination of stairstep effect[3][4][5][6]
- Higher printing speed compared to if variable layer height is used to improve surface quality[3]
- Main methods:
  - Conversion to spherical coordinates for spherical objects[6]
  - Non-planar outermost layer[4]



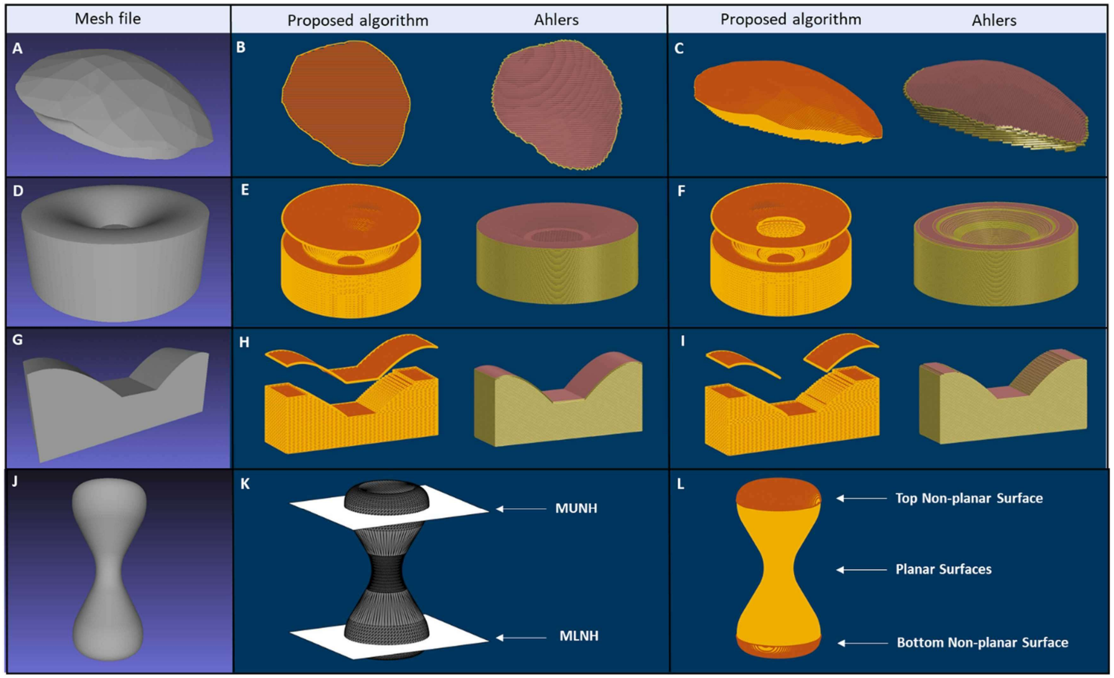
Stairstep effect[7]

[3] Maity et al, *Recent Advanced in Manufacturing and Thermal Engineering*, 2022
[4] *Fortunato et al, Additive Manufacturing, 2023*
[5] And et al, Advances in Additive Manufacturing and Metal Joining, 2023
[6] Yigit et al, Progress in Additive Manufacturing, 2020
[7] Hadley et al, *Innovative Developments in Virtual and Physical Prototyping*, 2011

Top and bottom layer decomposition

❖ Better surface quality for outermost layers[4]

- Decomposition of slicing path into
  - Top surface
  - Middle part
  - Bottom surface
- Planar slicing for middle layers
- Decomposed parts merged to one slicing path
- Robust collision avoidance based on safety height and advance angle based on nozzle geometry



Demonstration of proposed algorithm[4]

[4] *Fortunato et al, Additive Manufacturing, 2023*

Speaker: Aron D. Beck

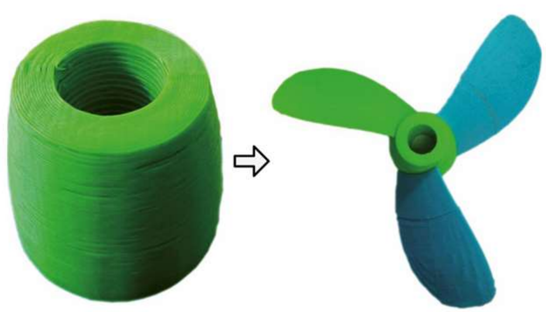
Support structure elimination

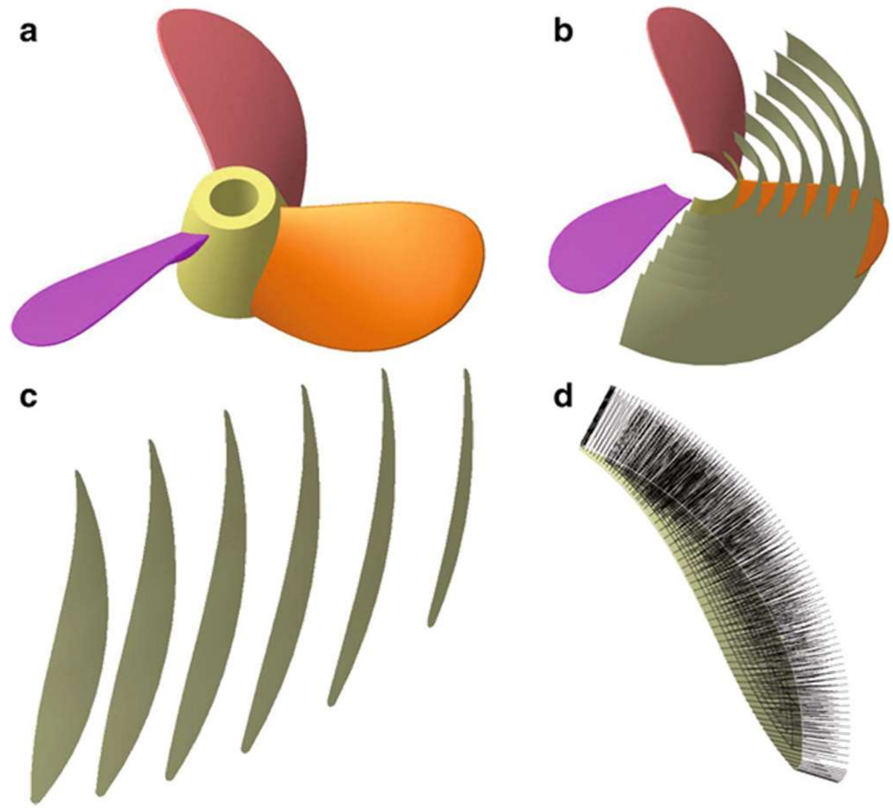
- Support structures can be consuming and costly[8]
  - Two main methods:
    - Volume decomposition
      - Complex geometries decomposed into simpler objects
      - Each object sliced from the most desirable direction[8][9]
    - Nozzle or bed tilting
      - Goal to make sure filament bonds with already extruded part[10][11][12][13]

[8] Zhao et al, Journal of Intelligent Manufacturing, 2020
[9] Zhao et al, *The International Journal of Advanced Manufacturing Technology*, 2018
[10] Sarma et al, *Next Generation Materials and Processing Technologies*, 2021
[11] Dai et al, *AMC Journals*, 2024
[12] Wu et al, *Cornell University*, 2024
[13] Murtezaoglu et al, *Procedia CIRP*, 2018
[14] 3D Printing Support structures, 2018

Support structure elimination

- Volume decomposition
  - Complex geometries decomposed into simpler subparts[8]
  - Geometrical shape identification used to select slicing method for each path[9]
  - Each subpart sliced from the most desirable direction[8]





[9] Zhao et al, *The International Journal of Advanced Manufacturing Technology*, 2018
[8] Zhao et al, Journal of Intelligent Manufacturing, 2020

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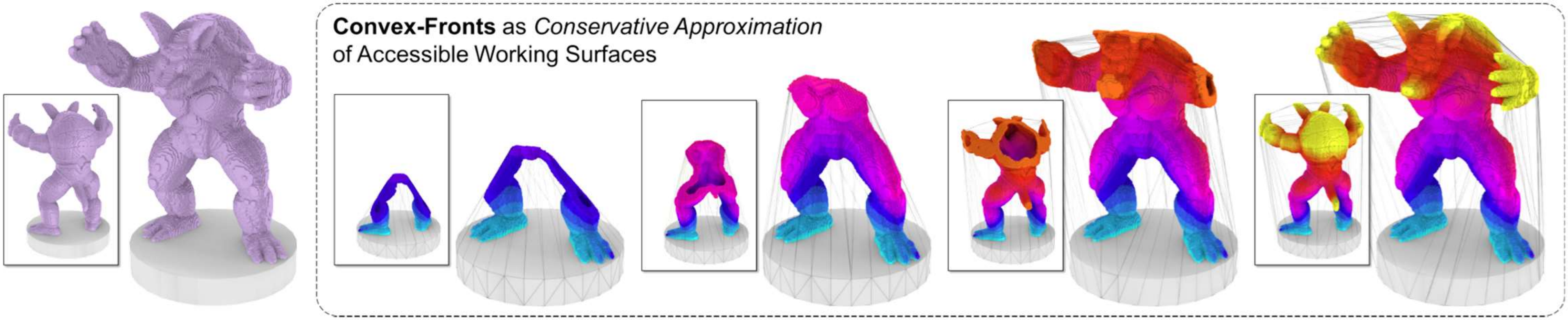
Continuous angle variation of the printing bed

- Goal to tilt printing bed so that filament is extruded on a level surface[11]
  - Part discretized into voxels
    - Stable neighbour sides defined as sides connecting to already layered voxels
  - Greedy optimization scheme used to calculate iso-layers that fulfill stability criteria

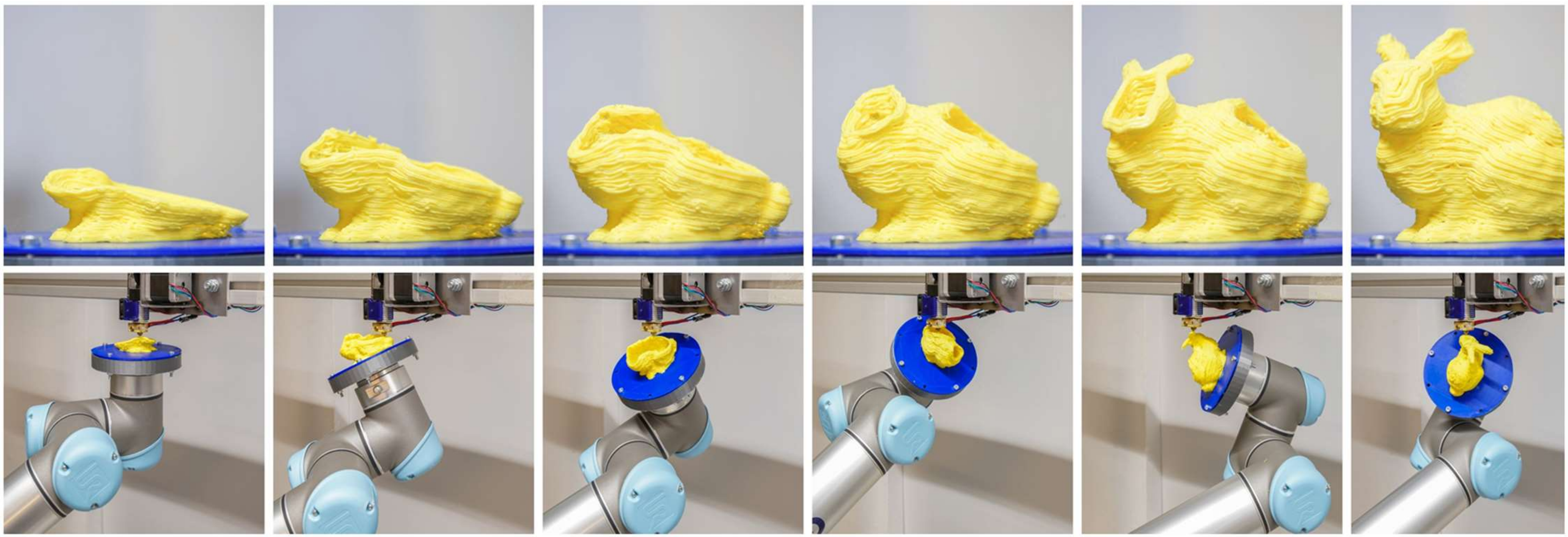


[11] Dai et al, *AMC Journals*, 2024

EPFL

Continuous angle variation of the printing bed

❖ Poor surface quality and large overhangs

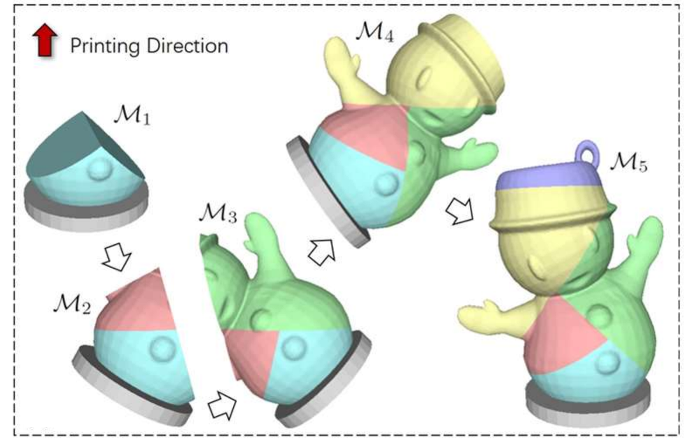


Printing of an object using the method of Dai et al[11]

[11] Dai et al, *AMC Journals*, 2024

Finite bed angle orientations

- Fewer tilting procedures
  - Wu et al[12] suggested a simpler method in slicing
  - User selects finite number of subparts
  - Greedy scheme used to find planes which minimizes risky area of fabricated part
  - Better overall surface quality but seams between subparts visible



Part decomposition[12]

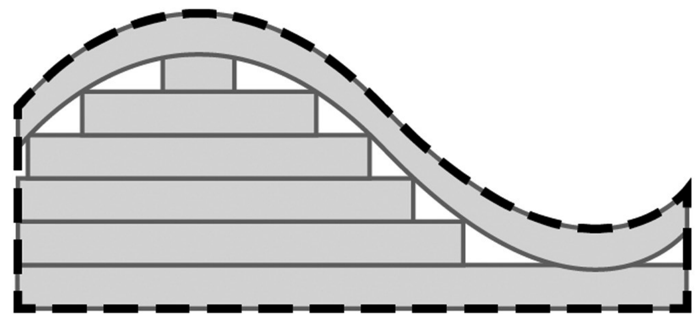
Comparison between fabrication with support structures and proposed method[12]

[12] Wu et al, *Cornell University*, 2024

Strength enhancements

- Problem with previous methods:
  - Poor bonding between layers using planar methods
  - Problem of large air gaps in algorithms used to improve surface quality
  - Search for criteria to impose curvature between layers

Mechanical testing machine [16]



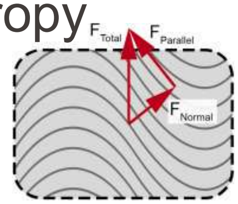
Air gaps between planar and non-planar layers [15]

[15] Pelzer et al, *Additive Manufacturing*, 2021
[16] Instron, 2024

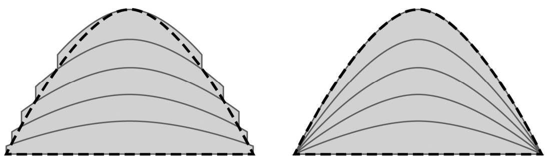
Speaker: Aron D. Beck

Variable extrusion height

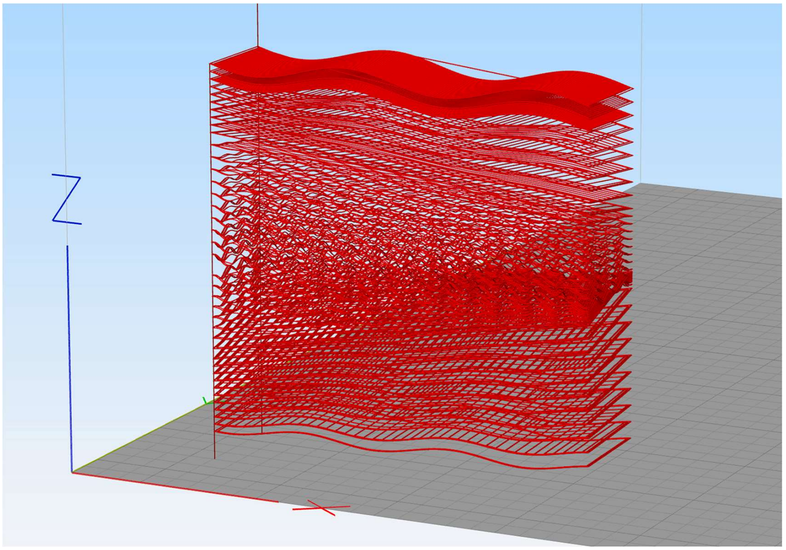
- Improved strength through increased isotropy
  - Goal of reducing normal force
  - Parts manually decomposed into subsection which each is either sliced with curved layers or titled parallel layers
  - Promising technology but unable to demonstrate increase in strength.



a) Surface forces[15]



b) Variable layer height [15]



c) Proposed slicing[15]

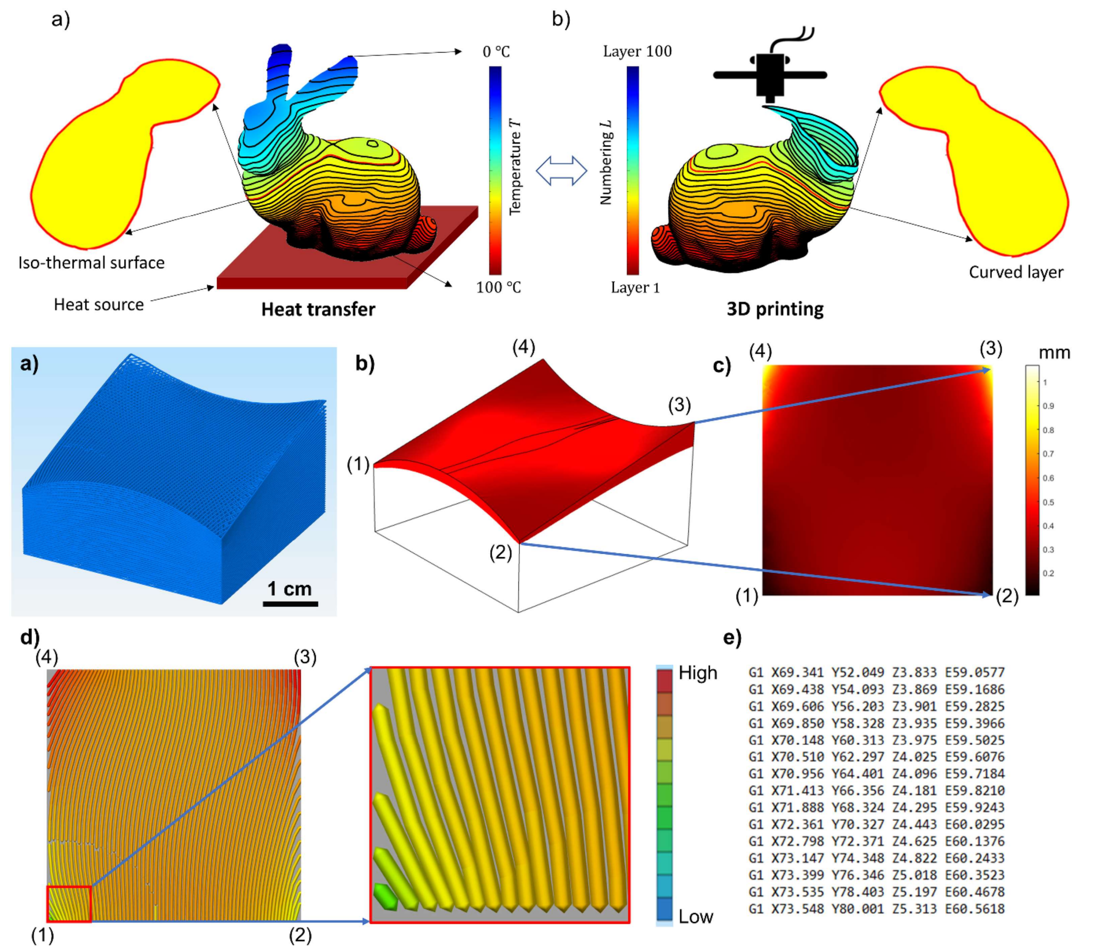
[15] Pelzer et al, *Additive Manufacturing*, 2021

Heat conduction modelling

- Method of generating curved layers:
  - Shan et al[15] proposed to create the non-planar layers with heat conduction modelling and used the isothermal layers to slice objects

$$\rho C_p \frac{\delta T}{\delta t} = \Delta(k\Delta T) + Q$$

  - Tensile strength improved by 14% compared to planar slicing and 63% better surface roughness reported.

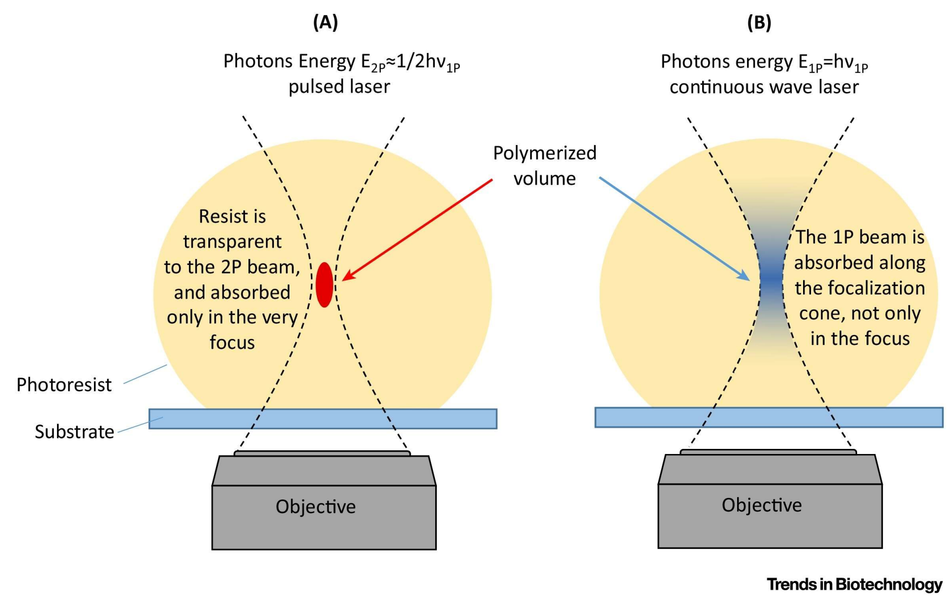


[15] Shan et al, *Journal of Manufacturing Processes*, 2024

Speaker: Aron D. Beck

Limitation to FDM

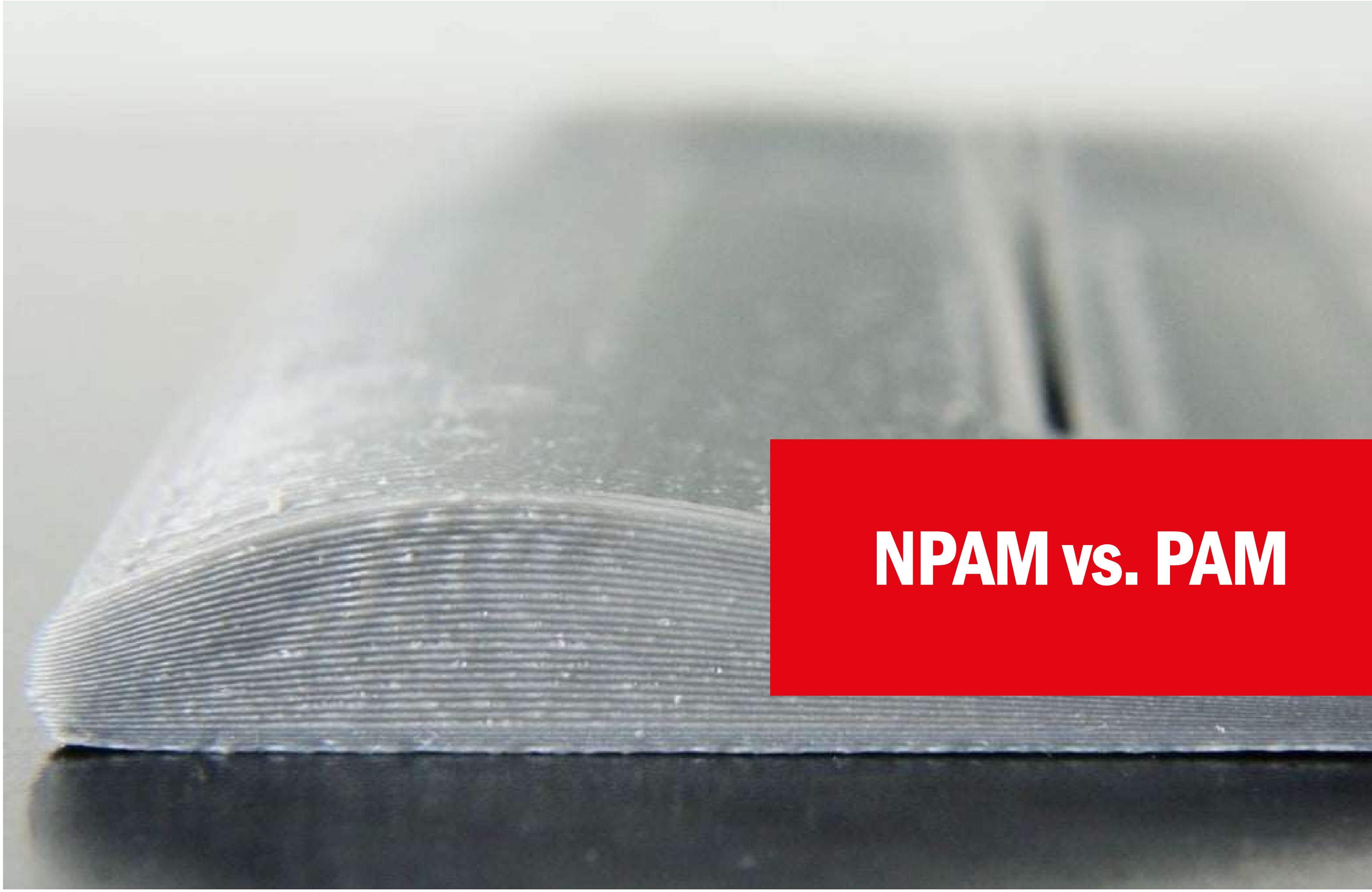
- Literature review has revealed that:
  - Most research on FDM due to poor surface quality and bonding of material
  - Not possible for powder-based processes due to a requirement of even spreading of powder
  - Not widespread in stereolithography but possible with 2 photon curing[17][18].
    - 2 photon curing machine available at EPFL



Explanation of 2 photon curing[18]

[17] Nanoscribe, *Photonic Professional GT2*, 2024
[18] *Enrico et al, Trends in Biotechnology*, 2019

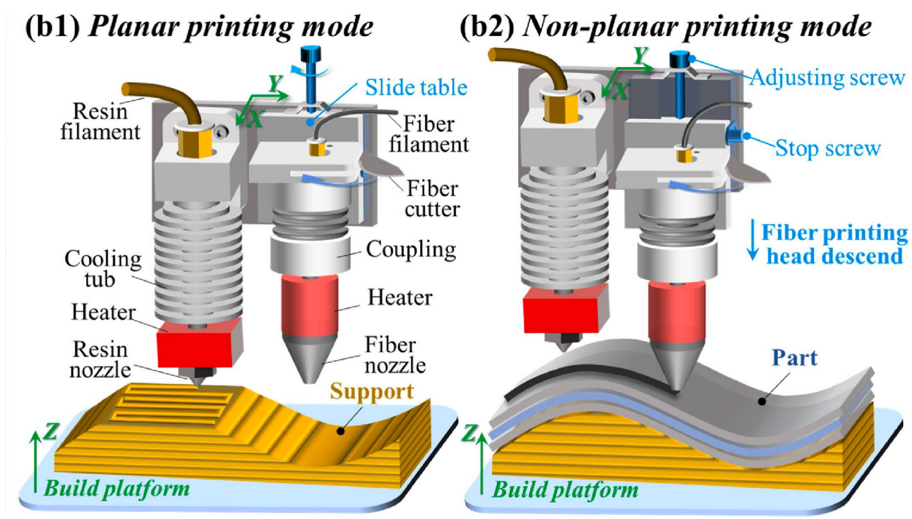
Speaker: Aron D. Beck



NPAM vs. PAM

Starting Point

- **Planar AM (PAM):** Traditional layer-by-layer stacking in flat, horizontal layers.
- **Non-Planar AM (NPAM):** Introduces curved or freeform layers aligned with the part's geometry.



Shouling Ding, Bin Zou, Qingyang Liu, Xinfeng Wang, Jikai Liu, Lei Li, Non-planar additive manufacturing of pre-impregnated continuous fiber reinforced composites using a three-axis printer, Journal of Materials Research and Technology, Volume 32, 2024,

![EPFL]

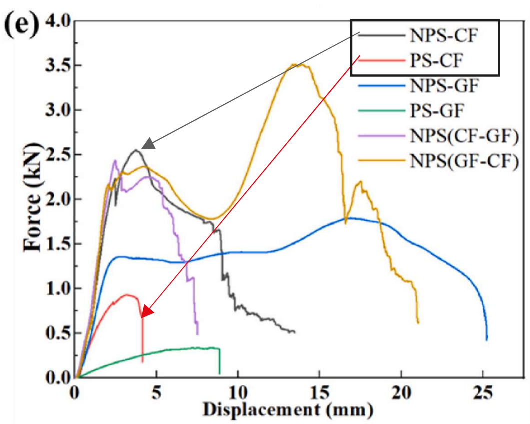
Mechanical Strength and Anisotropy

PAM:

- Layers stacked in flat planes, resulting in weaker strength along the Z-axis.
- Prone to delamination and anisotropic behavior.

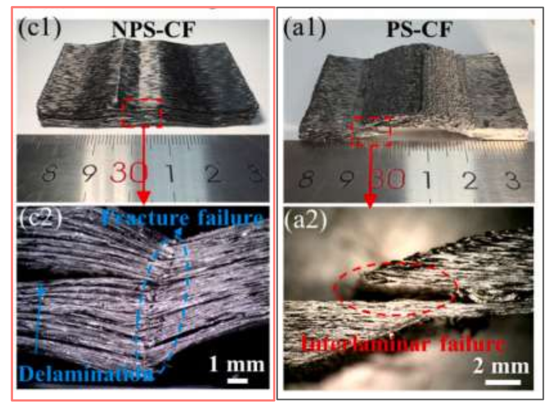
NPAM:

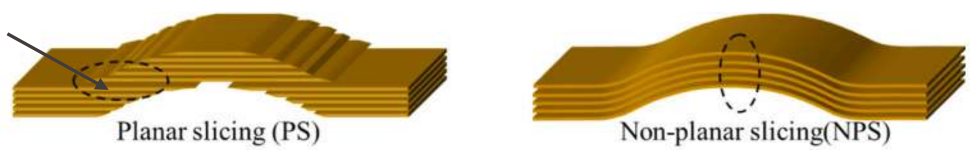
- Curved layers can be aligned with stress trajectories.
- Reduced anisotropy and enhanced overall mechanical strength.



a) force-displacement curves

+70% bending force (CF)
-63% roughness (CF)





b) The physical pictures of the failed specimens printed with single fiber and their side morphologies

Shouling Ding, Bin Zou, Qingyang Liu, Xinfeng Wang, Jikai Liu, Lei Li, Non-planar additive manufacturing of pre-impregnated continuous fiber reinforced composites using a three-axis printer, Journal of Materials Research and Technology, Volume 32, 2024,

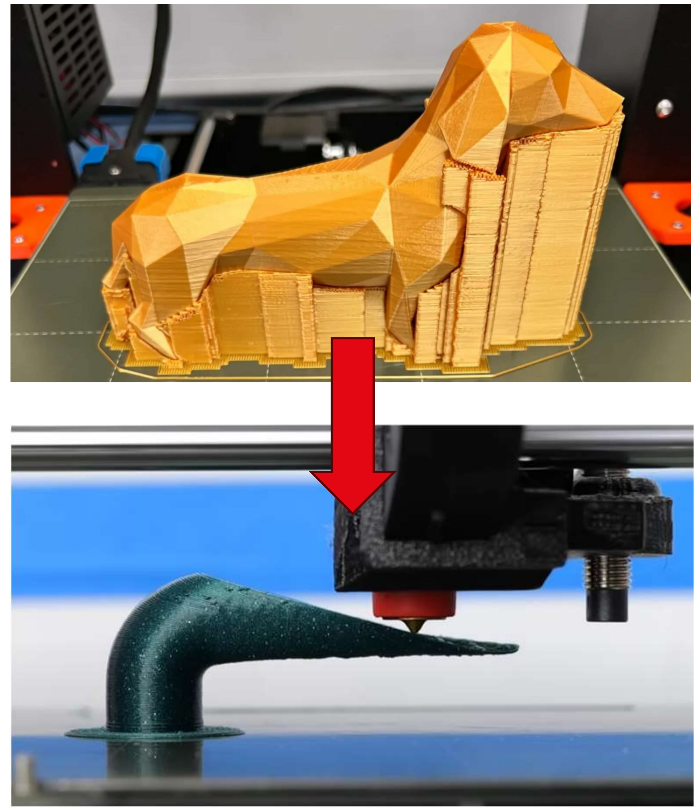
Support Structures

PAM:

- Necessary support increase waste and post-processing for complex shapes
- Material compatibility needs to be taken into consideration for supports.

NPAM:

- Layer orientation can eliminate/reduce supports.
- Techniques like conical slicing enable stable deposition at steep angles.



- https://all3dp.com/2/3d-printing-supports-guide-all-you-need-to-know/
  CNCKitchen. Conical Slicing: A different angle of 3D printing https://www.youtube.com/watch?v=1i-1TEdByZY
  https://xyzdims.com/3d-printing/slicer4rtn/

Speaker: Clément CHALUT

Concrete example

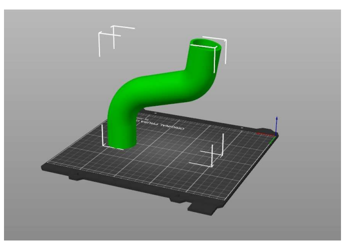
Parameters :

- **Material Cost:** 20.- per kilogram (PETG).
- **Labor Cost:** 33.-/h (hourly rate for 3D printing technician in CH)
- **Printing Parameters :**
- **PAM:** Prusa Mk3S (PrusaSlicer)
- **NPAM:** Prusa Mk3S optimized with opensource slicing algo (Slicr)

- https://www.salaryexpert.com/salary/job/3d-printing-technician/switzerland
  https://www.3djake.ch/en-CH/the-filament/the-filament-petg-filament
  https://www.prusa3d.com/category/original-prusa-i3-mk3s/
  https://github.com/makertum/non-planar-layer-fdm

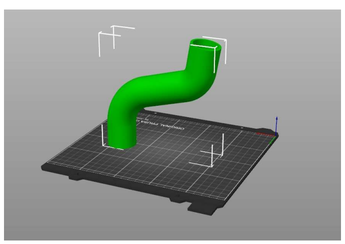
Speaker: Clément CHALUT

Printing Time

	PAM	NPAM
 3D benchy	1.5 – 2 hours	1.5 – 2 hours
 S-shaped cylinder	15 hours	8h30 hours

Material Cost

3D benchy

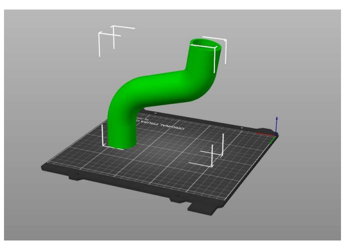


S-shaped cylinder

	PAM	NPAM
3D benchy	0.3.-	0.3.-
S-shaped cylinder	3.6.- (20% support)	2.9.-

Speaker: Clément CHALUT

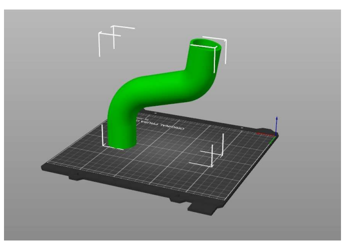
Post-Processing

	PAM	NPAM
 3D benchy	15min	10min
 S-shaped cylinder	20min	10min

Depends on application

Speaker: Clément CHALUT

Final cost

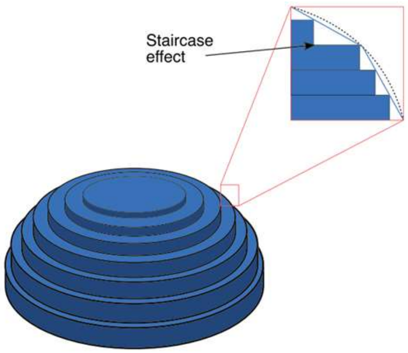
	PAM	NPAM
 3D benchy	1h45 / 8.55.-	1h40 / 5.8.-
 S-shaped cylinder	15h45 / 14.6.-	8h40 / 8.4.-

Speaker: Clément CHALUT

Surface Quality and Finishing

PAM:

- “staircase effect” on curved surfaces
- Smoother surfaces need finer layers, increasing print time.



-76% surface roughness

NPAM:

- Curved layers conform to the part’s shape, reducing visible stepping.
- Improved surface quality out-of-the-printer, minimizing finishing work.
- "Lines" of printing are still present.

- Georg Aarnes Nisja | Anni Cao | Chao Gao, Short review of nonplanar fused deposition modeling printing,

Speaker: Clément CHALUT

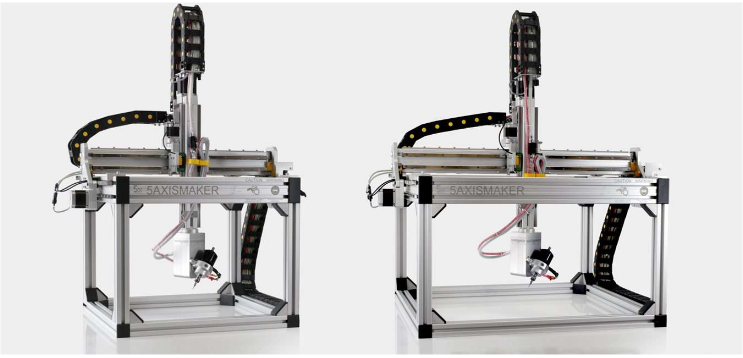
Equipment and Implementation Challenges

PAM:

- Standard 3-axis setups are simple and widely available.
- Straightforward slicing and toolpaths, making it cost-effective and beginner-friendly.

NPAM:

- Requires multi-axis systems or modified hardware for nozzle orientation.
- Advanced slicing algorithms and longer, specialized nozzles



- CNCKitchen. Conical Slicing: A different angle of 3D printing https://www.youtube. com/watch?v=1i-1TEdByZY. https://www.fabbaloo.com/news/innovation-alert-5-axis-fff-3d-printer-5x-developed-at-iwk-institute-in-germany

Speaker: Clément CHALUT

Case studies

Case studies

POLITÉCNICA

1. **Axisymmetric non-planar slicing and path planning strategy for robot-based additive manufacturing** [19]
   - Polytechnic University of Madrid, Spain
   - Lead to a "MAKE Project"
   - Focused on slicing and trajectory generation

2. **Supportless 3D-printing of non-planar thin-walled structures with the multi-axis screw-extrusion additive manufacturing system** [20]
   - Zhejiang Normal University, China
   - New approach to NPAM

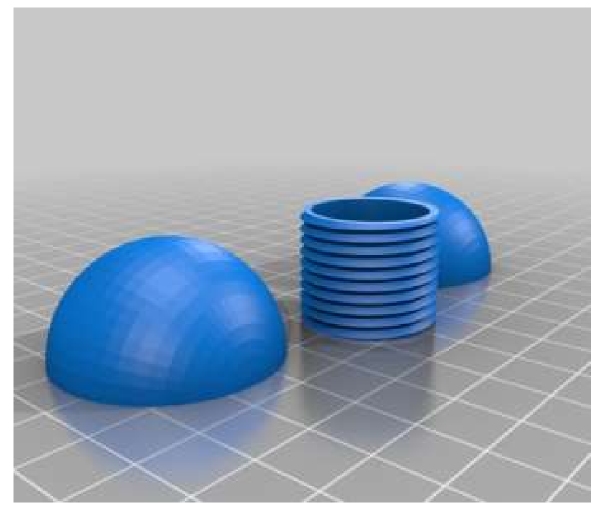
[19] López-Arrabal et al, *Materials & Design*, 2024
[20] Li et al, *Materials & Design*, 2024

Case study 1: Axisymmetric non-planar slicing

- **Axisymmetric elements**: those whose shape and properties remain unchanged when rotating a layer around the axis of symmetry.

- Slicing and trajectory generation:
  - ✓ Simple axisymmetric surfaces
  - ✗ Free-form surfaces

- **Contribution**:
  - Algorithm capable of slicing and generating trajectories for any kind of axisymmetric shapes
  - Use of commercial planar slicer software



cura.

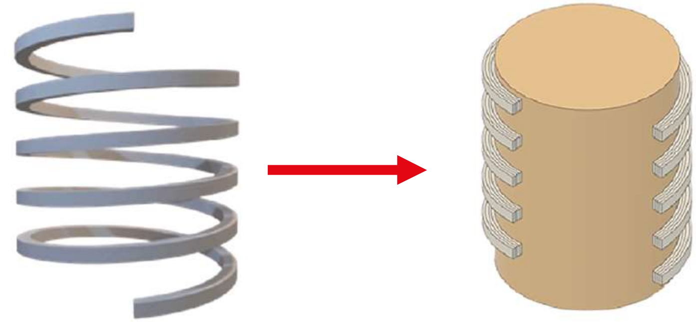
Case study 1: Axisymmetric non-planar slicing

❖ Methodology

- Two case studies:

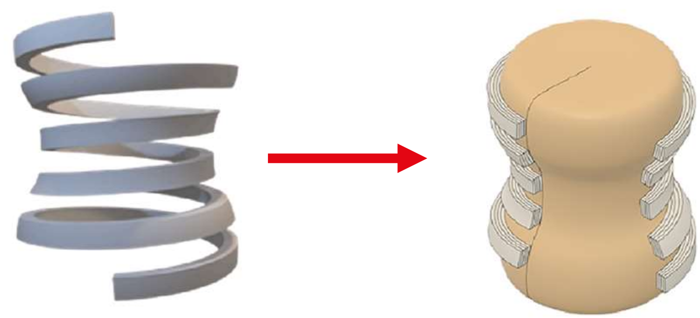
Cylindrical helical spring

- Cylindrical layers



Hourglass-shaped helical spring

- Hourglass-shaped layers




(c)


(d)

Motivations:

× Staircase effect

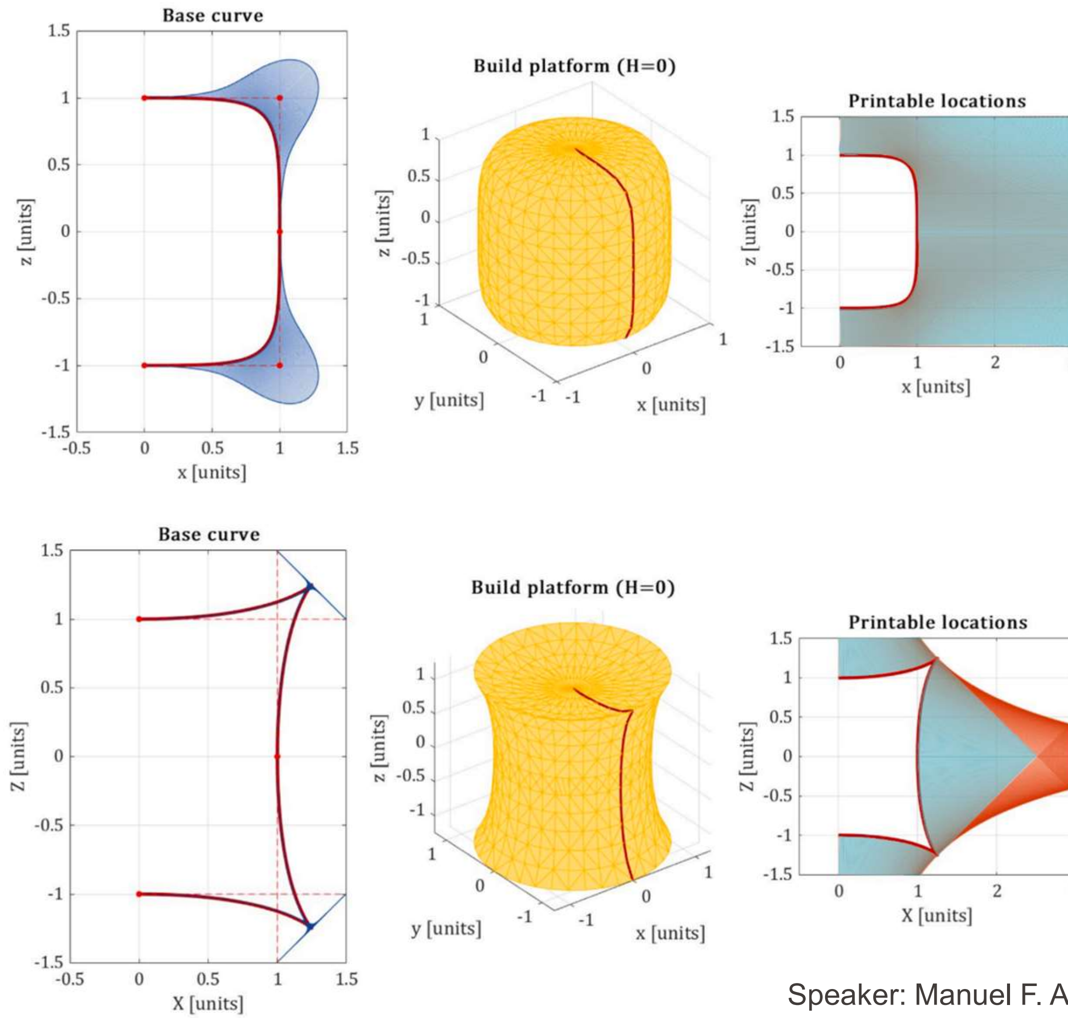
× Support structure

Speaker: Manuel F. Alonso

Case study 1: Axisymmetric non-planar slicing

❖Slicing and trajectory generation

- Slicing by surfaces of revolution parallel to the build platform
  - Cylindrical and hourglass surfaces
- Build platform ⇔ Composite Bézier
  - B-spline generatrix curve
  - Control points + polynomial = Spline
  - Spline: piece of curve
  - Rotation around the Z axis
- Cylindrical: 2 splines, 4 control points
- Hourglass: 4 splines, 4 control points



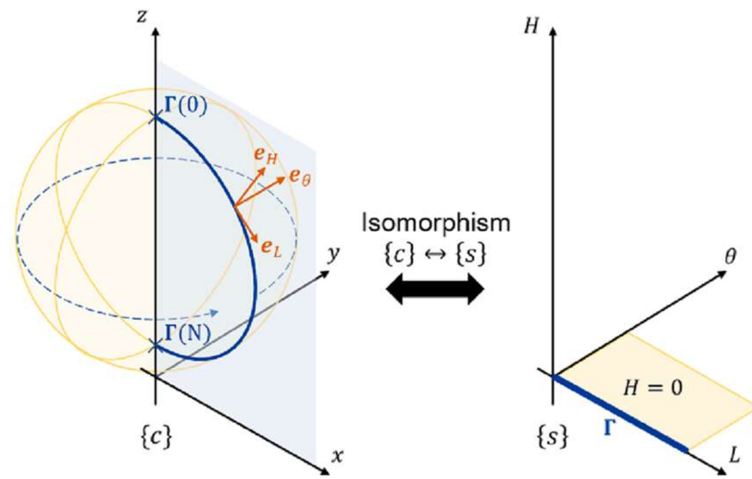
Speaker: Manuel F. Alonso

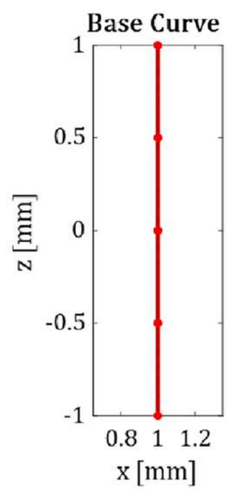
EPFL

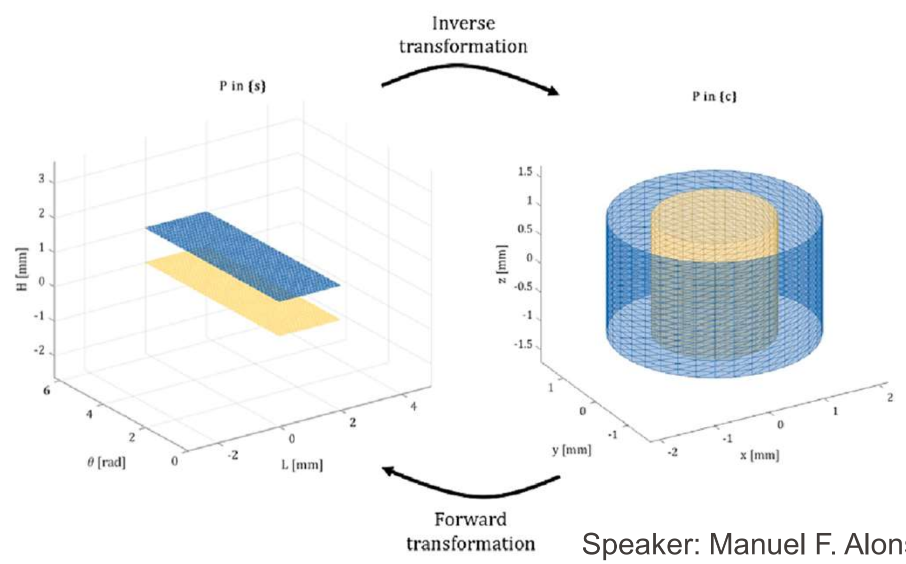
Case study 1: Axisymmetric non-planar slicing

❖ Slicing and trajectory generation

- Slicing by surfaces of revolution parallel to the build platform
  - × Commercial planar slicers
- Algorithm based on isomorphism:
  - Cartesian coordinate system {c}
  - Slicing coordinate system {s}
  - Mathematical transformation
- Algorithm:
  1. {c} ⇔ {s}: flat surface
  2. Planar slicing in {s}
  3. {s} ⇔ {c}: non-planar layers, conforming the object's geometry







Speaker: Manuel F. Alonso

EPFL

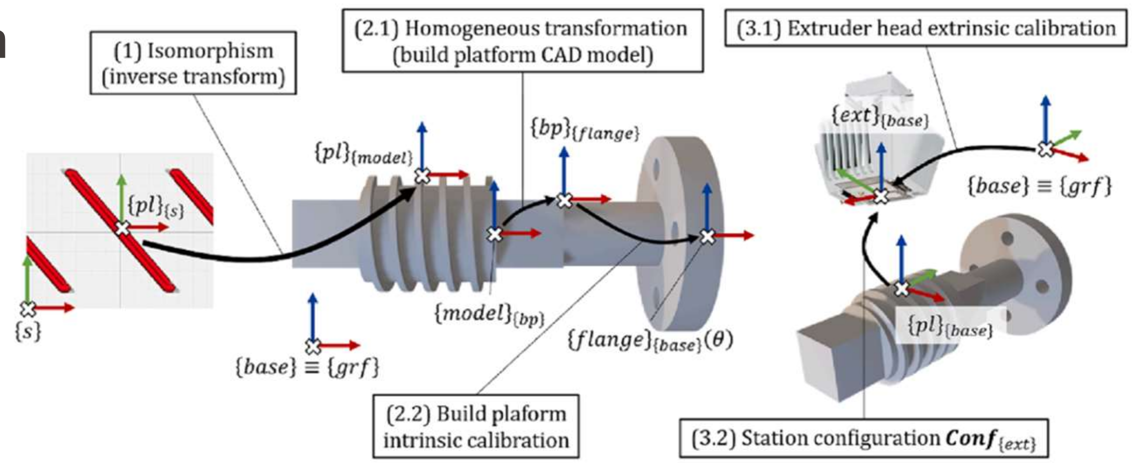
Case study 1: Axisymmetric non-planar slicing

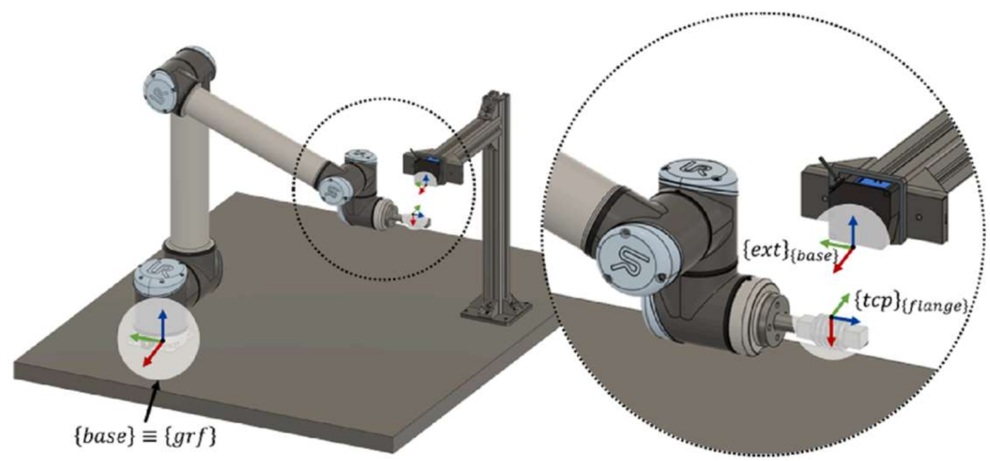
❖ Slicing and trajectory generation

- Algorithm:
  1. List of points and trajectories in {s} (nozzle always orthogonal)
  2. Inverse transformation to {c}
  3. Matrix multiplications ➡ fixed extruder reference frame

- Setup: robot + fixed extruder

- Robot:
  - Calibration workflow
  - Not focused on the study



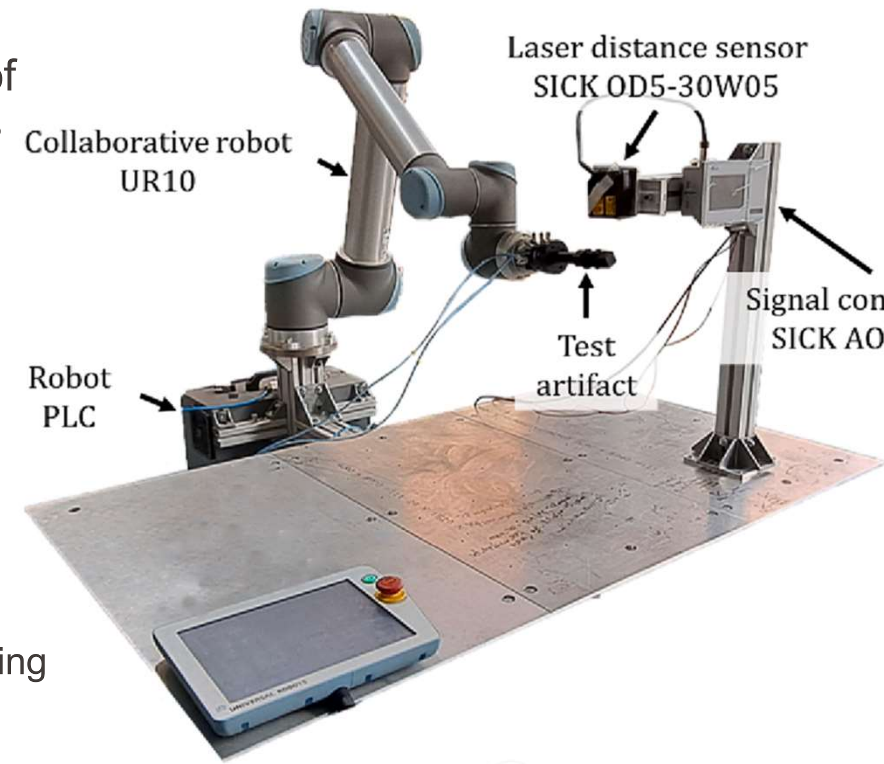


Speaker: Manuel F. Alonso

Case study 1: Axisymmetric non-planar slicing

❖ Experimental setup

- Objective: validate the accuracy of the generated printing trajectories
  - × Analysis of the printed object
- Extruder ➔ laser distance sensor
  - Distance {tcp} – {ext}
  - While executing trajectories
- Build platform + helical spring **planarly printed**
  - Measure the accuracy of maintaining a constant distance
- UR10 robotic manipulator

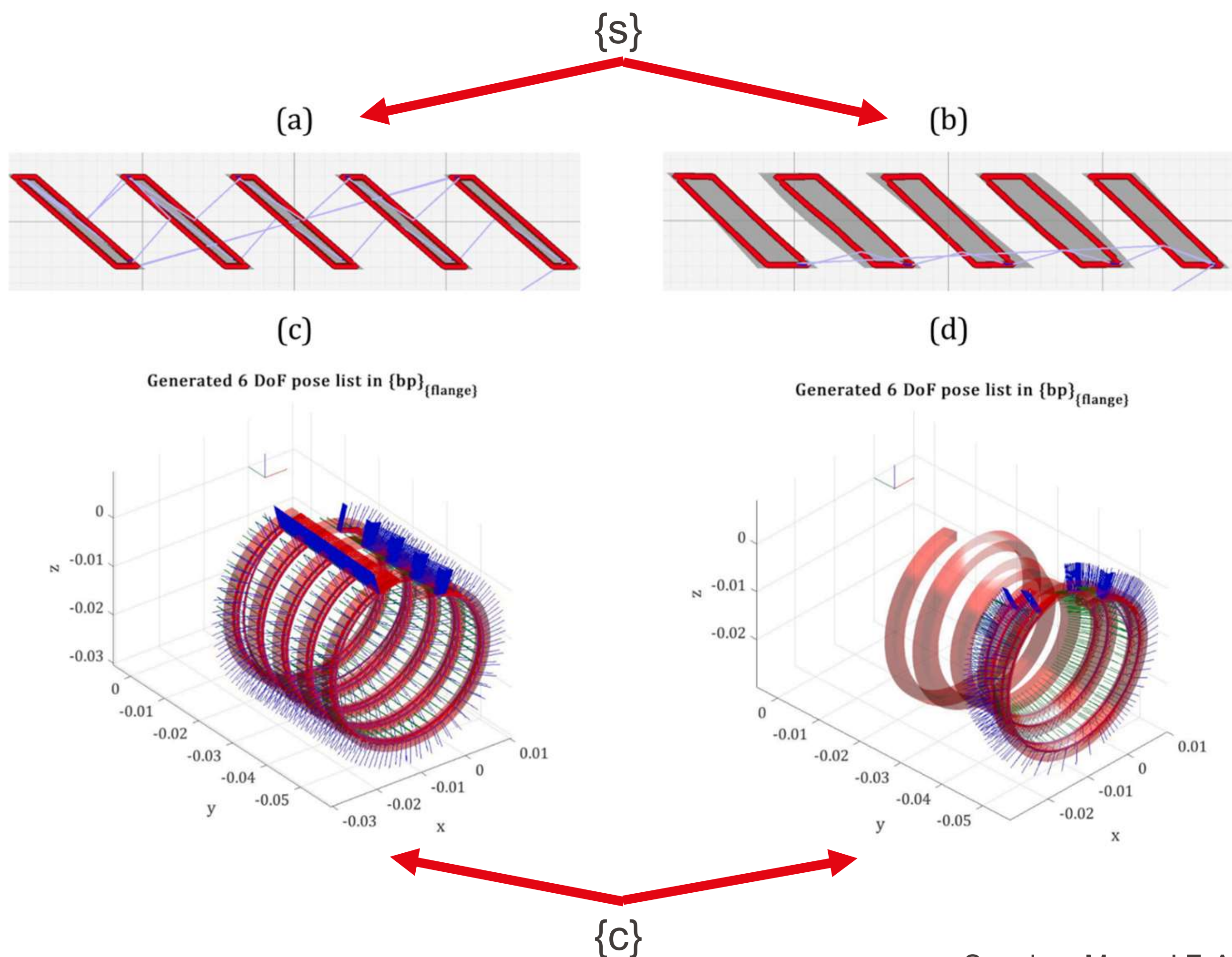


Speaker: Manuel F. Alonso

Case study 1: Axisymmetric non-planar slicing

❖ Results and validation

- Algorithm implemented in MATLAB 2023b
- Generated trajectories for both use cases
  - Only the first layer presented



Case study 1: Axisymmetric non-planar slicing

❖ Results and validation

- Trajectories tested for only one and a half coil of each spring

- Cylindrical helical spring

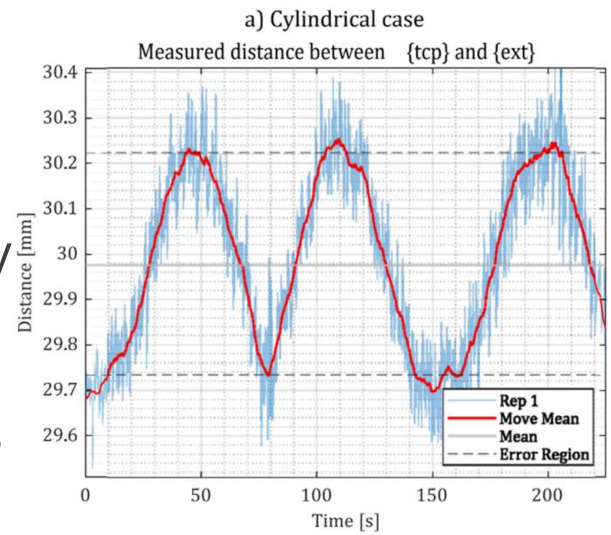
- Hourglass-shaped helical spring

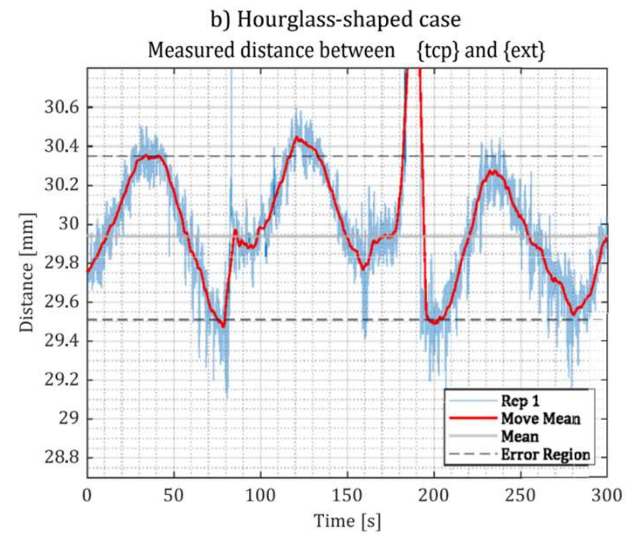
Speaker: Manuel F. Alonso

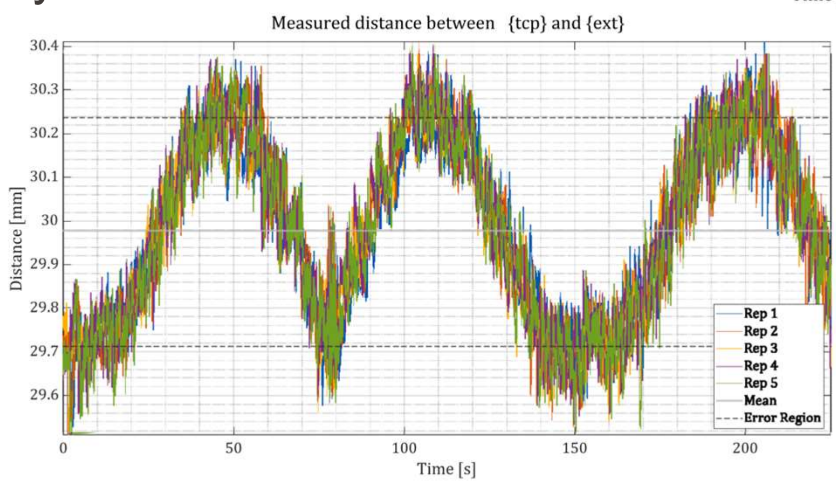
Case study 1: Axisymmetric non-planar slicing

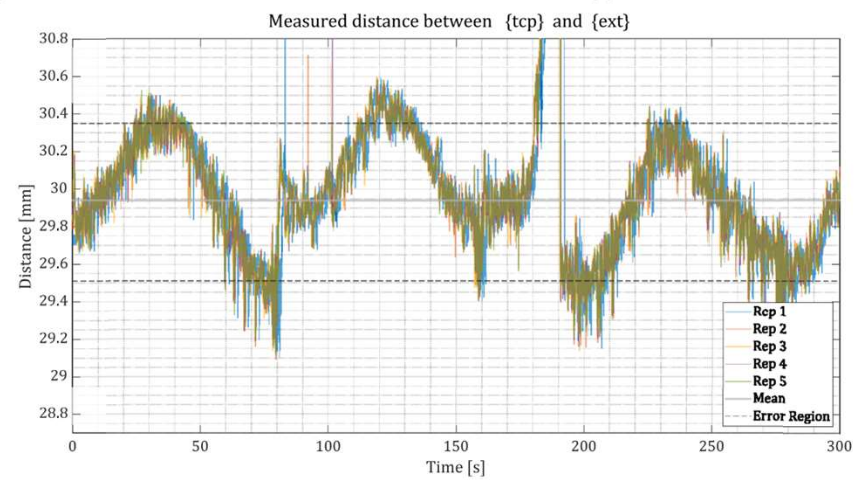
❖Results and validation

- ✓Constant distance {tcp} – {ext}
- ✓Error: planned – actual trajectory
  - Cylindrical: ±250 µm
  - Hourglass: ±350 µm
  - Intrinsic calibration + inverse kin.
- ✓Repeatability of the method









Speaker: Manuel F. Alonso

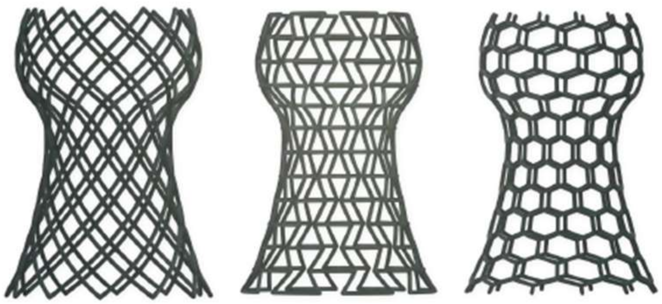
Case study 1: Axisymmetric non-planar slicing

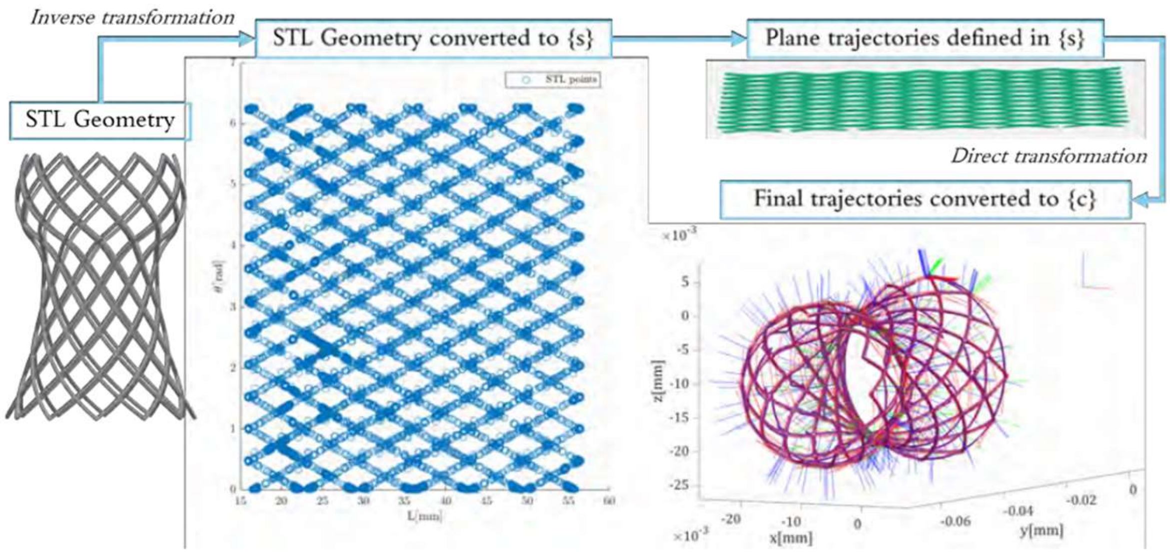
❖Ongoing research

CONFIDENTIAL

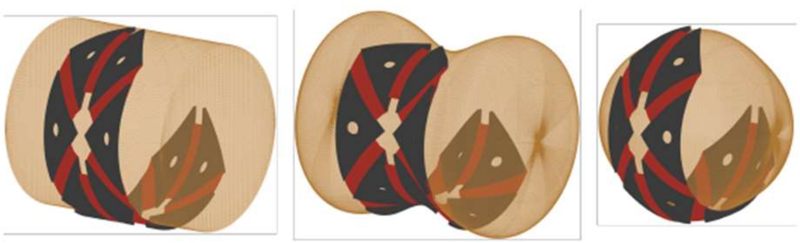
- Investigating two new case studies:
  - Soft robotic grippers
  - Coronary stents

- **Coronary stents**





- **Soft robotic grippers**



(a) (b) (c)

Speaker: Manuel F. Alonso

Case study 2: Supportless-3D printing

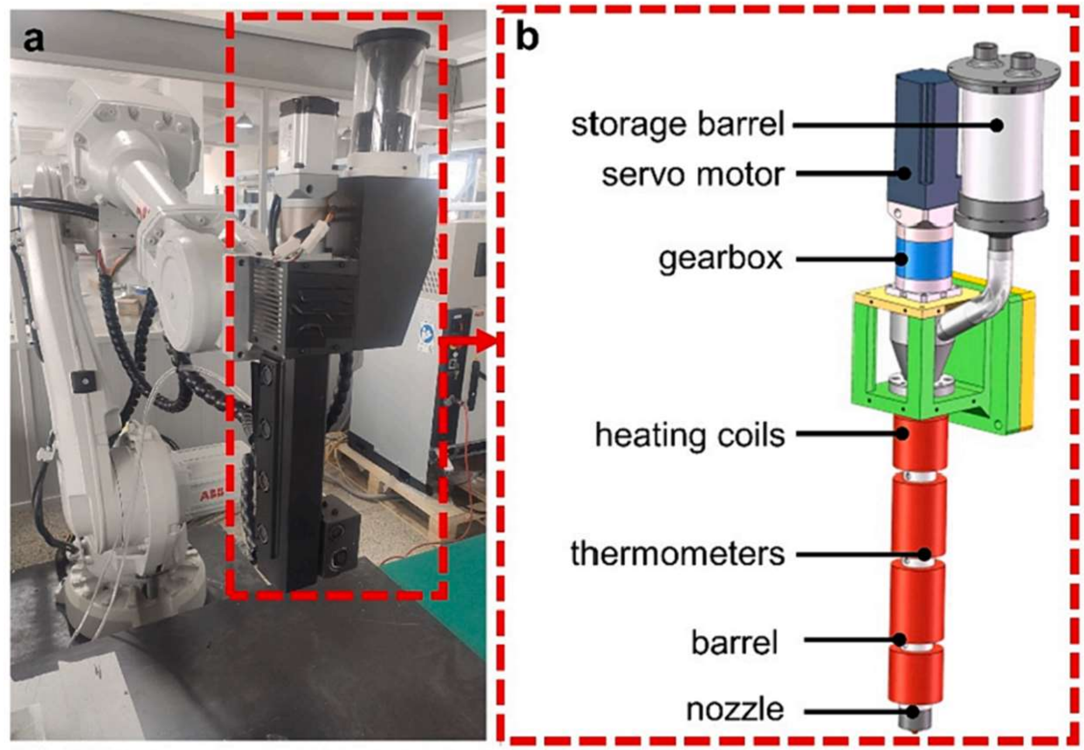
- **Thin-walled structures**: hollow tubes and thin shells are key elements in fields like aerospace, automotive and renewable energy
- 3D-printing:
  - ✓ Versatility, affordability
  - × Support structures, undesired weight
  - × Low throughput rates (< 0.05 kg/h)

- Screw-Extrusion Additive Manufacturing (SEAM)
  - Rotating screw + heated barrel = extrude molten plastic
  - ✓ Higher deposition rates
  - × Limited to PAM
- **Contribution**:
  - SEAM + 6 DoF robotic arm = NPAM

Case study 2: Supportless-3D printing

❖ Materials and methods

- SEAM + 6 DoF ABB arm
  - Extrusion system vertically attached to the 6th joint
  - Single screw, driven by a 400W servomotor
  - Extrusion can reach over 450ºC and 3 kg/h rate
- PLA and carbon-fiber reinforced PLA pellets
- Custom slicing algorithm:
  - Slicing paths that conform to the geometry
  - Nozzle always perpendicular

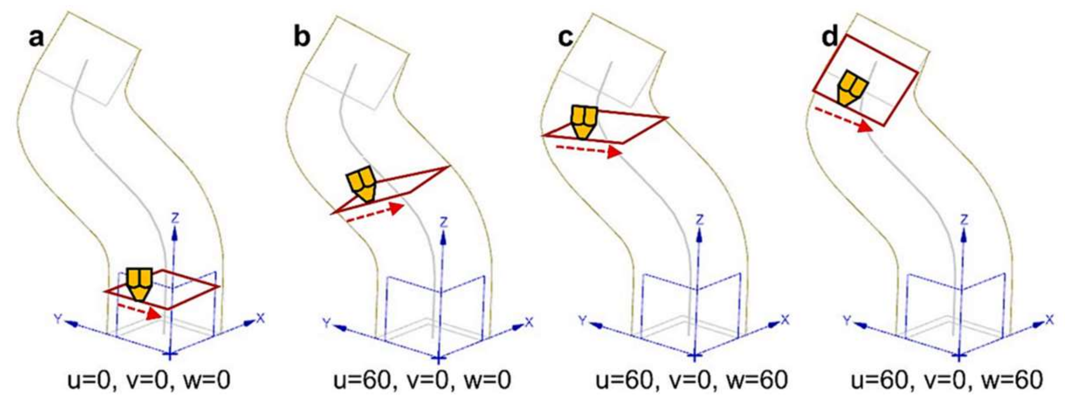


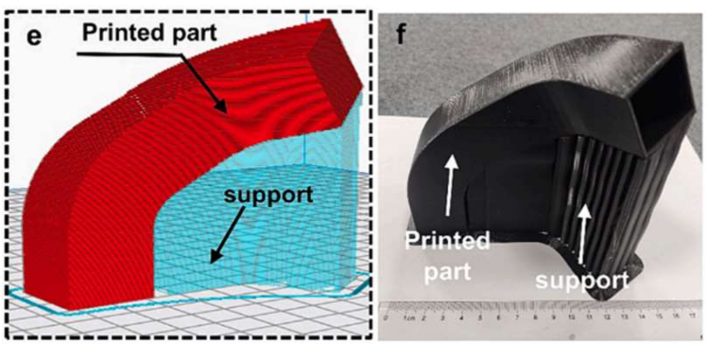
Speaker: Manuel F. Alonso

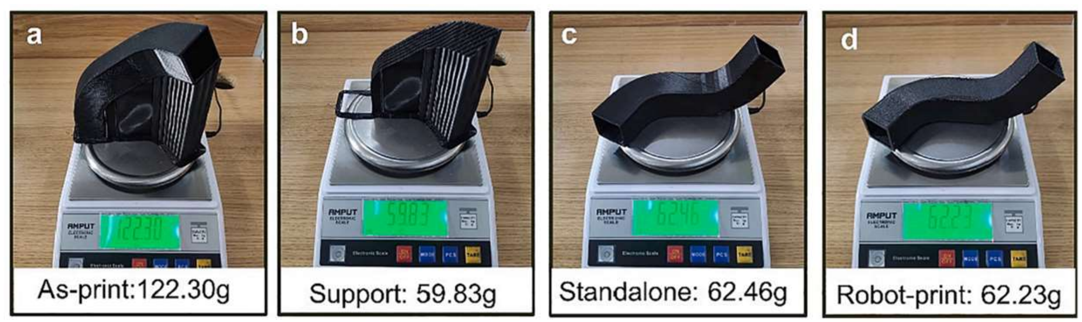
Case study 2: Supportless-3D printing

❖Experimental results – twisted hollow tube

- Key component for connecting pipes
- Support structure unavoidable in PAM
- Slicing algorithm:
  - Eliminate the support structure
  - Pivoting the nozzle along the normal direction of the deposition surface
- Result: support structure is 48.9% of weight

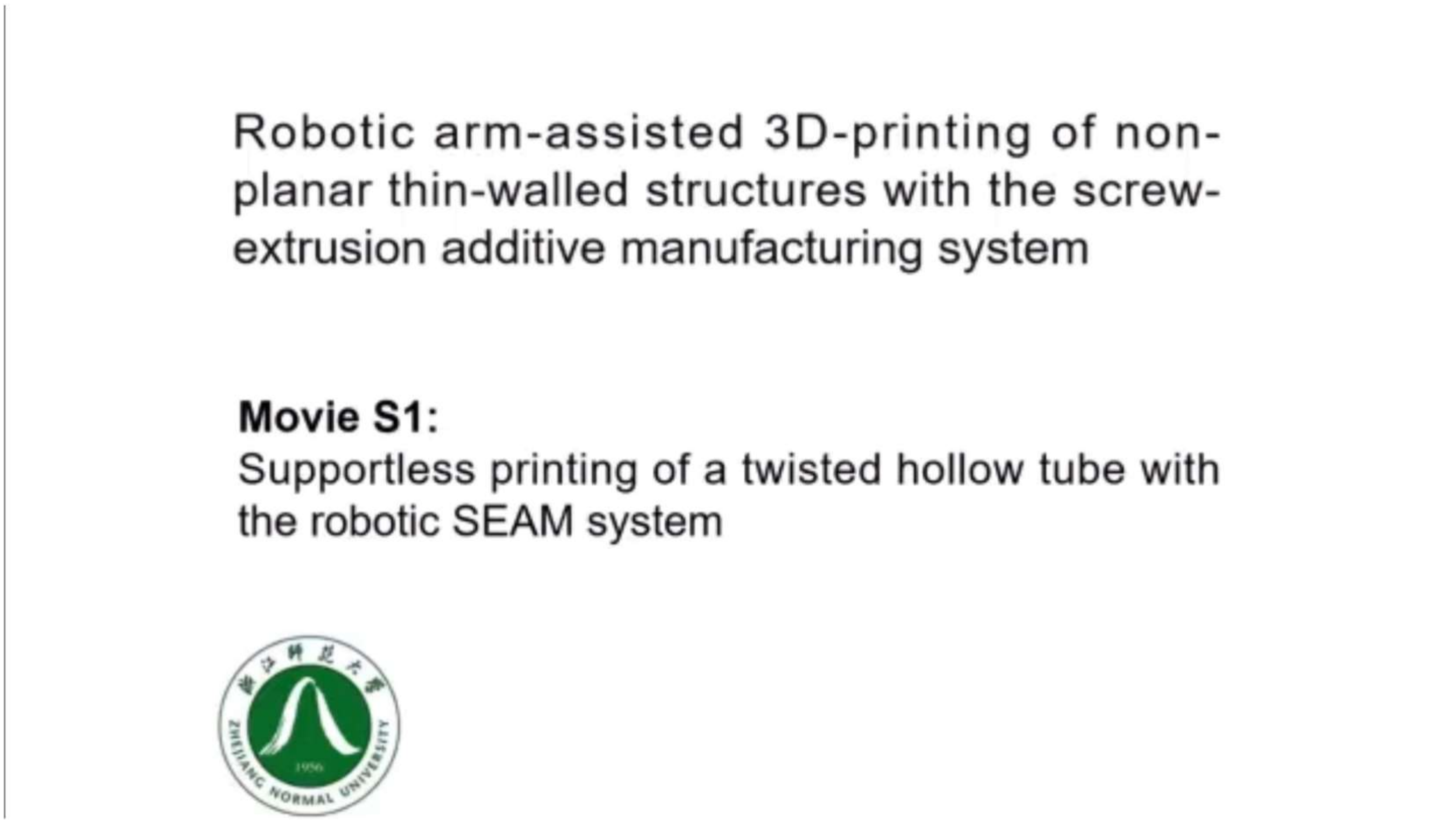






Case study 2: Supportless-3D printing

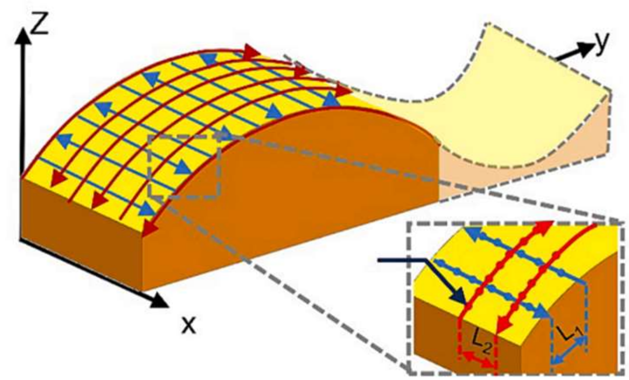
❖ Experimental results – twisted hollow tube



Case study 2: Supportless-3D printing

❖ Experimental results – curved surface

- Light weight load-bearing applications
  - Air foils, airplane skins
- Support structure unavoidable in PAM
- Robotic SEAM system ➔ directly print through conformal depositing layers onto a pre-made support structure
- Double-cross pattern:
  1. Parallel to X-axis
  2. Parallel to Y-axis
- Line spacing highly customizable

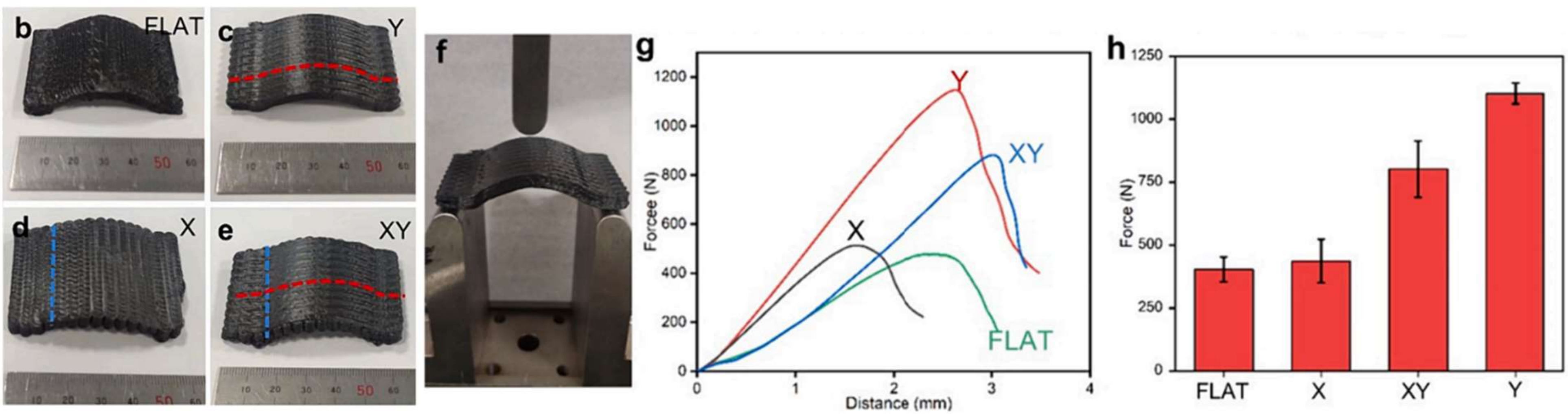


Speaker: Manuel F. Alonso

Case study 2: Supportless-3D printing

❖ Experimental results – curved surface

- Effect of the printing orientation ➔ Flexural tests
- Maximum bending force achieved by the Y pattern ➔ 1102.6 N



Speaker: Manuel F. Alonso

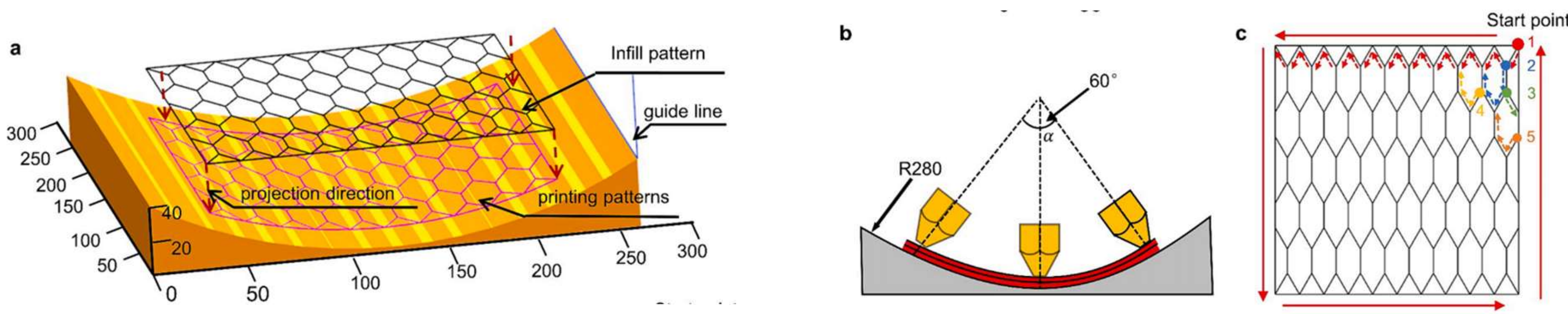
Case study 2: Supportless-3D printing

❖ Experimental results – 3D structure

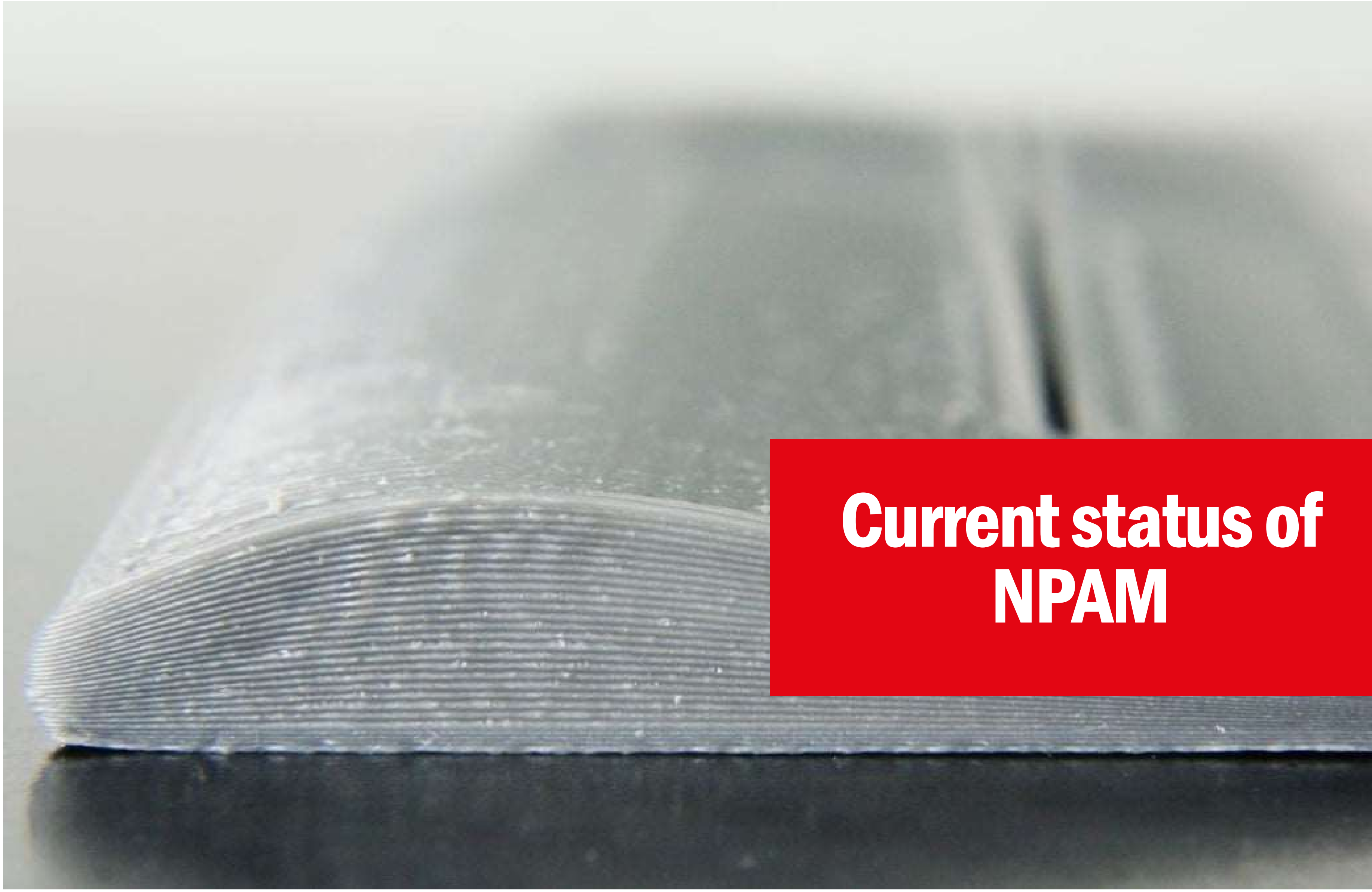
- Curved surfaces with infill patterns
  - Reduces structural weight
- Continuous conformal path cannot be used ➔ need for a different path planning
- Start-point and end-point of the nozzle need to be taken into account

Robotic arm-assisted 3D-printing of non-planar thin-walled structures with the screw-extrusion additive manufacturing system

Movie S2:
Curved printing with honeycomb filling on a concave surface.



Speaker: Manuel F. Alonso

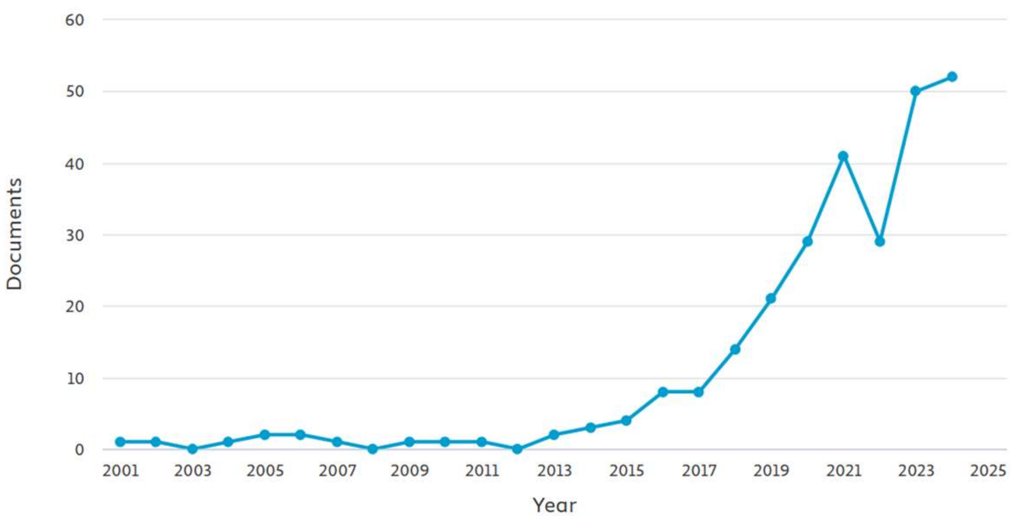


Current status of NPAM

Current status of NPAM - Research

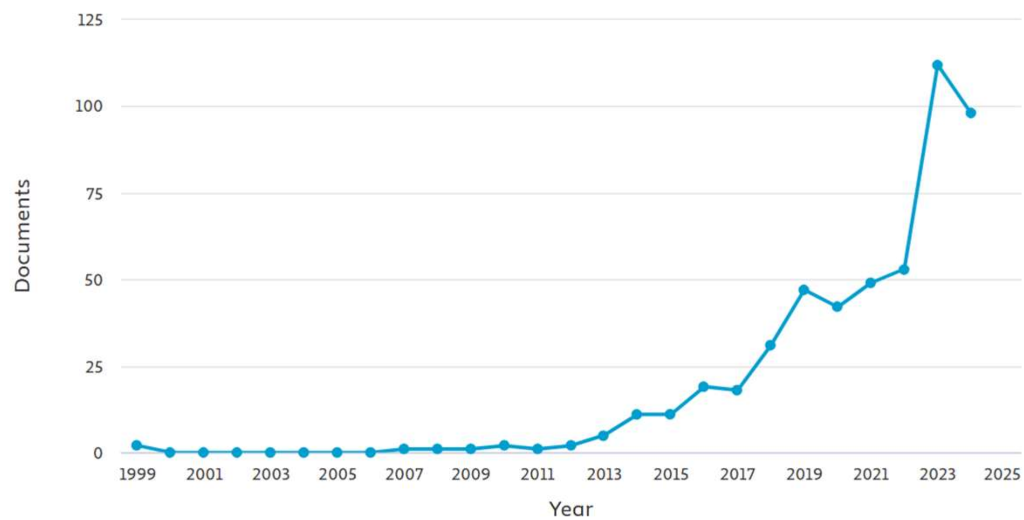
- Non-Planar FDM
- Curved Layer Printing
- Non-Planar Slicing
- Conformal 3D Printing
- Curved Surface Printing
- Freeform 3D Printing
- 3D Printing with Non-Planar Tool Paths

- Non-planar additive manufacturing



- 272 papers

- Curved surface 3D printing



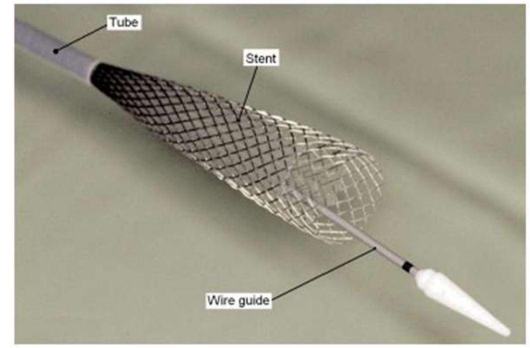
- 506 papers

ELSEVIER Scopus

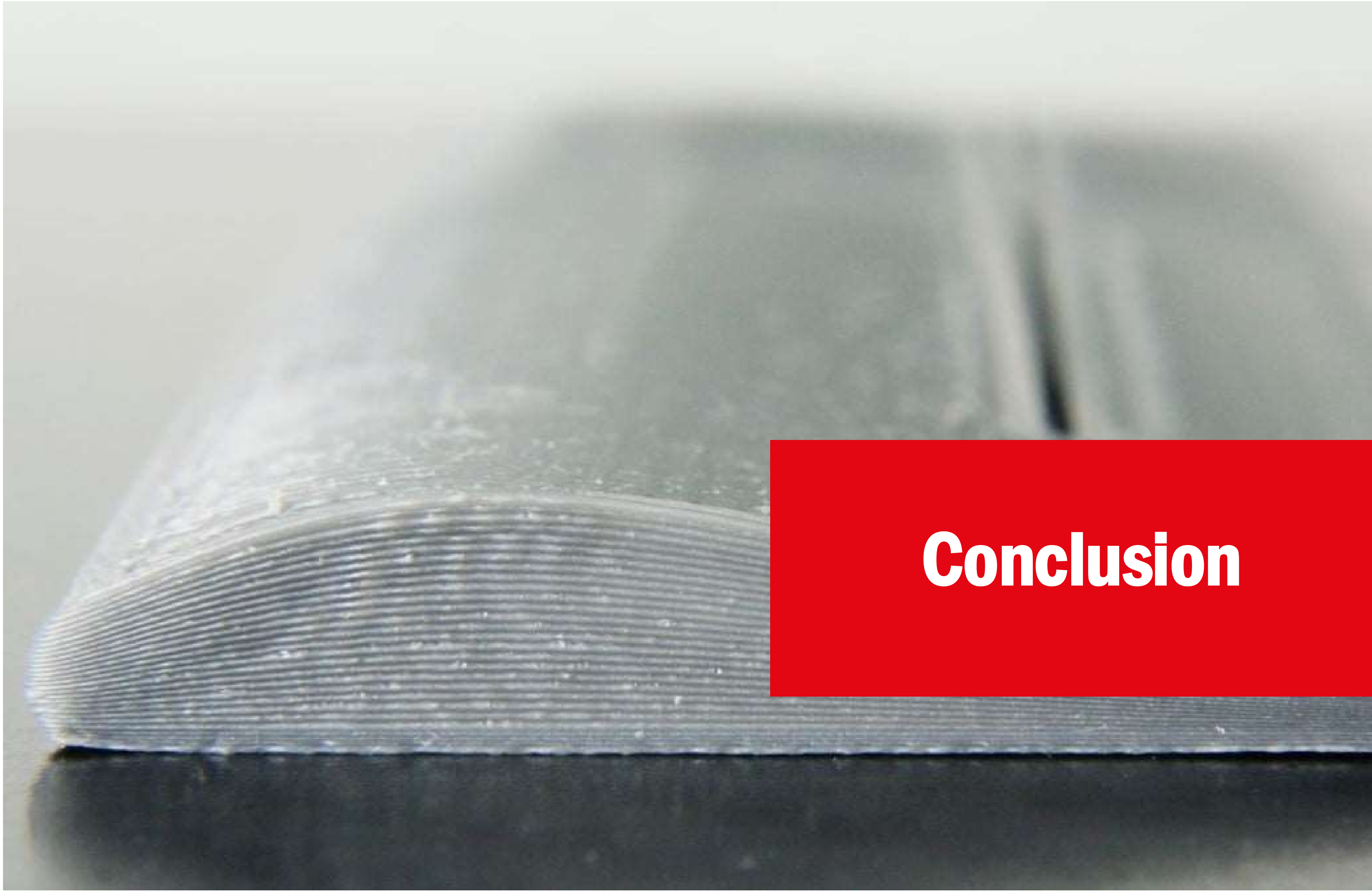
Speaker: Luciano Calcoen

Current status of NPAM - Applications

- Significant advances and some industries are incorporating NPAM
- Not yet widely implemented or commercialized
  - High costs: hardware and software
  - Lack of standardized processes (slicing algorithms are developed for specific applications)
- NPAM has great potential:
  - Aerospace: lightweight geometries
  - Biomedicine: personalized implants
  - Automotive: engine parts
  - Renewable energy: complex geometries
  - Tooling and molds: improved surface finish



Speaker: Luciano Calcoen



Conclusion

EPFL

Conclusion

Advantages of NPAM

- Overcomes PAM **Limitations**:
  - Reduces **anisotropy**
  - - **support structures**
  - - **staircase effects**.
- Enhanced **Mechanical Integrity**
- Improved **Surface Quality**
- Applicable to **aerospace**, **automotive**, and **biomedical engineering**.

Challenges of NPAM

- **Nozzle Design**:
  - Requires dynamic orientations and **thermal stability**.
- **Complex Trajectory Planning**:
  - Multi-axis movements without **collision**.
- **Algorithm Robustness**:
  - Needs wider adaptability for diverse **geometries** and **materials**.

Future Outlook

- Substantial improvements in mechanical performance, surface quality, and material efficiency.
- Focus on addressing technical challenges for wider adoption.

Thanks for listening!

Any questions?