Additive Manufacturing with Robots

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Desired Attributes of Manufacturing

- Offer features to deliver high performance
  - Geometric Complexity
  - Material Heterogeneity
- Low Cost
- Low Lead Time
- High Degree of Personalization
- Low Environmental Impact

Traditional Manufacturing: Observations

- Deliver low cost through custom tooling
  - Fast cycle times
  - Moderate complexity
  - High lead time
  - Lack of customization
- Achieve customization through general purpose tools
  - Moderate lead time
  - Moderate complexity
  - Slow cycle times
  - High cost

Injection Molding

Die Casting

Sheet Metal Fabrication

Machining

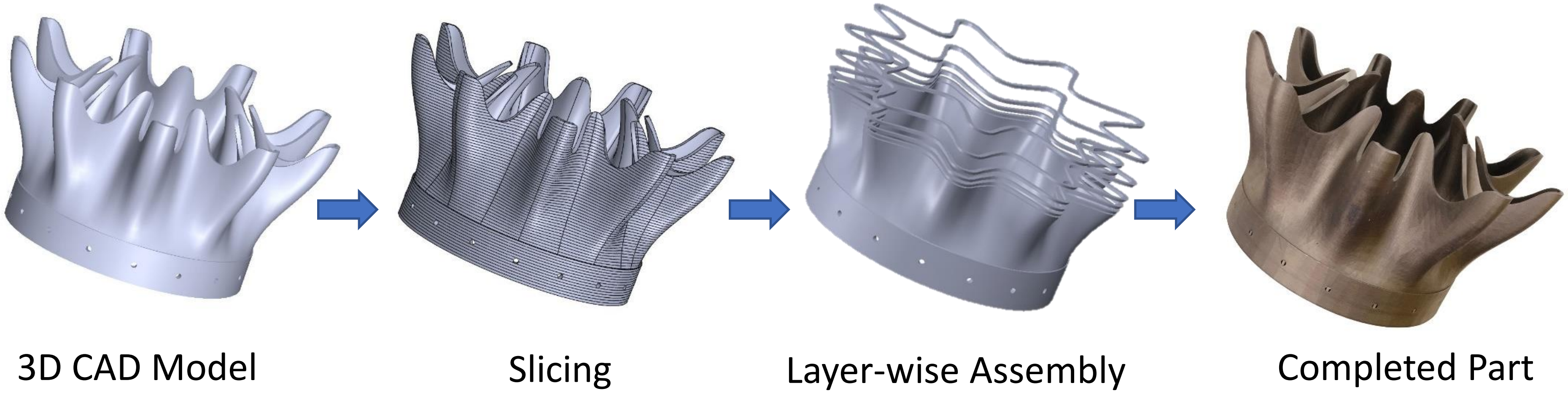
Traditional Manufacturing Vs. Nature

https://www.calmoto.com/bmw-motorcycles-for-sale-san-jose-san-francisco-ca--xAllInventory?make=bmw#page=xAllInventory&make=bmw

https://www.theplaidhorse.com/2020/08/31/types-of-horses-used-in-education/

What is Additive Manufacturing?

- Use of digital 3D design model to automatically build a component by depositing material(s) in layers
  - No part specific tooling
  - New geometry possibilities



Additive Manufacturing Benefits

- Ability to realize shapes that are not possible using traditional manufacturing
- Shape complexity without cost penalty
- Customization without cost penalty
- Elimination of post fabrication assembly operations

(Image Source: http://www.michaelschmidtstudios.com/dita-von-teese.html)

(Image Source: UCS Center for Advanced Manufacturing)

(Image Source: https://audicus.com/hearing-aids-3d-printing/)

(Herringbone Gear bearing)

(Image Source https://gereports.ca/slideshow/look-ahead-master-class-advanced-aviation/)

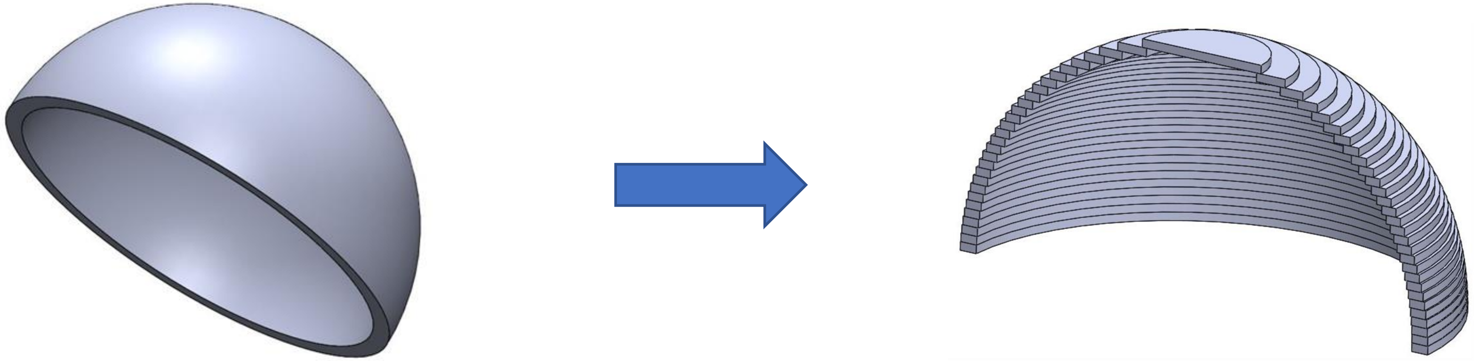
Traditional Additive Manufacturing Limitation

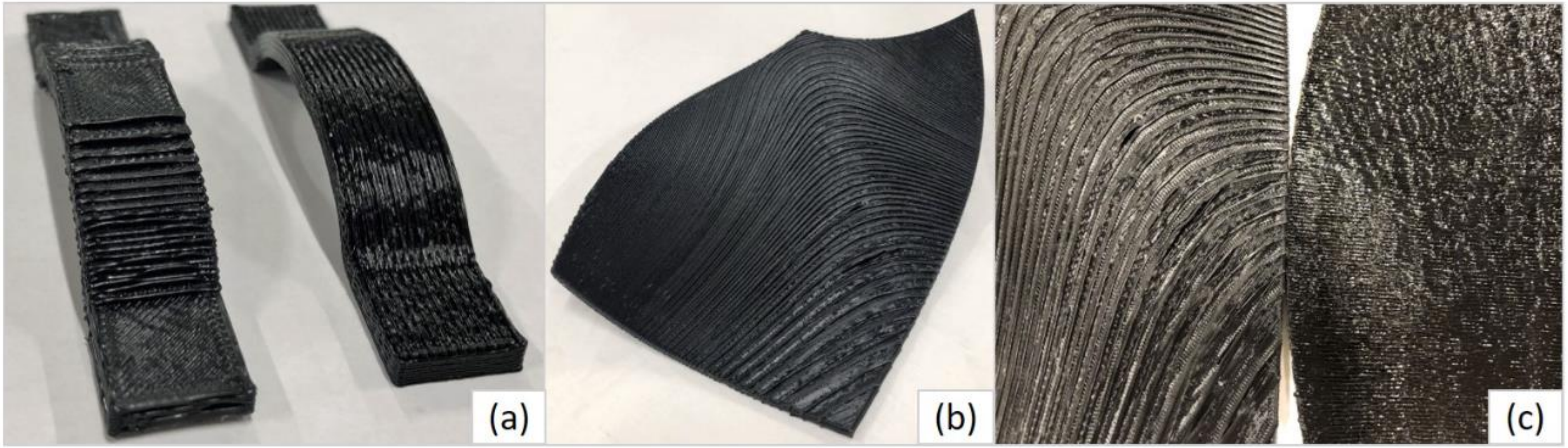
Build time 35 hours due to use of very thin layers!

80% time to build support structure

Most additive manufacturing processes have long build times

Traditional Additive Manufacturing Limitation

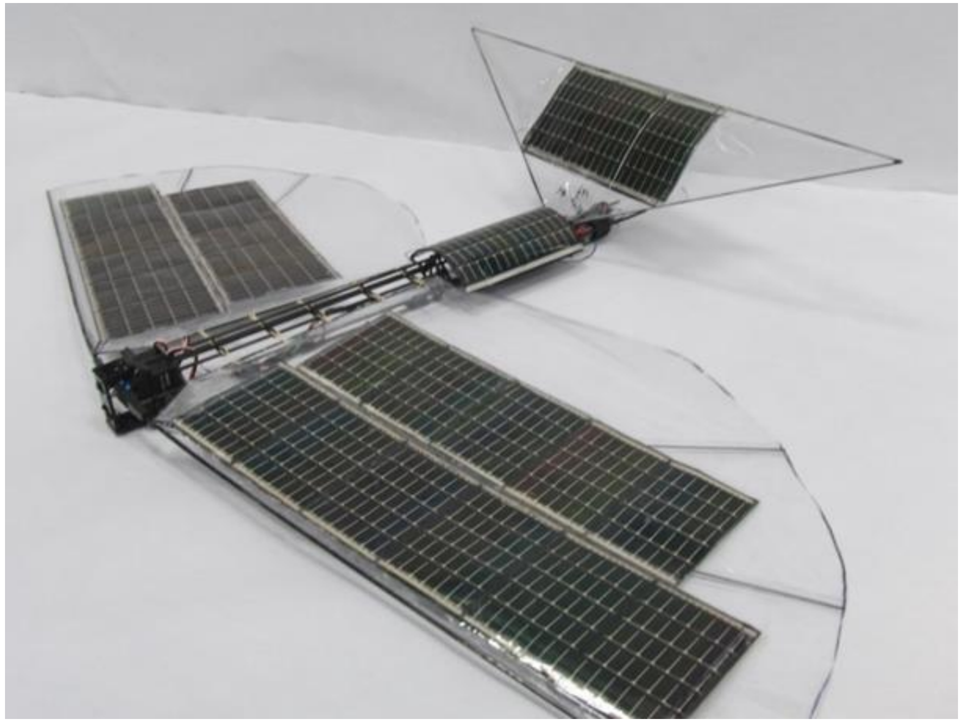




(a) Surface Finish Comparison for Specimen A
(b) Specimen C Printed by 3D Printer using Planar Layered Method
(c) Enlarged Pictures of Specimen C Printed by Planar Printing (Left) and Non-Planar Printing (Right)

Parts do not have the desired mechanical properties

Traditional Additive Manufacturing Limitation



Not possible to 3D print functional components with micro/nano scale features

Traditional Additive Manufacturing Limitation

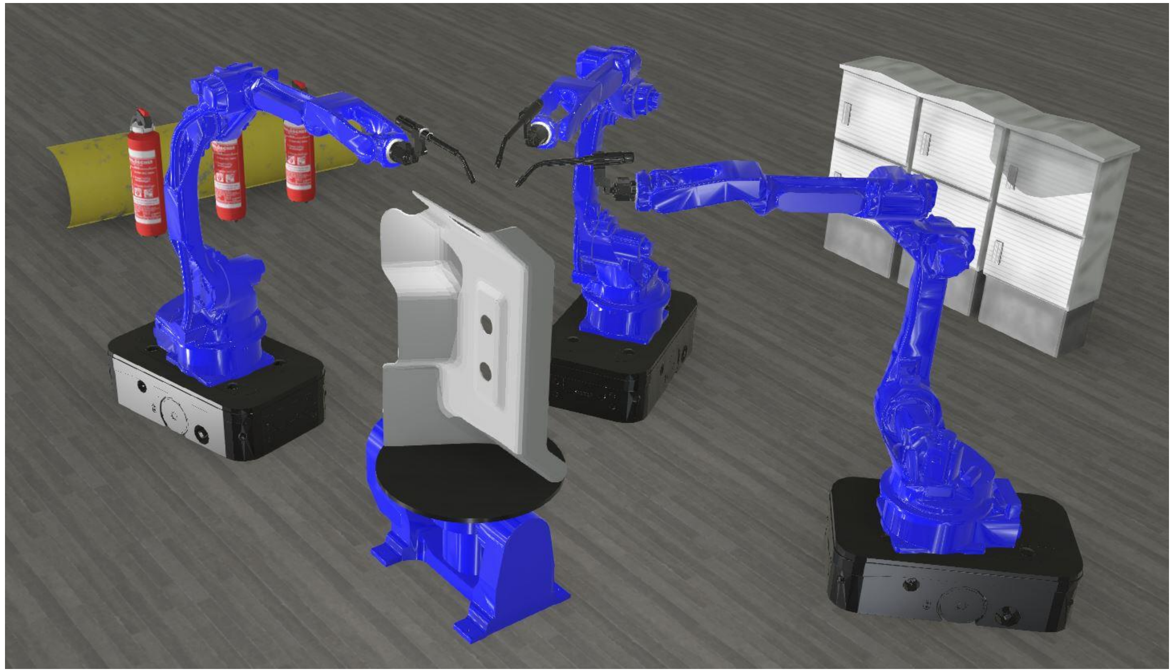
0.1 X

100 X

Need huge machines to build large parts!

Vision

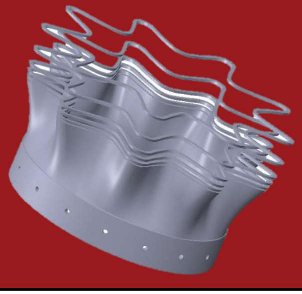
- Realize a flexible additive manufacturing process by using a team of robots
  - Utilize non-planar layers
  - Print large parts
  - New sensing technologies enable in-situ monitoring and control
- Cell will support
  - Material deposition
  - Placement of prefabricated components
  - Post-processing



Focus of Our Research

Artificial Intelligence

Robotics



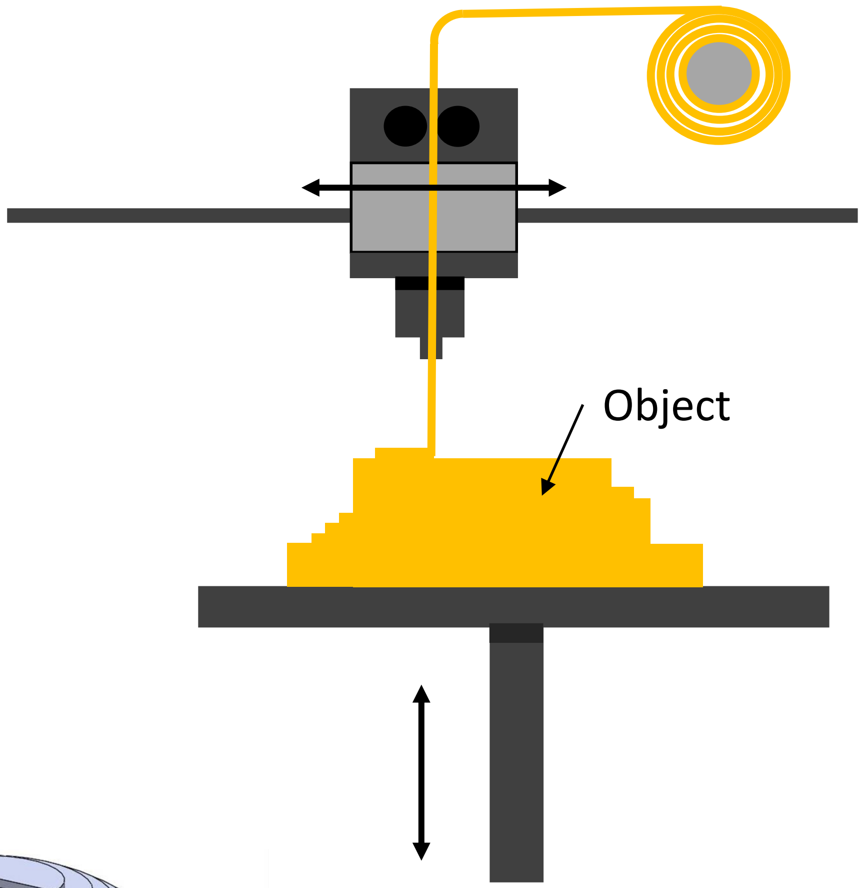
Additive Manufacturing

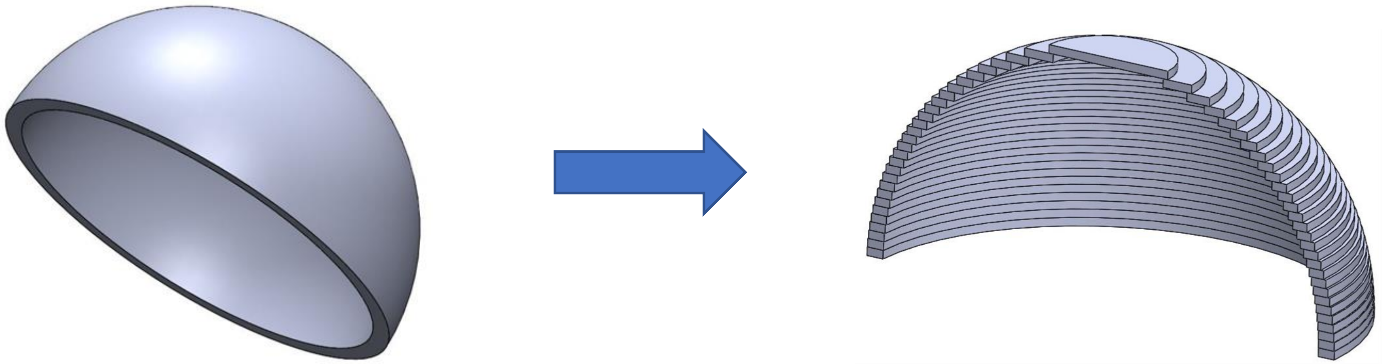
P.M. Bhatt, R.K. Malhan, A.V. Shembekar, Y.J. Yoon, and S.K. Gupta. Expanding capabilities of additive manufacturing through use of robotics technologies: A survey. *Additive Manufacturing*, 31:100933, January 2020.

Printing Using Conformal Layers

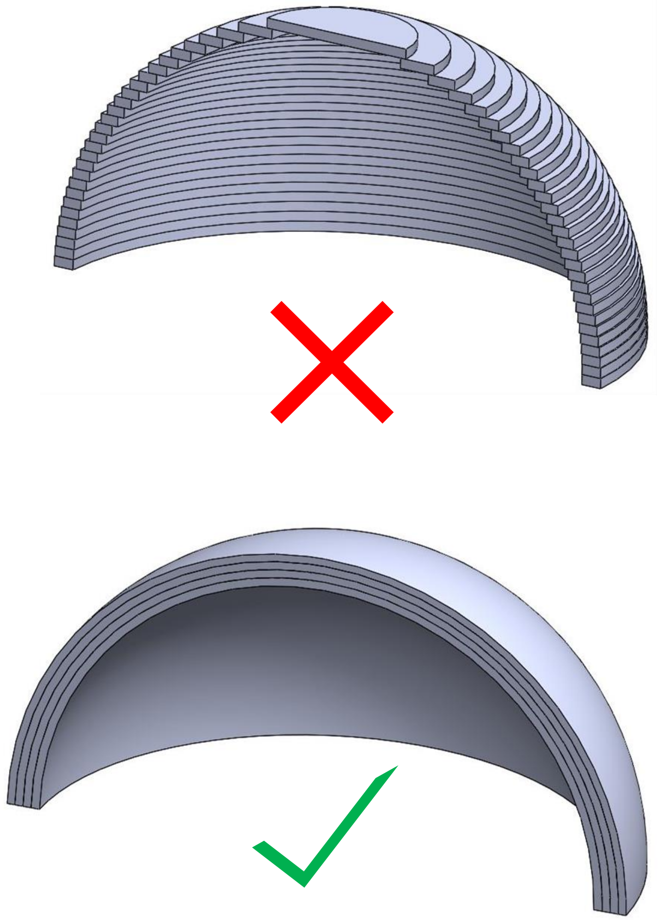
Limitations of Traditional AM

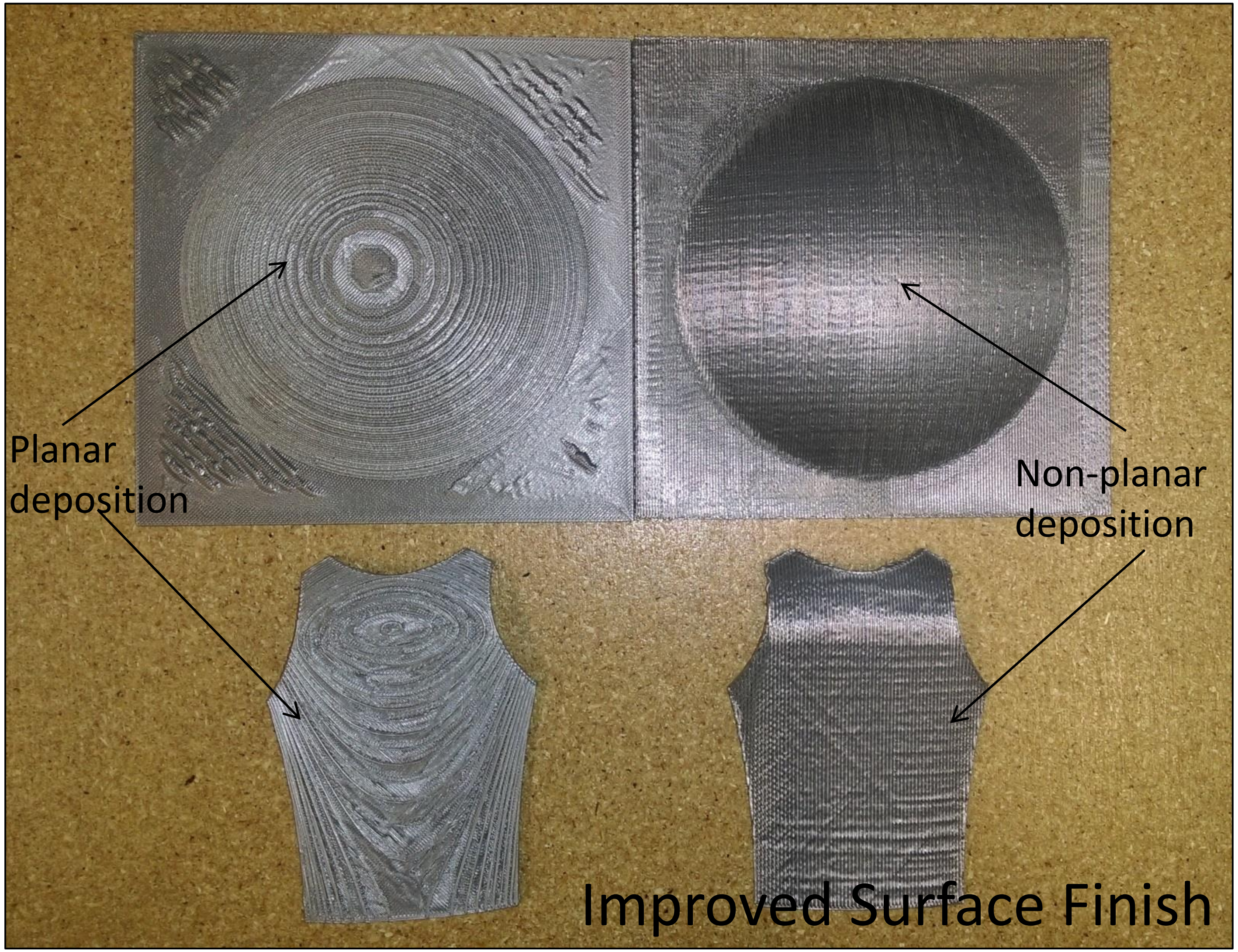
- Traditional material extrusion-based AM creates planar layers
- Planar layers can result in
  - Staircase effect
  - Poor surface quality
  - Limitation on part strength along a build direction
  - Difficult to print complex geometry





Benefits of Conformal AM

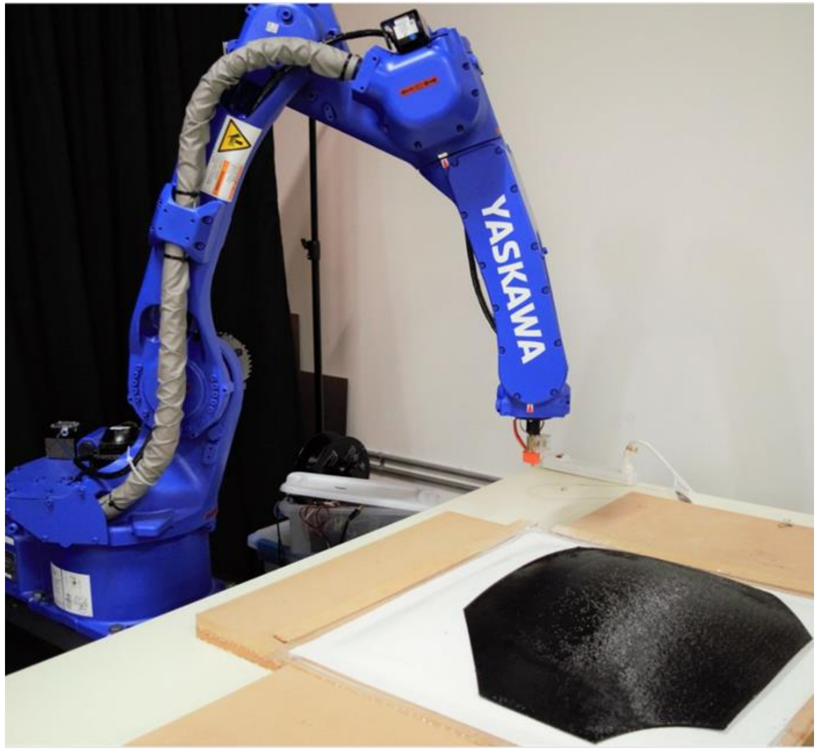




Conformal AM can improve mechanical properties and reduce inter-layer failures

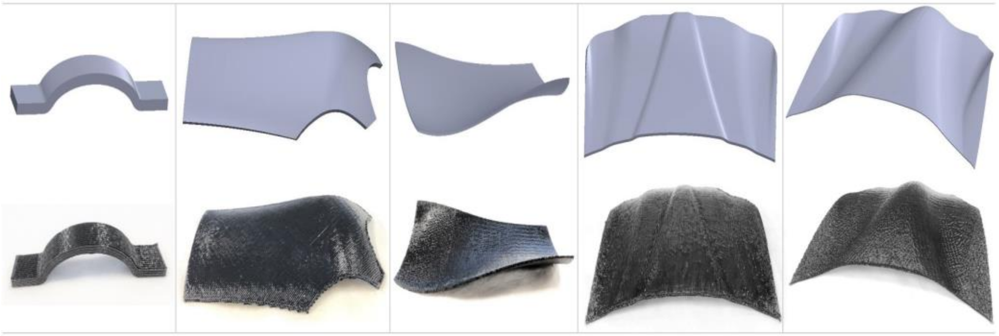
Conformal Layer Deposition

- Use 6DOF robot to perform conformal layer deposition
  - Minimize number of layers
  - Improve strength
  - Reduce support material
  - Enable use of continuous fibers in composite materials
- Requires complex trajectory planning and velocity regulation



Results

- Fabricated specimens of different sizes and shapes



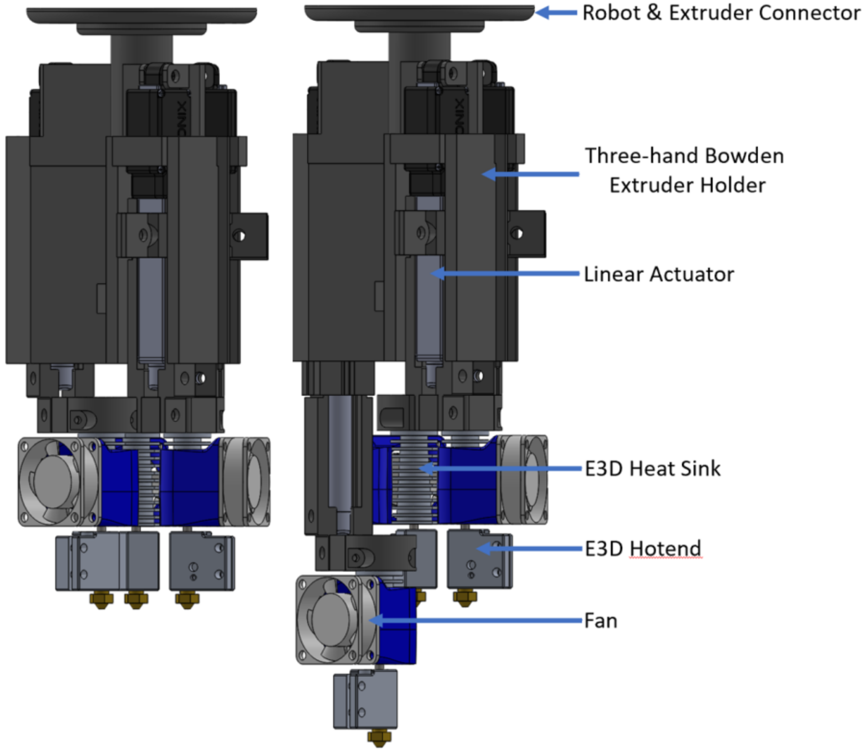
E

Specimen	Thickness(mm)	Number of layers	Weight(g)	Measured build time(min), Non-planar	Estimated build time(min), Planar
A	4	8	4.2	14	15
B	3	6	15.4	48	58
C	3	6	57.0	222	217
D	2.5	5	38.3	175	211
E	2	4	49.2	208	226

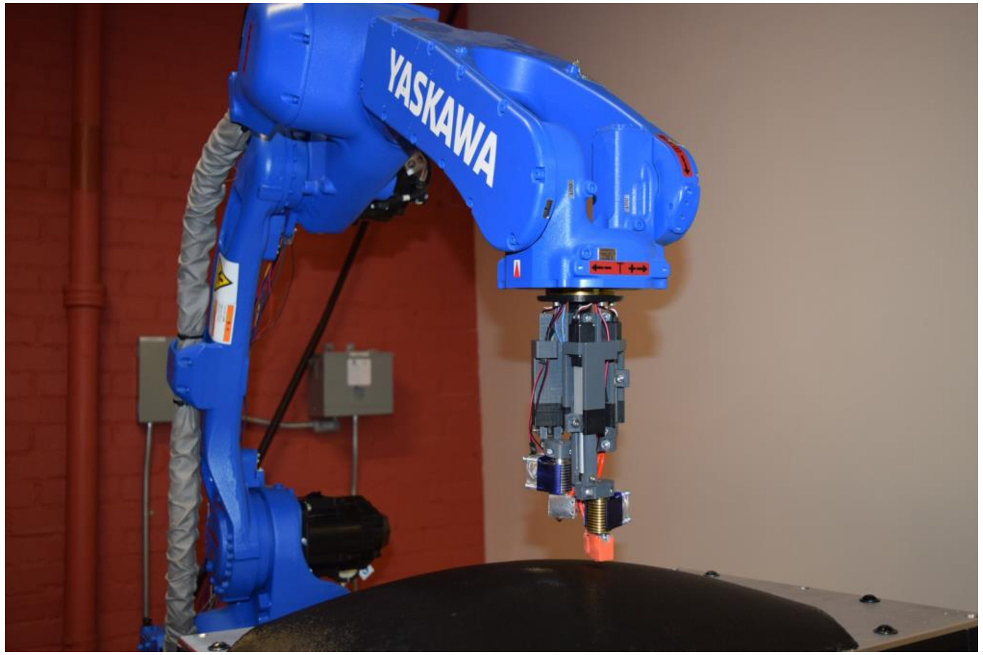
A. Alsharhan, T. Centea, and S.K. Gupta. Enhancing the mechanical properties of thin-walled structures using non-planar extrusion-based additive manufacturing. *ASME Manufacturing Science and Engineering Conference*, Los Angeles, CA, USA, June 2017.
A.V. Shembekar, Y. J. Yoon, A. Kanyuck and S.K. Gupta. Generating robot trajectories for conformal 3D printing using non-planar layers. *ASME Journal of Computing and Information Science in Engineering*, 19(3):031011, September 2019.

Multi-Material Printing

Three-nozzle Extrusion System

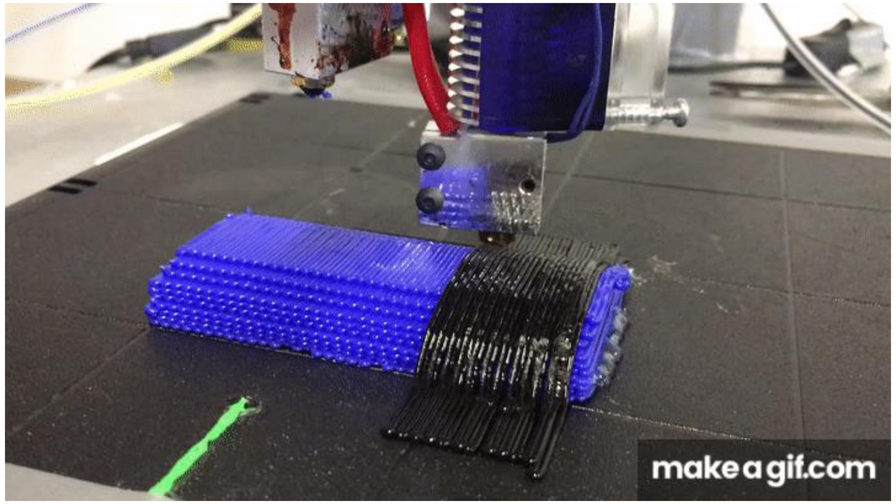


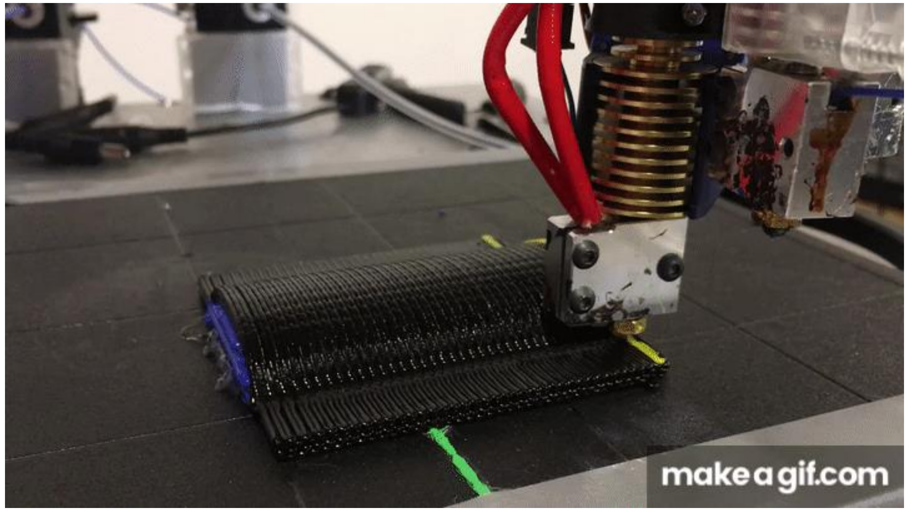
(Left) All linear actuators are at zero stroke
(Right) One linear actuator is at full stroke, two linear actuators are at zero stroke

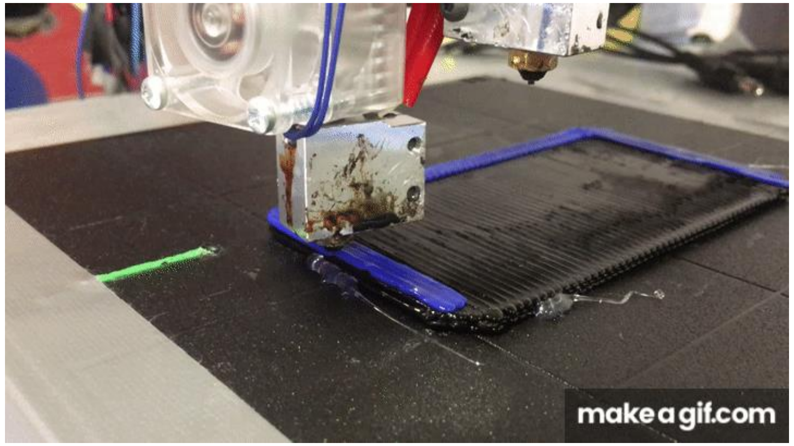


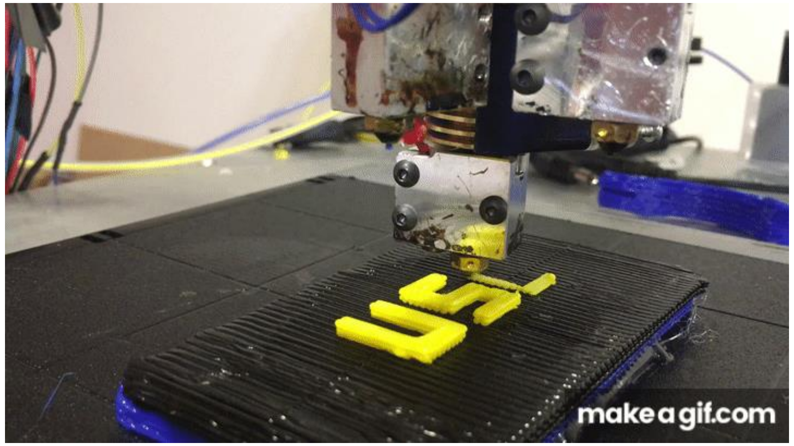
Three-nozzle extrusion system mounted on Yaskawa Robot

Example







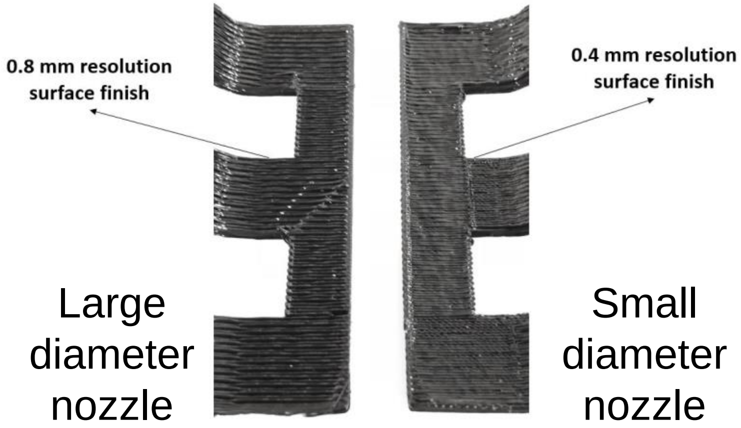


Y.J. Yoon, M. Yon, S.E. Jung, and S.K. Gupta. Development of three-nozzle extrusion system for conformal multi-resolution 3D printing with a robotic manipulator. *ASME Computers and Information in Engineering Conference*, Anaheim, CA, August 2019.

Multi-Resolution 3D Printing

Limitations of Fixed Resolution Printing

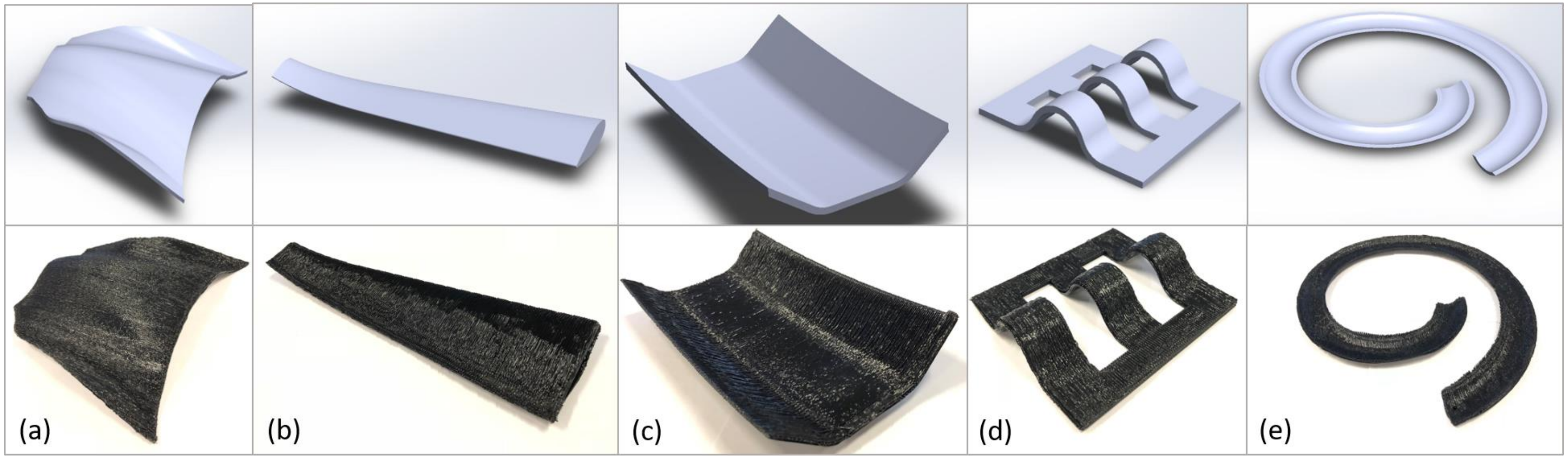
- Extrusion-based AM of large parts is challenging
  - Small diameter nozzle leads to good surface finish, but very long build times
  - Large diameter nozzle leads to fast build times but poor surface finish
- Traditional 3 DOF print head motion restricts the ability to orient fiber
- Poor alignment of the fibers compromises the structural integrity of the component

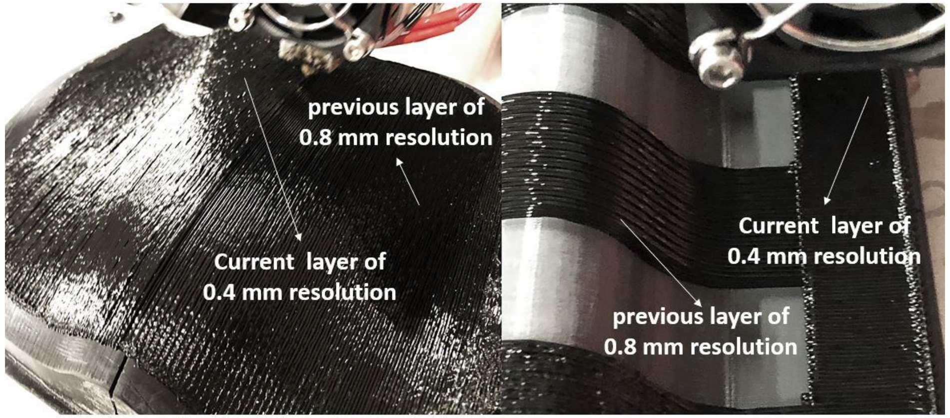


Non-planar Printing

Planar Printing

Two Robot Setup: Results



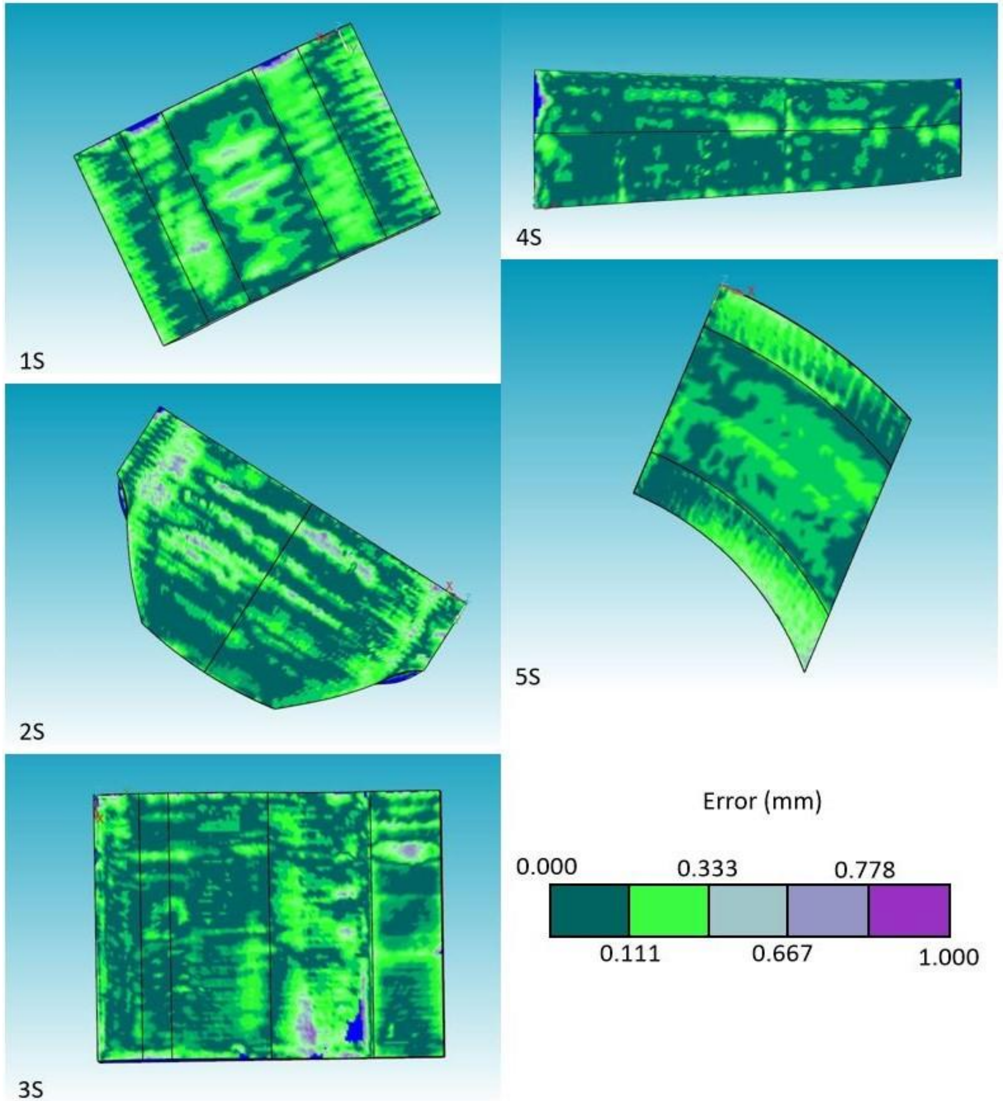


Part	Multi Resolution Printing Build time (in min)		
	0.4 mm nozzle	0.8 mm nozzle	0.4 / 0.8 mm nozzle
A	423	184	232
B	531	264	310
C	315	128	141
D	98	40	60
E	262	109	146

P.M. Bhatt, A.M. Kabir, R.K. Malhan, B.C. Shah, A. V. Shembekar, Y.J. Yoon, and S.K. Gupta. A robotic cell for multi-resolution additive manufacturing. *IEEE International Conference on Robotics and Automation*, Montreal, Canada, May 2019.

Single Robot Setup for Multi Resolution AM: Results

Slicing	Resolution	Build Time (hh:mm)		
		Part 1	Part 2	
Conformal	Constant	02:16	01:42	
	Multi	00:56	00:39	
	Reduction (%)	59.4	62.5	
		Part 3	Part 4	Part 5
Hybrid	Constant	04:59	02:34	02:38
	Multi	01:51	01:17	01:00
	Reduction (%)	62.8	50.0	62.2

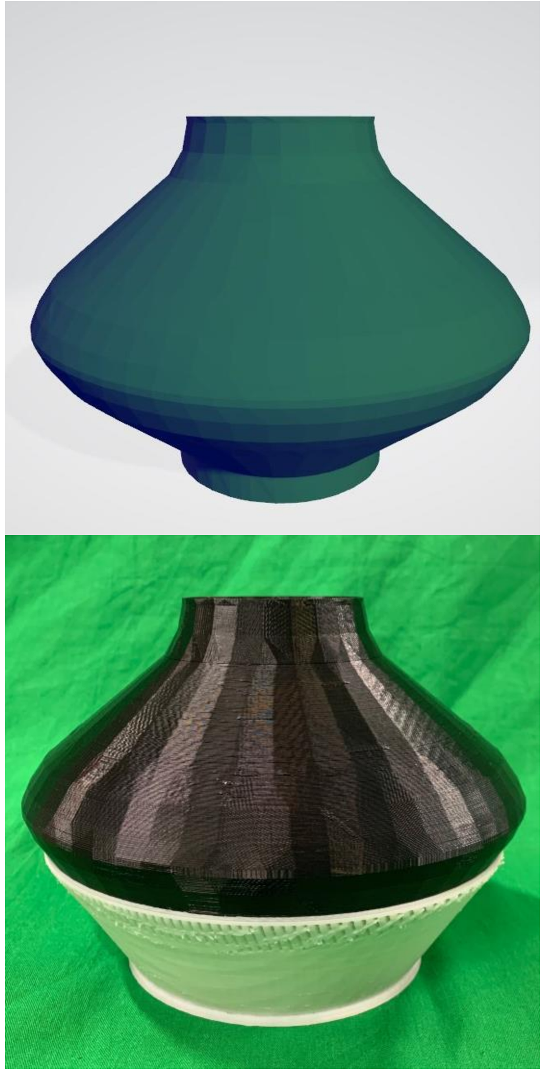


P. M. Bhatt, A. Kulkarni, R.K. Malhan, B.C. Shah, Y.J. Yoon, and S.K. Gupta. Automated planning for robotic multi-resolution additive manufacturing. *ASME Journal of Computing and Information Science in Engineering*, Accepted for publication.

Supportless Additive Manufacturing

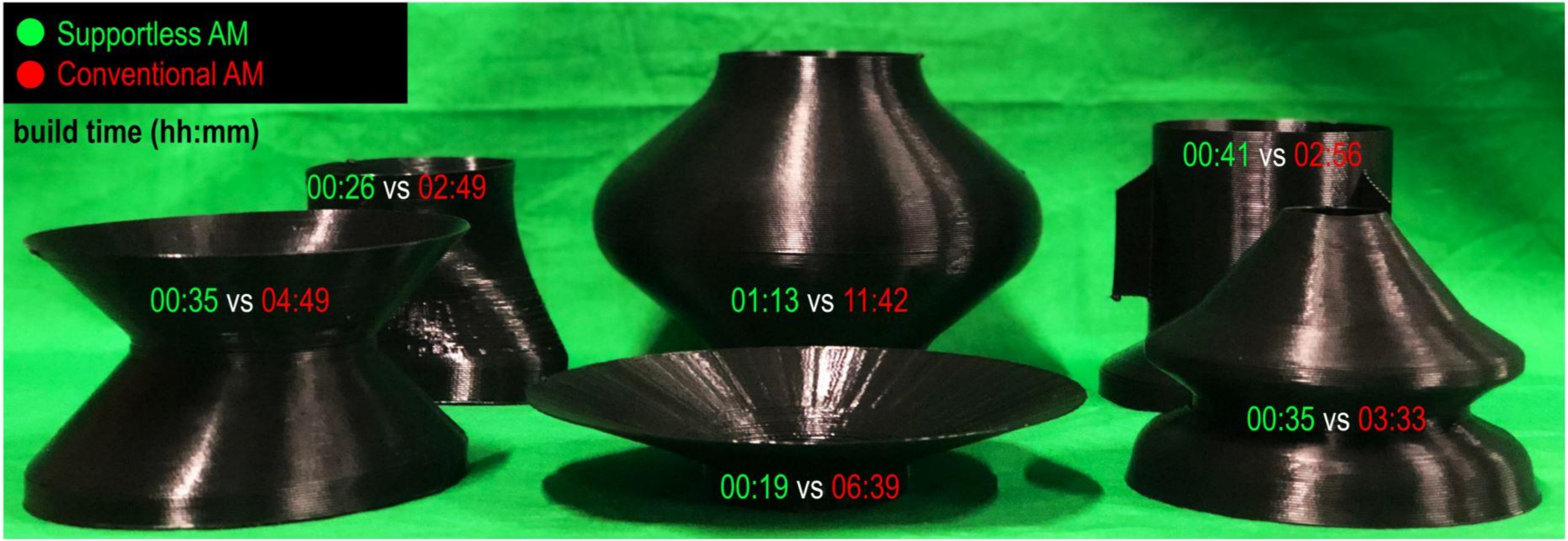
Motivation

- Standard 3-DOF material extrusion-based AM processes are not capable of printing at angles less than 45º without support structures
- Use of support structures leads to
  - Difficulty in removing support
  - Poor surface quality at steep slopes
  - Not suitable for hollow parts
  - High build time
  - Material wastage



CAD model vs the built part with support structures

Results: Build Time

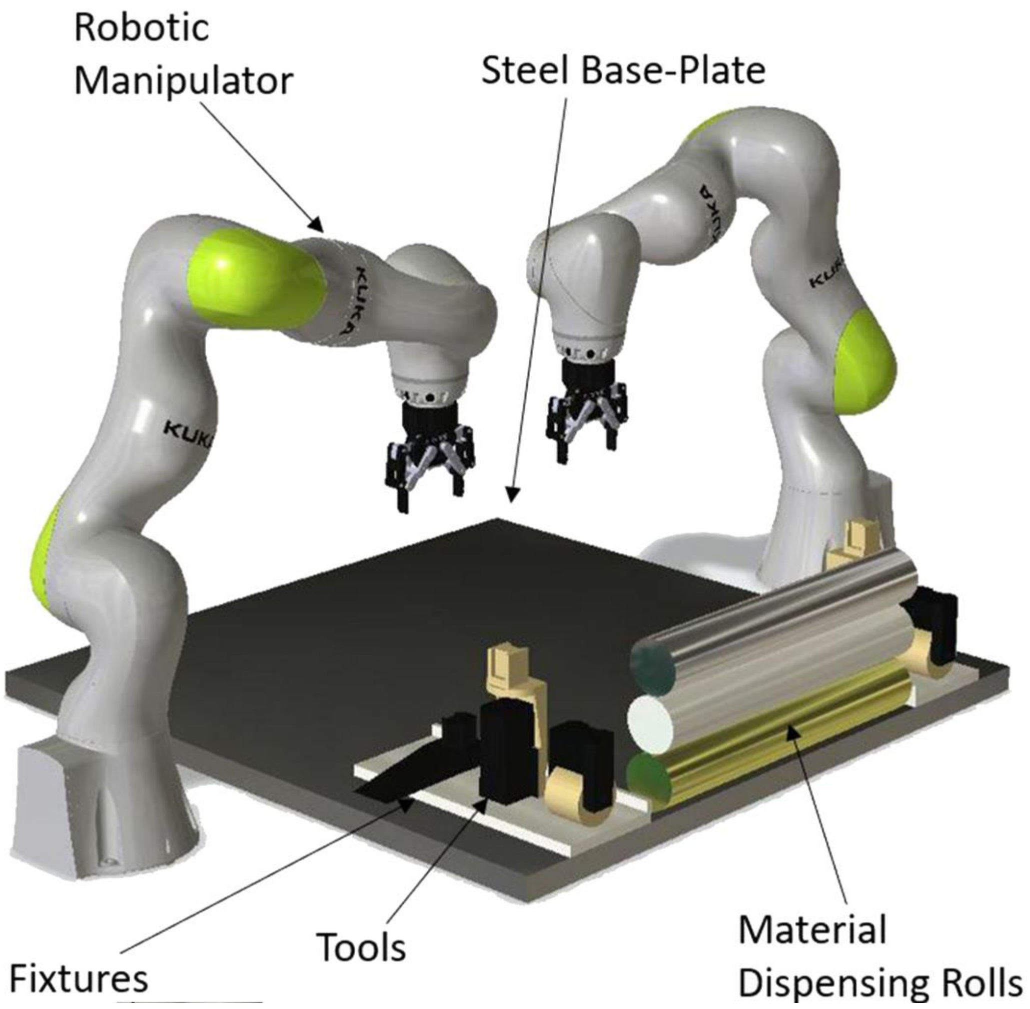


Build time comparison of conventional AM vs our supportless AM setup

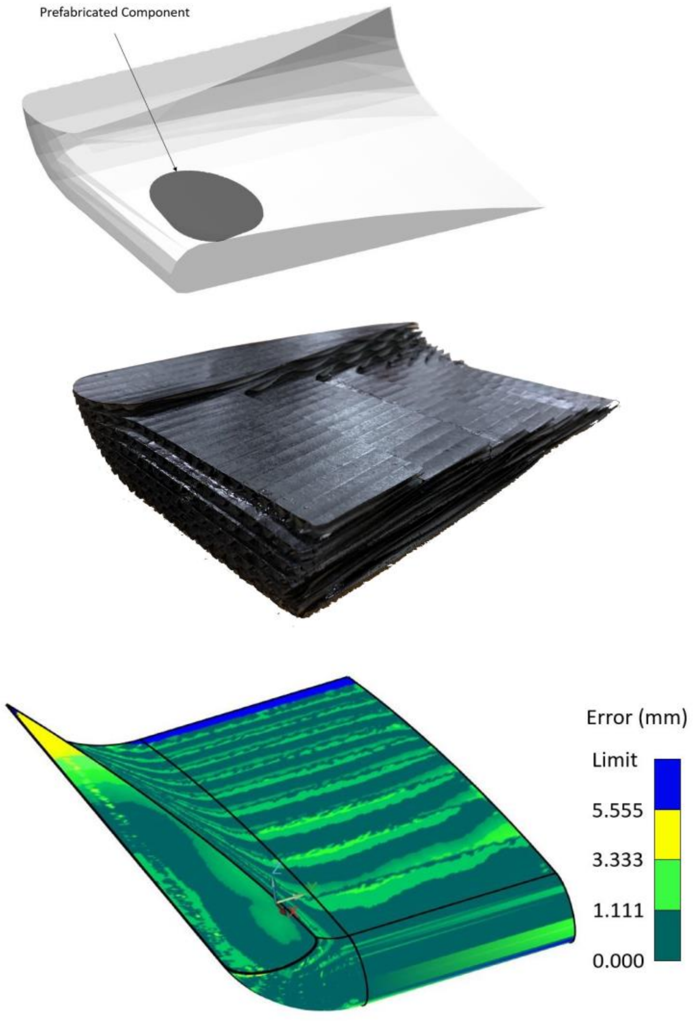
P.M. Bhatt, R.K. Malhan, P. Rajendran, and S.K. Gupta. Building free-form thin shell parts using supportless extrusion-based additive manufacturing. *Additive Manufacturing*, 32:101003, March 2020.

Fabricating Thin Composite Structures Using Sheet Lamination

- Modified existing sheet lamination AM to built thin structures
  - Enables embedding of prefabricated components between layers
  - Uses heterogenous material sheet for different layers
- Developed algorithms for CAD slicing, assembly instruction generation, trajectory generation, and task sequencing to build the parts



Results

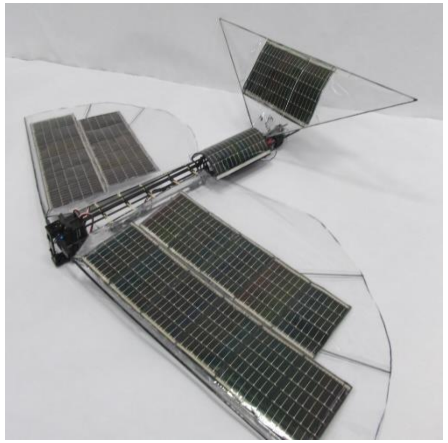


P. M. Bhatt, A.M. Kabir, M. Peralta, H.A. Bruck, and S.K. Gupta. A robotic cell for performing sheet lamination-based additive manufacturing. *Additive Manufacturing*, 27: 278-289, May 2019.

Embedding Prefabricated Components

- Use a robot to place externally fabricated component during deposition
- Integrates assembly and AM
  - Generate plan for picking and placing components
  - Generate deposition paths to ensure that the deposition tool does not collide with the component placed during AM

R2G2



Robo Raven

Sci-Fi Bot

Y.J. Yoon, A.V. Shembekar, O.G. Almeida, and S.K. Gupta. A robotic cell for embedding prefabricated components in extrusion-based additive manufacturing. *ASME Manufacturing Science and Engineering Conference*, Cincinnati, OH, June 2020.

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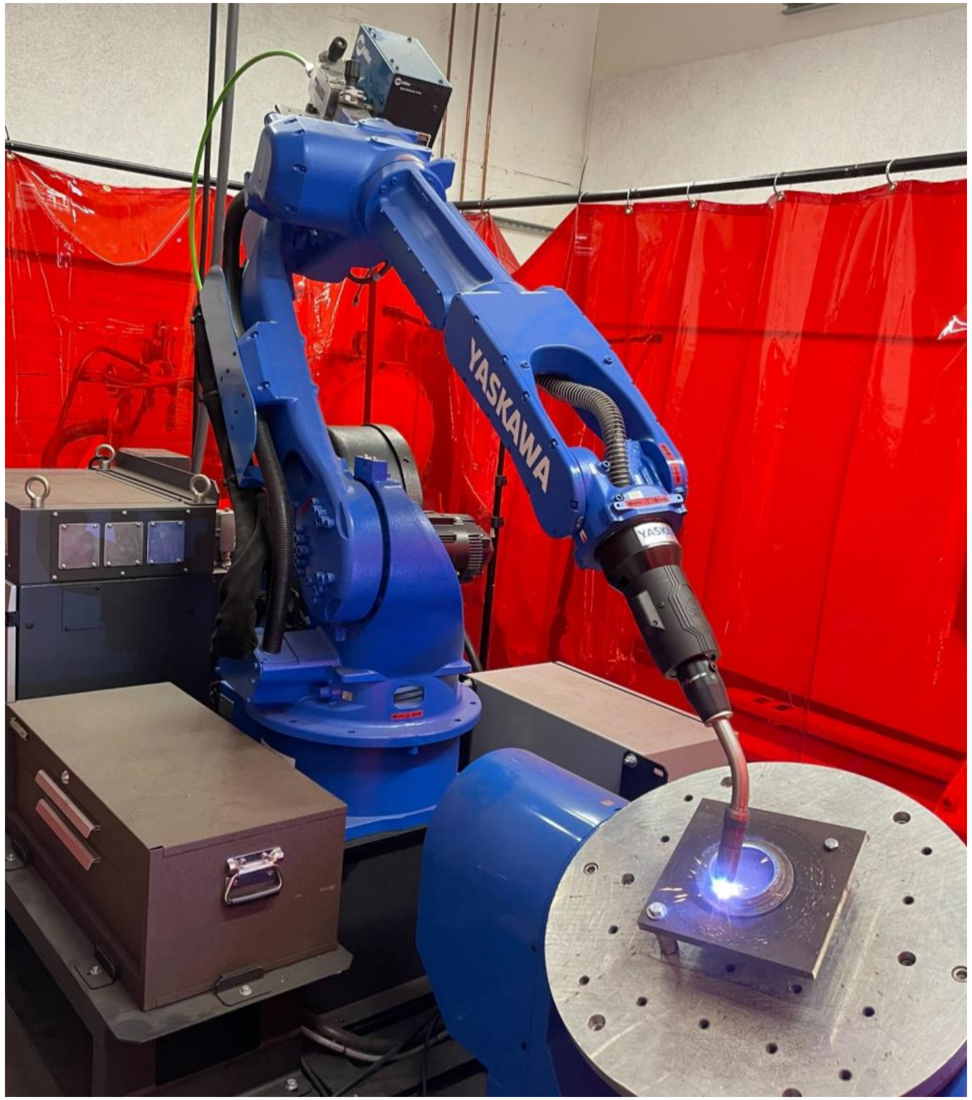
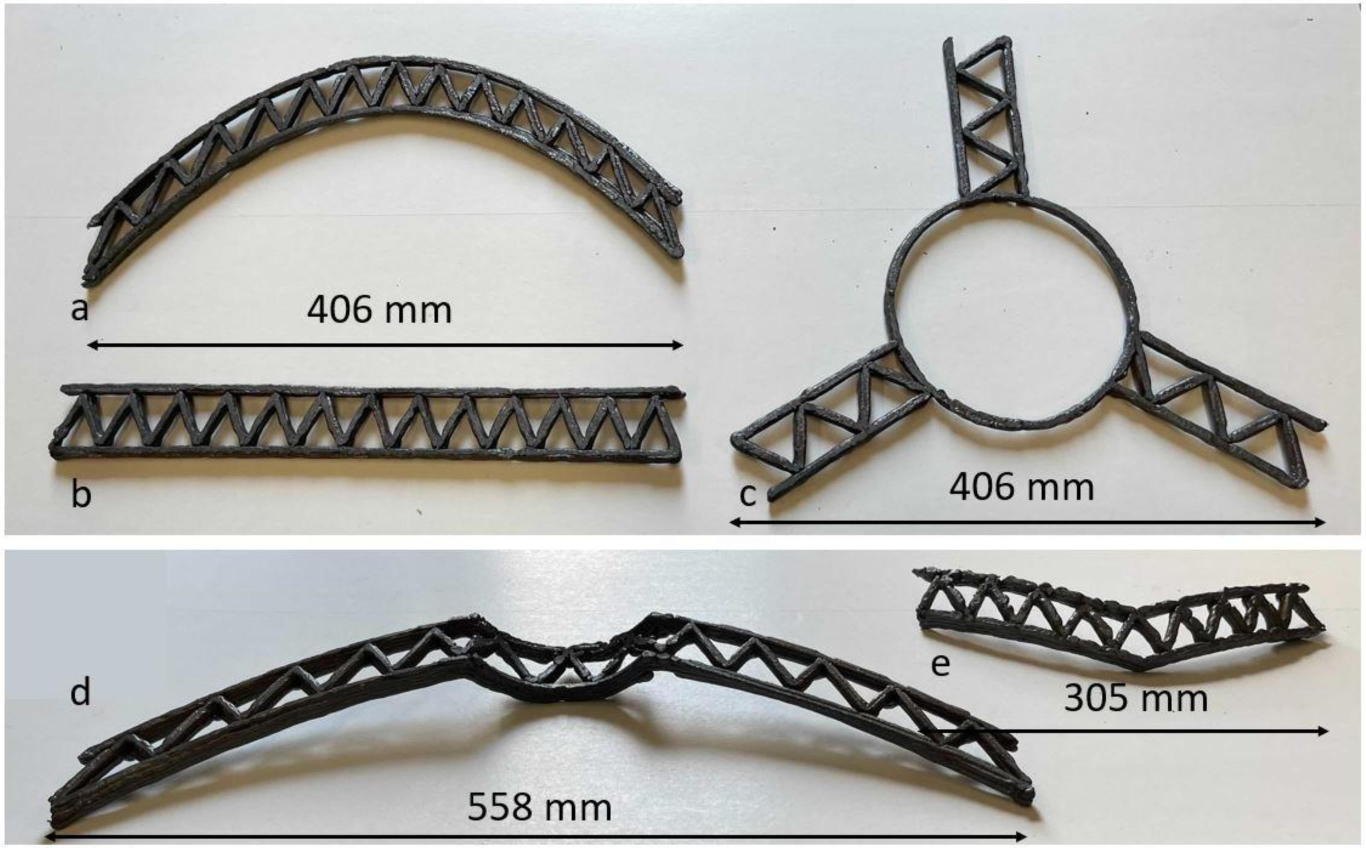
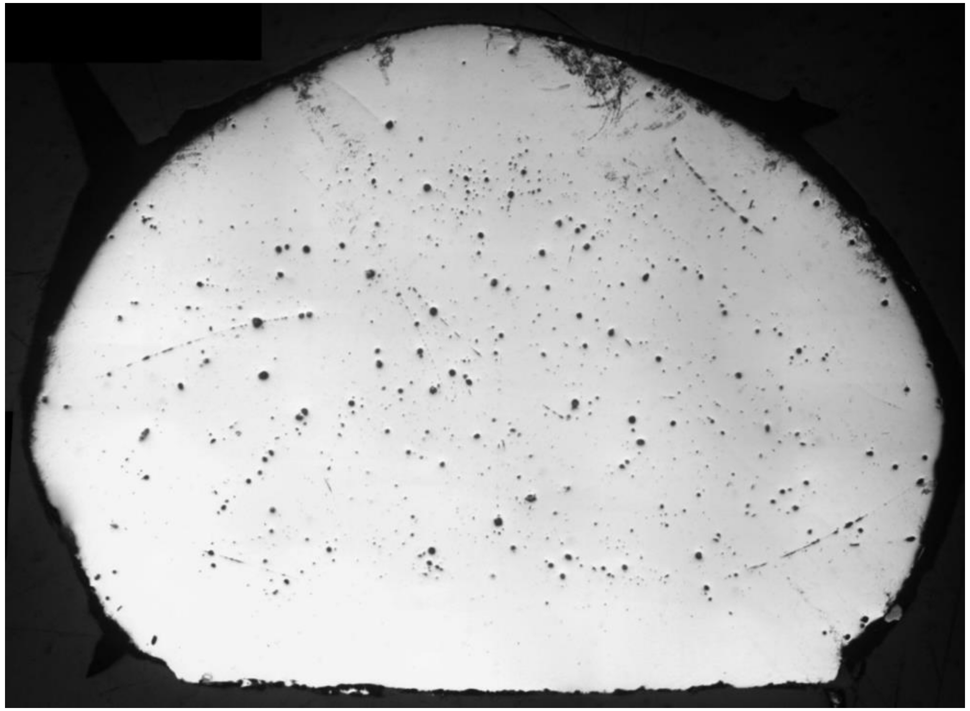
Conformal Wire Arc Additive Manufacturing



Results



Five parts build to showcase the capability of our experimental setup and developed algorithm
Part d and e has non-planar layers built using a conformal copper substrates



Polished cross-section of the built layer indicating a very low level of global porosity at 0.9%

P. M. Bhatt, A. Kulkarni, A. Kanyuck, R. K. Malhan, L. S. Santos, S. Thakar, H. A. Bruck, and Satyandra K. Gupta. Automated process planning for conformal wire arc additive manufacturing. *International Journal of Advanced Manufacturing Technology*, Accepted for Publication.

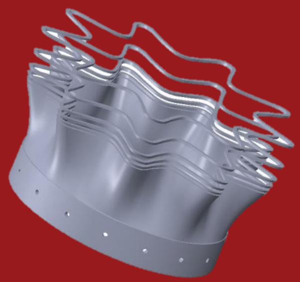
How Use of Robots Improves Additive Manufacturing?

- Improved mechanical properties due to conformal layers
- Reduction in build time due to supportless deposition and multi-resolution printing
- Insertion of prefabricated components to eliminate assembly operations
- Enabling more material choices in multi-material printing

Key Advancements

Artificial Intelligence

Robotics



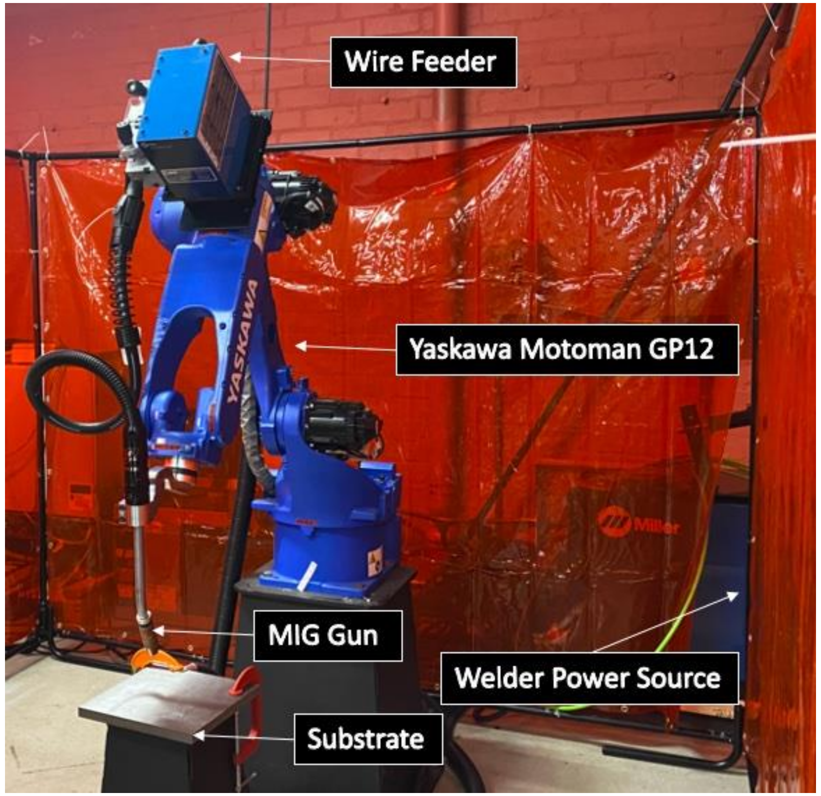
Additive Manufacturing

- Path constrained trajectory planning for high degree of freedom manipulators
- Learning of optimal process parameters
- Part placement planning to improve build accuracy
- Trajectory compensation to improve trajectory execution accuracy
- Multi-robot collaboration

Learning of Process Parameters

Motivation

- Process parameters govern task performance
- Physics-based models may not be available
- Need to quickly identify process parameters
  - Tool velocity
  - Tool inclination
  - Tool distance
  - Wire speed



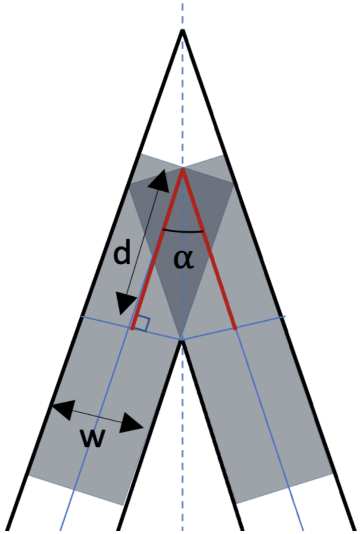
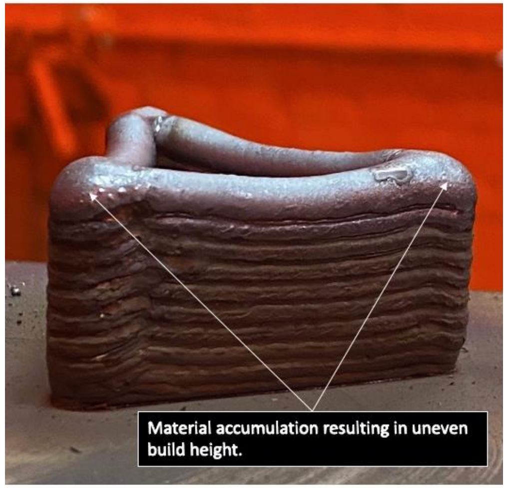


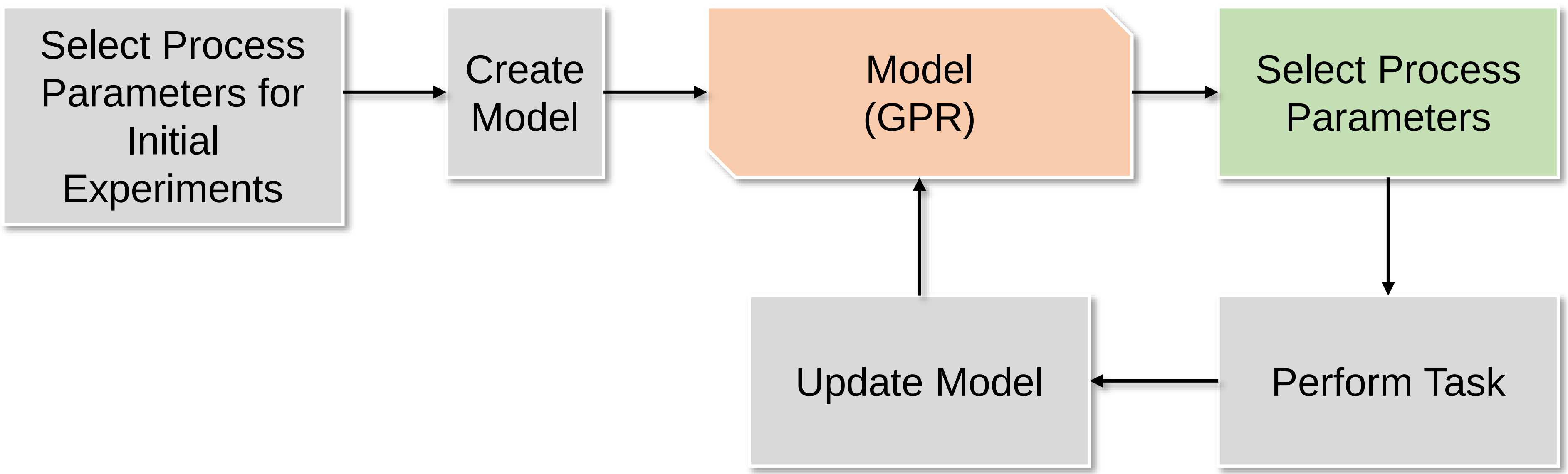
Illustration of bead overlap region; w is bead width; d is overlap length; α is corner angle



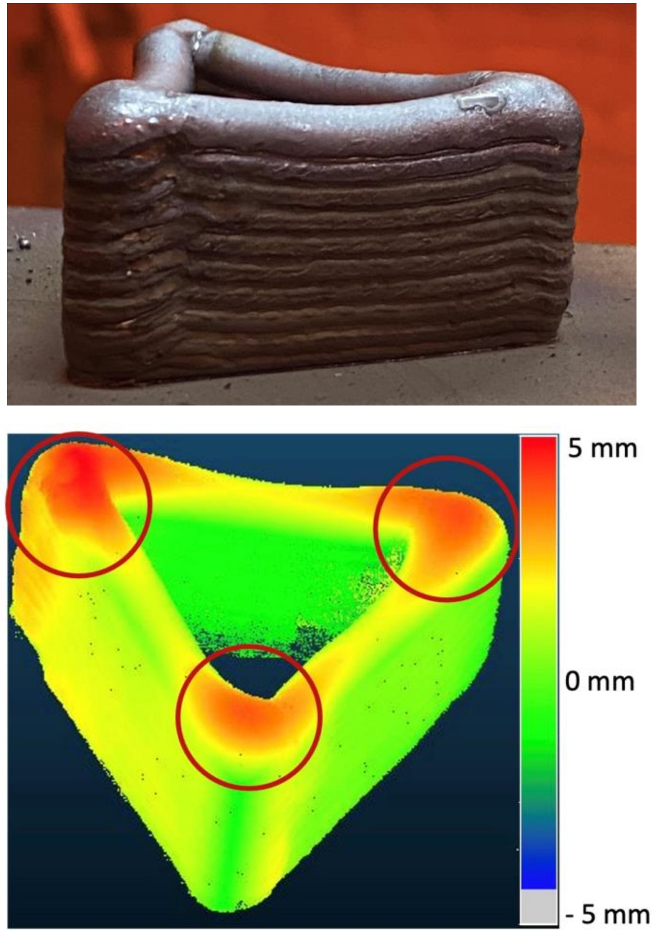
Part with uneven layer height

Overview of Approach

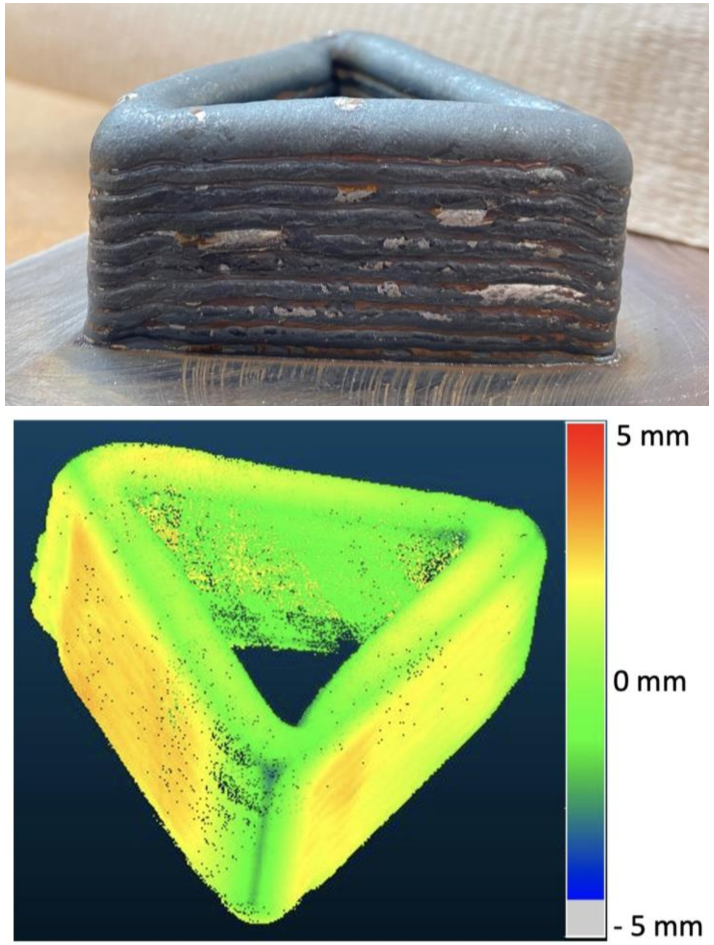
- Aim to achieve the right balance between exploration and exploitation
- Select process parameters for exploratory experiment(s)
- Update meta models for constraint satisfaction prediction after each experiment
- Reduce prediction uncertainty by conducting additional experiments



Results



Built part and scan without leaning parameters



Built part and scan after leaning parameters

A. Kulkarni, P.M. Bhatt, A. Kanyuck, and S.K. Gupta. Using unsupervised learning for regulating deposition speed during robotic wire arc additive manufacturing. *ASME Computers and Information in Engineering Conference,* August 2021.

Optimizing Part Placement for Improving Accuracy

Experimental Results

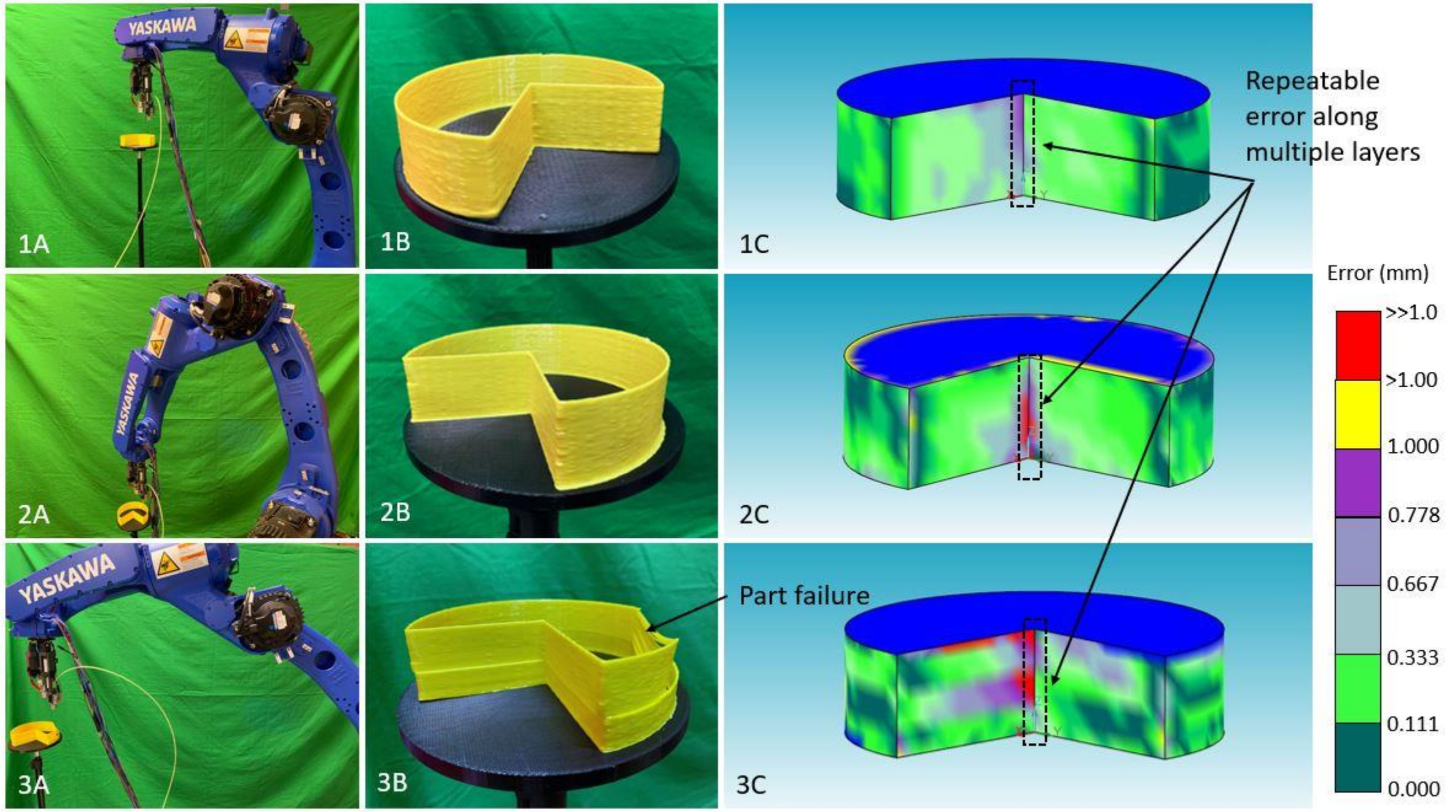
- Theoretical error calculated using the modeled matches the trend of the experimental results

Theoretical error (mm)

0.37

0.37

0.46



Additive manufacturing of same part at three manipulator workspace locations indicated by 1, 2, and 3

P. M. Bhatt, A. Kulkarni, R. K. Malhan, and S. K. Gupta. Optimizing Part Placement for Improving Accuracy of Robot-Based Additive Manufacturing. *IEEE International Conference on Robotics and Automation*, Xi'an, China, May 2021.

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Simulation Results

Initial error: 0.66 mm
Optimized error: 0. 54 mm
Reduction in error: 18.2%

Initial error: 0.82 mm
Optimized error: 0.65 mm
Reduction in error: 20.7%

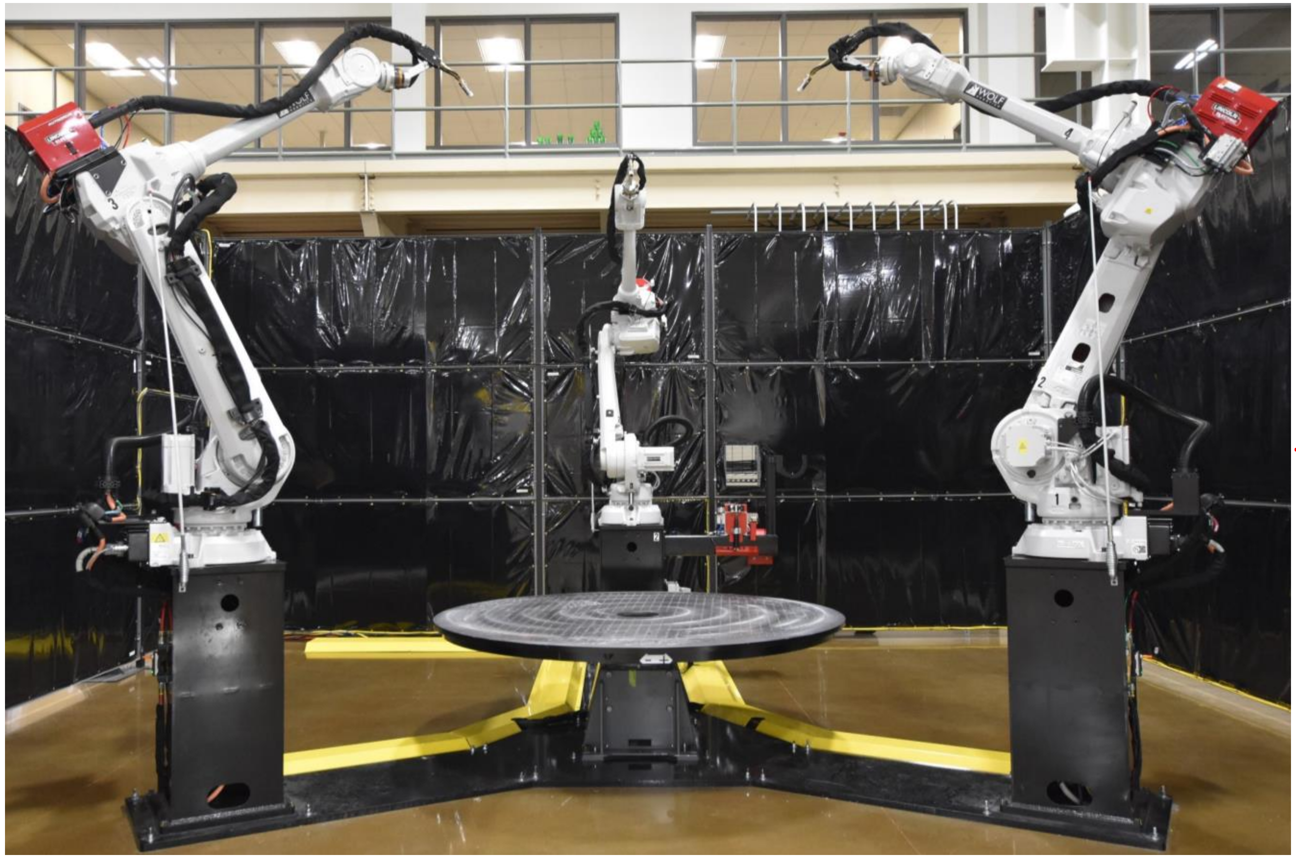
Initial error: 0.80 mm
Optimized error: 0.60 mm
Reduction in error: 25.0%

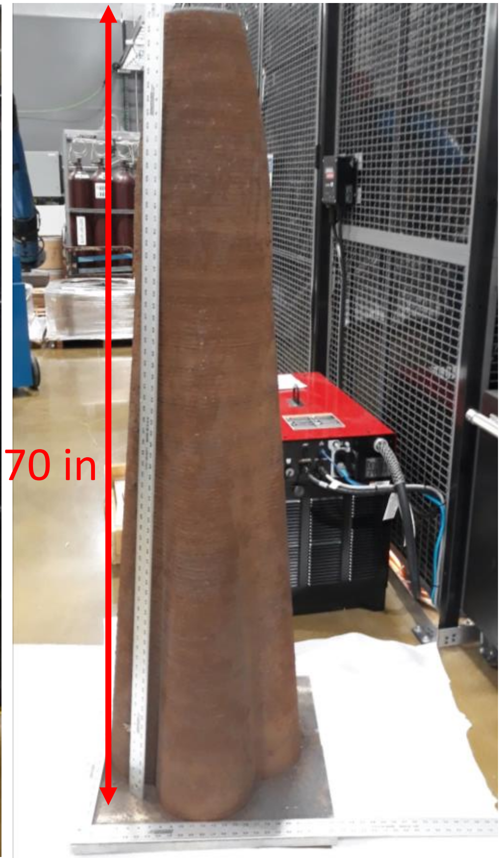
P. M. Bhatt, A. Kulkarni, R. K. Malhan, and S. K. Gupta. Optimizing Part Placement for Improving Accuracy of Robot-Based Additive Manufacturing. *IEEE International Conference on Robotics and Automation*, Xi'an, China, May 2021.

Multi-Robot Cells

Motivation

- Traditional powderbed AM process deposits material at few hundred grams an hour
- A single robot WAAM can provide 10 kg per hour build rate
- Three robot WAAM setup can provide 30 kg per hour build rate





The multi-robot cell developed at Oak Ridge National Laboratory and two large-scale WAAM parts built using the setup

Problem Statement

- Given a set of *n* manipulators, find the robot placement locations such that
  - The build time of part is reduced by decomposing the path segment
  - The manipulator has minimum Inverse Kinematics (IK) inconsistency in robot path

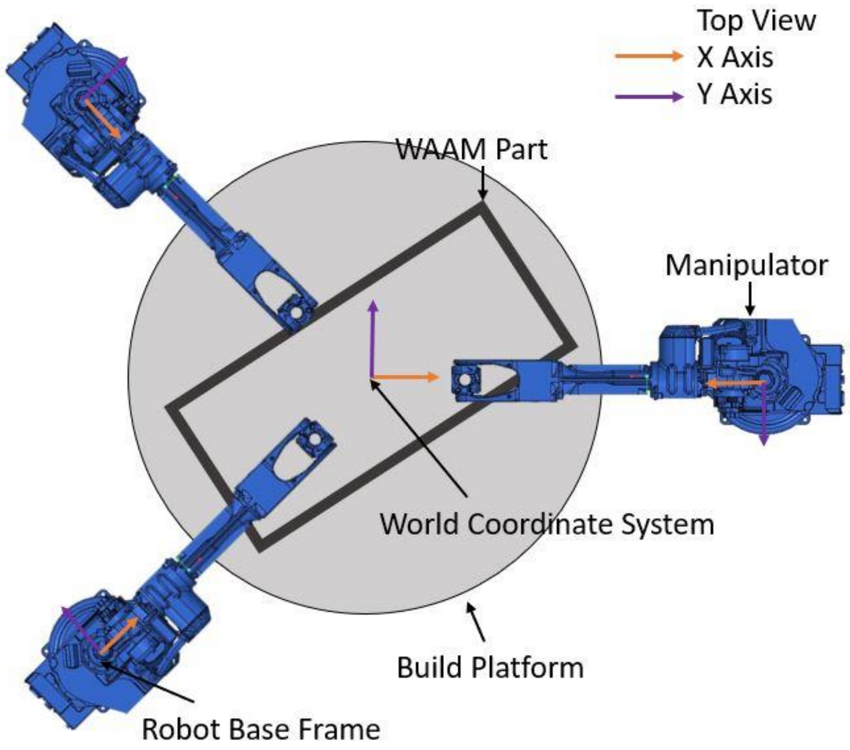


Illustration of a multi-robot cell to perform WAAM
The illustration shows the relative location of the WAAM part, build-platform, and the robot base frames in the word coordinate system.

Approach: Part Decomposition

- Planes are selected for decomposing the part due to their simple representation
  - $(cos\phi \cdot sin\theta) \cdot x + (sin\phi \cdot sin\theta) \cdot y + cos\theta \cdot z = 0$
- The minimization function reduces the build time by properly decomposing the part
  - $$\underset{\mathbf{u}}{\text{minimize}}\ \text{BT}(\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_n)\ \ s.t.$$
    $$\frac{\pi}{3} \leq \theta \leq \frac{2\pi}{3}$$
    $$0 \leq \phi \leq 2\pi$$

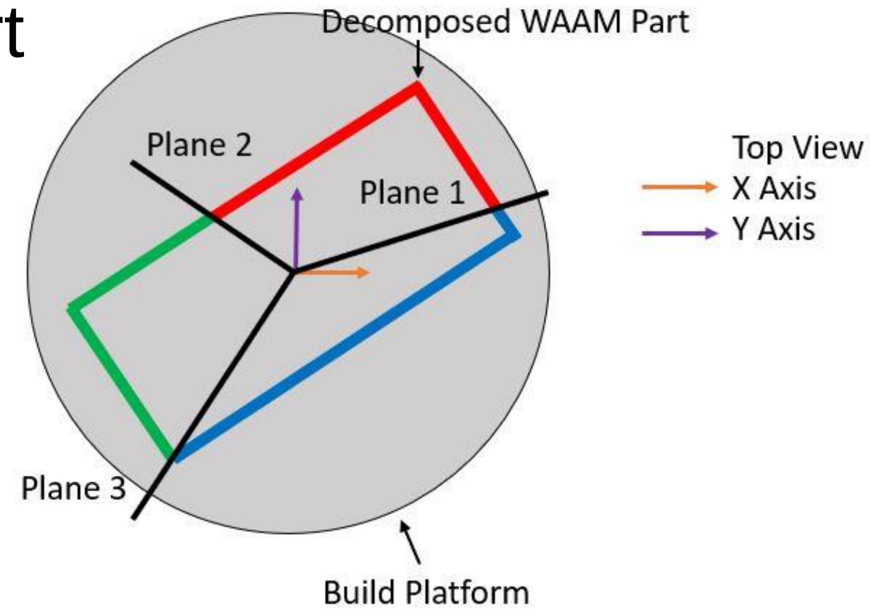


Illustration of the WAAM part being decomposed into three sections using vertical planes
Each of these decomposed section will be built using a separate manipulator

Θ is the inclination angle of the plane
φ is the azimuth angle of the plane
x, *y*, and *z* are coordinates of the points on the plane
S is the path segment containing the layers to be built by a manipulator
BT is the function representing build time of the part

Approach: Robot Placement

- Polar coordinates are used to place the manipulators near its decomposed segment
- The manipulator placements are optimized to improve the inverse kinematics consistency in robot path
  - $$\underset{v}{\text{minimize}} \sum_{i=1}^{k-1} \text{MAX}(\Delta \mathbf{q}_i(v)) \; s.t.$$
    $$C_{\text{reachability}}(v) = k$$
    $$C_{\text{clearance}}(v) \geq \lambda$$
    $$r_{lower} \leq r \leq r_{upper}$$
    $$0 \leq \phi \leq 2\pi$$

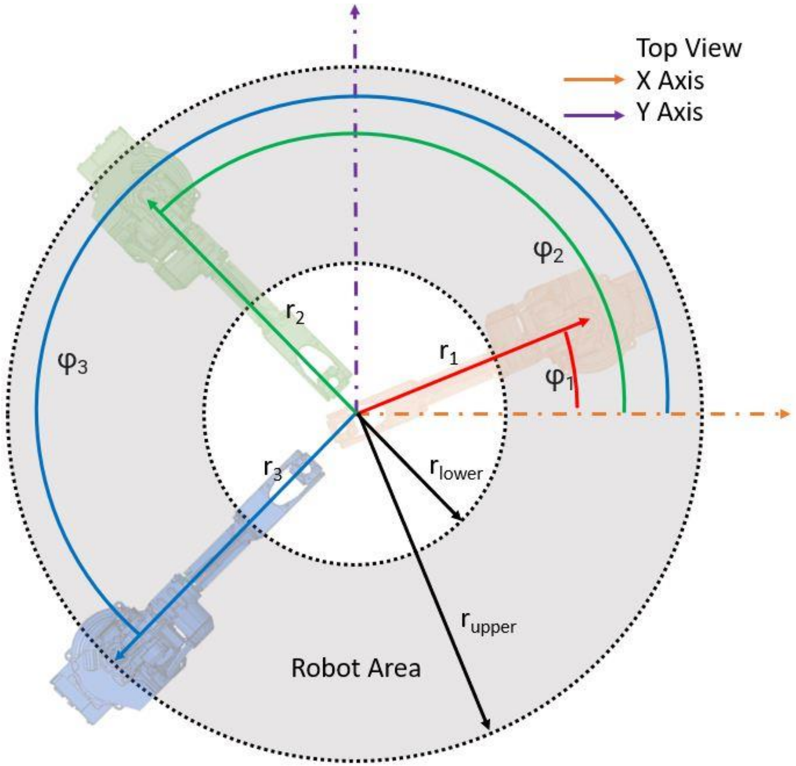
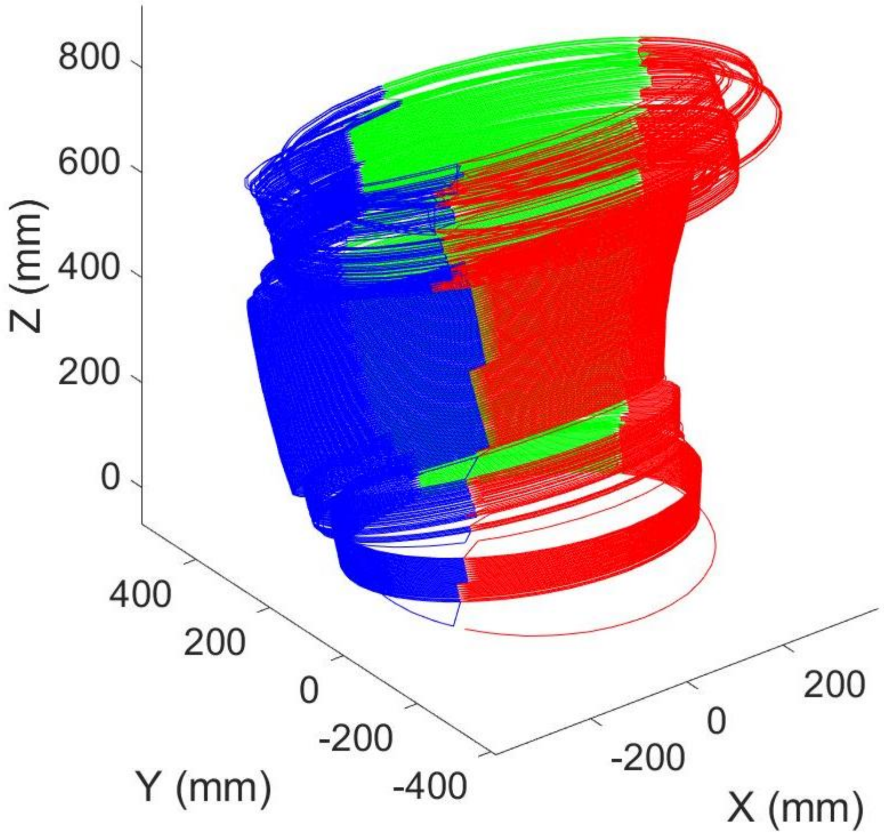


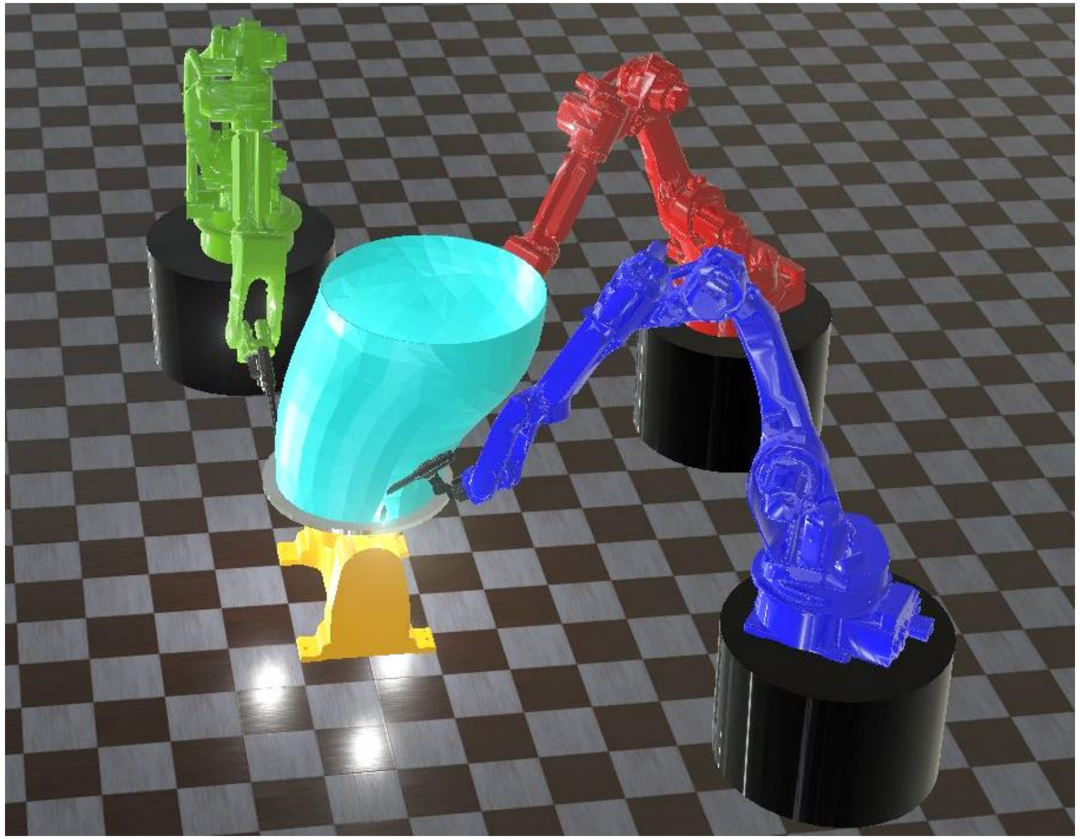
Illustration of three manipulators placed using cylindrical coordinates
The manipulator placement in bounded in the hollow circular robot area

q is the vector containing the joint variables
C is the constraint function
r is the radius of the manipulator placement
φ is the azimuth angle of the manipulator placement

Results: Part 1



The decomposed path segment sets

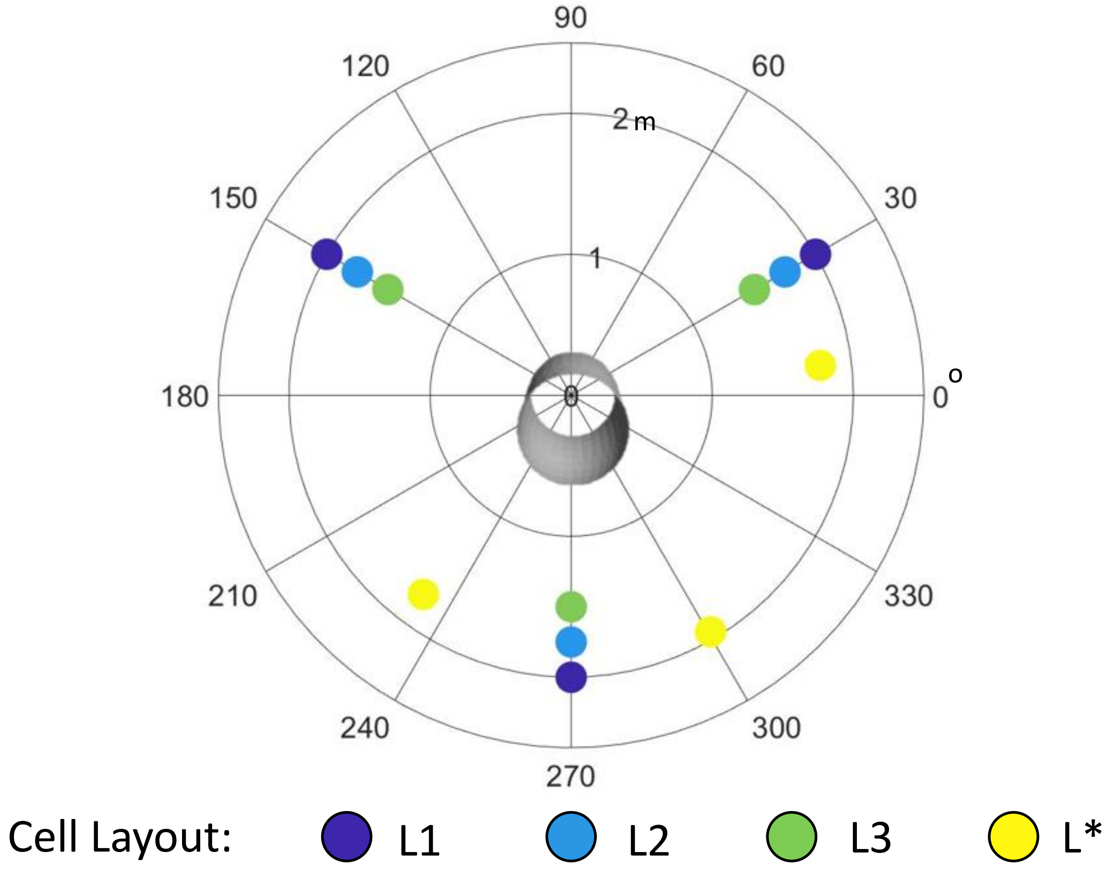


The WAAM simulation snapshot of the multi-robot placement solution

Results: Part 1

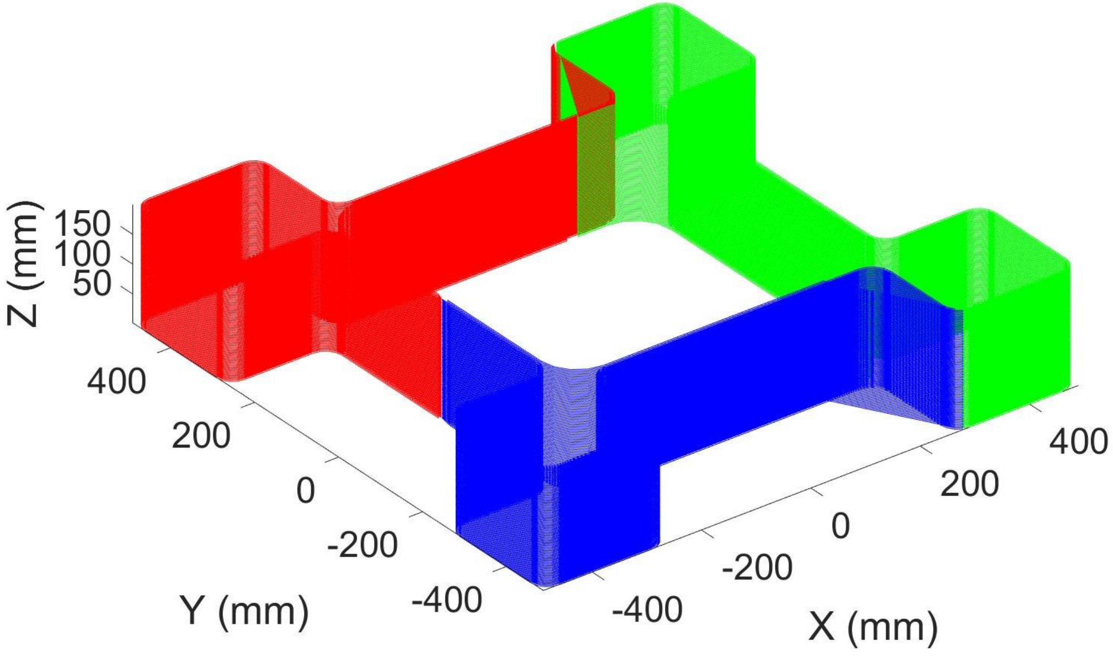
Multi-Robot Cell Layout	Build Time (hh:mm)	IK Inconsistency Count
L1	12:31	38
L2	12:31	6
L3	12:31	7
L*	12:28	3

The results of build time and IK inconsistency in robot paths for the three fixed cell layouts (L1, L2, and L3) and the optimized cell layout (L*)

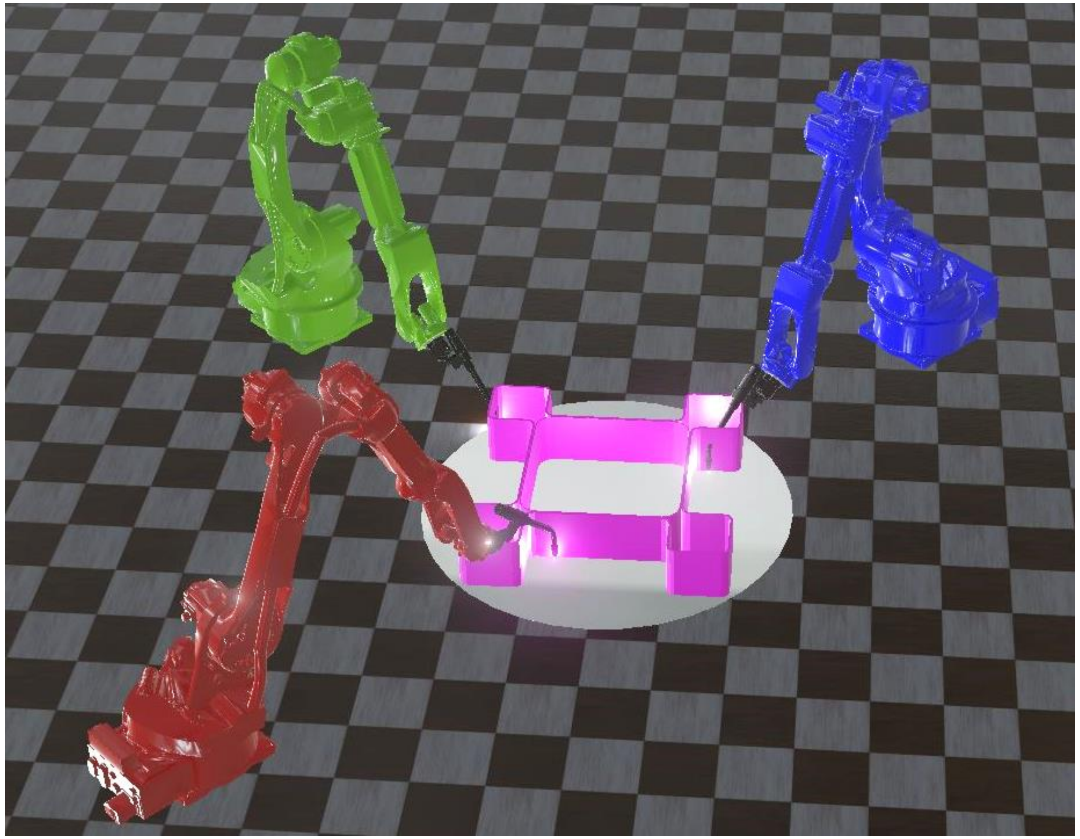


The plot to visualize the multi-robot placement locations of the fixed cell layouts and the optimized cell layout with respect to the WAAM part

Results: Part 2



The decomposed path segment sets

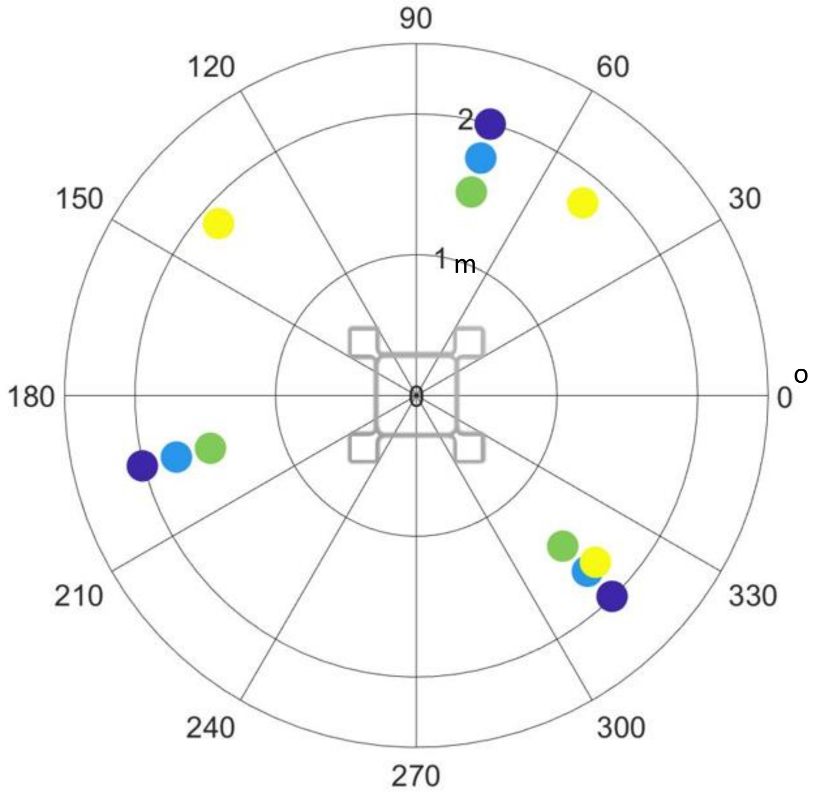


The WAAM simulation snapshot of the multi-robot placement solution

Results: Part 2

Multi-Robot Cell Layout	Build Time (hh:mm)	IK Inconsistency Count
L1	17:43	54
L2	17:43	0
L3	NR	NR
L*	15:43	0

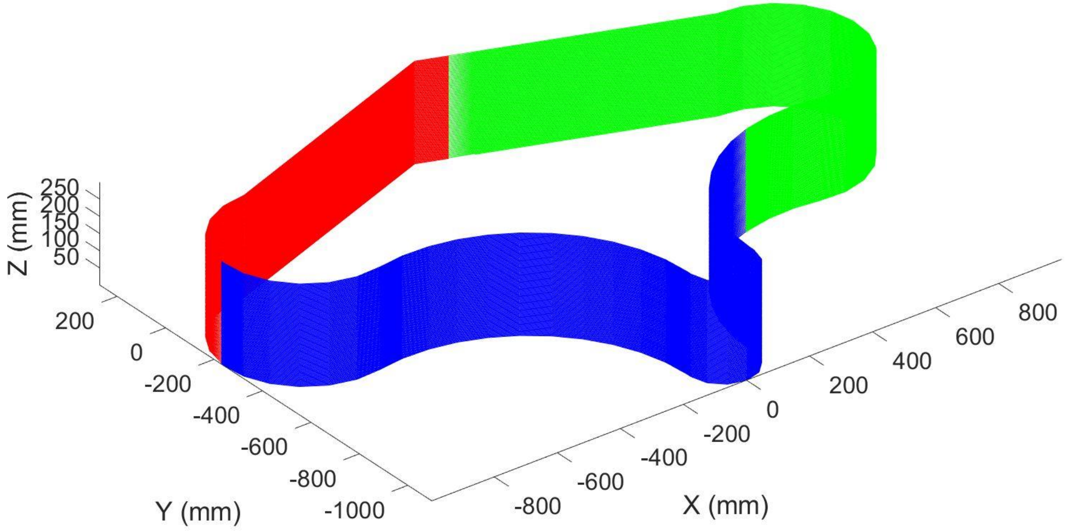
The results of build time and IK inconsistency in robot paths for the three fixed cell layouts (L1, L2, and L3) and the optimized cell layout (L*)
NR: Not Reachable



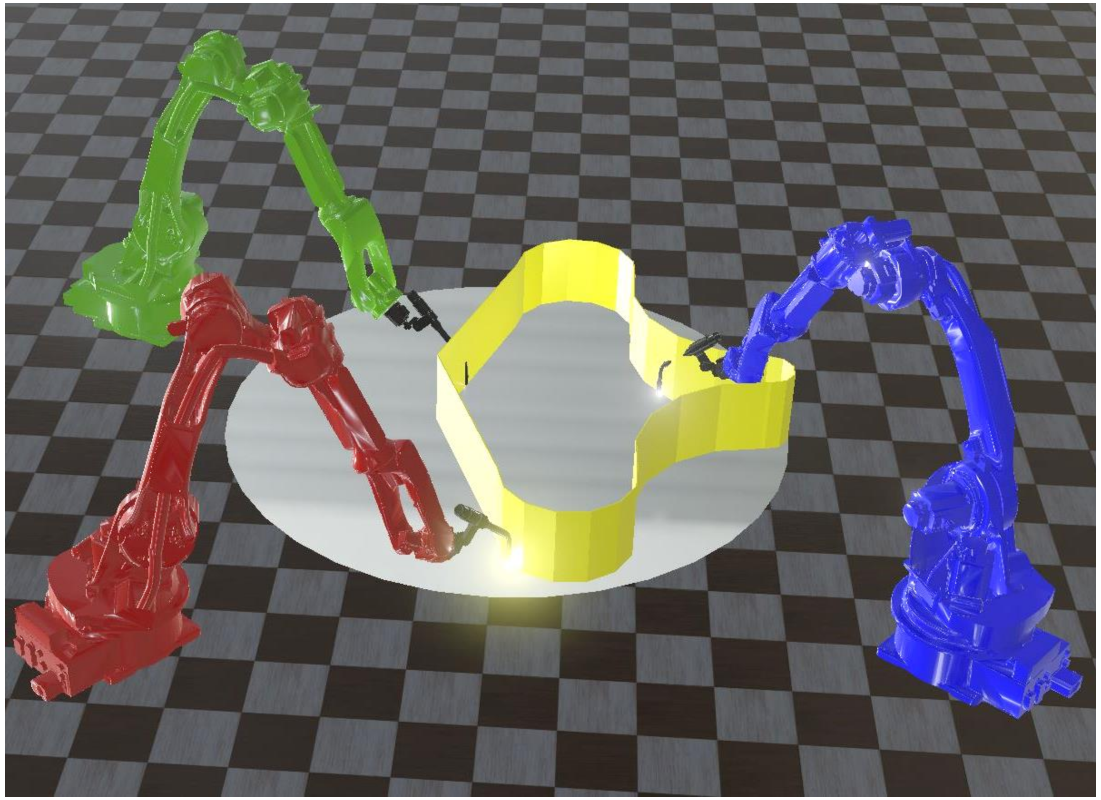
Cell Layout: L1 L2 L3 L*

The plot to visualize the multi-robot placement locations of the fixed cell layouts and the optimized cell layout with respect to the WAAM part

Results: Part 3



The decomposed path segment sets

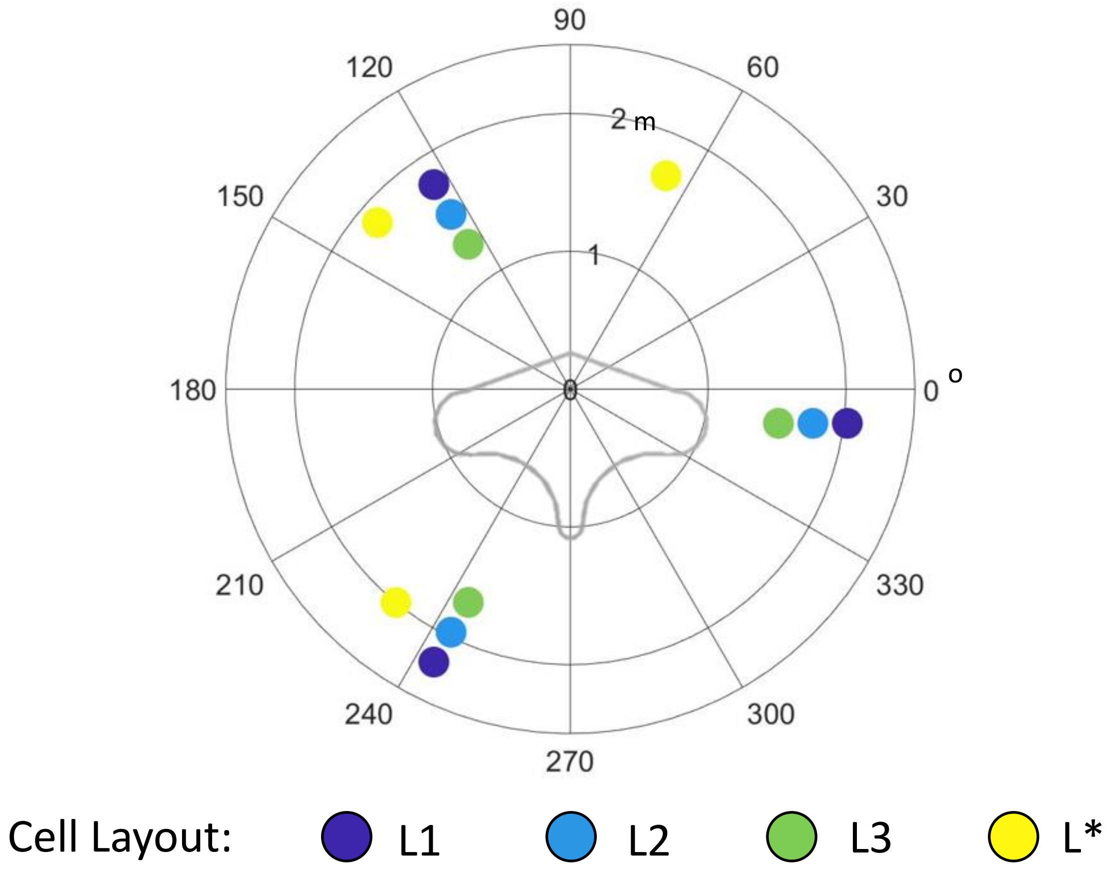


The WAAM simulation snapshot of the multi-robot placement solution

Results: Part 3

Multi-Robot Cell Layout	Build Time (hh:mm)	IK Inconsistency Count
L1	10:26	5
L2	NR	NR
L3	NR	NR
L*	12:09	0

The results of build time and IK inconsistency in robot paths for the three fixed cell layouts (L1, L2, and L3) and the optimized cell layout (L*)
NR: Not Reachable



The plot to visualize the multi-robot placement locations of the fixed cell layouts and the optimized cell layout with respect to the WAAM part

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Conclusions

- Building additive manufacturing cell using robots removes constraints associated with traditional 3D printing
  - Conformal layers
  - Multi-material fabrication
  - Supportless fabrication
  - Insertion of prefabricated components during AM
  - Integrated inspection, prognostics, and health management
- Using robots in additive manufacturing requires solving many challenging robotics problems using physics-informed AI
  - Trajectory planning
  - Trajectory compensation
  - Robot placement and cell design

Publications

https://sites.usc.edu/skgupta/publications/

Videos

https://www.youtube.com/channel/UCO82Tsg5Xc5vP_ZWkax4Wpg