DEPARTMENT OF MECHANICAL ENGINEERING
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Synopsis Of

Process planning for Multi-Robot and Multi-Axis Additive Manufacturing Processes

A Thesis

To be submitted by

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DOCTOR OF PHILOSOPHY

1. Introduction

Additive Manufacturing (AM) is the process of fabricating objects by slicing three-dimensional Computer-Aided Design (CAD) model data. Usually, three-axes Computer Numerical Control (CNC) machines are the most preferable cost-effective solution for printing parts using AM techniques. This three-axis CNC system can print only planar sliced layers, and additional external mechanisms are needed for printing non-planar sliced layers. Hence, multi-axis systems such as five-axis CNC or six-axis robotics systems may provide solutions for printing complex objects.

The success factors for AM implementation in industries are based on various factors such as processes, materials, and regulations [1]. Among those factors, surface quality, process speed, and build size are the major parameters, which determine the success rate of AM processes. Even though AM overcomes a lot of complex issues associated with conventional subtractive manufacturing, it can produce complex objects without any additional tooling requirement. But the process speed of AM is slower than the subtractive manufacturing processes. In addition, the usage of multi-axis systems such as five-axis CNC or six-axis serial manipulators in AM can enhance the part building faster with reduced usage or complete elimination of the support structures. Some industries and research groups have adopted multiple robots for enhancing the build speed as well as for better-quality parts. These techniques may require unique process planning activity by considering the process and machine constraints associated with printing parts. Process planning algorithms need to be developed for partitioning faceted solid models in various granularities for productivity improvements using multi-axis systems.

2. Background

Process planning for AM in this study involves volume decomposition to control or minimize the use of supports for overhang features and layer decomposition for simultaneous part printing for multiple deposition heads using robotic systems. DED is used for large-scale printing of parts with a high deposition rate [2]. Build orientation plays a significant role to control the staircase effect and volume of the support structure used for printing the part [3]. In addition to part printing issues, there are several problems associated with process planning for these multi-axis DED systems [4]. One such attempt was carried out with the help of robotic AM systems [5] to develop a collaborative part printing testbed for large-scale AM applications [6]. Time reduction is considered, but the material properties are not considered in this study.

From the literature survey, it is found that there is a need to increase the process speed of AM using multi-axis deposition systems without the use of support structures and layer decomposition by allocating part printing work between the dual deposition heads using robotic systems. Hence, in this work, a robust part-volume decomposition algorithm is developed to detect and decompose the overhangs in a respective build direction. In addition, there is a need to develop layer partition strategies for decomposing the tessellated models to increase the process speed of AM and minimize the part printing time. Hence, in this work, we proposed area based task allocation strategy for the dual robot arms considering the effect of anisotropy in the decomposed sliced layers.

3. Objectives

- Perform geometry decomposition of a faceted model to fabricate parts with overhang features considering the manufacturing constraints associated with the process.
- Identify the relationship between the surface roughness model and surface normal of a tessellated model to overcome the stair-step issues.

- Achieve homogeneity in the printed parts, which is obtained from the results of the decomposed sub-volumes of a tessellated model using layer decomposition.
- Develop layer-wise decomposition for task allocation to the multiple print heads attached to the robot arms, thereby increasing the process speed.

4. Overall methodology

This work proposes process planning algorithms for the faceted solid geometry decomposition in various granularities. The overall methodology for the tessellated part decomposition is presented in **Fig. 1**. with the help of a flow chart.

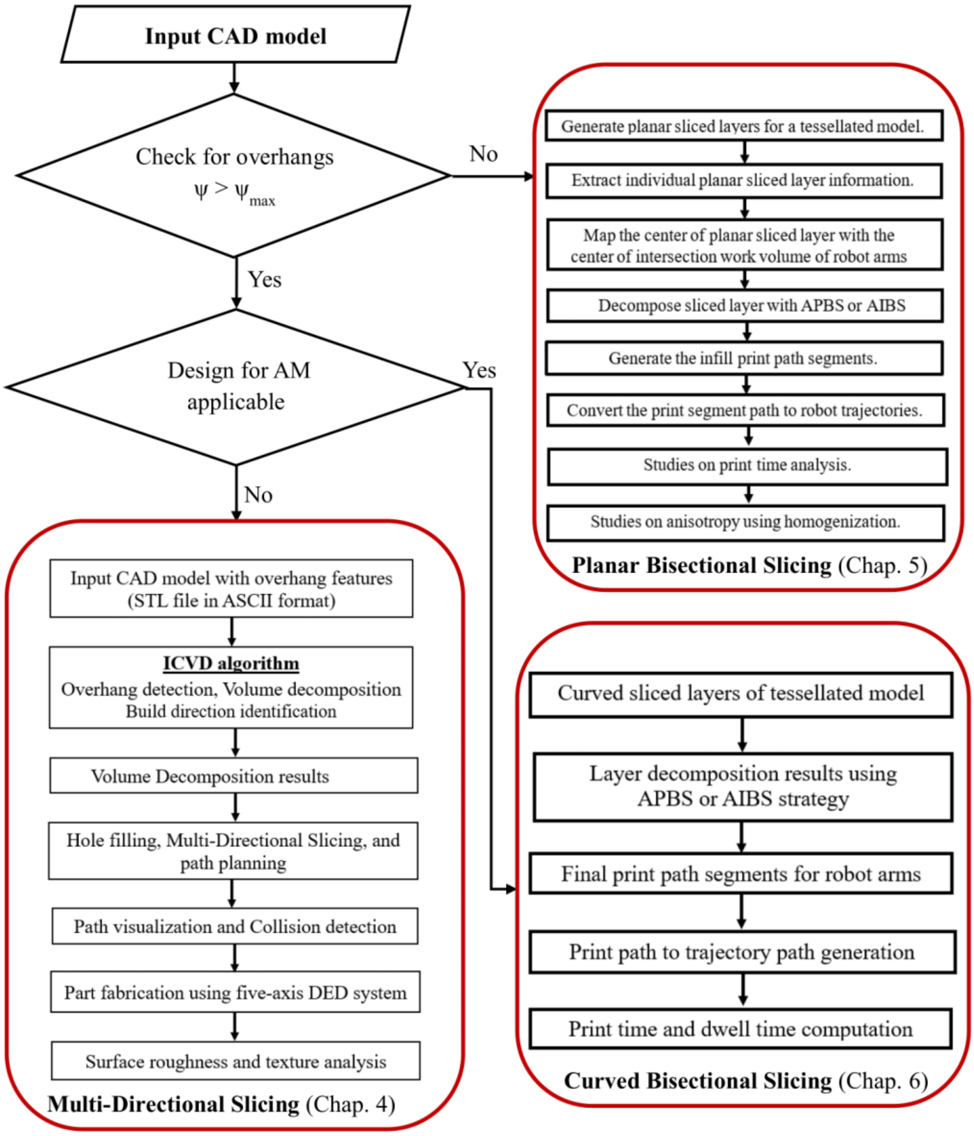


Fig. 1. Overall process planning methodology for multi-level decomposition.

The decomposition of geometry is usually based on function, design, technology, and feature [7]. To address the issues with surface quality, process speed, and anisotropy in the printed part, multi-axis robotic deposition systems are deployed by enabling complex decision control sub-systems. Volume decomposition is applicable for the tessellated part with overhang features. Further layer decomposition is used for the large-scale AM parts with minimum part print time using strength enhancement-based partitioning strategies.

4.1 Volume decomposition strategy for multi-axis CNC type AM system

In this work, a novel volume decomposition using the Improved Convex Volume Decomposition (ICVD) algorithm is developed to address the surface quality issues and also to increase the process speed. **Figure 2.** shows the overall process plan methodology for multi-directional printing using five-axis CNC-type DED systems.

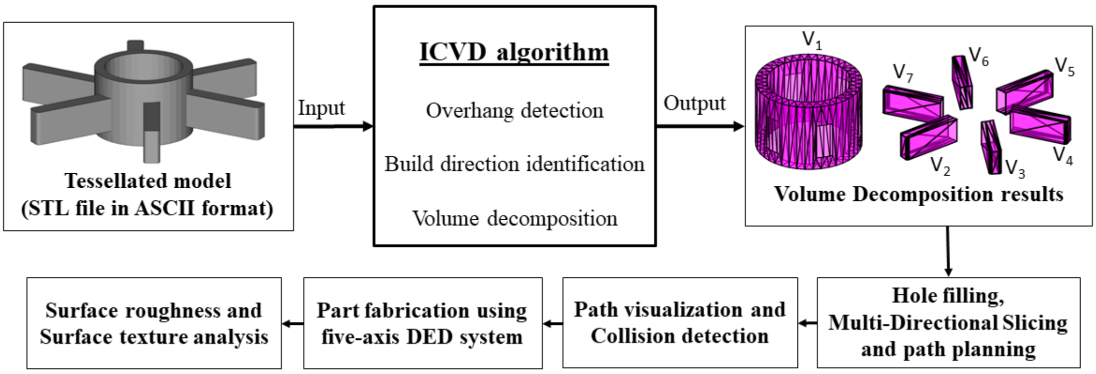


Fig. 2. Overall workflow of the developed volume decomposition methodology.

The NOSV in the case study part has two design features: a pentagonal prism and a cylindrical prism. These features are cumulatively decomposed as a single NOSV part. Hence, this technique eliminates the process of decomposition and regrouping the features in their respective build direction. The cosine of ψ in the **eqn.1.**, represents the relation between the build direction ($\vec{d}$) and surface normal $\vec{N_s}(p)$ of each triangle, p in the tessellated part.

$$-\cos(\theta + \psi_{max}) \leq \vec{N_s}(p) \cdot \vec{d} \leq \cos\theta \qquad \forall\, facets, p \qquad (1)$$

The maximum allowable overhang angle (ψ_{max}) represents the maximum allowable angle between the surface normal $\vec{N_s}(p)$ of the layer and the build direction, $\vec{d}$. The overhang angle (ψ_{max}) value is 18 degrees for DED processes. The fabricated case study part was then subjected to surface characterization studies for analyzing the surface roughness in the NOSV and OSV. The derived roughness (R_a) model in the **eqn. 2**, is generic for any powder-fed-based DED processes. However, the value of layer profile (φ) may depend upon several process parameters, and it can be calculated from the microscope images of the printed layers using powder-fed based DED processes.

$$(R_a)_{pred} = \frac{\propto}{4}\left[\sin\theta\tan\varphi + \cos\theta + \frac{\sin\theta}{18\,(cos^2\,\varphi)}\left(\pi - (90-\theta)\frac{\pi}{180}\right)\right] \qquad (2)$$

In this study, the value of φ is 1° for all decomposed sub-volumes printed in multiple build directions. $(R_a)_{pred}$ values are modeled by using the values of θ and φ. **Figure 3.** shows the results of the R_a plot for the angle, φ varying from 1° to 13°.

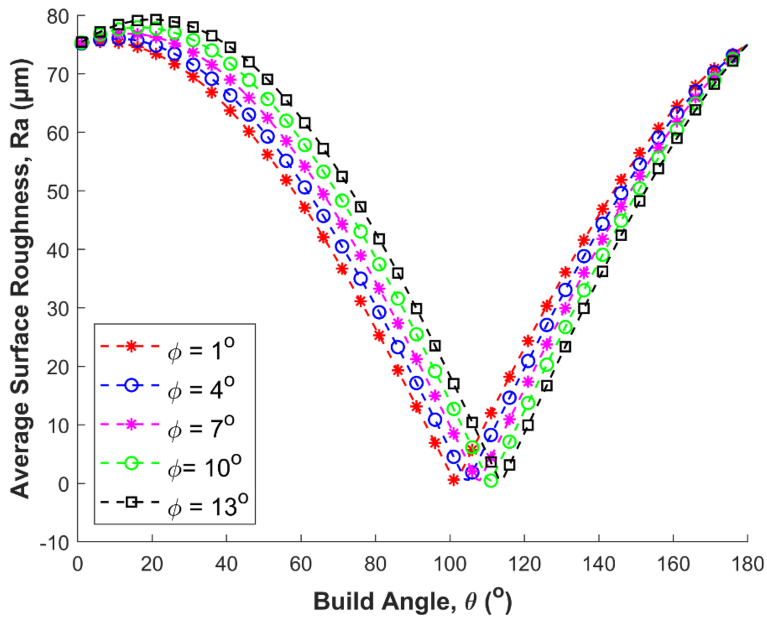


Fig. 3. R_a values plot by varying the build angle (θ) and layer profile (φ).

From the surface roughness graph in **Fig. 4.**, the predicted surface roughness is obtained for the θ value to be 90° for the NOSV of the case study test part.

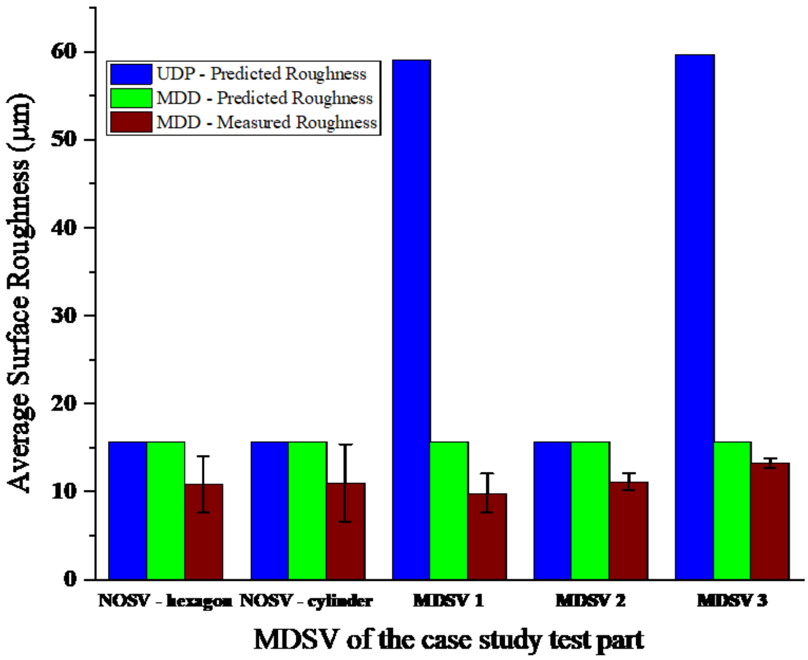


Fig. 4. Comparison of predicted and measured R_a values in the case study test part.

While the build angle value, θ is 48.76^o and 47.88^o for $MDSV_1$ and $MDSV_3$ respectively. The error bar graph shows the deviation of the roughness values measured at various surfaces in that particular sub-volume.

4.2 Layer decomposition strategies for multi-robotic AM system

In this work, Equal Area Task Allocation (EATA) strategy was used for part printing with dual serial manipulators, and its methodology is shown in **Fig. 5.**

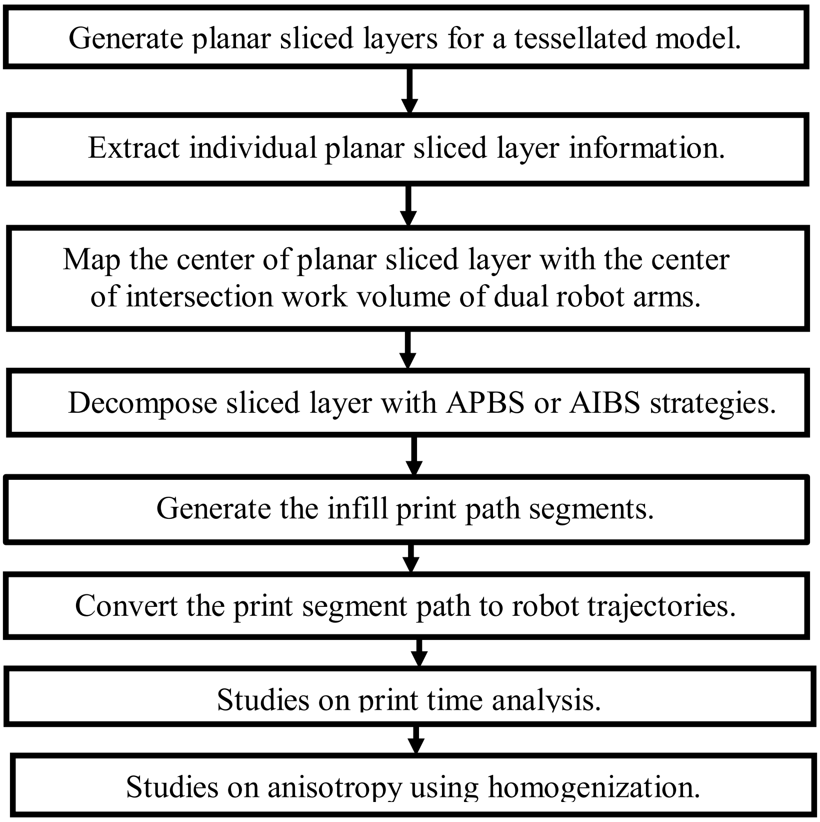


Fig. 5. Overall methodology of the current work.

Two decomposition methods for the EATA strategy namely Alternate Perpendicular Bisectional Slicing (APBS) and Alternate Intersection Bisectional Slicing (AIBS) are proposed, considering the orientation of the partition plane between adjacent planar sliced layers. The sliced geometries with Cartesian coordinate information are the input for the layer decomposition process, and those partitioned planar sliced layers are filled with zigzag infill patterns. The layer decomposition results using the EATA-APBS strategy are shown in **Fig. 6.** for part printing with dual robotic systems.

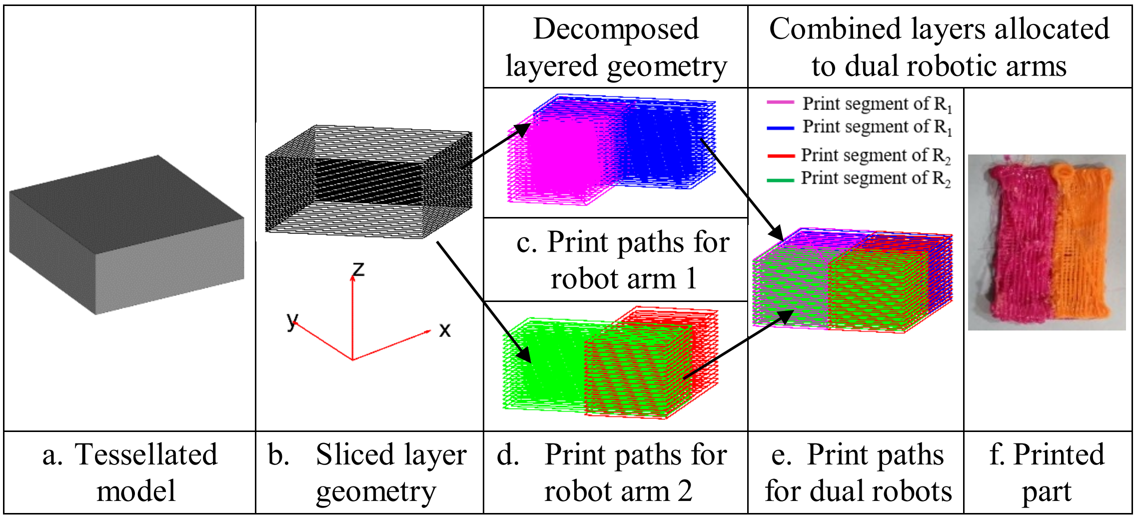


Fig. 6. Layer decomposition results of test part 1 (cuboid) using APBS strategy.

A dual-robotic AM system, as shown in **Fig. 7. a.**, was used to print parts simultaneously by studying the part-printing time and anisotropy. **Figure 7. b.** shows the work volume and its intersection work volume of the dual-robot configuration.

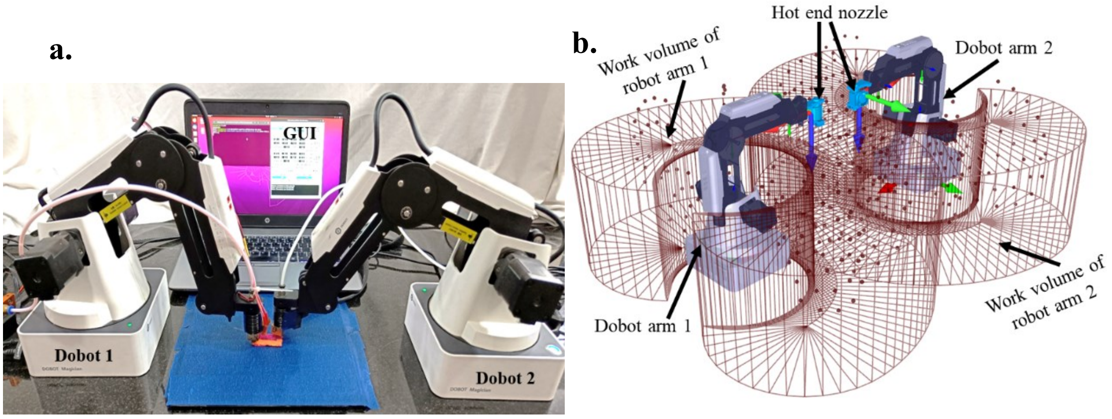
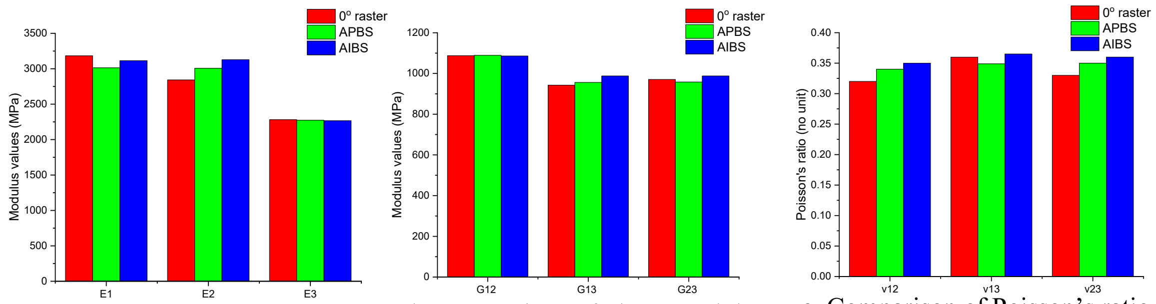


Fig. 7. a. Simultaneous part printing with Dobot arms, **b.** Work volume of Dobot arms

These layer decomposition strategies are developed to decompose parts into sub-volumes for task allocation to dual robots considering anisotropy. Path plan information is converted to path-constrained trajectories using the Inverse Kinematics principle.



a. Comparison of Young's Modulus. b. Comparison of Shear Modulus. c. Comparison of Poisson's ratio.

Fig. 8. a.-c. Comparison of material properties for different RVE elements.

As shown in **Fig. 8. a.**, Young's Modulus value varies along three axes for 0° raster orientation. In 0°/90° raster orientation (APBS strategy), Young's Modulus values remain the same in the two directions. This is because of the homogenization of the material properties in the principal direction. In the case of 0°/45°/90°/-45° raster orientation (AIBS strategy), the Shear Modulus value increases and homogenized in G_{13} and G_{23} with increased modulus values as shown in **Fig. 8. b.** In the APBS strategy, the Shear Modulus values are almost the same in G_{13} and G_{23}, which shows lower anisotropy results. Poisson ratio values for APBS strategy as shown in **Fig. 8. c.** is higher for ν_{13} and ν_{23}. In 0° raster orientation, Shear Modulus values varied along three principal directions. The AIBS strategy shows higher modulus values than the APBS strategy in the principal directions 1 and 2. Because the orientation of the printed path patterns continuously varies with an angle of 45° for every sliced layer, this AIBS strategy provides higher modulus results than the APBS strategy.

4.3 Curved bisectional slicing strategies for multi-axis AM application

Multi-Robotic AM test bed was developed as a platform to test the efficacy of the algorithm for multi-directional printing and for simultaneous part printing with Multi-Robots Collaborative Material Extrusion (MRCME) systems.

The non-planar sliced layers of the part are taken as the input for decomposing the sliced layers for task allocation to the dual robot arms. Figure 9. Shows the non-planar sliced layer decomposition results of a test part considered in this study.

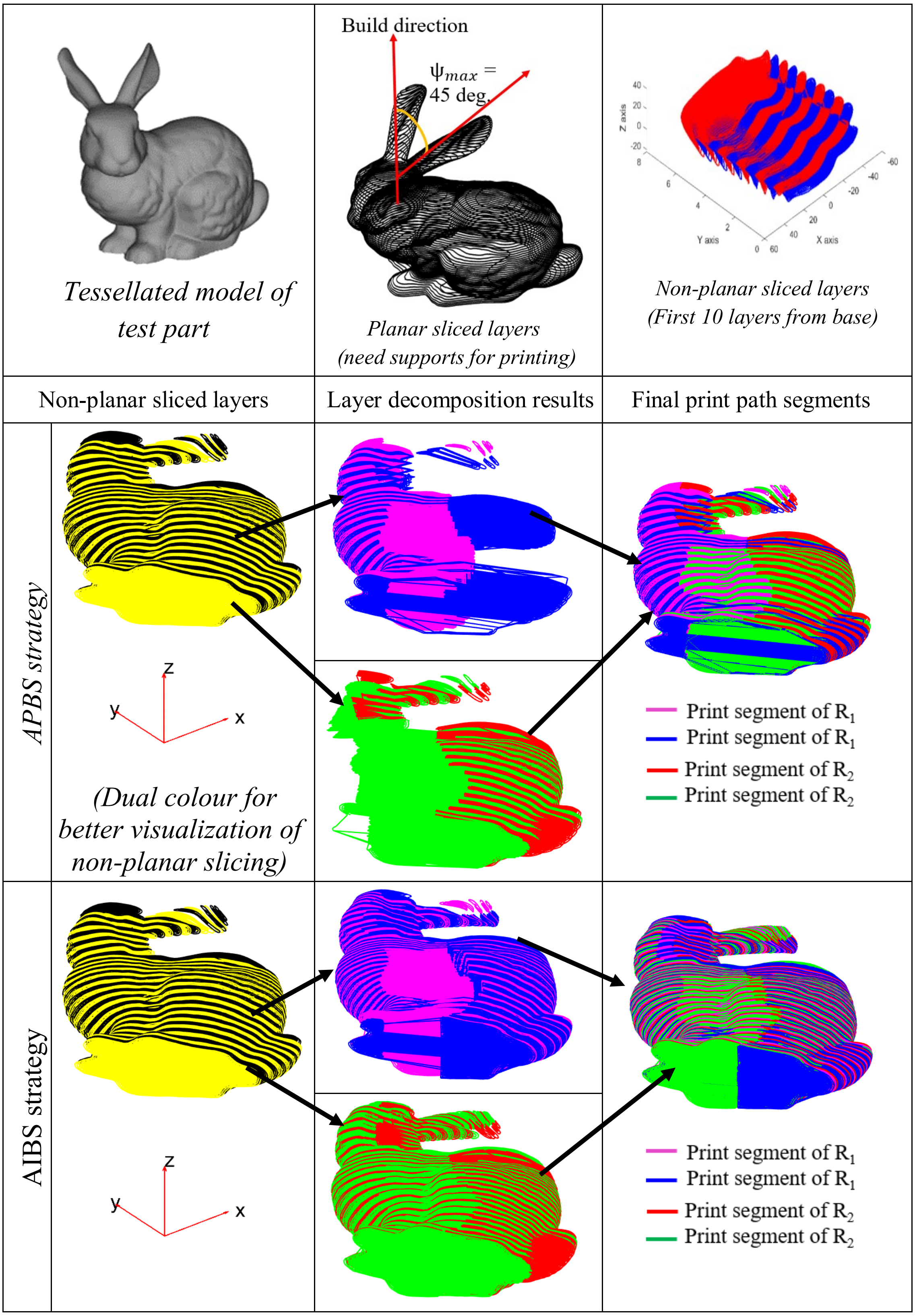


Fig. 9. Layer decomposition results of test part (Stanford Bunny)

Further the print time and dwell time of the layer decomposition strategies are computed and analyzed in this study. Multiple robots used are for the simultaneous deposition of parts for increasing the process speed in AM. The major problem of using multiple robots for AM is the generation of collision-free trajectories for these robot arms. This time study shows that there will be less variation in time between the robot trajectories of the equal volumes and the sub-volumes created with the CPISL methodology. Thereby the decomposition counters the increase in process speed between the printed sub-volumes.

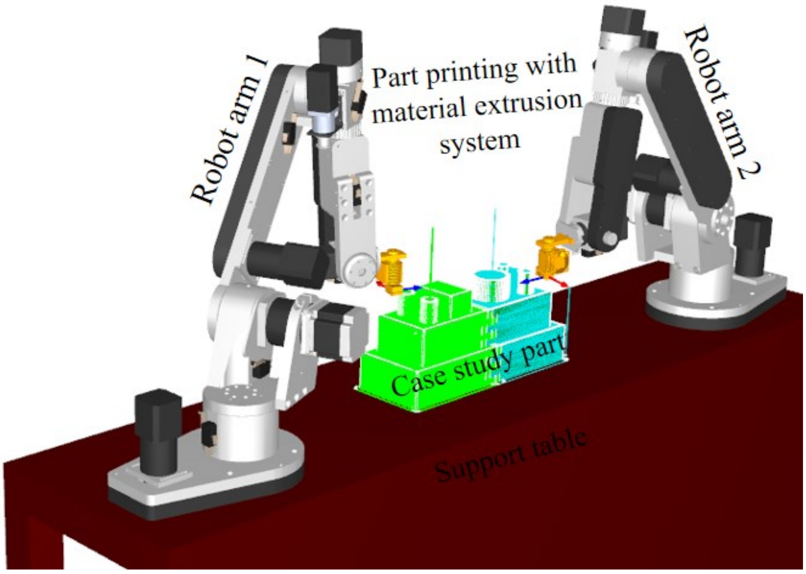


Fig. 10. Virtual simulation of the robot trajectories for AM application

The case study part was decomposed into two equal sub-volumes, and robot trajectories were generated to study the time taken by these dual robots for printing as shown in **Fig. 10.** The robot instruction commands for AM are generated with developed post-processor for Annin Robotics configuration.

5. Summary and conclusions

Volume decomposition is studied on faceted models considering the down-facing surface normal and predicted surface roughness models. A novel surface roughness prediction model for DED systems was proposed. This model was used to predict the surface roughness in the printed overhang features at various build angles and layer profile values. Experimental validation of a case study part is carried out using five-axis CNC-based DED systems, and surface roughness in various surfaces of the printed part was studied to check the efficacy of the developed algorithm. The Ra value in the printed part is in the range of 6.61 μm to 15.04 μm. These multi-directional part printing results prove that the surface roughness values are almost similar in the NOSV and OSV of the MDD part fabricated with DED systems.

We addressed EATA-based layer partitioning strategies to print parts using robotic AM applications to improve the process speed and minimize heterogeneity between subsequent sliced layers of the printed part. The printing time was considerably reduced by an average of 45% using the proposed EATA strategies. The robotic process automation solution is provided by the proper placement of the robot arms for printing complex parts without any collision between serial manipulators. In addition, the MRCME test bed was developed for multi-directional part printing to minimize or eliminate the use of supports and simultaneous part printing applications with dual six-axis robotic part printing systems.

6. Proposed thesis contents

The proposed outline of the thesis is as follows

1. INTRODUCTION

1.1. Introduction to process planning for AM
1.2. Process planning objectives associated with AM
1.3. Introduction to slicing strategies
1.4. Introduction to deposition systems in AM
1.5. Processes, systems, and comparison
1.6. Overall Motivation
1.7. Organization of the thesis

2. BACKGROUND

2.1. Background study on volume decomposition
2.2. Background study on layer decomposition
2.3. AM path planning solutions
2.4. Robot trajectory planning solutions
2.5. Problem description
2.6. Objectives of the thesis

3. METHODOLOGY

3.1. AM systems used in this current study
3.2. Overall process planning methodology
3.3. Volume decomposition methodology
3.4. Planar bisectional slicing methodology
3.5. Closure

4. VOLUME DECOMPOSITION STRATEGY FOR MULTI-AXIS CNC TYPE AM SYSTEM

4.1. Feature-wise decomposition strategy
4.2. Validation using five-axis CNC-based DED system
4.3. Closure

5. LAYER DECOMPOSITION STRATEGIES FOR MULTI-ROBOTIC AM SYSTEM

5.1. Strategies for planar sliced layer decomposition
5.2. Bisectional slicing strategies for MRAM systems
5.3. Implementation
5.4. Unequal Area Task Allocation (UATA) strategy
5.5. Homogenization to evaluate mechanical anisotropy
5.6. Closure

6. PRINT TIME STUDIES ON THE OPTIMIZED CURVED SLICING FOR MULTI-AXIS AM APPLICATION

6.1. Use of curved slicing for layer decomposition
6.2. MRAM setup using AR3 serial manipulators
6.3. Decomposition results of test part 1
6.4. Decomposition results of test part 2
6.5. Dwell time analysis
6.6. Closure

7. CONCLUSIONS AND FUTURE SCOPE

7.1. Summary and conclusions
7.2. Future scope

Appendix A: Volume decomposition
Appendix B: layer decomposition
References

7. Outcomes from the research

7.1 Journal publications (related to thesis)

[1] Madhanagopal Manoharan, Senthilkumaran Kumaraguru, "**Novel Process Planning approach for support-free Additive Manufacturing using Multi-Axis Deposition systems**", International Journal of Computer Integrated Manufacturing, 2022, pp. 807-829. DOI: 10.1080/ 0951192X.2022.2145020. (Q1, IF: 4.1)

[2] Madhanagopal Manoharan, Senthilkumaran Kumaraguru, "**Investigation of multi-directional bi-sectional slicing strategies on the anisotropy of parts in multi-robot Additive Manufacturing**" (Manuscript under review).

7.2 Conference publications (related to thesis)

[1] Madhanagopal Manoharan, Senthilkumaran Kumaraguru, "Path Planning for Direct Energy Deposition with Collaborative Robots: A Review", in Proc: of 2018 Conference on Information and Communication Technology (CICT'18), Jabalpur, India. Oct 26-28, 2018. (*Available in IEEE Xplore*)

[2] Madhanagopal Manoharan, Aditya Navghare Shridhar, Vivek Yadav Vinod, Senthilkumaran Kumaraguru, "A novel volume decomposition methodology for Multi-Robots Collaborative Additive Manufacturing", CICT conference 2020, India, December 3-5, 2020. (*Available in IEEE Xplore*)

[3] Madhanagopal Manoharan, Chitikena Hareesh, Senthilkumaran Kumaraguru, "Volume decomposition of faceted models to minimize post-processing issues for Multi-Robots Collaborative Material Extrusion systems", I4AM conference 2022, IISc Bangalore, January 10-11, 2022. (*Available in Springer as a book chapter*).

7.3 Conference publications (allied to thesis)

[4] Hemnath Anandan Kumar, Reginald Elvis Peter, Madhanagopal Manoharan, Jayakrishnan Jayapal, Senthilkumaran Kumaraguru, "Tailored Support Structures for Additive Manufacturing", in Proc.: of 7th International and 28th All India Manufacturing Technology, Design and Research (AIMTDR) Conference, CEG, Anna University, Chennai, India, December 13-15, 2018. (*Available in Springer as a book chapter*)

[5] Madhanagopal Manoharan, Potnuru Hema Praneetha Naidu, Midhun Joy, Senthilkumaran Kumaraguru, "Medial Axis Transformation Based Design and Process Planning Methodology for Discrete Multi-Material Additive Manufacturing", ASME IDETC conference 2022, Aug. 14-17, St. Louis, USA. (*Available in ASME digital collections*)

[6] Madhanagopal Manoharan, Karanam Shreedhar Sai Thilak, Senthilkumaran Kumaraguru, Collaborative motion synchronisation for affordable open-source Cobots, 2022 Conference on Information and Communication Technology (CICT'22), November 18-20, ABV IIITM Gwalior. (*Available in IEEE Xplore*)

[7] Madhanagopal Manoharan, Aditya Navghare Shridhar, Ranga Rakesh, Karanam Shreedhar Sai Thilak, Senthilkumaran Kumaraguru, Development of affordable Collaborative Robots for Engineering Education, 6th Joint International Conference on Multibody System Dynamics and 10th Asian Conference on Multibody System Dynamics, October 16-20, 2022, IIT Delhi, New Delhi. (*Available in Springer as a book chapter*)

7.4 Awards

- Best paper award in IEEE-sponsored CICT 2020 conference [hosted by IIITDM Kancheepuram].
- Springer distinguished paper award in I4AM 2022 conference [hosted by IISc Bangalore].

8. References

[1] Pinkerton A. J, “Lasers in Additive Manufacturing”, 2016, Optics and Laser Technology, vol. 78, pp. 25–32.
[2] I. Gibson, D. Rosen, B. Stucker, Directed Energy Deposition Processes. In: Additive Manufacturing Technologies, 2015.
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[7] X. Wang, L. Chen, T.Y. Lau, K. Tang, A skeleton-based process planning framework for support-free 3+2-axis printing of multi-branch freeform parts, Int. J. Adv. Manuf. Technol. 110 (2020) 327–350. https://doi.org/10.1007/s00170-020-05790-0.