Acta Mechanica Slovaca **28 (4): 70 - 76,** December **2024**
https://doi.org/10.21496/ams.2025.003

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Alternative CAM Solution for Adaptive Robotic Additive Manufacturing

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Abstract: The use of multi-purpose and gantry robots with 5 or more axes in large format additive manufacturing (LFAM) presents many opportunities and challenges. The ability to process large volumes of material and rapidly produce products of significant dimensions requires the formulation of an appropriate manufacturing strategy. This includes setting production parameters and selecting the right software to generate toolpath movements, considering the limitations of the technologies used in many applications as manufacturing of tooling and functional parts, composites or even for repairing of complex surface of parts. Slicing and printing strategies, especially in field of LFAM require specific approaches which lead researchers search for alternative solutions to conventional 3 axis planar principles by developing solution as non-planar, radial, cylindrical, spherical, load based tool path generation and other partial solution using different software techniques. Since no unified cost friendly solution has yet been developed that would allow the creation of such or similar results in a single software, this paper presents the principles on the basis of which such a solution could be created with the help of Rhinoceros ® Grasshopper™ (RG) software. In the individual chapters, current commercially available software slicers are presented, individual solutions of the researchers and possibilities of using RG with basic principles are shown whose functionality are verified by physical experimentation. Finally, the paper concludes with an evaluation of the experimental results and outlines the challenges but also the opportunities in the context of the use of RG in future applied research in the field of LFAM.

Keywords: LFAM; Grasshopper; slicing; parametric design; visual scripting; nonplanar printing

1. Introduction

Usually, computer-aided manufacturing (CAM) software is associated with machining technology, but thanks to the gradual adoption of additive technologies in the manufacturing sector CAM software is also used in this area. Typically, CAM software in additive manufacturing uses in-plane slicing which is related to manufacturing technology especially in desktop additive manufacturing on cartesian robotic devices that cannot take advantage of 4-axis and multi-axis manufacturing capabilities. New trends in advanced design for additive manufacturing require advanced slicing capabilities which is a key process in generating a set of flat or curved layers [1]. The use of 6-axis robots makes it possible to overcome the limitations of product design in additive manufacturing processes by using planar horizontal material deposition and brings with it an extension of the possibilities of applying materials to complex non-planar surfaces that can be used in a variety of applications such as:

1. *Manufacturing of composites where achieving the correct fibre orientation is crucial for the proper functioning of these parts. The conventional planar-layer material deposition process often results in undesirable fibre orientation as it orients fibres in the plane of the layer. To overcome this issue, the ability to position fibres along a 3-dimensional*

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curve is required. To meet this requirement, the ability to deposit material along non-planar layers is necessary.

2. Reducing Overall Fabrication Time in Large Part Printing: Many part geometries require a specific build direction to minimize the staircase effect in a conventional planar layer-based process. However, this can result in printing a large number of layers, which is time-consuming. Non-planar layers offer more options for minimizing the staircase effect. Several types of geometries can be printed faster using non-planar layers, minimizing staircase effects on curved surfaces. This can significantly reduce build time for large parts and reduce the need for post-processing by minimizing the staircase effect.

3. Repair and maintenance of complex parts what involves depositing material on non-planar surfaces and shaping it accordingly. Robotic 3D printing has the potential to enable near-net deposition, simplifying the overall process by allowing the same robot to be used for material deposition, grinding, and sanding. The ability to deposit material on curved surfaces will also increase automation in the repair of complex parts. Robots can be utilized for material deposition, allowing for in-situ additive manufacturing on prefabricated structures [2],[3],[4]. With the help of 6-DOF robot arms, it is now possible to fabricate 3D parts at various angles, which overcomes the limitations of conventional 3D printing methods. Recently, there has been growing interest in the use of industrial robots for additive manufacturing in both academia and industry [5],[6]. There are already a few companies on the market like Ai Build or Adaxis, that offer multi-axis LFAM CAM software known as slicer, but prices above €6000 per year could be limiting for some users. To overcome this limitation, users must create their own software solutions or use other alternative options to help them get closer to the same or at least similar results. One such option is the use of parametric modeling and visual programming (VP) as a powerful tool in planar, non-parallel, angular, and adaptive additive manufacturing at a fraction of the cost, approximately €1000 for a one-off payment. This paper explores the use of RG software as such software and discuss its possibilities in field of non-planar adaptive printing in such applications.

2. Related Work Discussion

Several methods of non-planar G-code generation using different approaches have already been addressed in past by researchers such as Etienne et al. [7] René K. Müller [8] Michael Wüthrich [9] Basit Khan [10] which are using different approaches of computation methodology for creating non-planar toolpaths such as model deformation using quadratic programming solver, trigonometry coordinates translation or scalar filed computation methodology and also new research paper showing different non-planar approaches to achieve radial slicing to print gravity separation spirals [11], spherical slicing using Matlab software [12] , non-planar helical paths for AM with adjustable contour dimensions based solved by computer generated intersection operations using where complex mathematical explanation is used written in C# programing language [13]. In some cases complete rewrite of a slicing tool is necessary to achieve 3-axis non planar printing so the non-planar variable layer height slicing script had to be created in Java programming language as partial addition to conventional slicers [14]. Also use of Python frameworks with other algorithms and external supported software or libraries like Numpy, Scipy, Abaqus and FEA analysis where implemented to achieve non-planar AM [15]. Even in new articles and studies, connection to older ones can be found where are using the same principles but focusing on a different area of concern. Although sometimes the title implies that they are related to the use in large-scale additive manufacturing, in reality this is not the case and the volume of parts with which the principles of generating non-planar layers have been verified reach dimensions in the tens of mm and thus their actual use in the field of large-scale additive manufacturing, which requires diametrically different approaches to the design of parts and the process of slicing, is questionable [16]. Rhino grasshopper software was used to create non-uniform cylindrical slicing algorithm for multiaxial deposition to reduce number of layers and need for support structures but again Python script was created as RG function [17] which is usable only for the specific application of cylindrical slicing.

To the best of the authors' knowledge, work in the area of layer generation using a visual programming software (VPS) which would at least give a direction for easy creation of a universal slicer for LFAM 6-axis material deposition needs has not yet been published, therefore our research aimed to create a viable trajectory for adaptive printing using non-planar material deposition in VP software RG. By adaptive printing we mean that the proposed approach allows adaptive tilting of the tool on a curved surface so that the normal vector at the current position of these points with respect to the surface on which the points are located is individually evaluated at the given points. The approach we present is not universal to any geometry yet but is customizable according to user needs and represents direction of future research trajectory on the way to true cost friendly multiaxial slicer for LFAM applications needs.

The feasibility of the planned trajectory was validated through robotic simulation. The proposed trajectory planning was implemented on the robotic AM system. The system comprises a 6-DOF robot arm manipulator, FANUC M-20iB/25 robot equipped with an MDPH2 pellet extruder. Our paper focuses on trajectory planning for non-planar layered printing and its feasibility. The trajectory was generated using a nonplanar planes intersection method in VP software RG and process parameters were determined through empirical experiments and future approach options are outlined.

3. Experimental Section

To generate a path on a non-planar surface, a RG script was made based on a plane's intersection method. The main objective was to create sequences of positions and orientations of the tool centre point (TCP). This is a crucial aspect of the adaptive printing process and greatly affects design possibilities. The grasshopper adaptive slicing script (fig. 1) was developed to generate G-code for a simple B-rep geometry which represents a curved surface to verify its functionality. To achieve this, several integrated function blocks and special position-obtaining blocks of RG software were used. The experiment was conducted on a FANUC M-20iB/25 robot equipped with an MDPH2 pellet extruder.

The adaptive slicing script developed in Grasshopper environment consists of 7 sections (Figure 1) which are parametrically connected and act as CAM data pre-processing system which convert input geometry and slicing parameters (Figure 3) into printable G-code. Section A (Figure 1) collects input data as B-rep geometry to slice, layer height, and surfaces which define the start and end of adaptive slicing. Section B (Figure 1) generates build plate adhesion-related features to secure the faultless creation of a nonplanar surface. In section C (Figure 1) layers, points, and vectors for of B-rep geometry representing non-planar surface are generated. The intersection curves generated serve as layer indicators and are displayed in Figure 2. The points and vectors

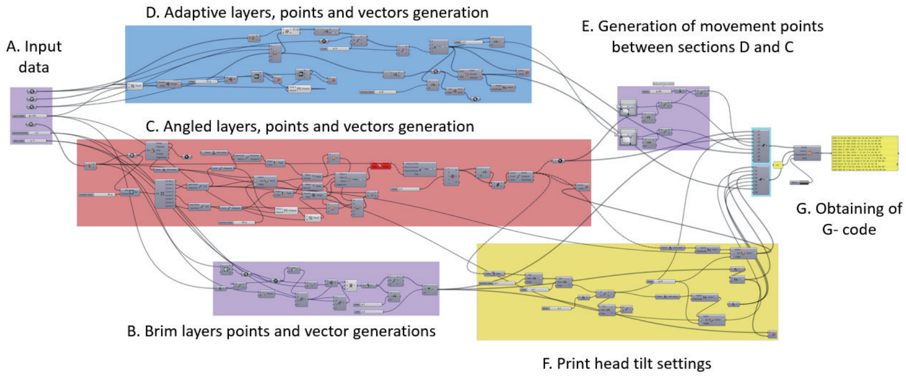


Figure 1: CAM data pre-processing workflow

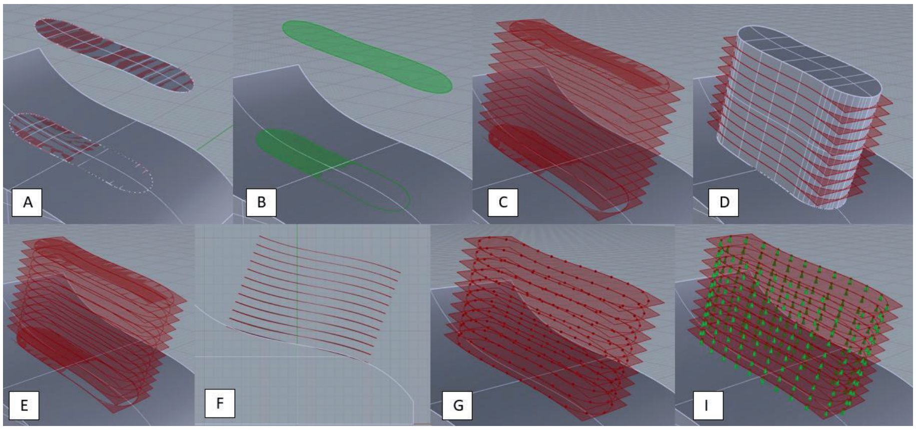


Figure 2: Adaptive layer generation process.

determine the motion and adaptive orientation of the extruder relative to the current extruder position.

To avoid collision between already printed part and ready to print start point on curved surface, movement for the extruder is settled in section E (Figure 1). Adaptive layers, points and vectors generation in section D (Figure 1) represent the experimental part of this paper to prove it's functionality. B-rep closest point function was used to acquire normal vector orientation pointing from generated points according to actual position on generated non-planar plane (Figure 2). Finally, the process of obtaining coordinates of points and vectors can be found in section G (Figure 1). The results of the grasshopper parametrically changeable non-planar and adaptive slicing script (Figure 3) can then be exported in G-code format. Once the G-code has been generated, it must be uploaded into the robot-simulating software RoboDK. This is where the robot's movement is programmed, and the G-code is translated into the robot's movement language. The final steps of the pre-processing of robotics 3D printing include setting up start/end procedures, final checking for possible collisions, and uploading the program to the robot.

Offline programming and simulation of the robot's movements was done in specialized RoboDK software for industrial robots with 3D printing plugin. Translated robot language was transferred to the control system of the robot and then executed (Figure 4).

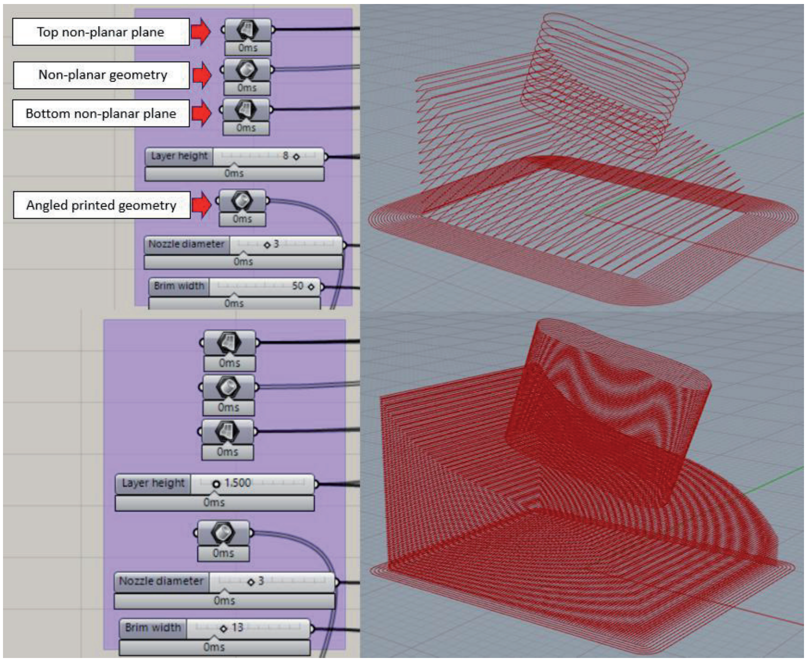


Figure 3: Preview of generated angled and adaptive layers of the part with a demonstration of input parameter changes.

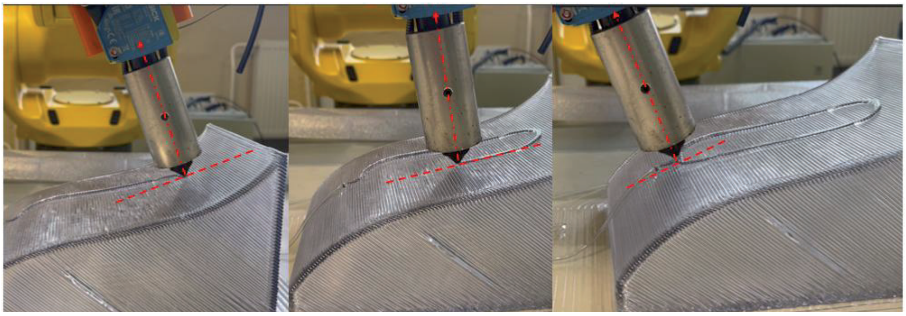


Figure 4: Experimental verification of printing on the non-planar surface with adaptive perpendicular tool orientation regarding actual position.

In this process, angled printing was used to create a nonplanar surface to test adaptive printing with minimal material consumption due to the ability to hollow print without the need for infill. Manufacturing parameters were settled according to Table 1.

Table 1: Manufacturing parameters of the final printed sample.

Printing speed	20 mm/s
Layer height	2 mm
Layer width	5 mm
Nozzle temperature	200 °C
Nozzle diameter	3 mm
Brim width	13 mm
Layer angle	48°
Tool head angle	33°
Used material	PETG

Layer angle and tool angle represents tilting of the layers and tool head accordingly: Tool head angle α was calculated as the angle deviation (α- Figure 5) of the actual tool position and neutral axis Z and layer angle β was calculated as the angle deviation (β- Figure 5) of the actual layer angle from neutral X axis.

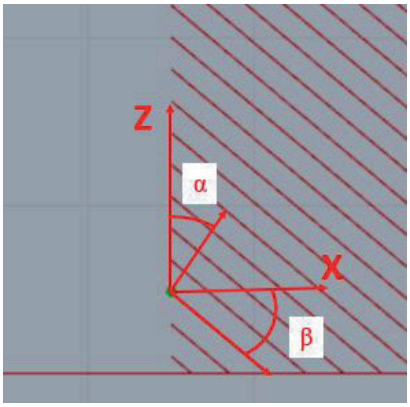
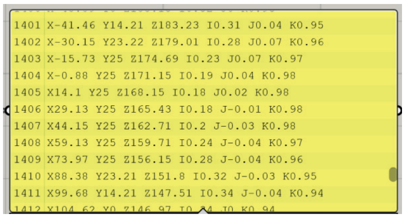


Figure 5: Tilt angle representation.

4. Results and Discussion

Proposed method of adaptive slicing had been designed and verified to test the AM options on a curved surface. Using the created script, the G-code of the print job was generated (Figure 6) and used for printing at the LFAM workstation. Experimentally, three samples were printed which differed in head tilt angle of 40°, 35° and 33°. Setting the angle higher than 40° was not satisfactory as it led to interruption of feeding of the material on the gravity principle and its subsequent jamming in the hopper.



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1401 X-41.46 Y14.21 Z183.23 I0.31 J0.04 K0.95
1402 X-30.15 Y23.22 Z179.01 I0.28 J0.07 K0.96
1403 X-15.73 Y25 Z174.69 I0.23 J0.07 K0.97
1404 X-0.88 Y25 Z171.15 I0.19 J0.04 K0.98
1405 X14.1 Y25 Z168.15 I0.18 J0.02 K0.98
1406 X29.13 Y25 Z165.43 I0.18 J-0.01 K0.98
1407 X44.15 Y25 Z162.71 I0.2 J-0.03 K0.98
1408 X59.13 Y25 Z159.71 I0.24 J-0.04 K0.97
1409 X73.97 Y25 Z156.15 I0.28 J-0.04 K0.96
1410 X88.38 Y23.21 Z151.8 I0.32 J-0.03 K0.95
1411 X99.68 Y14.21 Z147.51 I0.34 J-0.04 K0.94
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Figure 6: G-code of the print job

Totally three samples with box dimensions 400x300x300 mm were printed to calibrate and determine manufacturing parameters of final part which validate method functionality.

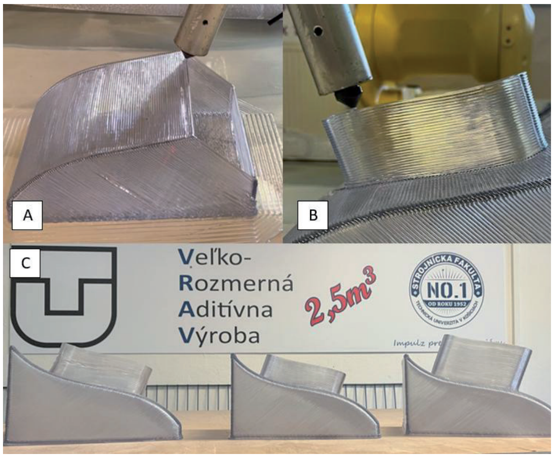

Figure 7: Preview of the manufacturing process of experimental verification. Creation of non-planar surface by angled printing (A). Adaptive printing on the non-planar surface (B). Calibration specimens printed first and final - from left (C).

The final samples (Figure 7 - C) were preceded by two unsuccessful attempts to print the non-planar base at an angle caused by poor choice of the tool head tilting of 43° and 45° angle of the generated layers in combination with high printing speed above 20 mm/s. After the successful calibration of the base print settings according to Table 1, the proposed adaptive printing slicing script of the top sample print demonstrated the ability to achieve the desired result.

5. Conclusions

The printed samples demonstrated the functionality of designed script and 3 samples were printed without bigger problems. The use of the Rhinoceros Grasshopper software extends the possibilities of designing the toolpath and due to its cost can significantly reduce production costs. CAM software for non-planar 3D printing is currently underutilized, which can be seen in the low availability of commercial solutions. With the context of 3D printing applications using industrial robots, the need for such CAM solutions will increase. In this work, a script in RG is presented to prepare G-code for out-of-plane 3D printing and its functionality has been experimentally verified. The validation process with 2 unsuccessful initial attempts reveals of need for further research focused on optimizing the manufacturing parameters like printing speed, base layer angle generation, tool orientation angle, and geometry design limits determination. The experience and the results gained can be used to determine the production limits of adaptive printing. Although the presented script can currently be used mainly for simple geometry, the overall method and the principles presented can also be used for more complex geometries, but this will require a modification of the script, the complexity of which depends on the expected outputs. In the figure Figure 7 - A demonstration of the possible use of RG in solving oblique, non-parallel and custom toolpaths with infill or rib reinforced structures can be seen, however a more detailed and comprehensive presentation of the results is not yet possible as it is in the testing phase. Also, our further research is actually focused on infill structure generation either for layers at an angle or adaptive, with the function of adding the number of walls and generating top and bottom skin layers.

Acknowledgments

This work was supported by the Slovak Research and Development Agency, project title: Research on the possibilities of forming and joining innovative metal-plastic composites in the production of lightweight thin-walled structures" project numbers: APVV SK-PL-23-0040. The authors are also grateful for the support in the experimental work to the project VEGA 1/0539/23: Research on hybrid sandwich structures with customized properties.

The authors would also like to express their special thanks to Fanuc Slovakia company for their support in the realization of the research.

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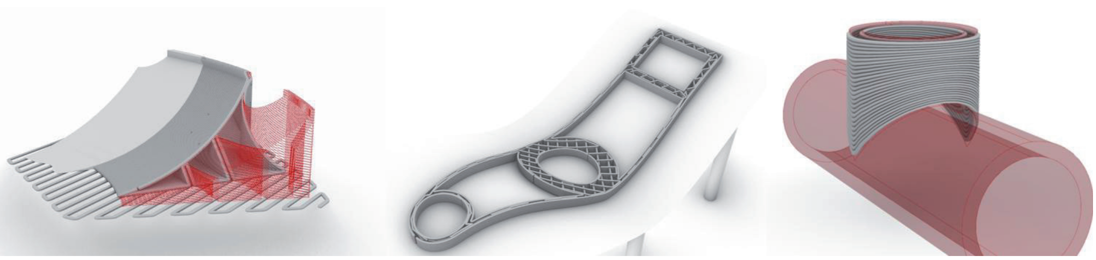

Figure 8: Using the RG software for different approaches to create the desired toolpath movements

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