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Angled G-Code Generator for Robotics Additive Manufacturing

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Abstract: The current state of the utilization of robotic arms in large-scale additive manufacturing (AM) has spurred the development of new hardware and software solutions stemming from the need to reduce the cost of preprocessing and production itself. The use of 6 degrees of freedom combined with the proper software solution for generating the machine motion paths can largely save the time and material required for production of the large-format products. Although several studies have been carried out in this area outlining the possibilities of generating non-planar layers exploiting the potential of 4 or more degrees of freedom all these studies have been carried out by users with programming and complex mathematics skills, which may be a challenge for some users. Therefore, in this paper, the use of Rhinoceros® Grasshopper™ software as a mean for generating non-planar layers is discussed, to offer an alternative option for users without these skills. To demonstrate this, a simple grasshopper system was created to generate angular layers. The challenges and user possibilities were outlined, and experimental verification was carried out on an industrial robotic arm FANUC M-20iB/25 equipped with an MDPH2 pellet extruder. Cube shape part with dimensions 100x100x100 mm was produced and analysed. The proposed method has considerable potential as an option for a non-planar robotics tool path generation, however further research has to be done concerning error free G-code generation and subsequent checking.

Keywords: Rhinoceros, Grasshopper; additive manufacturing; Robotics 3D printing; Large format additive manufacturing

1. Introduction

Industrial gantry 3D printers can produce small objects or thin and tall structures at a relatively fast rate. However, they are not as efficient at building large-section objects. The speed of these AM systems has become unsatisfactory due to the ever-increasing size of products, where even rapid build times take too long for emergency cases, limiting the use of AM in many situations [1]. That is why the use of industrial robots has found application in AM based on polymers, metals, ceramics, and concrete materials. A common approach related with these three-dimensional printing techniques is planar printing head movement only. This implies that the head does not require orientation change even in the X and Y plane (horizontally). However, by utilizing robotics additive manufacturing, this is not the case. The material deposition instrument requires at least one additional degree of freedom to overcome these limitations [2][3]. In the context of automated digital manufacturing, AM technologies are integrated with six degrees of freedom (6-DoF) robotic systems to enhance the printing process and boost produc-

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tivity [4]. Multiaxial deposition can also be achieved using specific hardware solutions with multiple degrees of freedom, enabling the deposition of material along multiple directions. Researchers are attempting to utilize shape topology optimization to reduce waste production, thereby ensuring the creation of the next generation of sustainable and efficient structures. The use of multiaxial deposition eliminates the need for support, thus reducing the overall time and risk of damage to the final product through the absence of post-processing. The extrusion response of the printed material, manufacturing parameters and the material properties influence the quality of the printed component in terms of structural stability and surface finish quality.

Non-planar slicing, non-uniform slicing, and volume decomposition are not available in most commercial slicing software [5][6]. Consequently, a tailored solution must be developed in order to achieve satisfactory results [7]. This will entail the development of a toolpath planning technique that considers the manufacturing constraints to secure a collision-free and effective toolpath trajectory [2]. This presents a significant challenge for contemporary automation and robotics, particularly when the objective is to manufacture larger components in a shorter timeframe [3]. The construction of tool paths represents a pivotal aspect of robotic additive manufacturing, with the role of the efficacy of the toolpath strategy in the production of parts that are geometrically accurate, defects-free, possess robust mechanical properties and exhibit minimal residual stress[4]. The scale of utilization and the method of robotic additive application vary considerably. Despite this, the challenge of designing robots with collision-free trajectories and effective tool paths persists [2].

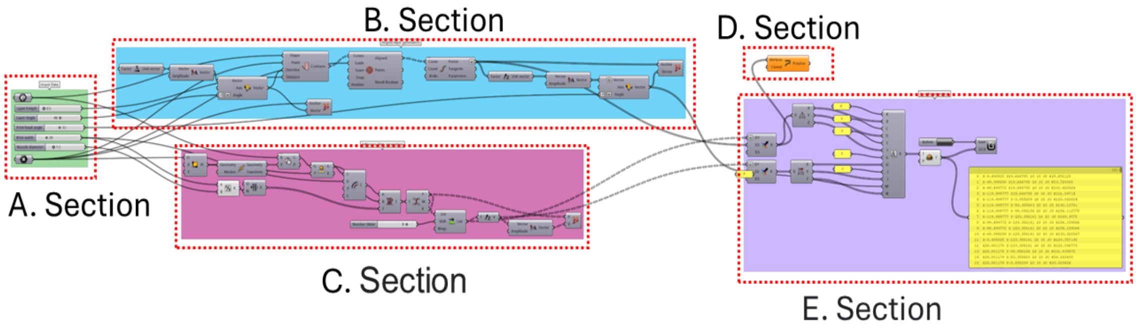
Several studies have already been carried out in this area, such as the study by Etienne et al. with Shape modelling computation methodology which is capable of creating non-planar objects by deformation of the model and use standard planar slicer in combination with quadratic programming solver [8], work of René K. Müller with EnochSlicer and MatatronSlicer in early development using trigonometry coordinate translation and G-code postprocessing [9]. Michael Wüthrich et al. slicing strategy focused on Geometrical pre- and post-transformation based on conical slicing, using python script executed on a custom 4 -axis printer RotBot with rotational printing head [10], research presented by Basit Khan with model integrating Bézier curve techniques in python programming language incorporating specialized algorithm for 5Axis FDM printer [11] and other slicing algorithms based on computation of a scalar field representing the accumulation sequence of material within the shape with dimension reduction strategy where result is a methodology to compute advancing fields for material accumulation by always performing material deposition along the surfaces of convex hulls [12] or volumetric curved layer decomposition method based on the computation of the optimal radial basis functions field to modify the fabrication sequence field, from which the iso-surface layers are extracted to design the corresponding multi-axis printing tool paths [13].

However, these are all solutions that require knowledge of advanced mathematics, programming skills, and in some cases additional software for post-processing and browsing G-code, which can be a challenging process for people with a lack of these skills. In addition, most of these solutions are related to Fused Filament Fabrication (FFF) techniques for production of complex small parts, and the advanced features of these methods may not be necessary in the context of true large-format additive manufacturing where the final product needs to be designed and produced quickly, simply even at the cost of additional machining.

The study aimed to design an algorithm for non-planar slicing in the visual programming language, software environment of Rhinoceros® Grasshopper™ (RGH) and experimentally verify it by manufacturing on an industrial robot by the Fused Granular Fabrication (FGF) method. The results of the experiment showed that such an approach of non-planar slicing and subsequent AM is possible; however, during the experiment itself, the errors of the algorithm became apparent and pointed to the necessity of further optimization.

2. Experimental Section

To demonstrate RGS capabilities the integrated tool and functions were used to generate angled tool path movement and experimentally verified. The main objective was to create sequences of positions and orientations of the tool centre point (TCP) by intersection of user-defined inclined planes and B-rep geometry of the test sample. To achieve this,



several integrated function and position-obtaining blocks were used. The experiment was conducted on a FANUC M-20iB/25 robot equipped with an MDPH2 pellet extruder. Designed angled slicing system-script, consists of 5 sections which are parametrically connected and convert input data into printable G code. The principle of how the script works is explained step by step below.

In Section A (Figure 1) of the Grasshopper Script, input manufacturing data parameters are defined. Users can set individual printing settings as layer angle generation parameter, layer height, tool orientation angle, nozzle diameter, and adhesion brim width. Input Geometry to be sliced must be imported in B-rep format and loaded into the B-rep component, also start point reference (Figure 2) served as the start point of layer generation and in this case as a seam alignment reference for generated layers to secure proper layer direction and point order in process of tool movement.

The contour's function is used for layer generation in section B (Figure 1). The curve divide function must be used to obtain points on those layers, and vectors are computed and generated from these points to orient the print head accordingly. The cube geometry with side length of 100 mm was adopted to validate the script and present the approach. A graphical view of the generation of layers, points, and vectors can be seen in Figure 3. For better adhesion to the build plate, Section C was created for Brim generation where tool vectors are generated perpendicular to the build plate, as can be seen in (Figure 3 F). In the Figure 3, a 5 mm layer height is used for better presentation of the graphical preview of the script.

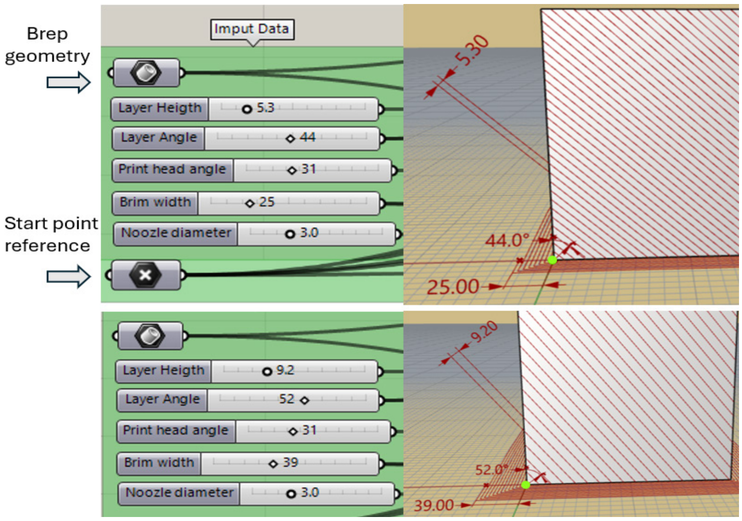


Figure 2: Detailed View of section A with input parameters interpretation in graphical preview.

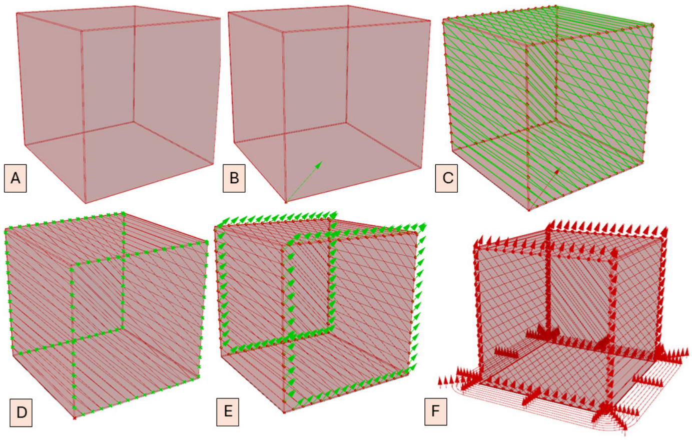


Figure 3: Graphical preview of the script workflow: (A) Input Brep geometry. (B) Start point and vector as a reference. (C) Preview of generated angled layers. (D) Generation of points for tool position. (E) Generation of vectors for tool orientation. (F) Final preview of generated points and vectors as input data for robot tool movement instructions.

After points and vectors generation, a simple polyline function can be used marked as section D (Figure 1) to connect all generated points to verify point order and make corrections if necessary. Connecting the lists of points and vectors from sections B and C is made in section E (Figure 1) with the Merge function. Points are subsequently deconstructed into X, Y, Z coordinates, vectors into I, J, K coordinates and stored in proper order to the g.code format or .txt if desired. The final preview of the script result while verifying in section D (Figure1) can be seen in Figure 4. As demonstrated when layer count increases by lowering layer height to 0.5 mm, misinterpretation of the point position occurs and affects the point order which leads to layer merge shifting (Figure 4, Detail A.). After analysing the error, we concluded that at the stage of experimental development of the G-code with the need to make a test print of the samples, this error is not such an obstacle that would prevent this, and therefore we still decided to use the generated G-code even with the error.

Generated G-code was uploaded into the robot-simulating software RoboDK® where was translated into the robot's movement language program. Start/end procedures setup, final checking for possible collisions, and final steps of the robotics 3D printing workstation preprocessing were made. The robot program was then uploaded to the control unit and executed. The process of 3D printing can be seen in Figure 5. The printing parameters were settled according to Table 1 with continuous extrusion of the material.

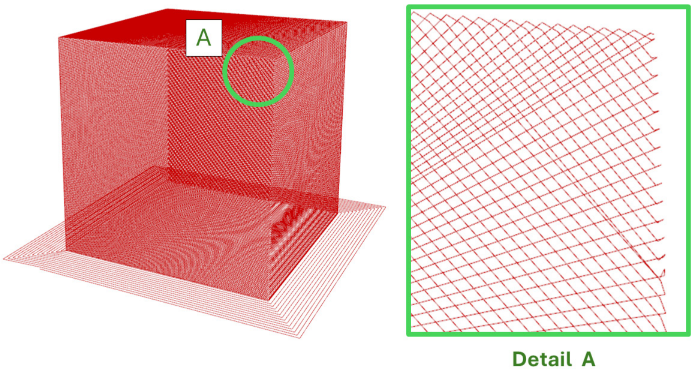


Figure 4: Preview of the final script generated.

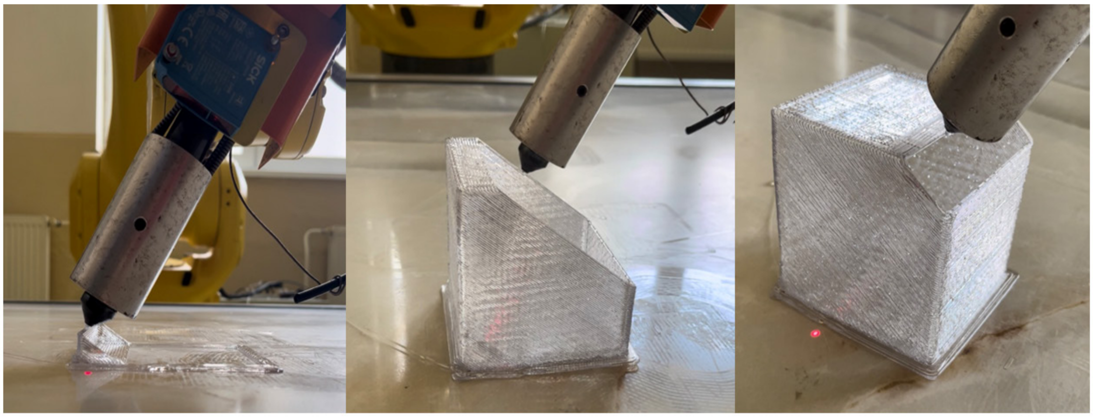


Figure 5: Test sample printing process for script verification

Table 1: Manufacturing parameters of the printed sample

Printing speed	20 mm/s
Layer height	0.5 mm
Layer width	1.5 mm
Nozzle temperature	220 °C
Nozzle diameter	1.5 mm
Brim width	20 mm
Layer angle	48°
Tool head angle	33°
Used material	PETG

Compressed air was used for cooling layers to help solidify the bridged top layers of the part. The angle of generated layers and tool head angle was set according to our previous experience of angled printing experiments to avoid interruption of granule feeding from hoper.

3. Results and Discussion

We have implemented the proposed method of non-planar tool path trajectories generation for multiaxial deposition. Robot simulation software RoboDK was used to translate generated G-code into robot's movement language and executed on FANUC M-20iB/25 robot equipped with an MDPH2

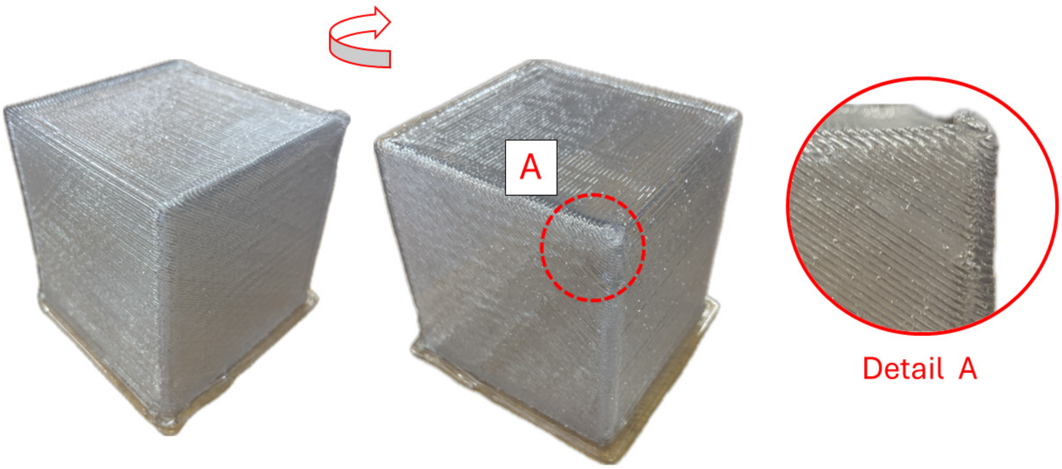


Figure 6: Results of the printed sample with a defect in detail A

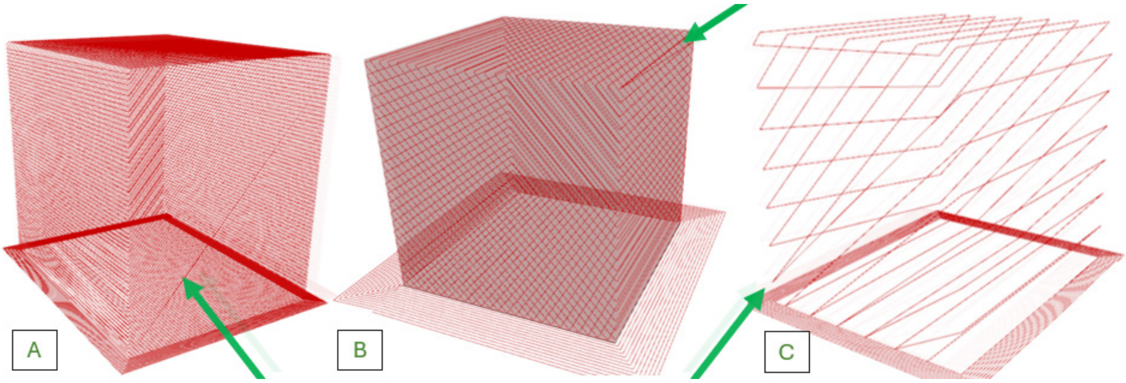


Figure 7: Error persistence despite changed parameters: (A) Cube with dimensions 300x300x300 mm (B) 1.5 mm layer height (C) 15 mm layer height.

pellet extruder. Based on the established parameters, the final cube shape part with dimensions 100x100x100 mm was produced in 35 minutes. A detailed preview of the result can be observed in Figure 6. Detailed view A represents the result of the printing with the error that we assumed in the pre-printing stage Figure 4. .

Different combinations of input data (Fig.2) were tested to determine the cause of the error (Figure 7) but the error persisted and appeared randomly, regardless of the change of the input parameters such as layer height value, layer angle, or geometry size including changing input CAD data format from B-rep to STL. This leads us to the fact that the error is not caused by malicious geometry, but it can be caused either by incorrect functioning of seem alignment function which has to ensure the correct sequence of points during the tool movement, or contour function which, for reasons not yet known, causes the direction of the created curve to change. Therefore, an additional sub-system must be created to detect and correct such changes.

The work also resulted in the finding that manually checking the G-code for large parts can be a challenge as the G-code display becomes incomprehensible due to software rendering. The software allows a system to be created using integrated functions to display the complex G-code in smaller parts (Figure 8.), allowing for a more manageable inspection. Therefore, further research will focus on creating systems that could automate this process, as well as detect and highlight such errors.

4. Conclusions

By successfully printing a sample Figure 5. the proposed method demonstrated the potential of using Rhinoceros ® /Grasshopper™M as a software alternative in the field of non-planar large-scale additive manufacturing. The script has met expectations, and the development in this direction has

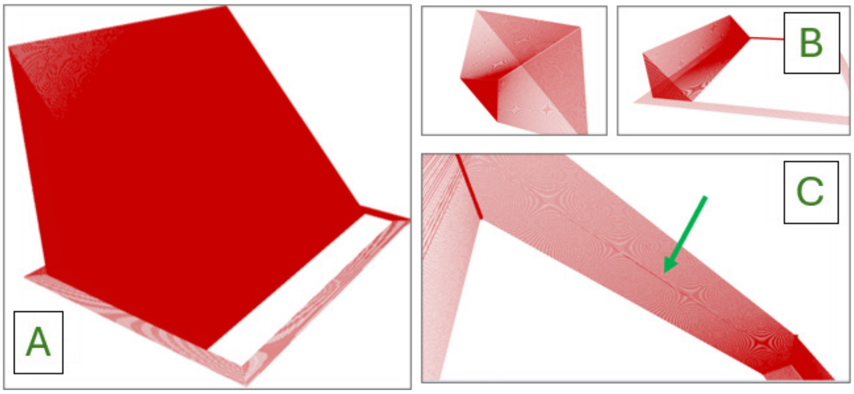


Figure 8: Large size parts G-code checking: (A) Incomprehensible preview of G-code, (B) Partial view of G-code,(C) Determination of the error.

considerable potential. The Rhino software with the Grasshopper plugin appears to be an applicable option for robotic tool path trajectory generation so far with capabilities to design complex algorithmic structures with customization. As predicted misinterpreted point position in Figure 4. the same error appeared in the final results on Figure 6 as indicated in detail A. Ensure the correct sequence of points which define robot tool movement path is crucial. Equally important is the user's ability to quickly and efficiently review the generated movements and take corrective action if necessary, therefore, further research will focus on automation of aforementioned tasks and optimizing the script for the most error-free G-code generation tool and expanding its user capabilities.

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