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Determination of Design Limitations of Curved Profiles Manufactured by Robotics Non-Planar Additive Manufacturing

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ABSTRACT

The emerging trend of employing 4 or more axes multi-purpose and gantry industrial robots in large format additive manufacturing presents numerous opportunities as well as challenges. The capacity to handle substantial material quantities and rapidly produce prototypes, instrumentation, and final products of considerable dimensions necessitates the formulation of a well-suited production strategy. This involves setting production parameters to minimize material consumption and production time, considering the limitations of the utilized technologies, and ensuring the final product's quality. While slicers are commonly employed for establishing manufacturing strategies and production parameters, most additive manufacturing slicers are optimized for planar 3 axes 3D printing. This limitation hinders their ability to generate non-planar and freeform toolpaths. To overcome this constraint, this paper delves into the utilization of parametric modelling as a potent tool in the realm of non-planar additive manufacturing. It explores the possibilities offered by Rhinoceros Grasshopper software in designing toolpath strategies and fabricating non-planar layers. The paper addresses the associated challenges and limitations of parametric modelling, including computational complexity and the requirement for specialized software and expertise. It emphasizes the crucial need to strike a balance between design complexity and manufacturability to ensure the successful implementation of non-planar additive manufacturing processes.

Keywords: robotics additive manufacturing, parametric modelling, grasshopper, non-planar printing, G-code, large format additive manufacturing

INTRODUCTION

The development of manufacturing strategies, particularly concerning the slicing and creation of tool paths for Large Format Additive Manufacturing (LFAM), poses a significant challenge due to various factors such as complex geometries, material properties, and the range of available technologies. Although the widely used planar slicing method is simple and reliable, it often necessitates support structures, resulting in increased time and costs. In contrast, alternative techniques like multi-directional slicing and non-planar slicing (involving curved layers) have been proposed. These approaches aim to reduce reliance on support structures, improve surface quality, and enhance the strength of manufactured parts. Departing from the traditional practice of uniformly applying planar slicing or employing intricate methods like decomposing and regrouping to determine optimal slicing directions, the suggested approach primarily concentrates on the strategic use of both planar and non-planar slicing. At its core, slicing aims to create a sequence of flat or curved layers, crucial in the subsequent path planning process. This path planning significantly influences the precision and performance of the final 3D printed object [1].

In the past few years, novel manufacturing techniques in additive manufacturing and advanced robotics have emerged and gained traction across various industrial sectors, ushering in a transformative shift in the production of goods. The integration of multi-axis robot systems with additive manufacturing technologies has paved the way for multi-axis additive manufacturing, enabling the creation of diverse geometries in various manufacturing settings. The utilization of robotic additive manufacturing is also creating opportunities for in situ fabrication, extending the capabilities of robotic fabrication beyond the confines of the production platform. A predominant application of robotic-assisted extrusion-based systems involves the production of freeform organic shapes, construction elements and the manufacturing of large-scale objects. This signifies a departure from traditional manufacturing methods, offering new possibilities and expanding the scope of robotic fabrication processes in diverse industrial contexts [2].

Common planar slicers as UltiMaker Cura, PrusaSlicer and Slic3r are limiting the multi-axis fabrication to XY plane what largely restricts its possibilities. This is due to the inherent character of the planar construction, where the materials are deposited layer upon layer causing weaker inter-layer bonding and even layer disconnections while printing curved wall surfaces (Figure 1).

As common planar slicers (above) are solutions created for wide range desktop 3D printers used by many users, some attempts of non-planar slicing have been made in this area to by applicable for. The study by Etienne et al. Shape modelling computation methodology is capable of creating non-planar objects by deformation of the model and use standard planar slicer in combination with quadratic programming solver [3] or work of René K. Müller with EnochSlicer and MatatronSlicer in early development using trigonometry coordinate translation and G-code postprocessing [4] are solution which are requiring complex math, programming skills, software for post processing and G-code viewer may be difficult for people with lack of this capabilities. Our solution is focused on certain specifics application in field of robotics arm additive manufacturing where individual customization is needed in case of nonplanar additive manufacturing and individual setting for user specified segments, direct customization and viewing of the G-code in house of Grasshopper software.

A significant challenge in adopting multi-axis 3D printing with robotics is the complexity associated with obtaining or creating a slicer capable of generating a curved toolpath. While several non-planar 3D printing slicer software solutions exist in the market, another option involves personally developing multi-axis slicing algorithms using numeric computing environments. However, the affordability of non-planar slicers and the potential limitation in the programming skill set of mechanical engineers pose hurdles to their widespread use. In addressing these challenges, the extension of Rhinoceros 3D modelling software, particularly using Grasshopper parametrical visual scripting, emerges as a viable and practical option. This approach provides a reasonable solution, offering a user-friendly interface that may be more accessible to mechanical engineers who may not have extensive programming skills. The integration of Grasshopper into Rhinoceros 3D facilitates the development of customized and intricate toolpaths for multi-axis 3D printing with robotics, potentially overcoming some of the barriers associated with this advanced manufacturing technique [5, 6].

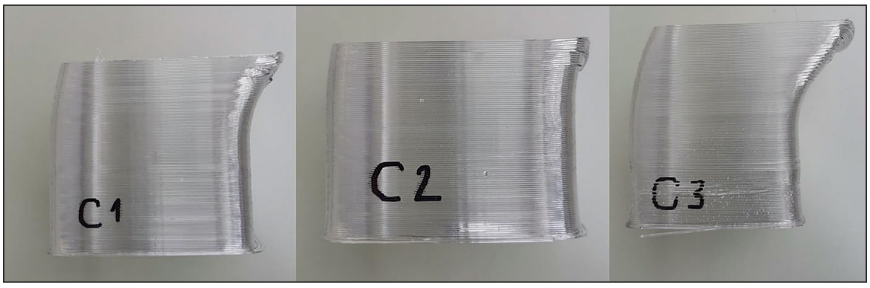

Figure 1. Samples with overhang defect as result of planar slicing

METHODS

Related to the layer height change of the non-planar layers generation which is an integral part of the non-planar printing process, to the authors' knowledge within today, there is not a script in Grasshopper 3D that performs determinations of layer height related limits for non-planar additive manufacturing which are greatly affecting the design possibilities. Based on this knowledge to determine these limitations the multi-axis slicing script (Figure 2) for simple parametric changeable model of profile extruded along curve was made to generate G-code. With the help of several integrated function blocks and special positions obtaining blocks custom script was made using the Grasshopper environment, and the experiment was performed on FANUC M-20iB/25 robot equipped with MDPH2 pellet extruder (Figure 7). According to the Figure 1 compressed air with constant pressure of 0.15 MPa was used for cooling of layers. PETG material in form of pellets was used to print the samples.

Grasshopper 3D facilitates the parameterization of graphic design, enabling the creation of virtually any shape by leveraging a comprehensive set of mathematical tools. One of Grasshopper 3D's notable strengths lies in its openness to third-party developers, empowering them to design their own plugins within the program. These plugins can be accessed through the Grasshopper marketplace, often available for free after acquiring the Rhinoceros software. The seamless interoperability between Rhinoceros and Grasshopper plugins enhances the capabilities of the software. Users can perform intricate operations such as meshing solid elements directly in Grasshopper 3D, engage in parametric B-rep modelling, generate points and vectors, and solve intersections, among other functionalities. Consequently, modifications to the design or its appearance are not labour-intensive; they can be automatically updated within Grasshopper 3D and analysed by engineers. This dynamic integration streamlines the design process, offering flexibility and efficiency in responding to changes or optimizations in the design [7, 8]. Engineered and analytical model can be linked using the presented tool inside Grasshopper 3D. The opportunity to get performance feedback during design exploration and backward use it to enhance of design is presented and tested in practical part [9]. This study present determination of design limitations for non-planar printing by creating and slicing of extruded profile along curve made in Rhinoceros Grasshopper Script. Script results are presented as preview in graphical interface of Rhino software are presented at Figure 4, Figure 5 and Figure 6.

In the section A (Figure 2) of the Grasshopper Script, profile geometry, dimensions, profile centre and orientation on build plate are defined. User can set individual setting to profile size, curvature radius of profile, layer height, position of measurement, Dimension plotting parameters and save G-code to desirable folder Figure 3. Section A (Figure 3) is the only user editable section of the script. Sections B, C, D, E (Figure 2) have computational and preview purpose only and shouldn't be edited by user. Functionality explanation of every single function block can be accessed in software interface directly which is also helped by the individual function icons and descriptions of their functionality therefore the article is focused on the description of the sections as a whole in which these functions are located and perform the calculation. The pilot version of the Script and its functionality can be explored by downloading it from the web link [12]. Generation of profile guide based on user

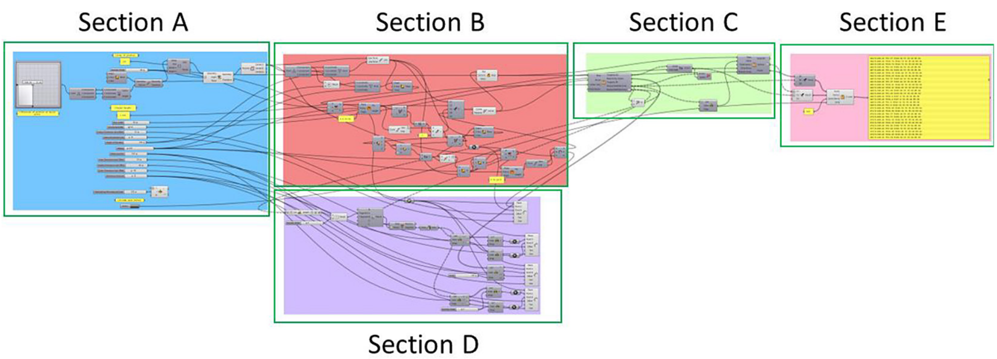

Figure 2. Multi-axis slicing script for the parametric changeable model

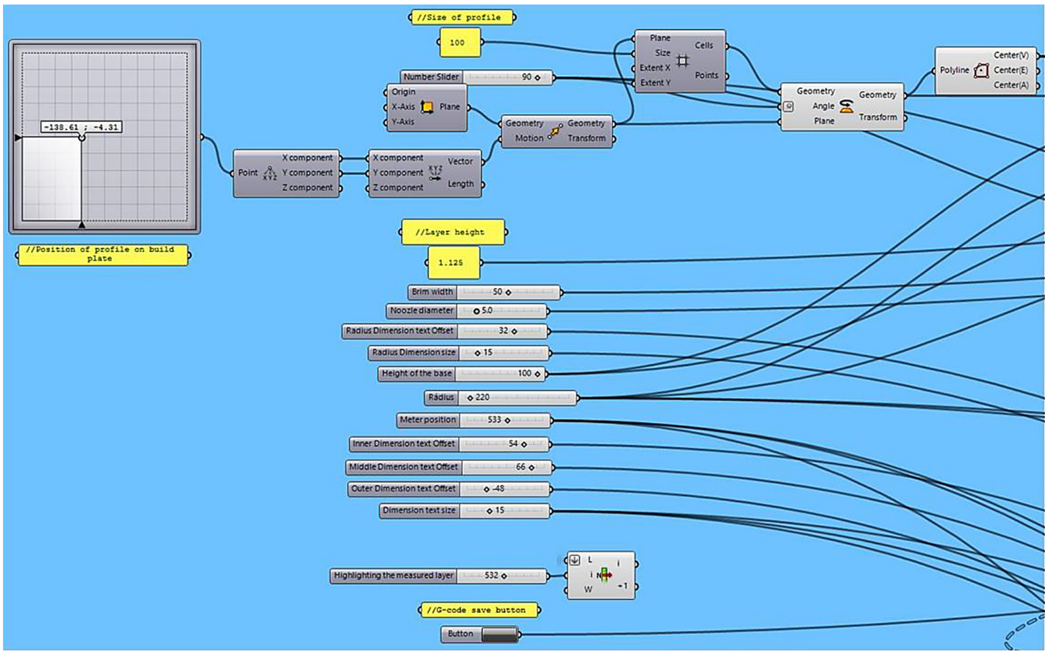

Figure 3. Detailed view of section A with user defined parameters of the script

settings is defined in section B (Figure 2). B-rep loft is created from defined profile and guided curve. The intersection of the profile guided curve generated planes and B-rep loft is made in section C (Figure 2) Script is creating points on user defined curve with user defined range pattern (layer height). Construction planes are created with origin in these points and normal of the planes are aligned with tangents of these points to created curve. B- rep geometry (profile) is intersected with created planes which define new variable for further processing in section C Figure 2 where points and vectors are created Figure 5. Generated intersection curves served as layer indicator Figure 4. Points and vectors are generated at the intersection curves for target movement and nonplanar orientation of the extruder in these points. The orientation of the extruder is represented by the generated points and their normal identical to the intersection planes normal. Curvature radius can be parametrically modified in section A (Figure 2) to get an optimal layer height in curved areas. Distance between minimum and maximum layer height is parametrically updated depending on change of layer height and curvature angle of the profile guide curve. Layer heights in user determined position are computed in section D Figure 2. where points at determined layers are obtained from the list of points in section E Figure 2 and distance is measured and plotted in section D Figure 2.

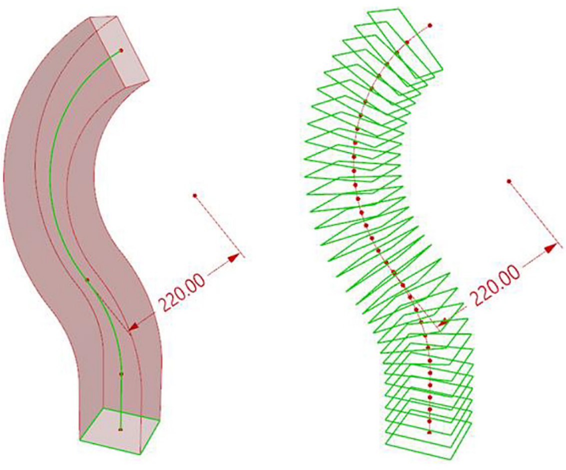

Figure 4. Curve leaded planes generation and intersection

Finally, position obtaining of points and vectors can be done in section E Figure 2 and exported in G-code format. After generating of G-code it is necessary to upload the G-code into robot simulating software RoboDK where the robot movement is settled, and G-code is converted into robot movement language. Set up of start/end procedures, checking of possible collision and upload of program to the robot are final steps of preprocessing of robotics 3D printing. At this point, extrusion speed control of the extruder tool is controlled separately. Ratio between nozzle and maximum layer height should be in range 25% to 80% of nozzle diameter to secure appropriate

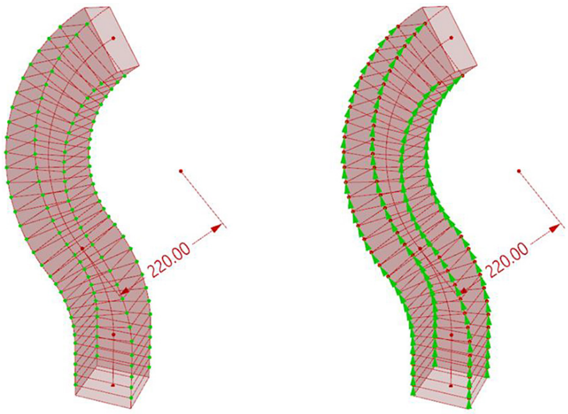

Figure 5. Points and vectors generation

layer bonding but from our experience we settled the range from 25% to 75%. The range serve as layer height boundary limits for created non-planar printing script in Grasshopper. Considering this we choose 37.50%, 50% and 62.5% ratio to determine maximum curvature angle of designed profile as shown in Table 1 [10].

In the Grasshopper Script, squared shape profile was designed with dimensions of 100x100 mm and curvature radius with nozzle diameter changed according to Table 1. Results of non-planar slicing can be observed in graphical interference of Rhinoceros (Figure 6). All parameters can be parametrically modified and layer heights dimensions at inner, middle and outer curvature plotted at desirable height. With the setting of parameters like nozzle diameter, middle layer height and curvature angle it is possible to find maximum curvature radius with subject to the conditions of border layer height limits.

TEST SAMPLES PRINTING

Offline programming and simulation of the robot's movements was done in specialized RoboDK software for industrial robots with 3D printing plugin (Figure 7). Converted robot language was transferred to the control system of the robot and then executed. The script tests the dependencies between profile dimensions, radius of the profile guide curve, nozzle diameter and layer hight and their impact on the design limitation for non-planar additive manufacturing. Several samples were printed for validation of method functionality and used for further analyse.

In process of non-planar printing constant extrusion speed was settled (Table 1) which is immutable to this testing. Setting of the

Table 1. Manufacturing and design parameters of printed samples [11]

Sample	Nozzle diameter [mm]	Layer height [mm]	Radius of guide curve [mm]	Cooling [on/off]	Extrusion speed [RPM]	Printing speed [mm/s]	Extruder temperature [C°]
A1	1.5	0.56	150	off	4	50	220
A2	1.5	0.75	100	on	7	50	220
A3	1.5	0.937	250	on	10	50	220
B1	3	1.12	150	on	18	50	220
B2	3	1.5	100	on	21	25	220
B3	3	1.87	250	on	24	25	220

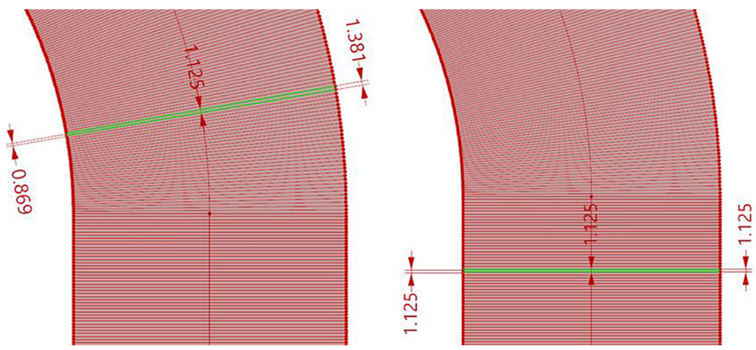

Figure 6. Preview of plotted dimensions of layer height at inner, middle and outer curvature in graphical interference of Rhino software

extrusion speed value was based on experimental verification by planar printed samples where extrusion and printing speed was settled according to layer height and layer width dimensions. The goal was to keep the width of the layer equal to the diameter of the nozzle. Adaptive extrusion change related to actual limit layer height is not implemented in the script yet, samples A1, A2, A3, B1, B2, B3 where printed and analysed (Figure 8).

RESULTS

Printed samples proved that designed script is working and 5 from 6 samples were printed without problem even through over extrusion at inner curvature caused by constant extrusion speed. Sample A1 was printed without cooling because layer height was small enough to cool itself, but compressed air had to be used when printing other Samples. Printing of Samples B2 and B3 by same

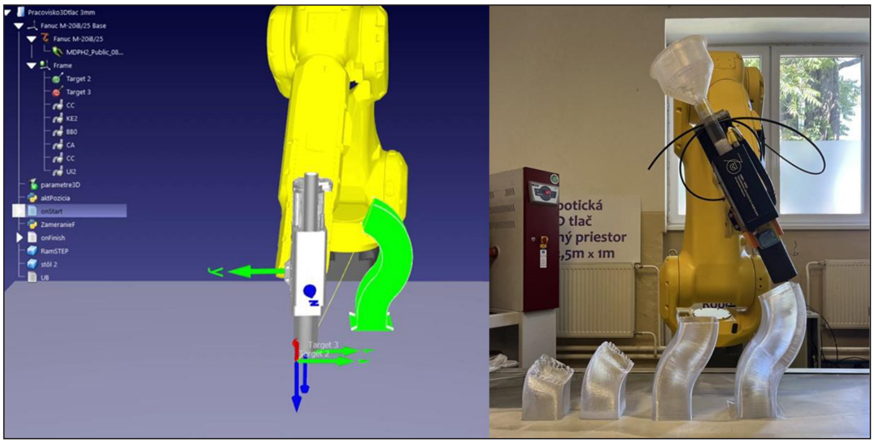

Figure 7. Simulation in RoboDK software (left) and test samples printing process (right)

Figure 8. Printed samples (top) and graphical preview of samples (bottom) [11]

speed of 50 mm/s the failure of the print occurs because of increasingly amount of extruded material due to increasing layer height and thus printing at lower speed was required to extend time for cooling off the layers. Due to the absence of active controlling of extrusion speed, layer width gets thinner when layer heights increased that's why printing process of B2 sample was stopped due to a critical over extrusion at inner curve so there was no point in continuing. According to the set parameters (Table 1) and the results of the printed samples (Figure 7), of 100×100 mm profile extruded along a curve, the maximum radius of curvature is 100 mm and can only be achieved in combination with a layer height equal to 50% of the nozzle diameter. Future research will be focused on controlling of extrusion speed and creation of script that will secure uniform adaptive extrusion related to layer height.

CONCLUSIONS

There are a lot of potential and challenges associated with the growing trend of using gantry industrial robots and multi-purpose robots with four or more axes in large format additive manufacturing. Setting production parameters to reduce material consumption and manufacturing time, considering the constraints of the design and technologies used, guaranteeing the quality of the finished product are all part of this. Their ability to create non-planar and freeform toolpaths are essential part of new generation slicers and used methods. The investigated possibility of generating non-planar layers using parametric modelling proves that this method can be used as an alternative to commonly used programming software for generating non-planar layers and can offer wider possibilities with individual settings of G code generation and obtain the desired results. Further research will focus on improving the existing script and applying it to determine the manufacturing parameters of more complex shapes.

Acknowledgments

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