Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2018
August 26-29, 2018, Quebec City, Quebec, Canada

DETC2018-85459

AN ALGORITHM FOR GENERATING 3D LATTICE STRUCTURES SUITABLE FOR PRINTING ON A MULTI-PLANE FDM PRINTING PLATFORM

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ABSTRACT

Manufacturing processes for the fabrication of complex geometries involve multi-step processes when using conventional machining techniques with material removal processes. Additive manufacturing processes give leverage for fabricating complex geometric structures compared to conventional machining. The capability to fabricate 3D lattice structures is a key additive manufacturing characteristic. Most conventional additive manufacturing processes involve layer based curing or deposition to produce a three-dimensional model. In this paper, a three-dimensional lattice structure generator for multi-plane fused deposition modeling printing was explored. A toolpath for an input geometric model with an overhang structure was able to be generated. The input geometric model was able to be printed using a six degree of freedom robot arm platform. Experimental results show the achievable capabilities of the 3D lattice structure generator for use with the multi-plane platform.

INTRODUCTION

Additive manufacturing (AM) is a process of joining materials to make 3D objects from a 3D geometric model. Additive manufacturing processes are usually carried out layer upon layer to fabricate the 3D objects. Additive manufacturing processes have growth over the last thirty years from prototype development to the direct production product [1]. The AM process is capable of fabricating complex geometric structures which have limitations in fabrication using conventional machining. Three dimensional (3D) lattice structures are one of the complex geometric structures which involves a multi-step fabrication process in order to be produced using conventional manufacturing processes. With the AM process application, the 3D lattice structure can be fabricated in a single manufacturing process. For polymer based material, fused deposition modeling is one of the processes that can be used to print a 3D lattice structure.

Fused deposition modeling (FDM) is an AM process that utilizes the material extrusion process to print an object. The material extrusion process is performed by extruding a filament through a heated nozzle. The extruded material is then extruded layer upon layer to complete the 3D object. Most of the conventional 3D printing systems utilize single-plane layering to print a 3D object.

In recent years, multi-plane 3D printing platforms have been getting attention from both industry and academia. One example is from a company called VSHAPER. VSHAPER introduced a five-axis FDM machine for multi-plane printing applications [2]. The VSHAPER five-axis machine is capable of creating three-dimensional models with the simultaneous use of all of the machine's axes. In addition to the industrial machine from VSHAPER company, multi-plane printing platforms using a robot arm have been explored by other companies such as AiBuild [3], Mataerial [4], and Branch Technology [5].

As research has progressed, multi-plane 3D printing platforms have been utilized in architectural fabrication and 3D printing process improvements. For applications in the architectural fabrication, Iridescence Print by Volker et al. [6], Huang

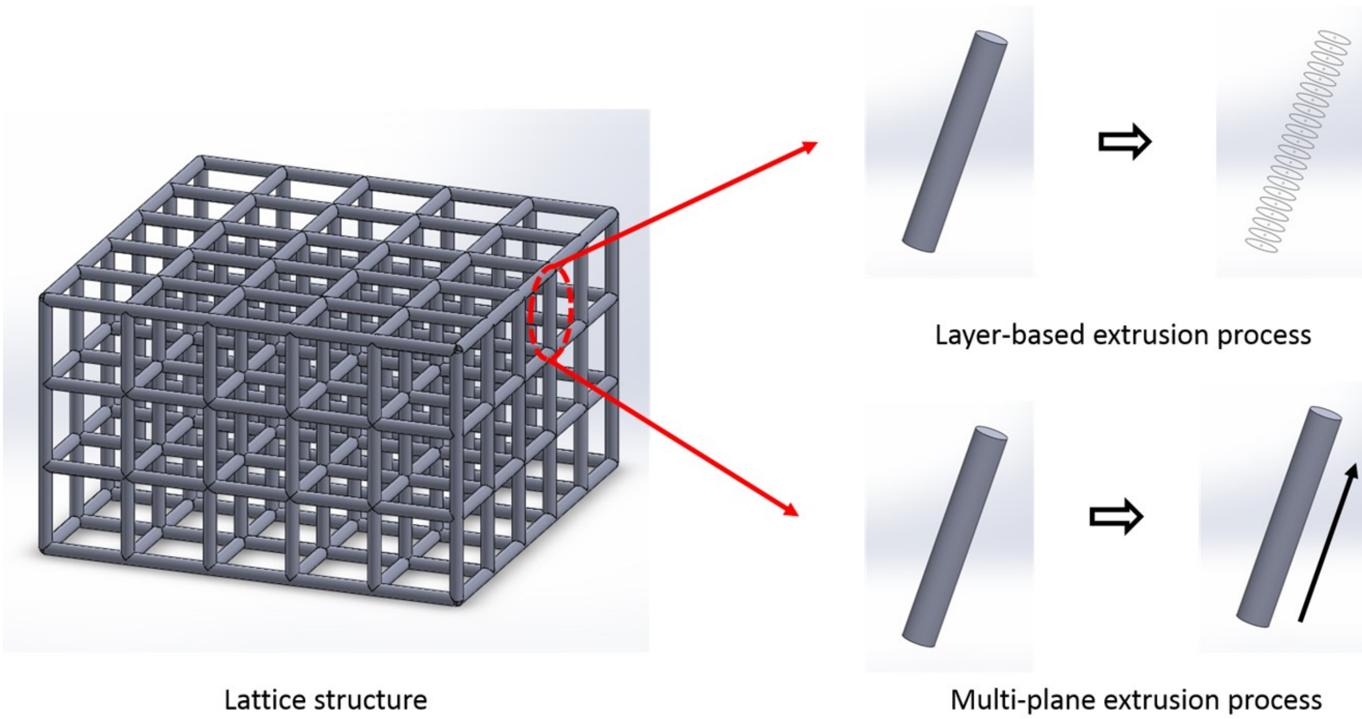

FIGURE 1: COMPARISON OF 3D LATTICE STRUCTURE FDM PRINTING BASED ON DIFFERENT APPROACHES.

et al. [7], Yu et al. [8], Yuan et al. [9], and Mesh Mould by Hack et al. [10] are using a robot arm platform for spatial 3D printing applications. One of the improvements is creating faster prototype fabrication. Faster prototype fabrication can be done by having a wireprint print structure instead of having a solid print object. Mueller et al. [11] introduced a WirePrint concept for fast prototyping applications by printing a wireframe stucture model in spatial space based on the object's outer surface. Similarly, Huang et al. [7] introduced the FrameFab system for printing frame shape's structure and Wu et al. [12] introduced the arbitrary meshes printer for wireframe printing. All of this research was completed to print a 3D model as a wireframe structure based on the object's outer surface geometry. There were no internal structures on the wireframe model developed from these research projects.

Another advantage of using multi-plane platforms for the 3D printing process is that support structures can be eliminated for printing an object with an overhang. Algorithms for multi-plane slicing have been explored by Singh and Dutta [13] in 2001. Song et al. [14], Lee and Jee [15], and Lee et al. [16] demonstrated the capability of printing an overhang structure without support material using a multi-directional printing platform. Meanwhile, Keating and Oxman [17] used a multi-plane build platform using a robot arm with a stationary FDM extruder for the multi-plane printing application. The capability of printing an overhang structure was done by aligning the overhang structure orthogonal to the build direction.

In summary, the above studies are geared towards multi-plane printing processes for wireframe printing and utilizing the capabilities of the multi-plane platform to print an overhang structure without support material. The wireframe printing only considered the object's surface model to print the object. The internal structure for the wireframe printing is void. In this research, we present a 3 dimension lattice structure generator for multi-plane FDM printing applications. The proposed 3D lattice structure generator will generate a symmetrical cube lattice to replicate the input geometric model. The cube lattices are extruded along the geometric shape without the need for the struts to be sliced as shown in Fig. 1. With the capability of the multi-plane platform to perform multi-plane motion, the input object with an overhang structure can be printed without using any support structures.

ROBOT ARM FDM PLATFORM

The multi-plane printing platform used for printing a 3D lattice structure was a six degree of freedom industrial robot arm from Motoman, model SV3X. This work using a robotic arm FDM printer is the continuation of previous work by Ishak et

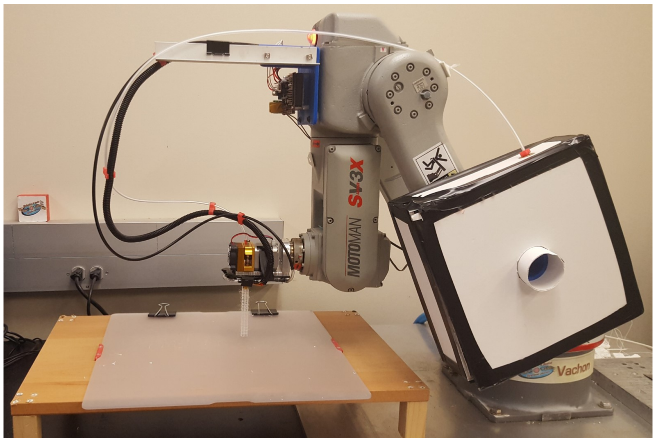

FIGURE 2: ROBOT ARM FDM PLATFORM.

al. [18] involving robotic arm printing applications. The robot arm was integrated with an FDM extruder which extrudes filament made of polylactic (PLA) plastic. A 0.4 (mm) extruder nozzle was used for the FDM extruder. The repeatability of the robot arm platform is 0.03 (mm). The robot arm platform that was used as the multi-plane printing platform is shown in Fig. 2.

3D LATTICE STRUCTURE GENERATOR

The 3D lattice structure generator for multi-plane FDM printing was written in Matlab scripts. The input to the generator is a 3D geometric model in the stl file format. The 3D lattice generator produces a toolpath for the input 3D geometric model to be printed using a multi-plane printing platform. The robot motion is planned to position the FDM nozzle along the output toolpath. The overview for the algorithm is shown in Fig. 3 and an example of the input geometric stl model is shown in Fig. 4.

Region Based Segmentation

In the first stage, the imported 3D geometric stl model was segmented based on the model region. The objective of the region based segmentation is to exploit the capability of printing the object on multiple planes. There are five possible segments that can be used for printing the input 3D geometric stl model that has overhang structures in all directions. The first assigned segment was a base structure. The base structure was defined by the segment of the input 3D geometric stl model without the overhang structures. The base structure was defined to be printed in the x-y plane (Z+). The next two assigned segments were segments protruding from the base structure in the Y-axis direction. The protruding segment's width was defined to be within the base width limit in the X-axis direction. The segments width limit was used to ensure the other planes printing process could be executed without collision. The protruding structures can only be

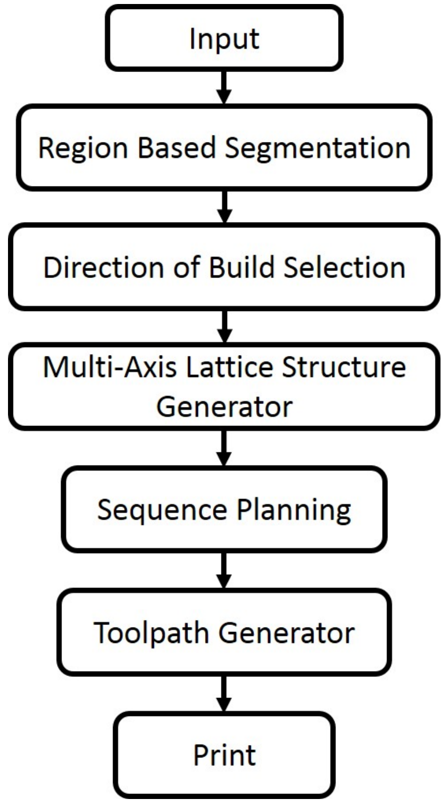

FIGURE 3: OVERVIEW OF THE ALGORITHM.

printed from the base structure. The base structure becomes the build platform structure to be printed in the Y-axis direction. The Y-axis direction was printed in the x-z plane (Y+,Y-). The two segments were based on the protruding structures in the Y-axis positive and Y-axis negative directions from the base structure. Last two assigned segments were segments protruding from the base structure in the X-axis direction. The printed segments from the Y-axis direction and the base structure become the build platform structure on which the next segment that will be printed in the X-axis direction. The X-axis direction was printed in the y-z plane (X+,X-). The two segments were based on the protruding structures in the X-axis positive and X-axis negative directions from the base structure.

In order for the object to be printed without a support structure, two criteria were used to segment the input geometric model. These criteria are:

1. Determine a set of build directions for the input model (Z+,Y+,Y-,X+,X-).
2. Decompose the input model into segmented regions based on the overhang structures.

For the example input 3D geometric stl model, five different segments were used to utilize different build directions. The top

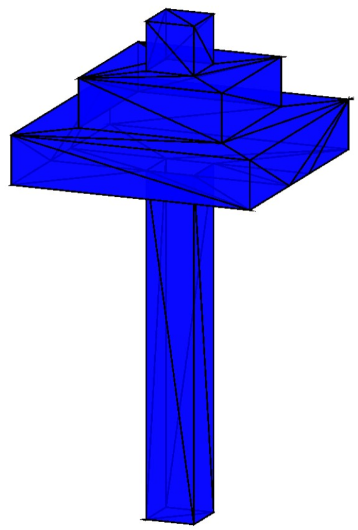

FIGURE 4: INPUT 3D GEOMETRIC STL MODEL.

view of the segmented model is shown in Fig. 5.

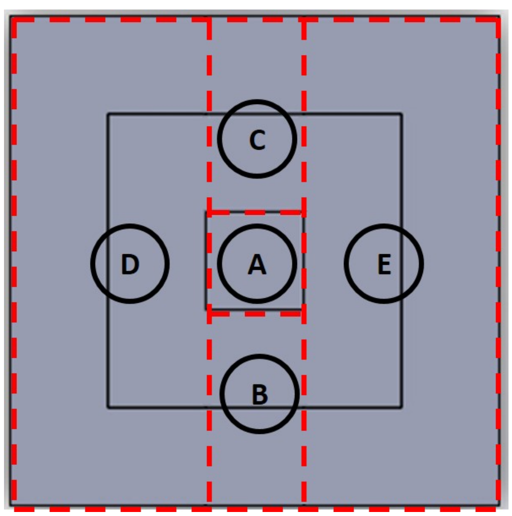

FIGURE 5: TOP VIEW OF THE MODEL SEGMENTATION.

Direction of Build Selection

The segmented model corresponds directly with the build direction of each segment. The generation of the direction of build is assigned X+, X-, Y+, Y-, or Z+ based on the region segmentation criteria defined in the previous section. There is no Z- since the Z+ direction is defined orthogonal to the build platform. The number of build directions depends on the number of segmented regions.

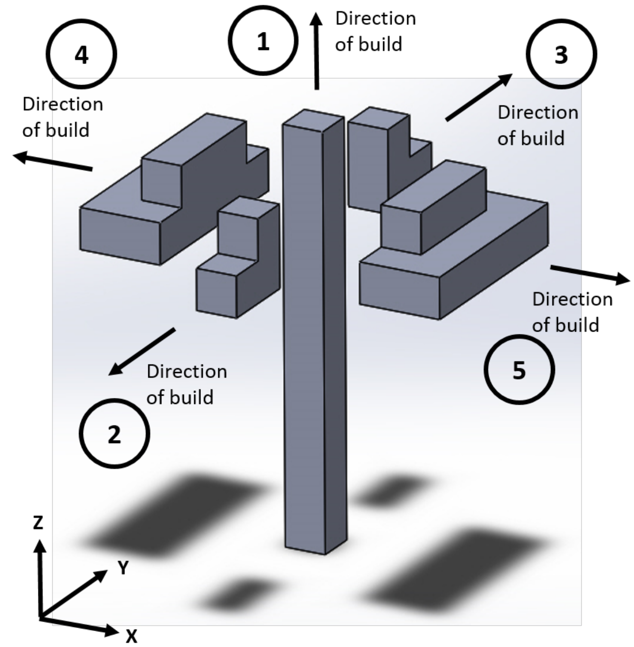

FIGURE 6: BUILD DIRECTION SELECTION.

Figure 6 shows the five build directions to print the input model. For this example, three different planes were used: One build direction in x-y plane (Z+), two build directions the in x-z plane (Y+,Y-), and two build directions in the y-z plane (X+,X-).

Lattice Structure Generator

With the assigned segments and build directions, lattice structures can be generated from the segmented models. A lattice structure is defined by a structure with a combination of connected network of struts on nodes. Nodes are define by the edge points of the lattice structure. The lattice structures for the segmented models were generated based on the build directions. The process to generate a 3D lattice structure is:

1. Input segmented model (see Fig. 7 (a)).
2. Slice layer upon layer along the build direction with each layer being the length of a predefined strut (see Fig. 7 (b)).
3. Generate node points along outside contour for each layer (see Fig. 7 (c)).
4. Generate grid of nodes between outside contours (see Fig. 7 (d)).
5. Check if above layer has intersecting orthogonal lines between the generated nodes on both grids.
6. Generate struts along the build direction connecting nodes (see Fig. 7 (e)).

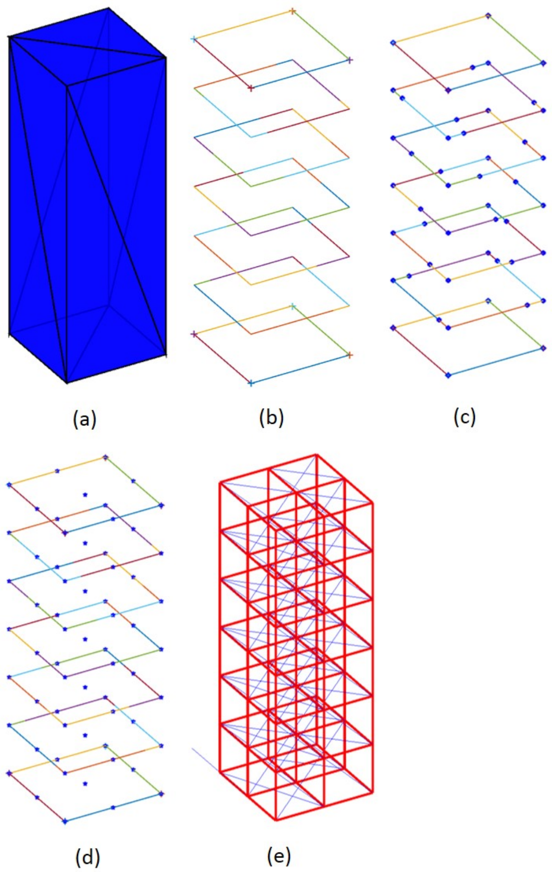

FIGURE 7: STEPS PROCESS FOR 3D LATTICE GENERATOR.

For the example input geometric model, cubic lattice structures were used to generated the lattice structure. Cubic lattice structures have a connected network of struts in the X-axis, Y-axis, and Z-axis for the node connections.

Sequence Planning

Sequence planning is a crucial element in order for the object to be printed without the traveling extruder nozzle colliding with previously printed struts. There are two important elements for the sequence planning process. These are:

1. Build direction printing sequence as described previously.
2. Extruder nozzle transition motion between the build directions.

The sequence used to print the input geometric model was started on the segment with label A (see Fig. 5) on the x-y plane (Z+) followed by the segment with label B in the x-z plane (Y-), followed by segment with label C in the x-z plane (Y+), followed by segment with label D in the y-z plane (X-), and lastly segment with label E in the y-z plane (X+). Transition motion between each of the build directions must be executed outside of the already printed segment in order to avoid collision with the printed part. The order is based on build direction sequencing defined by the user during the direction of build phase of the algorithm.

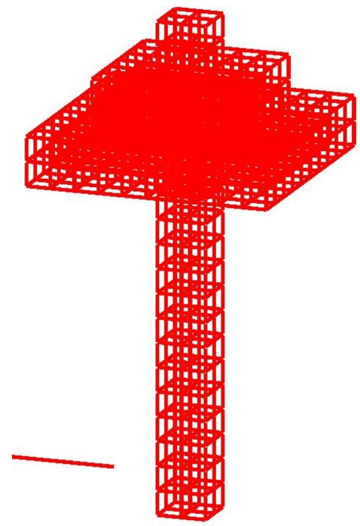

FIGURE 8: SIMULATED TOOLPATH.

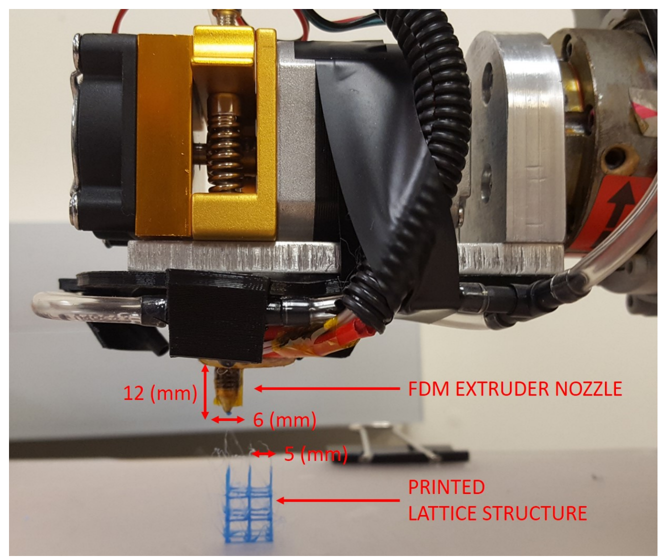

FIGURE 9: FDM NOZZLE CLEARANCE.

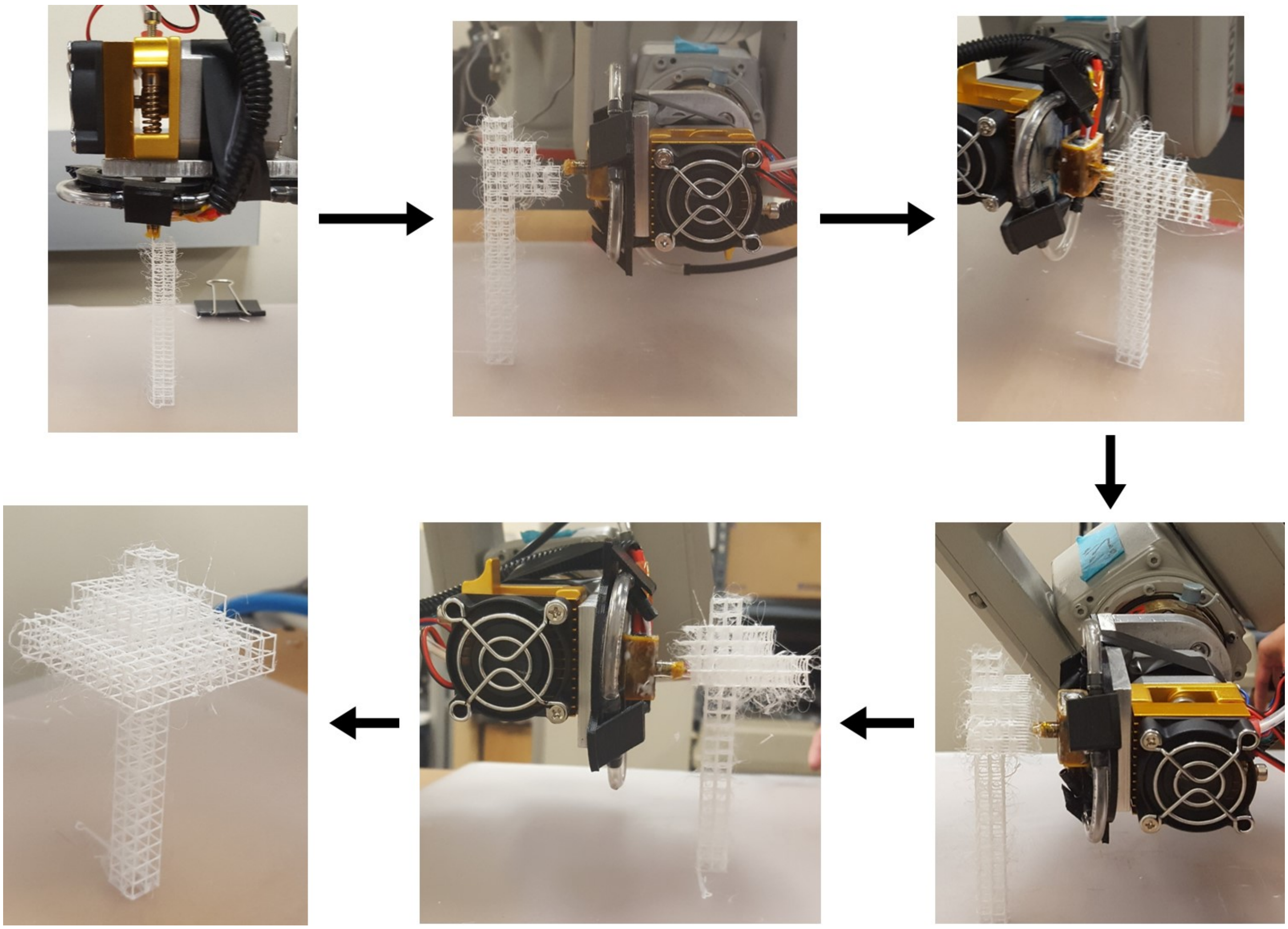

FIGURE 10: PRINTING PROCESS.

Toolpath Generator

In order to be able to be printed on a multi-plane platform, a custom G-Code containing the toolpath motion for the printing process was produced. The custom G-Code consists of generated Cartesian coordinates that define the part to be printed, wrist angles of the nozzle as build plane changes, the speed of motion, volume of extrusion, and speed of extrusion. Simulation of the output toolpath is shown in Fig. 8.

EXPERIMENTAL RESULTS

To test the algorithm for generating a 3D lattice structure for multi-plane FDM printing, a multi-plane FDM robot platform was used which is a continuation of the work by Ishak et al. [18]. The multi-plane FDM platform used was a six degree of freedom robot arm integrated with an FDM extruder head. The toolpath from the input geometric model generated using the algorithm was printed using the robot arm platform.

3D Lattice Structure

The input geometric model from the 3D lattice structure algorithm for the multi-plane FDM printing was able to be printed. The model was printed with 5 (mm) strut lengths for all of the cube lattices. The diameter of each strut is 0.48 ± 0.02 (mm). The extruder nozzle used for the setup was capable of printing struts with the range between 5 (mm) to 11 (mm) for cubic lattice structures. The range was based on the clearance between the nozzle and the printed strut as shown in Fig. 9. The dimension chosen was based on the range of the strut length that was capable to be printed by the FDM nozzle used by the robot arm platform without interference with the printed area. The algorithm used to generate the 3D lattice structure toolpath for the input 3D geometric stl model example was designed with increments of 5 (mm) x 5 (mm) x 5 (mm) cubic lattice structures. The printing speed was set to 1 (mm/s) for the extrusion motion speed and 75 (mm/s) for the traveling (not extruding) motion speed. The extruder nozzle is equipped with forced air cooling from compressed air outlet to assisted the output filament solidification process. The forced air cooling will eliminated the sagging problem on the output filament while printing the strut in the spatial space. The example input model with multi-plane overhang structures was able to be printed as shown in Fig. 10.

FUTURE WORK

For future studies, this research can be expanded to test the algorithm with different case studies based on the input geometric stl model. Many different input geometric models can be tested, for example, branching overhang structures and connected suspension structures. Besides the different case studies, different types of lattice structures can be explored, for example Voronoi patterns, hexagonal, and octahedral structures. The algorithm can be expanded to accommodate input 3D geometric stl models with curved surfaces. For models with the curved surfaces, variable strut lengths must be used. By utilizing variable strut lengths, lattices may be generated that approximate the curved surfaces of the input 3D geometric model. The variable strut lengths can accommodate the curved surfaces on the 3D geometric stl model. Diameter of a 3D lattice structure strut can be change by using different extruder nozzle outlet diameter.

CONCLUSION

In this paper we presented an algorithm for producing a 3D lattice structure for multi-plane FDM printing. The algorithm was able to generate a toolpath for multi-plane printing applications based on the input geometric model. The input model with an overhang structure was able to be printed using a six degree of freedom robot arm platform. The input model was printed based on the geometric features of the lattice instead of slicing it in single-plane layering used by conventional 3D printers.

The objective of this study was to provide an algorithm to generate a 3D lattice structure toolpath for multi-plane FDM printing applications. A step by step approach for the 3D lattice structure printing process, including region based segmentation, direction of build selection, lattice generation, printing sequence planning, and generating the toolpath has been explained for the use with the multi-plane printing platform. The multi-plane printing platform is not limited to a robot arm to achieve the multi-plane motion; other multi-plane printing platform configurations can be used for printing the 3D lattice structure. Using the algorithm for multi-plane lattice structure toolpath generation with the FDM 6 axis robot arm printing platform, a multi-plane example was able to be successfully printed.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Yaskawa Motoman U.S.A for providing the software resources needed for this project.

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