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A Novel Path Planning Approach for Multi-Directional 3-D Printing

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Abstract

Although Three-Dimensional (3-D) Printing has unique capabilities over traditional manufacturing processes, it has limited applications due to lower productivity, poor dimensional accuracy along oblique build angles, support structure requirements and variation of material properties with the build direction. Some of these limitations are primarily due to linear 3-axis Cartesian motions which led to development of configurations having capability to deposit material along multiple directions. The development of multi-axis configurations improved building capabilities of the printer but presented challenges in the form of innovative slicing and path planning methodologies. This paper presents a new slicing technique which can be implemented on a Fused Deposition Modelling (FDM) based 3-D printer. Path planning is another important step in 3-D printing as it has a remarkable effect on overall building time of the component. A new path planning technique has been proposed in this paper which reduces building time significantly in comparison to conventional *zig-zag* motion. The slicing methodology and path planning algorithm has been developed in the form of a computational tool to generate input for the FDM based multi-axis 3-D printers. Based on outcomes of the present work, it has been realized that the application of proposed methodology can reduce building time of components significantly for multi-axis 3-D printers.

Keywords: 3-D Printing, Fused Deposition Modeling (FDM), Slicing, Path Planning

1. INTRODUCTION

3-D Printing, also referred as Rapid Prototyping (RP) or Additive manufacturing (AM) is a fundamentally different process from conventional manufacturing techniques. The process integrates Computer Aided Design (CAD), Materials Science and Computer Numerical Control (CNC) to fabricate physical prototypes from virtual models directly by depositing material in the form of layers. Recent decades witnessed rapid development in 3-D printing technologies for potential applications in prototype fabrication, product development, biomedical engineering, electronic devices, architecture etc. [1]. As per classification of ASTM International Committee F42, seven 3-D printing technologies are available currently: material extrusion (Fused Deposition Modeling, FDM), material binding (using inkjet printing process to deposit material), binder jetting (using inkjet printing process to deposit liquid bonding agent), sheet lamination (Laminated Object Manufacturing, LOM), vat photo-polymerization (Stereo-lithography, SLA), powder bed fusion (Selective Laser Sintering, SLS) and directed energy deposition (Direct Metal Deposition, DMD).

Among these technologies, extrusion-based process i.e. FDM is one of the most popular and widely used process in various applications [2]. In FDM, the material is fed into an extruder by motor driving force or pneumatic force, and melted in a liquefier which is subsequently extruded from a nozzle. The movement of nozzle is controlled by a moving platform in the horizontal plane while depositing extruded material on the build plate line by line based on the pre-designed paths to form a layer. It implies that the process fabricate 3-D parts by deposition of layers in 2-D using three linear motions in the Cartesian axes. The layer based approach of the process has many advantages which includes simplified tool-path planning and capability to manufacture complex parts which cannot be built by conventional manufacturing processes.

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However, it suffers from major drawbacks such as stair-casing (aliasing) effect, non-uniform material properties along different directions, support structure requirements and inability of building around inserts which limits its potential as an alternate to conventional manufacturing processes. [3].

To address these limitations of conventional 3-D printing, various solutions are proposed in the literature e.g. post-processing techniques [4], controlled cure depth [5], hybrid process development [6], model shape modification [7] etc.

Most of these approaches improve one or few limitations of the process only. It has been highlighted in recent studies that these limitations are due to single build direction and uniform layer thickness [8]. It has been demonstrated that the addition of material with non-uniform thickness along multiple directions using multi-axis 3-D printing can address these limitations collectively. The multi-axis motion between extruder and build platform can be achieved in two ways; orienting the build platform or orienting the extruder. The platform based approaches result into simple machine configuration but accumulative tool orientation approach is considered more flexible in achieving desired relative motions.

Chen et al. [8] proposed use of parallel robotic architecture, Stewart Gough Platform (SGP) with 6-axis motions to enhance building capability of a 3-D printer. The robotic configuration proposed in the study was not optimized for the given workspace dimensions. The SGP configuration was optimized further by Shastry et al. [9] which offers larger workspace and better dexterity for multi-axis 3-D printing systems. The multi-axis configuration demonstrates great potential in addressing the limitations of existing 3-axis printers but present challenges in terms of hardware design and implementation, workspace evaluation, efficient slicing and path planning algorithms, integration of real time sensors and implementation of closed loop control. Among theses, the present work addresses two important issues namely, development of slicing technique and path planning methodology while implementing multi-axis 3-D printer using accumulative tool approach. It is planned to integrate algorithms developed in this paper with the machine configuration presented in Shastry et al. [9] for building of components. Some research attempts in the similar direction can be found in the works of Singh and Datta [10, 11] which aims at developing slicing and path planning algorithms for multi-axis 3-D printers having platform based configuration. On the contrary, the present work develops slicing and path planning algorithms for entirely different configuration of multi-axis 3-D printer which involves orientation of nozzle instead of the platform.

Henceforth, the paper is organized as follows; Section 2 presents slicing algorithm for dividing 3-D objects into 2-D slices along particular direction. The section also presents an algorithm to convert output of slicing algorithm into nozzle path using path planning algorithm. Section 3 summarizes implementation of the proposed methodology by considering various case studies. Finally, the paper ends with summary of findings from the present work in Section 4.

2. MODEL DEVELOPMENT

The process planning of multi-axis 3-D printing involves following steps; determining orientation of the object, support structure generation, slicing of the model, path planning of the extruder and calculation of leg lengths with platform angles. Among these steps, slicing methodology and path planning algorithm are addressed in this paper. The slicing module divides 3-D object into 2-D layers representing boundaries of the object in a given layer. Meanwhile, path planning module generates definite nozzle patterns to fill the area within boundaries of each layer with several line elements. The planned paths fill the entire area within each layer.

2.1 Slicing of a Model

In conventional 3-D printers, slicing is done parallel to the XY plane and perpendicular to Z-axis. Therefore, slicing methodology is restricted to XY plane generating series of layers perpendicular to Z-axis. The path planning problem is restricted to the XY plane movement for a particular layer. The limitation of slicing direction result into stair-casing effect as shown in Fig. (1) for models with curved surfaces or oblique planes along the slicing direction. This necessitates post processing operation for improving surface finish of objects. The machine configuration considered in the present study allows for multi-axis motion between extruder and build platform therefore, build direction is not restricted to the Z-axis. The object can be sliced along any arbitrary direction as shown in Fig. (1).

The slicing algorithm (referred as slicer hereafter) developed in this work generates slices along arbitrary direction defined by the user. The input to the slicer are as follows; 3-D geometry to be sliced along with orientation, slicing direction, and offset distance between two layers or slices. The methodology divides normal vector into segments depending on offset distance between two layers. This results into generation of planes at offset distance representing each layer. The methodology determines intersection of each plane with oriented 3-D geometry to generate boundaries of the object corresponding to each layer. Figure 2 shows slicing of an oblique cuboid generated using proposed slicing algorithm. The computation time increases with increase in number of slices as the methodology consumes considerable time in computation of intersections. The layer thickness is function extruder material, nozzle diameter, raster width etc. and variety of models are available in the literature to determine the same [12]. The future work will focus on implementing efficient slicing techniques with selection of proper layer thickness.

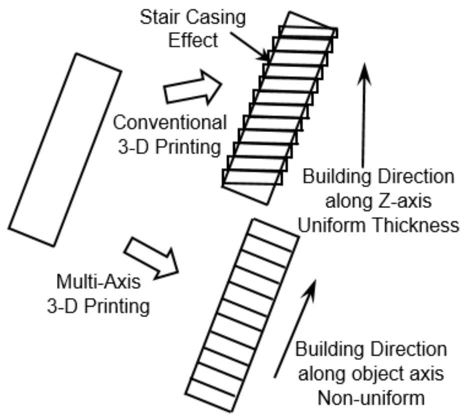
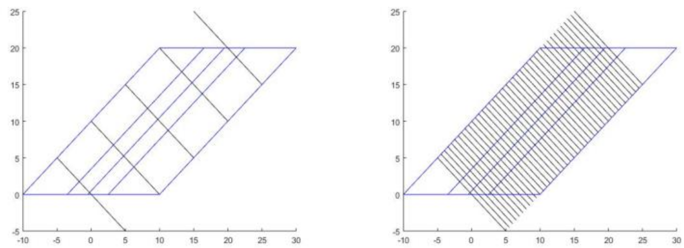


Fig. 1: Slicing techniques for Oblique Objects



(a) Offset Distance = 0.5 **(b) Offset Distance = 0.01**

Fig. 2: Slicing of Oblique Cuboid

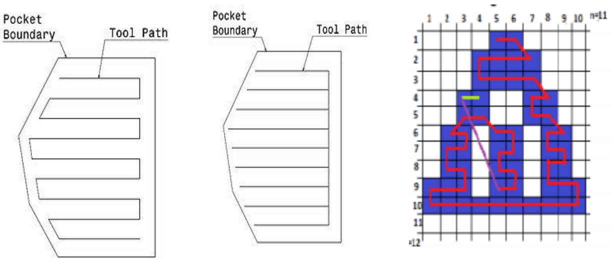
2.2 Path Planning

The objective of path planning algorithm is to determine trajectory of the extruder to deposit the material for filling the area in each layer. The path planning is crucial function in the 3-D printing process as it has significant effect on build time and surface quality. The path planning problem involve two stages; path generation and path optimization. The path generation algorithm creates extruder paths to fill the contour in each layer. Meanwhile, an optimization algorithm proposes methodology to link these paths in an optimal manner. During path generation stage, various segments can be used to fill the contour geometry in a given layer. These segments correspond to either contour paths or raster paths. The raster paths are used for filling interior section of the geometry and are followed after contour paths. Some of the most commonly used raster paths for 3-D printing application are *zig-zag* and one-way (*zig*) which are shown in Fig. 3 (a) and 3(b) [13, 14]. The majority of commercial 3-D printing systems use these raster paths in building of the components. It has been observed that *zig-zag* path is not preferred for geometries with cavity or islands as it increases building time considerably [14, 15]. Wojcik et al. [15] proposed modified *zig-zag* path (MZZ-GA) to plan extruder path in an optimized manner for conventional 3-D printing systems. The schematic diagram of MZZ is shown in Fig. 3(c). This paper extends the application of MZZ algorithm to multi-axis 3-D printing systems.

2.2.1 Path Generation Algorithm

The path generation algorithm divides slice geometry generated using slicer into planner grid with controllable grid size. This results into cluster of grid points within an oblique plane through which the extruder is required to pass to print a given layer. The cluster does not generate points that are lying inside cavities or vacant spaces. The algorithm minimizes total distance to be traveled by an extruder while traversing through each of these points once only. The classical approach such as

Traveling Salesman Problem (TSP) will not work in this case as the point cluster is quite large resulting into computational complexity.



(a) *zig-zag* **(b) one-way (*zig*)** **(c) MZZ-GA**

Fig. 3: Algorithms for Path Planning

The present work uses MZZ algorithm to traverse through the point cluster on a given plane. The problem statement for the path generation in a single layer can be stated as follows;

Given:

- Cluster of points on the layer to be printed, $P_i\ (x, y, z)$;
- Lengths between two points $d=\|P(n) - P(n\text{-}i)\|$ where n is the present index of point to be printed

Determine:

- The order in which points has to be traversed, V = [P_1, P_2, ……, P_n],
- Ensure that all points are visited,
- Ensure that no point is visited twice,
- Calculate optimum length of the path within the slice

A unique feature of the MZZ is unique search pattern of the algorithm which permits search in multiple directions depending upon the shortest distance in three dimensions. The flow chart of path generation algorithm is summarized in Appendix I.

2.2.2 Path Optimization Algorithm

The path optimization algorithm optimizes the path determined using MZZ described in the previous section. The algorithm begins with determination of each path segments followed by joining last point of the given path with the first point of subsequent path, and so on. The procedure for optimization is summarized as follows;

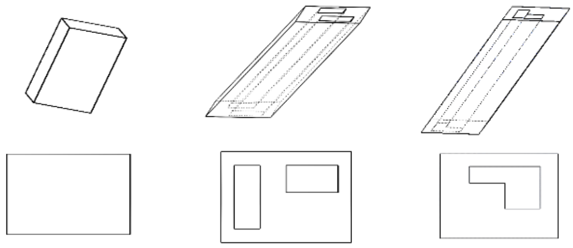
- Execute path planning algorithm presented in Section 2.2.1 and store the total length travelled by extruder.
- Examine alternate coordinates as starting points and evaluate each option determining total distance to be traveled by an extruder with lowest distance as the optimized path
- If all segments for a given slice are generated, search for the nearest point in an immediate layer and initiate path planning and optimization algorithm for the subsequent layer.

Based on above methodology, the path planning algorithm generates line segments to be traversed by the extruder while printing the component using multi-axis 3-D printer. The proposed methodology has been implemented in the form of a computational program to generate instructions for the micro-controller. The further work will focus on transforming these instructions into link lengths, platform orientation and extruder velocities using inverse kinematic formulation of the SGP.

3. Algorithm Implementation

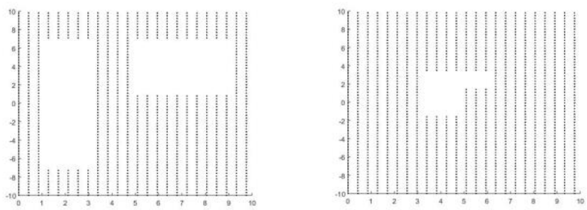
The path planning algorithms viz. *zig-zag*, one-way and MZZ discussed in the previous section has been implemented in the form of computational programs using MATLAB and computational experiments are carried out on various objects shown in Fig (4). The primary difference between geometries under consideration is the shape and dimension of cavities inside oblique cuboid. The first step in the path planning algorithm is to generate cluster of grid points for the given slice. The mesh size of 0.3 mm has been chosen in the study for generating cluster of grid points. Figure (5) shows cluster of grid points corresponding to geometries in Fig. 4(b) and 4(c) generated using path generation algorithm proposed in the paper.

The extruder path corresponding to each geometry has been determined using three different path planning algorithms and the total distance traveled by an extruder is used as a measure to determine the effectiveness of each algorithm in printing of objects using multi-axis FDM system. Table 1 shows comparison of different algorithms in generating extruder path for geometries under consideration.



(a) Oblique Cuboid **(b) Oblique Cuboid with convex cavities** **(b) Oblique Cuboid with non-convex cavity**

Fig.4: Representative Geometries for Multi-axis 3-D Printing



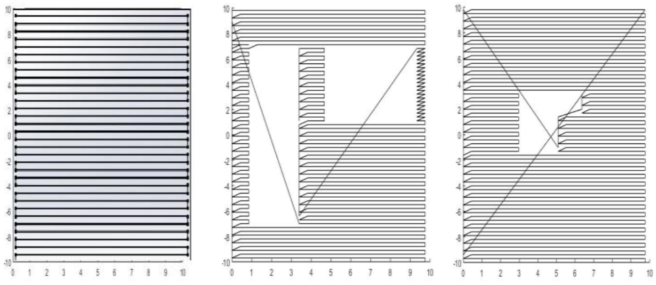
(a) **(b)**

Fig. 5: Cluster of Grid Points for Representative Geometries

Table 1: Comparison of Distance Traveled by Extruder

	Computed Distance			Saving in Distance Traveled with MZZ (%)
	zig-zag	one-way	MZZ	
Geometry (a)	687	1354	687	-
Geometry (b)	687	1354	473.81	31.0
Geometry (c)	687	1354	628.72	8.48

It can be seen from Table 1 that the MZZ algorithm is quite effective in minimizing total distance traveled by an extruder for cases having inside cavities. The MZZ and *zig-zag* algorithm covers the same distance for components without hollow spaces (Fig. 4(a)). Meanwhile, the distance travelled by an extruder is about 31% and 8.48% shorter for MZZ in comparison to *zig-zag* path for components having hollow spaces. This will lead to significantly lesser build up time for components if extruder path is generated using MZZ algorithm while building of components (Fig. 4(b) and 4(c)).



(a) **(b)** **(c)**

Fig. 6: Extruder Paths for Representative Geometries

Figure 6 shows extruder paths corresponding to geometries in Fig. 5(b) and 5(c) generated using MZZ. The MZZ algorithm has number of options for the moving directions in comparison to *zig-zag* and one-way paths and it attempts to generate the extruder path without discontinuities. Also, MZZ chooses the closest starting point while switching from one continuous path to the other path. This is represented by smaller slant lines connecting continuous horizontal segments in Fig. 6. This results into generation of longer continuous paths with shorter overall distance in comparison to the other algorithms. The horizontal and smaller slant lines in Fig. 6 are printing paths whereas the longer slant lines are non-printing and rapid movement paths.

4. CONCLUSION

Path generation is an important activity during process planning of 3-D printing process as it has a significant effect on deposition efficiency and build-up time. This paper presented a methodology for generation and optimization of extruder paths for multi-axis FDM process. The machine configuration achieves multi-axis motions between extruder and build platform by using SGP. As a first step in process planning, the study developed a slicer which generates layers perpendicular to local normal of the component. The slicer output is converted into a cluster of grid points which facilitates generation of extruder paths using three different algorithms viz. *zig-zag*, one-way and MZZ. It has been observed that the MZZ algorithm results into significantly shorter extruder paths for geometries with hollow cavities in comparison to zig-zag and one way algorithms. The shorter extruder paths are generated in case of MZZ due to unique search pattern of the algorithm which ensures nearest search point within the same layer as well as immediate layers. The shorter extruder paths will save build-up time for components produced using a multi-directional 3-D printer. The further work will aim at focusing on complex geometries, development of universal path planning module, generation of instructions for the micro-controller to print components directly from CAD models using multi-axis 3-D printer.

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APPENDIX I: Flow Chart of Path Generation Algorithm