Intelligent Toolpath for Extrusion-based LM Process

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1. Abstract

At Rutgers University, in an ONR funded MURI program, we've built the hardware and developed the corresponding advanced computer software for multi-material layered manufacturing. Based on our ongoing research, we determined that the build characteristic is heavily dependent on the material being used. This has direct implications on toolpath creation. Therefore, it is important to develop the hardware/software that will accommodate this requirement. In recent past, we have developed CAD models and their .stl files using commercially available software such as I-DEAS and ProE. Using this information, the slice file is generated in QuickSilce. To fabricate high quality part's, to have better control on the toolpath in relation to the materials, and to make the development generic yet compatible with our hardware, we are developing an in house intelligent toolpath generation system. This new development includes the issues such as multiple fill-toolpaths for the same material, deposited road characteristics, the interface mismatch between adjacent materials and the intelligent toolpath features needed for machine control. After the component toolpath file generated by the in house toolpath software, our multi-material build file algorithm, systematically, layer by layer, integrates all component toolpaths into one multi-material toolpath. The existing virtual graphical simulation as well as well selected part fabrication experiments are being used to validate the current development. The development is kept modular and it is developed with the intention to be used for the majority of Layered Manufacturing systems.

2. Background

LM refers to the process of fabricating three-dimensional objects from CAD-generated solid models layer by layer [1]. Since the first commercial inception of Stereolithography technology in 1988, LM technologies have been developed rapidly. There are many success stories giving specific comparative examples of time and cost savings relative to the more traditional ways of completing the same steps in the product development and commercialization cycle [2]. A representative list [3] [4] includes: 3D System's Stereolithography Apparatus (SLA) series, Stratasys's Fused Deposition Modeling Process (FDM), DTM's Selective Laser Sintering (SLS), Helisys's Laminated Object Manufacturing (LOM), Sanders, and 3D Printing. Each technology has various materials options before starting the manufacturing process; Yet typically, they can only handle one component material during one building process.

Multi-material LM technologies are needed. For example, there is already a need for multi-color parts for surgical applications. There are two kinds of multi-material solids, those where material distribution is changing gradually from one material to another, and those made of a collection of discrete materials. Multi-material solids are also called heterogeneous solids [5]. Multi-material LM refers to a process of fabricating a part consisting of more than one component material from CAD models layer by layer. The multi-material LM system under development at Rutgers University is designed to fabricate parts consisting of a collection of discrete materials with boundary interfaces. This multi-material LM system should be able of generating CAD models, slicing files, toolpath files and fabrication of multi-material parts in one manufacturing process. The development of our multi-material LM system is still at the research stage. At university of Texas at Austin, Multi-material Selective Laser Sintering (M^2SLS) is under development. This process could allow fabrication of functionally gradient materials (FGMs) in which blended material interfaces exist [6]. A new development of M^2SLS for an application in complex sand casting core arrays is discretely laying down two different materials and removing one after sintering. This will allow more complex geometries and drastically decrease the production times of sand cores [7]. At Sandia National Laboratories, Robocasting technology is a direct fabrication technique that relies on automated extrusion of highly concentrated ceramic slurries, which is able to fabricate either single material or multi-material parts [8].

3. Objective

Currently, at Rutgers University, under an Office of Navy Research (ONR) funded MURI program [9], An Intelligent Layered Manufacturing System (Fig 1) for fabrication of multiphase electromechanical parts has been developed. This program requires design and construction of an intelligent multi-material LM system, processing science for multi-material LM, CAD based design and manufacture of multi-phase electromechanical components. The intelligent multi-material LM system should include a high quality multi-material layered manufacturing machine (hardware) and a CAD based intelligent multi-material LM software system. In the recent past, the MURI hardware as well as corresponding software has been developed and several multi-material parts have been successfully fabricated.

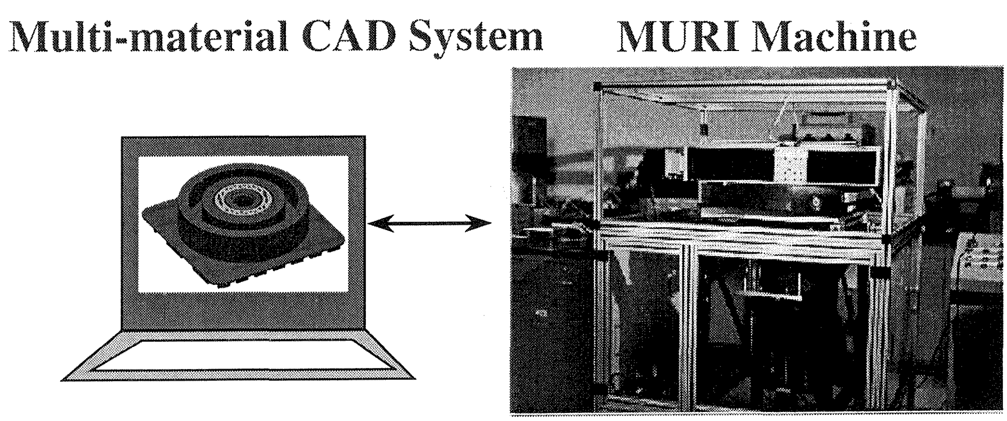

Figure 1: An intelligent Layered Manufacturing System

The multi-material CAD system in the intelligent Layered Manufacturing System will to generate toolpath data file ready for the MURI machine and virtually fabricate defect free multi-material parts. In the present program, quality of a part is considered to be very important. To have full control over the building toolpath, which has important influence on the part's quality, an in house intelligent toolpath generation software is needed. This paper discusses the implementation of the intelligent multi-material toolpath generation algorithm and it's results. The objective of this study is to develop a virtually void free toolpath file for the multi-material LM process. The toolpath file generated here will be input to the simulation software developed last year [10] to visualize the virtual LM process. If the virtual part has voids and defects, the toolpath parameters will be adjusted and the toolpath will be regenerated until the virtual part is defect free.

4. Method

Multi-material CAD

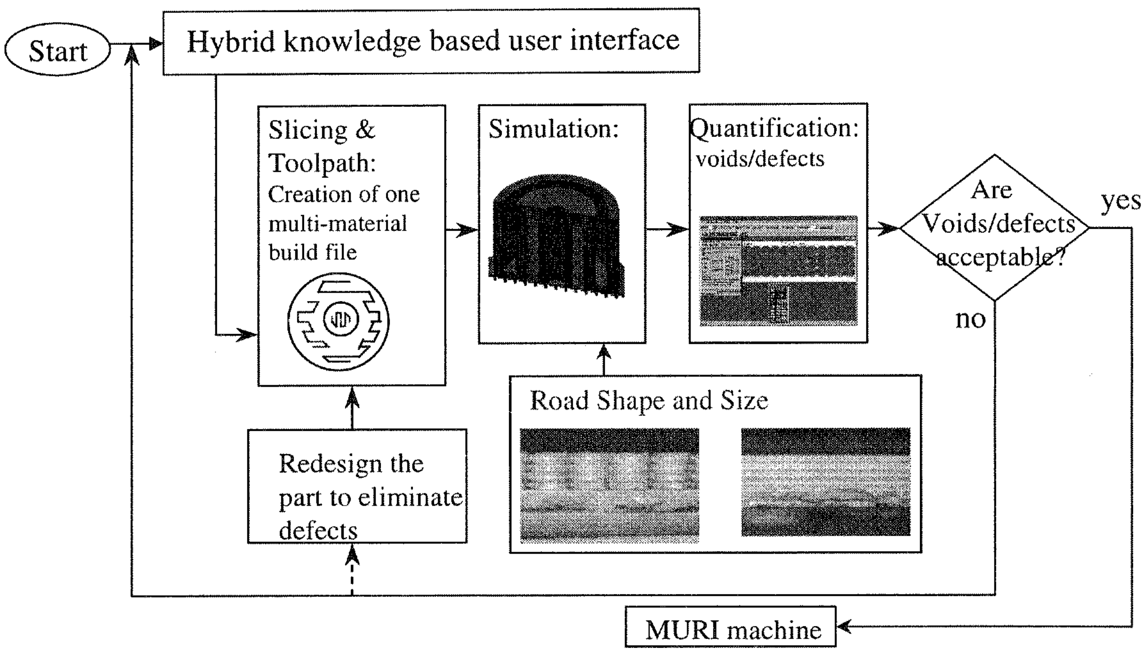

Figure 2: Multi-Material CAD System

The Multi-material CAD system (Fig 2) includes multi-material build file generation, virtual simulation and quantification of the defects in virtual part. The virtual simulation [10] uses the in-house multi-material build file as the input data and virtually fabricates the multi-material part. Surface and internal defects can be quantified from the images captured from the outside view or sectional view of the simulation. If the part quality is not acceptable, modifying the toolpath parameters to regenerate the build file or redesigning of the part is needed. The iteration runs until the virtual part quality is acceptable. Finally the multi-material build file is ready for the hardware – MURI machine.

To create the multi-material build file, we use IDEAS, ProE, or Auto CAD to generate a n-material solid model and orient the part for the "best" build direction. For the n-material solid model, n .stl files and n-slice files (.slc file currently) are generated while maintaining their geometric relationships [11]. The open issues related to the fabrication are the offset between the material boundaries and the order of the solid models. Once the slice files are loaded, the toolpath parameters are defined for each material and for all intersecting boundaries, the in-house toolpath software can generate n-build files for n-slice files. The in-house integration software integrates the n-build files with their locations into one multi-material build file.

Toolpath generation software

The toolpath generation software developed here is designed to create a single-material build file for the MURI machine, which has toolpath information mainly. Taking a slice file as the input data, the program extracts one slice from the file at a time. Boundary path and raster path for the slice are generated and written into the output file. The program continues to extract the next available slice and generate paths until all the slices in the file are finished (Fig 3).

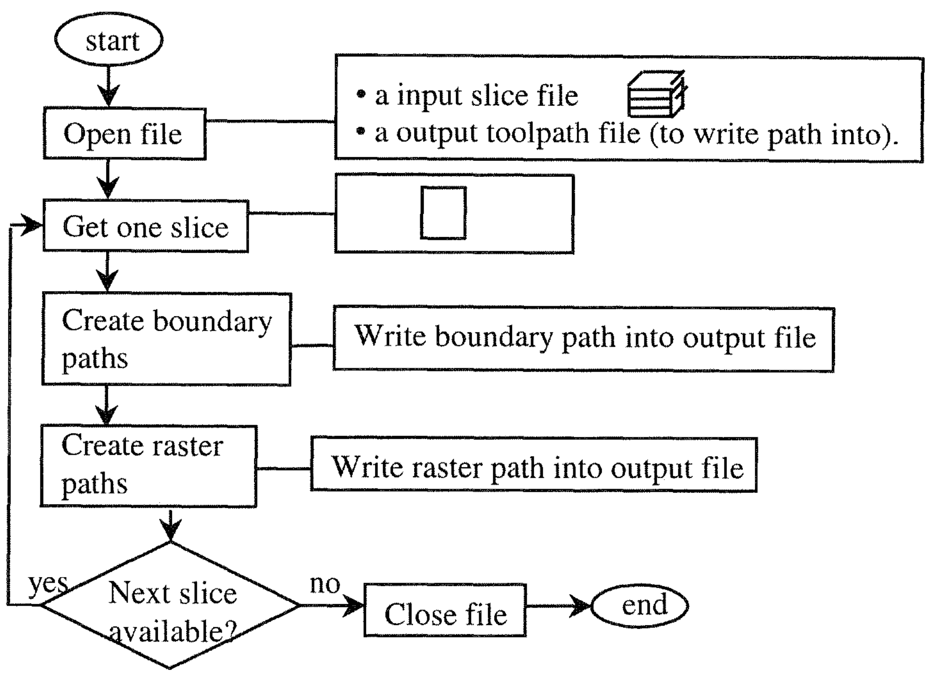

Figure 3: Toolpath generation process

The main data structures in this program are a file manager structure, a surface structure, a boundary structure and a quantized point structure. The file manager structure contains all the toolpath parameters and the method, which extract a slice from the input file. A surface structure contains boundaries on this slice, quantized points structure, and methods which rotate and reduce boundaries, write boundary paths, quantize boundaries into points and write vector paths respectively. A boundary structure contains boundary points, methods that rotate boundary points and calculates the reduced boundary point locations respectively. The quantized point structure contains all the quantized points and the information related to the point, which help to form the raster paths.

5. Results

First version

The first version of the toolpath generation software was able to successfully handle simple convex shapes such as a triangle and a square. To test the software, two representative complex-shaped surfaces are generated. One is a hollowed circular surface; the other one is a concave polygon. For these two shapes, the first version of the software gave the following results (Fig 4): 9 zigzag paths, 3 straight-line paths are generated for the hollowed surface; 6 zigzag paths and one erroneous jump were generated for the concave polygon. The number of paths on each surface is high, which will make the depositing nozzle jump many times and will likely result in poor surface quality.

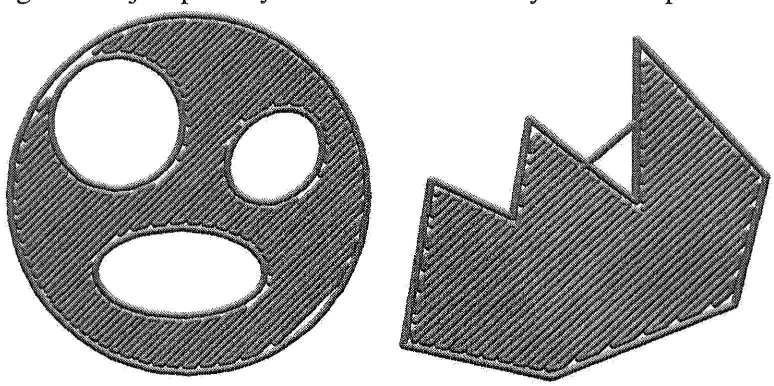

Figure 4: Simulated toolpath generated by 1st version of the software

Second version

We learned from version 1 that the location and occurrence of any discontinuities in the different toolpaths. Additional logic was added to create version 2. This improved the toolpath. The result is as follows (Fig 5): 5 zigzag paths generated for the hollowed surface; And 3 zigzag paths and no erroneous jump for the concave polygon. The toolpath generated in version 2 is comparable to the results generated for a commercial software result like QuickSlice.

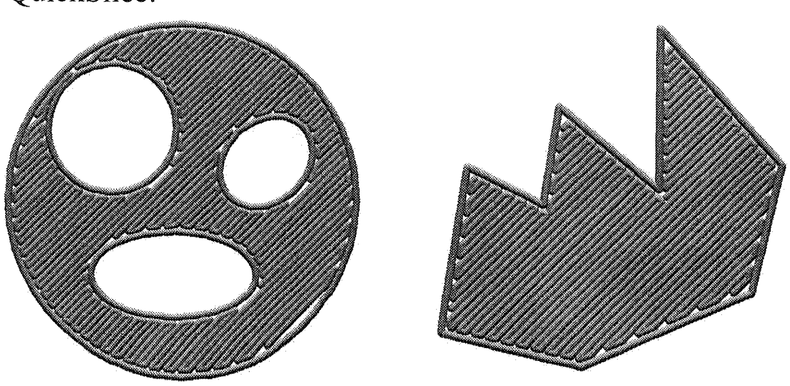

Figure 5: Simulated toolpath generated by 2nd version of the software

Third version

To improve the toolpath further, the third version of the software was developed.

The third version has two intelligent features: a "least number of paths" and the "closest next starting point identification" algorithms. From this version of the software, 4 zigzag paths were generated for the hollowed surface and 3 zigzag paths for the concave polygon. The start and end for each path are marked in Figure 6. Except for the starting point of the first path, each start point of the current path is the closest one to the end point of last path.

There are many voids at the road turns and road ends in the results of version 2. To make the part full dense, two toolpath parameters are altered: roadwidth and offset. As can be seen from the simulation image (Fig 6), the surfaces are much denser, fewer voids exist on both surfaces. Most existing voids are located at the road ends and sub-perimeters. New intelligent toolpath features need to be developed deal with these kinds of voids.

To test if the software can handle different road raster angles, the -45° raster angle toolpath was also generated. For the hollowed surface, the same number of zigzag toolpaths was generated. For the concave polygon, one zigzag toolpath was generated (Fig 6).

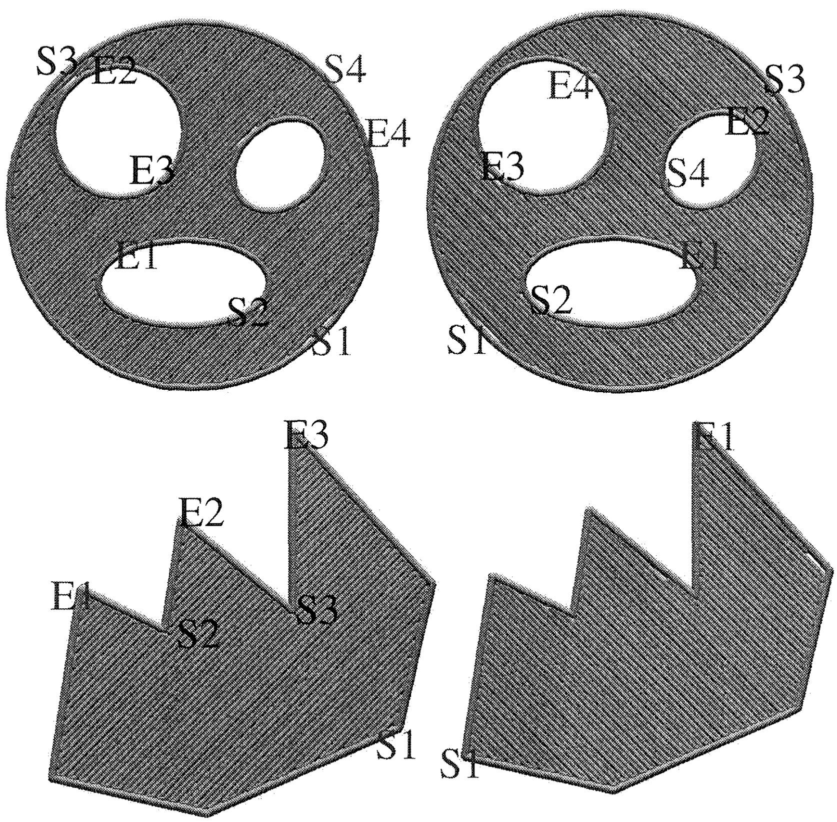

Figure 6: Simulated toolpaths of ±45° raster angles generated by 3rd version

A two material part

A two-material square-in-square part (Fig 7) was designed to investigate material boundary mismatch problems. The toolpath for this two-material part was generated by the in house toolpath generation software version 3. This part was simulated. The two materials touch at the inner square boundary. For the first set of toolpath parameters, there are voids at this boundary (Fig 8). After changing the material offset and sub-perimeter offset, the voids were eliminated (Fig 9).

Specifications:

Nozzle:	15 mil
Roadwidth:	20 mil
Layer Thickness:	10 mil
Number of layers:	20
Red material: (0.5"X0.5")	Wax
Green material: (1"x1")	PZT
Blue material: (Can be any material)	support

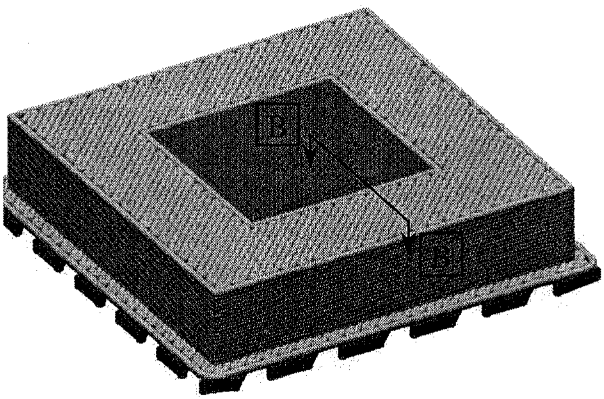

Figure 7: A two-material square-in-square part

Sub-perimeter offset for wax (red material): -2 mil
Offset between two materials: 0 mil

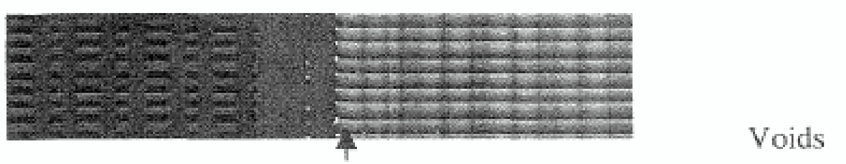

Figure 8: B-B cross section view of Figure 7 (the 1st set of parameters)

Sub-perimeter offset for wax (red material): -4 mil
Offset between two materials: -3 mil

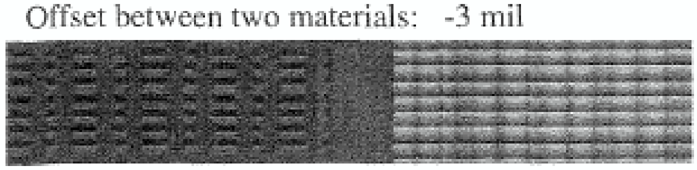

Figure 9: B-B cross section view of Figure 7 (the 2nd set of parameters)

A two-material telescope part

To demonstrate the capability of the in house toolpath generation software, a more complicated two material telescope actuator part was designed. Toolpaths for both materials and the support layers were created and merged into one multi-material build file. The telescope part was visualized (Fig 10). This part has 59 layers high. The multi-material build file can also be created by manually editing the commercially available single material build files. But this takes approximately 2 hours for this part. Using our in house software, this multi-material build file was generated in seconds.

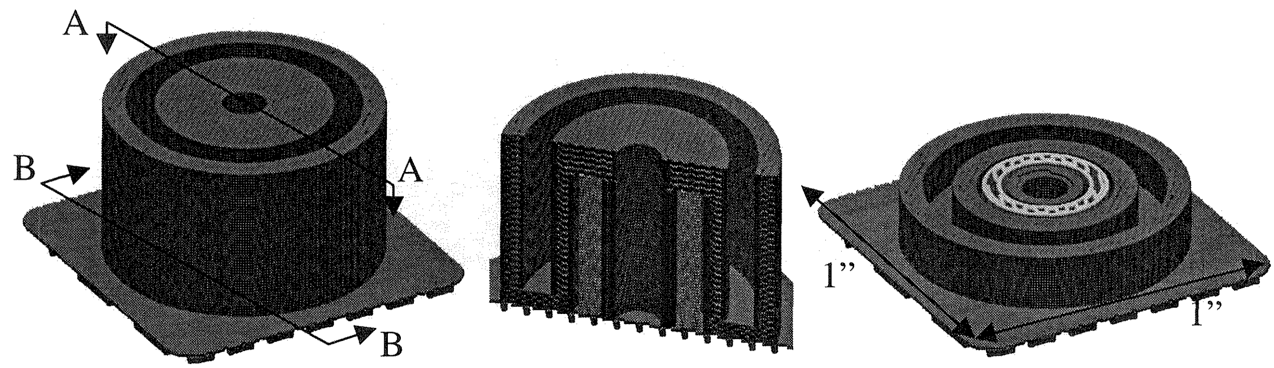

Figure 10 A telescope part

8. Conclusion

A multi-material toolpath generation system (Version 3) with new intelligent features has been developed. A variety of parts with complex boundary shapes and multi-material parts with interconnectivity have been visualized and quantified. The multi-material CAD system provides tools to investigate the multi-material toolpath parameters, alter the toolpaths to create defect free green parts. This software is flexible and general purpose and should be applicable to a number of SFF methods.

9. Acknowledgments

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Key words:

Layered Manufacturing, Multi-material, Toolpath Generation