



Integration of Additive Manufacturing and Virtual Verification Strategies within a Commercial CAM System

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ABSTRACT

Additive manufacturing (AM) processes are becoming more common; however, there is little process planning control. Standalone proprietary software is used by AM systems to create a build file that displays the travel paths, but not a complete representative model, which may not be optimal. Integrating AM into existing CAM systems provides a direct link between the CAD model and the AM build file, as well as allowing planners to directly combine additive and subtractive operations. When considering the number of entities and constraints related to the travel paths, most of the AM processes are a derivative of the Fused Deposition Modeling (FDM) process; consequently, modeling the FDM process within a commercial CAM system is the focus of this research. An AM user interface and a process verification system based on the X3D standard is developed, as current machining verification solid modeling kernels have been found to not be suited due to the number of entities to be processed. Various examples are presented to highlight the merits of the approaches taken.

Keywords: additive manufacturing, tool path generation, CAM simulation tools.

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1 INTRODUCTION

1.1 Background

Additive manufacturing (AM) methods consist of tool-less processes that are capable of producing complex 3D parts and assemblies from layering two dimensional cross sections of material successively to create the final components. No fixtures or specialty tooling is required for additive manufacturing processes; however, support material may be required to support overhanging geometry and **floating geometry** as illustrated in Fig. 1. There are minimal process planning

requirements and limited human intervention is necessary during the build process. Unfortunately, the actual fabrication time is long and depends on the layer resolution, curing time, and other post processing requirements. There are limited material choices (AM materials are often limited to the machine supplier) and anisotropic properties can result, depending on the process [1]. There are also limitations with accuracy (due to shrinkage and warpage) and surface finish [9]. Despite these negative aspects, the AM technologies are growing and developing quickly in several areas [7]

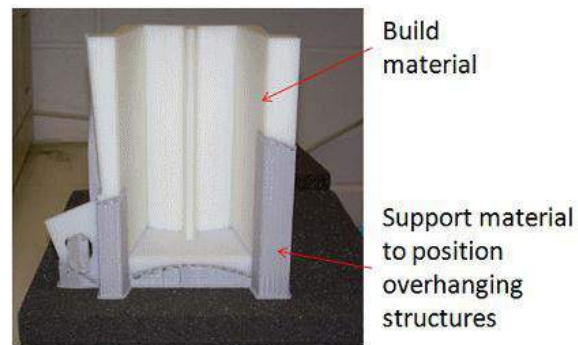


Fig. 1: Build and support material for a part built by the fused deposition process.

There are several AM processes commercially available (summarized in Tab. 1), which are used for visual aids, ergonomic evaluations, quotation purposes and fit and assembly tests (Fig. 2 (a) [3]). AM trends are documented in the annual Wohlers Report [15]. The 2008 **1**Additive Manufacture State of the Industry World-wide report**1** documents prominence of different AM technologies in the additive manufacturing industry (Fig. 2 (b)).

To fabricate a physical model using AM processes, a **Valid** geometric model is converted into *.STL format. The boundary surfaces of the model must enclose a finite volume, and cannot contain non-manifold geometry. Either a solid or surface model can be used as input, but care must be taken when using a surface model, as there are no defined associations between the various surfaces. The presence of gaps, overlap, duplicate surfaces, or missing surfaces will lead to fabrication problems.

Within the machine vendor software, the user selects a layer thickness, the position and orientation of the part, and other process related parameters (i.e., color for 3DP processes). The proprietary software then slices the *.STL file into layers, and generates travel path geometry and process parameters (travel speed, material feed rates, and so forth) in a manner transparent to the user.

Due to the layering, stepped surfaces result. Support material may also have to be removed. As well, distortion can occur due to thick wall **1** thin wall conditions [12]. It would be desirable to be able to control the amount of additional stock to allow for any subsequent material removal processes. To this end, research for manipulating STL files using techniques such as STL-based 3D offset methods is currently being conducted [11]. Other researchers are investigating the integration of layered manufacturing with material removal processes [4].

Complementing these AM processes are welding and cladding processes [5] used for refurbishment and surface coatings. Presently laser cladding based processes are being leveraged to create metal components, complementing planar layered AM processes [8]. Ideally, it would be advantageous to utilize a single software package for layered fabrication, non-planar material addition processes (welding, laser cladding) and finish machining. It would be desirable to be able to visualize

the build process and associate the part geometry directly to the build parameters. Virtual model verification tools are used extensively for subtractive processes, but limited virtual modeling research and development has been performed for additive processes [2, 6, 10, 13].

1.2 Material Deposition Process Modeling Research Goals and Approach

The long term goal is to develop a set of virtual modeling tools to support advanced tool motions and process planning strategies for a variety of material deposition processes, and integrate them with material removal strategies. This includes developing material deposition equivalents for roughing and finishing, various travel path fill patterns, and layering approaches, as well as investigating combined deposition and removal methods.

<i>AM Type</i>	<i>Case</i>	<i>Raw Material</i>	<i>AM Characteristics</i>	<i>Fusing Technology</i>	<i>Curing</i>	<i>Support Removal</i>	<i>Comment</i>
LOM	1	Solid bulk (sheets) layered	Stacked assembly c/w adhesive	Laser	N	Y	Layers of plastic or paper are cut at the boundary for each layer; excess material must be perforated and removed
SLA	2	Photo sensitive liquid layer	Polymerization process	Ultra violet Laser	Y	Y	Part is formed by a helium-cadmium or argon ion laser that solidifies the polymer where the focused laser beam strikes the resin surface
SLS	2	Solid particulate layer	Melting and solidification	CO ₂ Laser	N	N	Part formed by CO ₂ laser melting the particulate matter; which is deposited in a layer
EBM	2	Solid particulate layer	Melting and solidification	Electron Beam	N	N	Wide material ranges available for these processes
3DP	2	Solid particulate layer	Loose adhesion via binding material	Binder on a print head on X & Y axes	Y	N	Color cartridges can be used; surface coating required for strength (very friable)
FDM	3	Solid wire	Melting and solidification:	Resistance heater on X & Y axes	N	Y	Two types of materials are extruded in a semi-liquid state: the build material for the part and support material Dissolvable support material is available; else, the support material must be manually removed

Tab. 1: AM processes: LOM (Laminated Object Manufacturing), SLA (Stereolithography), SLS (Selective Laser Sintering), EBM (Electron Beam Melting), 3DP (3D Printing), FDM (Fused Deposition Modeling).

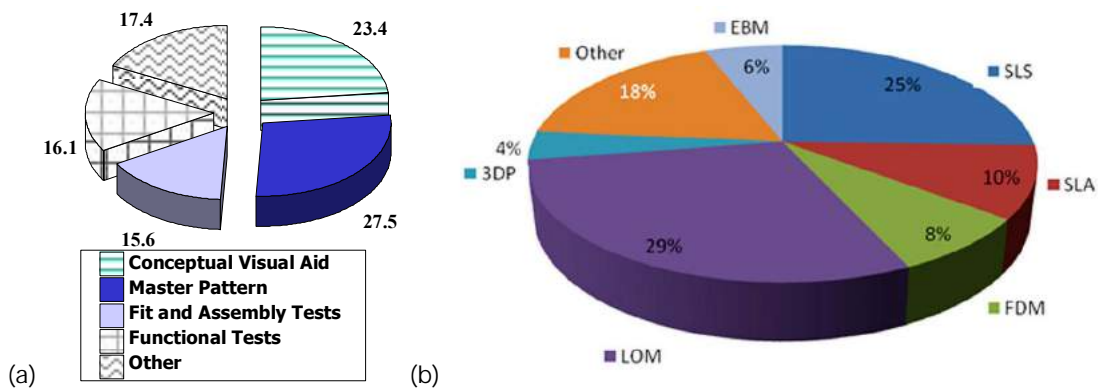


Fig. 2: (a) Main AM applications [3] and (b) Industry trends in AM technologies [15].

The modules required to realize this application are illustrated in Fig. 3. All are inter-related, as the process flows from input geometry through to sending a program to the machine; however, the core elements can be developed independently. The focus for this research is on determining methods and approaches for developing modules which integrate AM travel path and virtual verification strategies within a commercial CAM system.

First a comparison of the layered additive manufacturing tool path characteristics and machining tool paths is performed. A $\frac{1}{2}$ inch slice is used for illustrative purposes. The AM implementation strategy depends on the process case type defined in Tab. 1. Within a commercial CAM system, a slicing module is developed to create edge curves to be subsequently used for travel path geometry. Based on the AM process, travel path strategies are proposed. Algorithms for virtual simulation strategies are developed using different tool boxes for the different deposition strategies, and compared. Most effort is focused on line type deposition processes, as this are the most challenging with respect to number of entities to be managed in the data base and displayed.

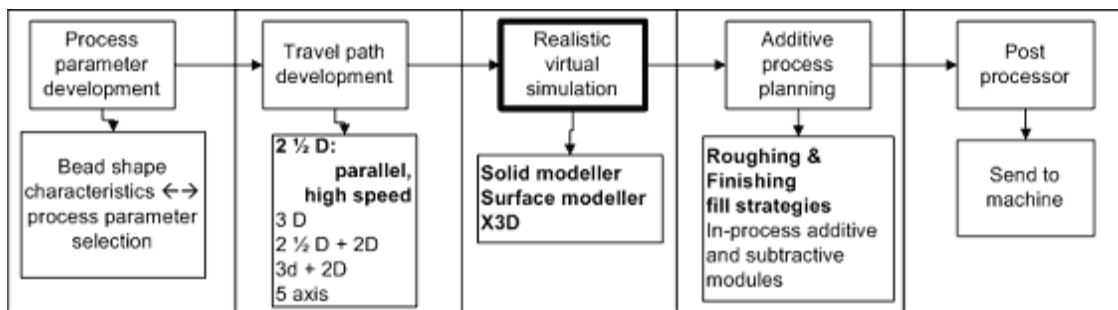


Fig. 3: AM processing development modules.

2 MACHINING VERSUS ADDITIVE MANUFACTURING

2.1 Travel Path Comparisons: Laminated Object Manufacturing (Case 1)

For the laminated object manufacturing (LOM) process type (case 1 in Tab. 1), the travel path consists of an outer contour to cut the material, and a cross hatching pattern to divide extraneous material for easy removal. The kerf width is the width of the cutting beam, and the compensation is to the **Outside** of the boundary for outer contours, and inside the boundary for holes, etc. The cross hatch pattern

consists of two roughing pocket or parallel surface tool paths. The cross hatch pattern corresponds to roughing angles for a one way or zigzag pattern, which can be set to any desired value. The cross hatch distance corresponds to the step over distance or step over percentage used in machining. As the LOM process consists of cutting operations, it can be modeled and simulated using existing travel paths, as shown in Fig. 4. Each layer consists of a minimum of 3 cutting tool paths: (i) contour, (ii) zigzag pocket @ angle 1, and (iii) zigzag pocket @ angle 2. Inner contours are processed in a similar fashion. The step over may be modified easily to optimize material removal (Fig. 5).

The process flow for incorporating LOM processes within a CAM package are illustrated in Fig. 6. In the machine definition, the defaults related to the machine size, travel limits, sheet feeding, feed rate limits and the relations between the process parameters and the cutting should be stored. From the key geometry information (bolded in Fig. 6), the travel paths are generated. The virtual model consists of stacked extrusions, where the thickness of the extrusion maps to the layer thickness. Draft options (for an average angle) can be leveraged if the laser beam angle produces an edge that is not orthogonal to the sheet, and this effect is desired to be captured. Most required elements to support LOM processing exist within contemporary commercial CAM systems. Additional elements that need to be incorporated are slicing, and a virtual stacking algorithm. As well, a special post processor to drive the LOM machine would be required.

2.2 Travel Path Comparisons: Raw Material Layer Transformation Processes (Case 2)

For the processes in which a layer of liquid or powder raw material is deposited to be subsequently transformed (case 2 in Tab. 1), the travel path consists of an outer contour to define the boundary curves, and a parallel travel path fill strategy to bind the interior material. The contour compensation is on the inside of the outer contours and vice versa for inner contours (Fig. 7).

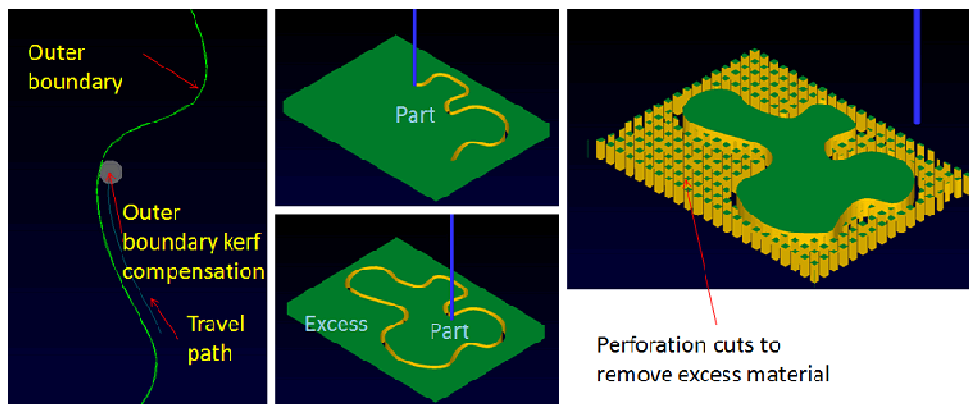


Fig. 4: LOM processing using a commercial CAM system.

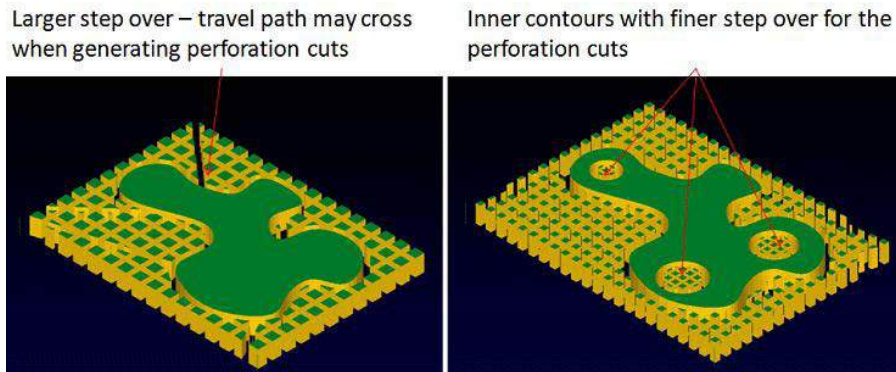


Fig. 5: Modified travel path step overs.

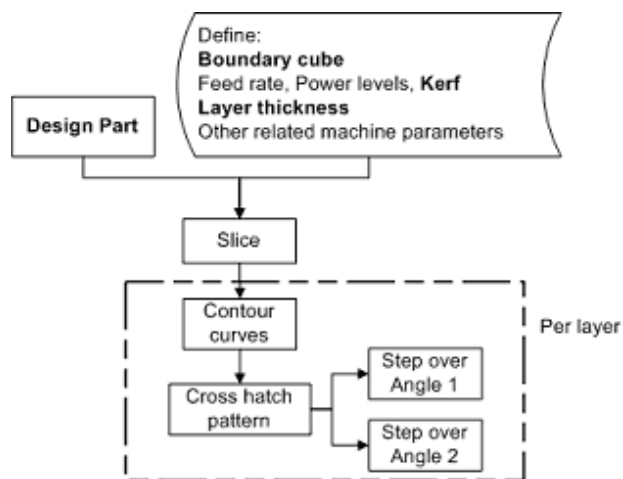


Fig. 6: LOM process flow.

The raster scan element of the AM travel paths correspond directly to a zigzag pocket or parallel path surface finish operation. However, this may include non-value added rapid moves that increase the cycle time. High feed rate travel paths exist to reduce acceleration forces for machining centers as well as machining time; these tool path types could also be leveraged for a planar surface bounded by the contours. Travel path overlap is not an issue, as the material has already been deposited; however, extraneous crossing moves can be filtered out by performing an intersection check. Transition moves can also be filtered out as they provide no added-value. Filtering unnecessary retract and plunge Z axis moves, which are included in the travel paths for material removal clearance and rapid moves (Fig. 8), is also required.

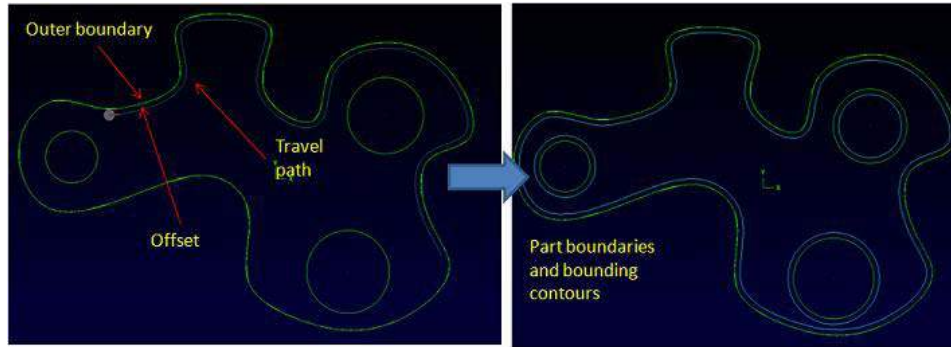


Fig. 7: Boundaries and travel path contours.

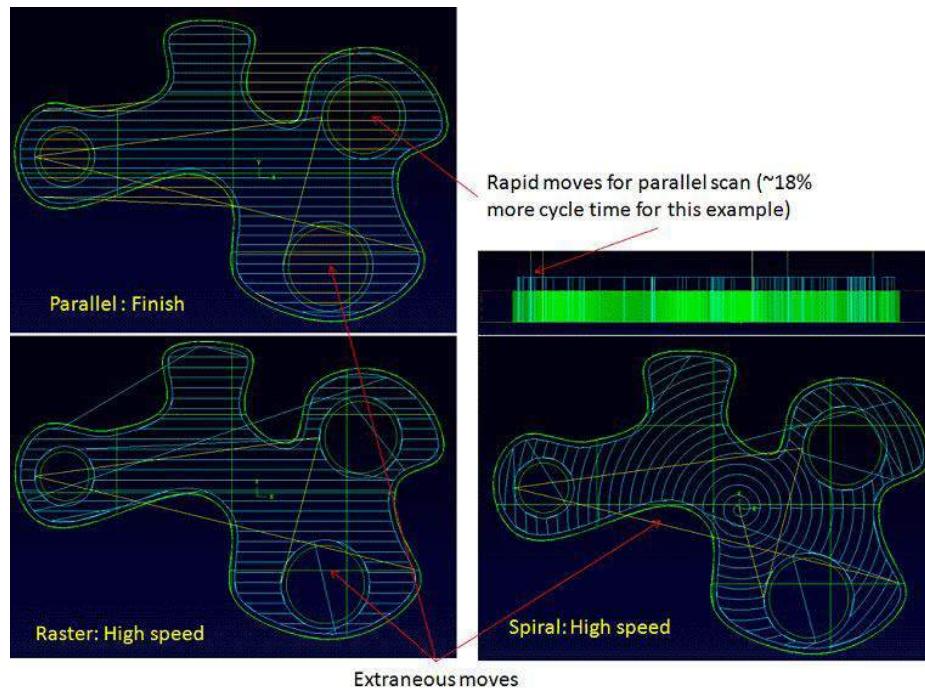


Fig. 8: Fill strategies and extraneous moves.

These clearance values can default to **DN** in the program, or can be readily recognized and filtered out by the software. A power on/off or material binder on/off status bit needs to be toggled in the program lines as appropriate, and included in the build file.

The conventional material removal verification system can be leveraged to illustrate regions where the travel path does not reach a target area, which could provide relevant insight. For example the presence of material in the virtual model represents untouched raw material. However, this is time consuming, and automatic overlapping can be readily incorporated to adjust for this condition.

When manipulating the build file, first the extraneous crossing and ΔZ moves related to rapid or clearance positioning must be filtered out. Then for each layer, the next step consists of creating representative virtual bounded models for each travel path segment using the bead cross section geometry and the travel path geometry (sweep and extrude operations). The main challenge for

creating an additive visual simulation is based on entity management. For large components, there could be over one million entities, depending on the layer thickness, bead width, and component size. For a build envelope of 250 mm³, with a layer height of 0.125 mm and a bead width of 0.25 mm, 2×10^6 raster scan elements could exist for a block built to this maximum size.

To summarize, existing machining travel paths can be leveraged, and there is potential for optimization techniques to be utilized (minimum time, reduced accelerations, etc.). In the machine definition, the defaults related to the machine size and the relations between the process parameters (power, travel speed, etc.) and the bead width are critical for input parameters. For these processes, the travel path and virtual simulation issues focus on filtering, bead representation, and entity management. It is understood that support geometry needs to be created for the SLA process for overhanging geometry, thin features, and undercuts; however, the travel path and virtual representation issues are not unique for this additional geometry once the support regions are defined. The process flow for incorporating raw material layer transformation processes within a CAM system are illustrated in Fig. 9.

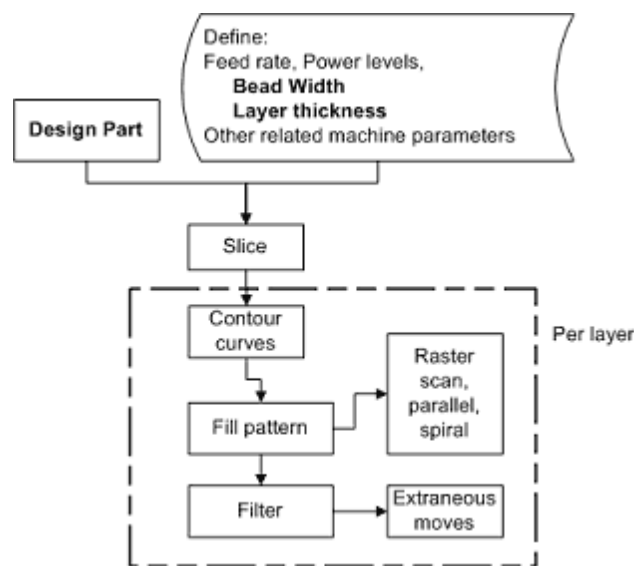


Fig. 9: SLA/SLS, EBM, and 3DP process flow.

2.3 Travel Path Comparisons: Fused Deposition Modeling (Case 3)

For the fused deposition modeling (FDM) process, welding, laser cladding and other similar processes in which the material is deposited along a curve, there are unique challenges [13]:

- The tool motion cannot cross itself (collision issue or create undesirable overlapping material condition);
- The bead that is created is not necessarily cylindrical (elliptical for FDM processes, non-symmetrical complex bead shape for welding processes);
- The **Dead** width, height, penetration and related overlaps are not independent variables; and
- There is the potential for voids and gaps.

There are issues related to the potential for self-intersecting geometry at each end point of a travel path segment as well as the negative overlap condition (conservation of mass) that need to be addressed (Fig. 10). For a characteristic virtual model and to address the self-intersection issue,

standardized intermediary geometry can be introduced to create a representative model of the tool path corner transitions. These transition entities would be created from the bead cross section by revolving the cross section, and appending them to the end of the travel path segment. As they are utilized in addition to extrusions for linear segments, and sweep models for the arc or spline segments, the numbers of entities for the virtual model would be almost doubled due to adding this transition component. The bead shape needs to be adjusted when there are overlap conditions due to conservation of mass.

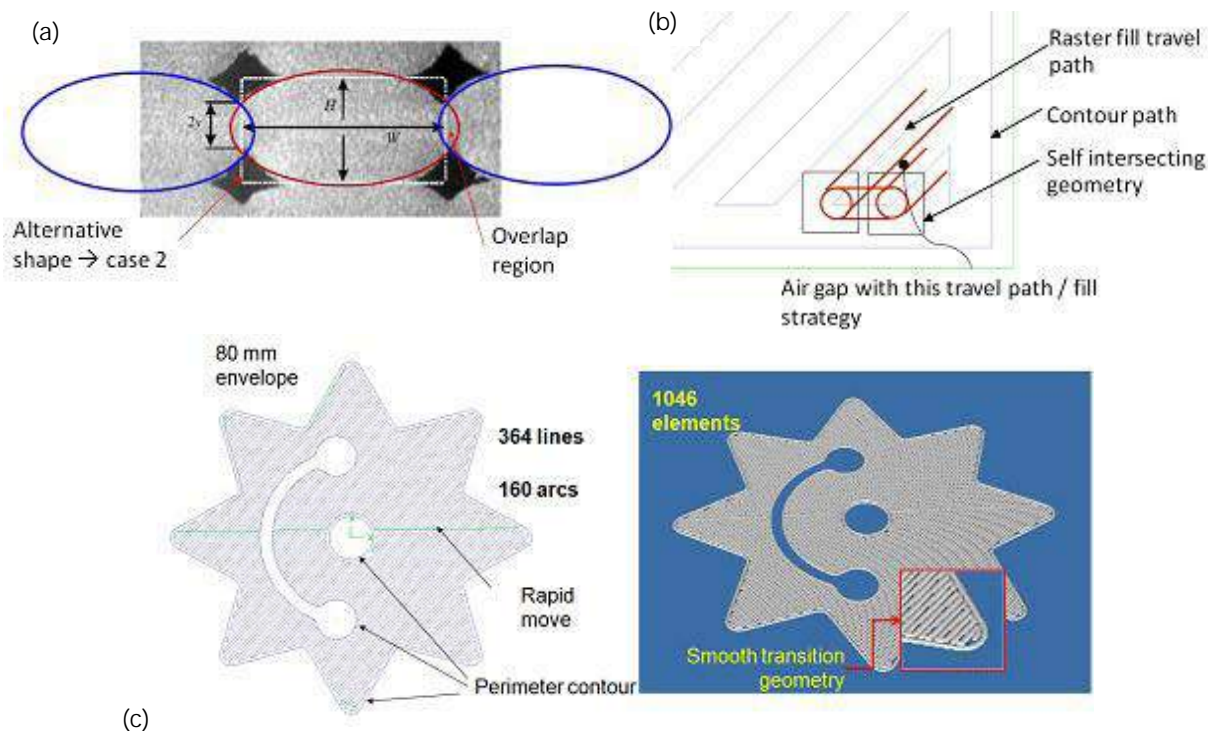


Fig. 10: (a) Overlap, and (b) Self intersections, (c) star pattern layer (adapted from [13]).

Unlike the previous cases, unique additive 2D tool paths strategies need to be created for this process family. If it is required to control the surface finish, or determine 5 axis deposition travel paths, additional travel path strategies must be developed. In this work, the tool motion is restricted to a planar surface. As with the SLA process, it is understood that support geometry needs to be created for the FDM process for overhanging geometry, etc., but again this introduces no new travel path or virtual modeling issues.

Although the 2 ½ D layering process is the simplest scenario for this process family, the entity management and visualization issues for the previous cases are subsets of this situation; hence, the focus is on modeling the FDM process within a CAM system. This will still allow for some preliminary process planning (Fig. 11) for build up sequences, and provide a stock model for downstream machining tasks, if required. In the next section, implementation strategies are developed and compared for the LOM and the FDM processes.

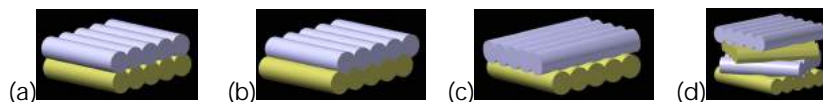
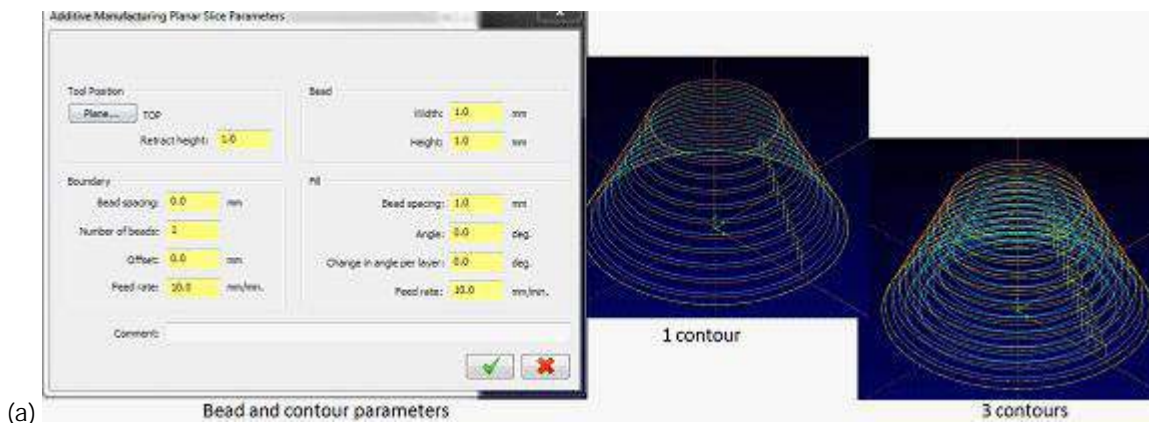


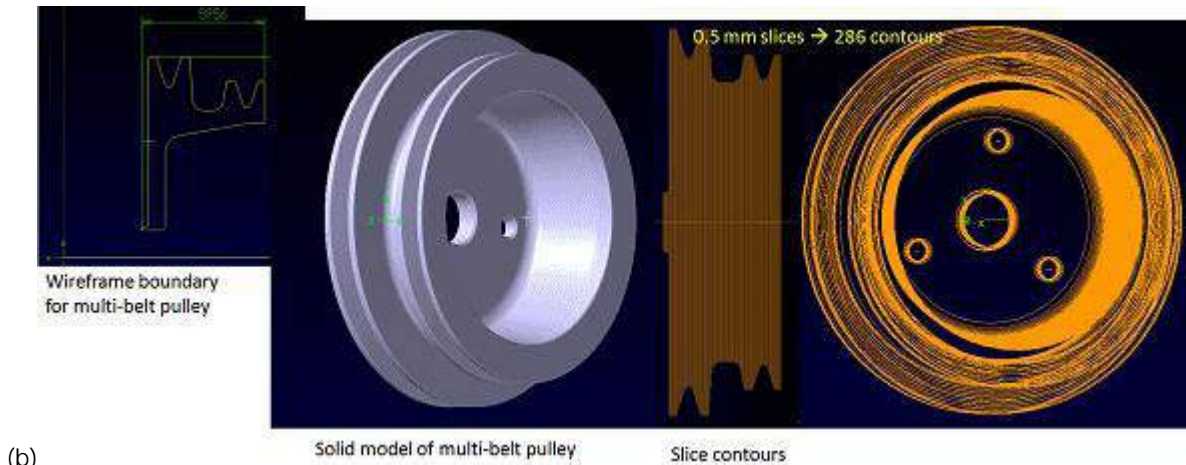
Fig. 11: (a) Direct layering, (b) Staggered overlap layering, (c) Lattice layering, and (d) Variable angle layering.

3 AM IMPLEMENTATION STRATEGIES WITHIN A CAM ENVIRONMENT

3.1 Slice Module

To develop an AM module within a CAM system, three sub-modules are required: (i) a slice module, (ii) a travel path module, and (iii) an Extrude and stack module for verification. The input solid model needs to be sliced at the desired layer thickness (bead height). The solid model is first analyzed to determine its bounding box with respect to a reference plane, and is then sliced in the reference plane. A Beiling value is used to determine the number of slices for a solid-layer thickness combination. Boundary contours are created at the intersection where the planes slice the solid. Inner and outer contours must be defined in order to offset the contours appropriately for the process being modeled. The boundary curves must be closed; consequently, some trimming or extension operations are required. If stock is to be left on for subsequent machining, the contour offset value can be increased to reflect this. If multiple passes around the perimeter are desired, multiple contour offsets are generated to reflect this, as shown in Fig. 12.





(b)

Fig. 12: (a) Input screen and slice contours, (b) Slices for a pulley.

3.2 Travel Path Module and Virtual Simulation: LOM

The travel modules vary for each process. For the LOM process, no additional geometry is necessary other than the boundary contour. All of the slice contours on the window can be selected, and the contouring travel path automatically generated using default values as follows:

- Tool diameter = bead / beam width;
- Z depth is the layer depth;
- Stock on walls = 0;
- Stock on floor = 0;
- Rapid and clearance planes are disabled, or set to a value for ease of filtering;
- Breakthrough and tab features are disabled;
- Spindle speed is disabled;
- Feed rate is the desired travel speed; and a
- Corner feed rate adjustment can be incorporated (if necessary).

If there are variable power settings, the spindle speed field can be utilized. The cross-over perforation tool paths have similar parameters, but the step over distance and roughing angle need to be included. If stock is to be left on for subsequent machining, the contour offset value can be increased to reflect this.

Extrusion operations are utilized to create the virtual simulation model. It was time prohibitive creating a solid model of incremental Boolean unions:

$$Model_i = Model_{i-1} \cup entity_i \quad (1)$$

where i is the i th solid entity undergoing a Boolean union

Therefore, a variant of the divide and conquer approach for using a solid model kernel for displaying a virtual AM model is taken [13]. Layer pairs are combined in sets, and the history tree for each set removed to create a solid $Body_N$ (Fig. 13). Those pairs are combined again, and the process repeated until the final solid model $Body_N$ is created. This model can be analyzed, trimmed to a surface, etc. Alternatively, extruded surface models from each layer can be created, blended into one model, then

an *.STL file can be created either for input as a stock model or to be converted into a **DodyN** solid model for subsequent analysis.

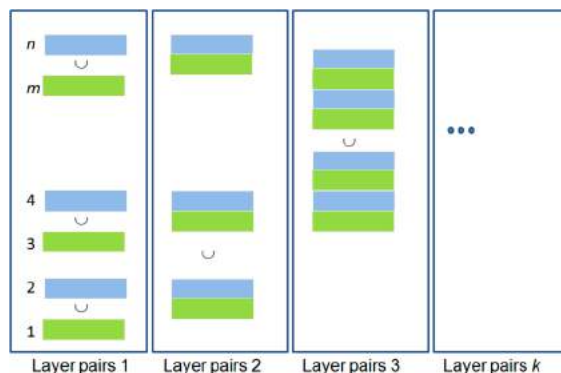
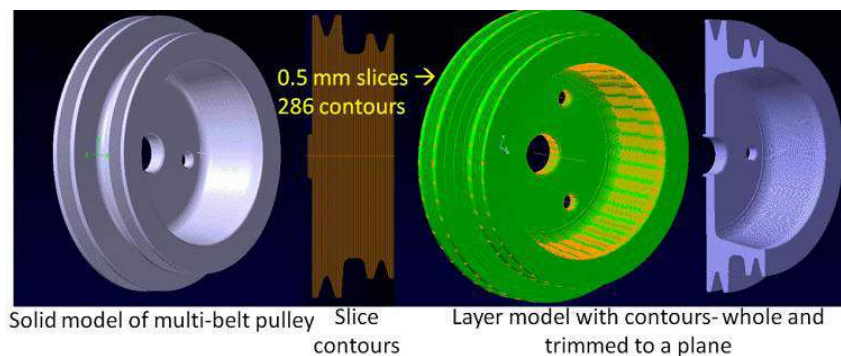


Fig. 13: Divide and conquer approach to combining Boolean union operations.

Once this virtual layered model is created, it can now be used as a stock model for material removal operations. Outer diameter turning, facing, and inter diameter facing and boring operations are performed to remove 0.25 mm stock from the AM model. This is illustrated in Fig. 14.

3.3 Travel Path Module and Virtual Simulation: FDM

With the Case 2 and 3 processes, there are no additional input parameters that need to be provided. However, for Case 3 travel path geometry that does not overlap needs to be created, and more problematically, a methodology to display the virtual additive model in a timely basis is vital. To create a representative virtual model significant processing time is required when using an **DTL**-solid modeler. Typically utilized for material removal operations, simulations. This is due to the number of entities in a Case 2 and Case 3 additive model. Therefore, a different approach is taken here. An X3D environment is employed to represent a virtual additive model. X3D is the successor to VRML (virtual reality modeling language), and can support a wide array of applications. VRML was the first web based 3D format and was unique because it supported 3D geometry, animations, and scripting. X3D is an ISO ratified standard that provides a system for the storage, retrieval and playback of real time graphics content embedded in applications [14], which is why it is leveraged in this research.



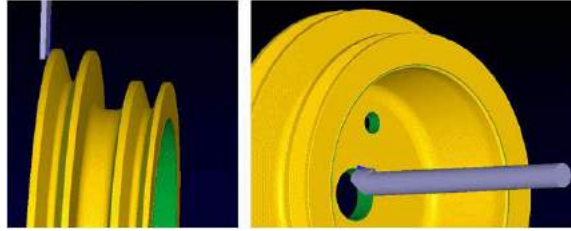


Fig. 14: LOM processing for a pulley and virtual simulation of machining an AM model.

Within the CAM program, the solid model is selected and sliced, the contour and fill tool path geometry is created, and then exported into an intermediary file format. This file is used as input for the X3D virtual model simulation module developed for the AM process. The arc and spline contours are broken into line segments for a given chordal deviation. These line segments for the contours and fill paths are represented by cylinders with spheres appended onto the end of the line segment elements for smooth transitions. The layers created, and stacked as appropriate. Any cross section can be utilized, but for the proof of concept presented here, these X3D basic primitives are employed as previous research indicated that data management is a significant challenge that needs to be addressed [13]. The base entity elements, a double contour + Case 2 type fill, and the contours for the pulley example in Fig. 12 are illustrated in Fig. 15.. Solid models that generate arc contours are chosen for testing as this represents a worst case condition with respect to entity management.

A comparison between the X3D virtual simulation developed in this research and a previously tested machining simulation solid modeling kernel [13] is presented in Tab. 2 for a star pattern and a 25 mm square solid block. As cylinders are presently being used, in lieu of a 25 mm³ block with a 0.66 bead width and 0.33 bead height tested in the original case, the input model for the X3D test is a 25 mm² x 50 mm block with a 0.66 bead width and height. Both models generate 76 layers total, and the equivalent number of the travel path geometric entities. It can be readily seen by the observed process times that the X3D approach is orders of magnitude faster. It took almost no time to create the X3D input file and to display the X3D model in the viewer.

3.4 FDM Virtual Modeling Case Studies

There are 3 steps to generate a virtual model: (i) slice and create the travel paths, (ii) post process the travel paths into X3D format, and (iii), load the X3D file into the viewer. The pulley and a complex bracket are used to test the travel path generation and the display times. The bracket is 280 x 80 x 40 mm, and contains curvilinear surfaces, a pocket, and several chamfered holes. The times for selected bead sizes for these parts are summarized in Tab. 3. The virtual models are illustrated in Fig. 16. Note: there are some graphic artifacts in the image.

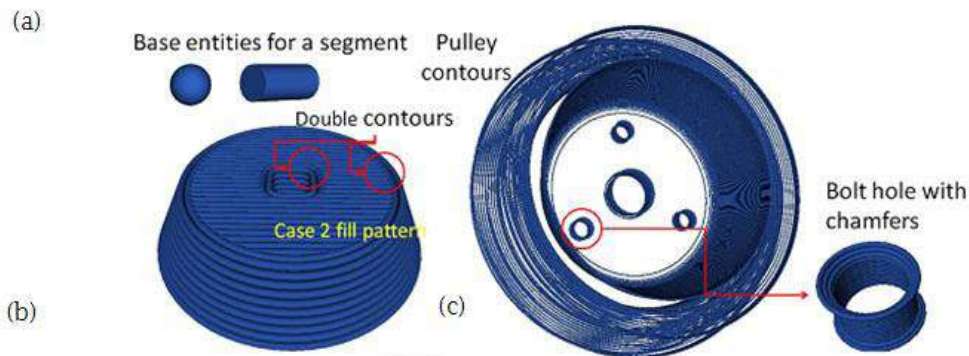


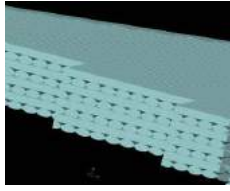



Fig. 15: (a) Modeling entities, (b) X3D Case 2 AM model and (c) contours for pulley.

<i>Input model</i>	<i>Optimized STL-solid model illustration</i>	<i>Optimized STL-solid model process time (s)</i>	<i>X3D model process time (s)</i>
Star pattern from Fig. 10 with a 0.66 mm bead width		186 sec.	 < 2 sec.
25 mm block (8 layers shown here) 0.330 mm height, 0.66 bead thickness		872 sec.	 < 3 sec.

Tab. 2: A comparison of virtual simulation model processing times.

Example	AM Bead Size (mm)	No. of Contours	AM Travel Path Processing Time	X3D Processing Time (Post)	X3D Processing Time (Display)
Pulley	0.76 mm	3	38 sec.	3 sec.	45 sec.
	0.50 mm	3	1 min. 2 sec	4 sec.	1 min. 57 sec.
Bracket	0.76 mm	1	16 sec.	2 sec.	14 sec.
	0.50 mm	1	31 sec.	3 sec.	43 sec.
	0.20 mm	1	1 min. 6 sec.	17 sec.	3 min. 42 sec.

Tab. 3: Processing times for the case studies.

3.5 Functional Application

The additive manufacturing tool path generation and virtual simulation model tools presented here will be tested at a facility that specializes in weld repair, micro welding, laser welding, and laser cladding processes using a laser cladding work cell. The work cell consists of fiber coupled diode laser, and an ABB 6 axis robot with a 2 axis stack rotary table for positioning. As these modules have been developed using a commercial platform, existing post processors are to be used for translating the tool path information to robotic motion. Presently laser cladding based processes are being

leveraged to create metal components, complementing RP processes [5, 8]. An example is illustrated in Fig. 17. The interface to this robotic system is currently under development. The tool path geometry and settings will be refined based on experimental data.

4 SUMMARY AND CONCLUSIONS

Additive manufacturing (AM) processes are becoming more common for conceptual visual aids, master patterns, fit and assembly tests, functional tests, and so forth. Unlike CAM systems for machining that give the user control over tool motion and output the code to drive the machine tools in an open source format (G-code), the user has very little control over the AM build strategy, and the commands to drive an AM machine are typically in a proprietary format, although open source systems are available. This makes the systems easy to use, but gives the user very little ability to experiment with different build strategies, which could be more appropriate for the application. There are also AM systems being developed that use multi-axis robots to build parts using a weld bead or laser cladding technology, which can be considered a complex variant of the AM process family.

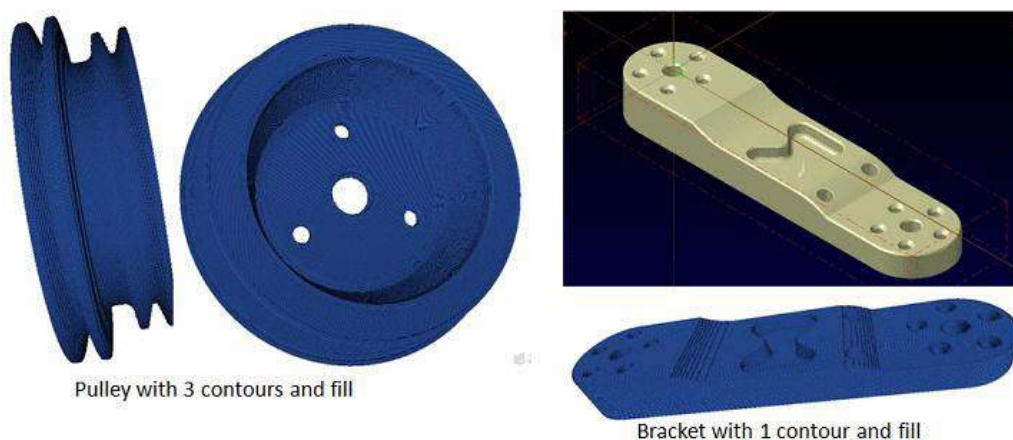


Fig. 16: Pulley and complex bracket virtual AM models.

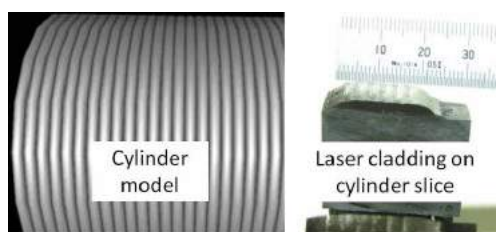


Fig. 17: Virtual AM cylinder and physical laser clad models.

There is much similarity in machining and AM; hence, the focus on adapting machine travel path programming strategies for AM processes. Integrating AM into existing CAM systems provides a direct link between the CAD model and the AM process. Changes to the CAD model can readily cascade to the AM travel paths, which is standard for machining processes within CAM systems. Stock can be added to the model via offsets for subsequent material removal or the CAD model adjusted where necessary for downstream machining processing. The AM model can be the stock model for the material removal operations and virtual simulation. For a truly representative stock model, an

understanding of the bead geometry characteristics and the fill strategy is important in order to properly capture voids and represent the surface initial conditions. This will allow planners to directly combine additive and subtractive process planning in an effective manner.

A user interface for machining is replaced with parameters suitable for 2 ½ D AM processes. The user selects the solid, enters the slice and bead parameters, and the travel paths are generated. Associations are established between the CAD and AM module. Changes to the CAD model are recognized in the AM files, which are marked "changed" similar to existing CAD/CAM processes. For the LOM process, existing tool path and virtual simulation modules require minimal modification for implementation and optimization. For the Case 2 and 3 process families, a process verification system is developed based on the X3D standard, as current solid modeling kernels for machining have been found to not be suited to modeling AM processes due to the processing time associated with handling many entities. For the FDM process, non-overlapping travel paths are required, as well as intermediary geometry is introduced to provide a realistic representation of smooth corner.

To conclude, a CAM system can be readily adapted to incorporate 2 ½ D AM processes, and beyond. Specialized machine specification defaults and post processors would need to be developed to drive the AM machines. For testing the additive manufacturing modules developed in this research, a robotic work cell is to be utilized to refine and test the tool path modules. The X3D environment can be leveraged to create realistic virtual models on a timely basis, and opens the door for new opportunities.

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