AUTOMATIC PROCESS PLANNING FOR A FIVE-AXIS ADDITIVE HYBRID MANUFACTURING SYSTEM

A Dissertation in
Industrial Engineering
by
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ABSTRACT

A multi-axis additive manufacturing (AM) system allows for reorienting of the geometry during a build to gain greater building flexibility over that of traditional planar layer by layer additive manufacturing processes. A hybrid manufacturing (HM) system integrates computer numerical control (CNC) machining with multi-axis AM into one process that can switch between each of these two processes, reaping the benefits of both. Currently, these two systems require significant manual work to transform the CAD design into a manufactured part. With the lack of automated process planning algorithms to avoid the significant amount manual work necessary, adoption of HM technology has been slow. Critical components of process planning in multi-axis AM and HM include: 3D model decomposition, sequencing of production of the decomposed volumes, and toolpath generation. Three process planning approaches are presented in this dissertation which seek to reduce the manual work required by automating each of the critical components. The first two approaches rely on the concept of generating decomposed volumes that are self-supported, and sequencing these volumes in a manner that avoids collisions between the build and the AM or HM system, then mapping tool path strategies to each of these volumes. The first approach treats the five-axis machine as a 3+2 axis machine, where the rotational axes are only used for positioning and the decomposed volumes only accommodate planar tool paths. The 2nd approach uses the full five-axis capability and 3D tool paths are used to decompose the part into self supported volumes that can be built without additional support structures. The 3rd approach, referred to as direct five-axis slicing, eliminates the volume decomposition and can directly generate the 3D slices, associating each slice with a tool path. All the approaches are focused on eliminating support structures and avoiding local collision between the tool and the part.
Algorithms for decomposition are developed based on the process of identifying concave edges in a part’s geometry and segmenting the part along these edges using the surfaces generated by the concave edges. For each decomposed volume, a build direction is identified along with the building sequence and toolpath strategy that can be used to generate the detailed toolpaths. Several case studies using the developed algorithms are presented, along with simulations and experimental results, to validate and showcase the capabilities of the three proposed process planning approaches. A comparison of the three approaches is also included to highlight the features and the limitations of each approach.
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Chapter 1

Introduction

Traditional additive manufacturing (AM) is a layer by layer material deposition process. The deposited layers are planar and located in the x-y plane while the z-axis is used to control the height of the part. Typically, 2-1/2 axis machines are used to build the parts. Seven different types of AM processes, Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Photopolymerization, have been acknowledged by the American Society for Testing and Materials (ASTM) [21], and all follow a similar workflow in converting a CAD model into a final AM part, as shown in Figure 1.1.

![Figure 1-1. Overall Workflow in Traditional AM process](image)

From the desired CAD model to the near net shape finished geometry, process planning activities play an essential role. An example of process planning used in traditional 3D printing is
shown in Figure 1.1. A large proportion of the process planning steps have been automated in traditional AM to enable the development of the machine instructions.

While traditional AM has several advantages such as being capable of building complex geometry, multi-material parts, and less material waste, it also has its disadvantages – poor surface finish, need for support structures which can be expensive to remove, limited material choice, and a slower speed for production. Hybrid manufacturing has been proposed as a solution to address some of the problems associated with AM. By combining subtractive manufacturing, hereon referred to as machining, with AM in a single multi-axis machine, the process benefits from both processes by allowing switching between these two processes in a single platform.

Of the seven AM methods identified by ASTM, only some of them are suitable for multi-axis implementation and currently are used by hybrid machines. Table 1.1 shows an overview of the current combination of hybrid manufacturing systems.

Table 1-1. A timeline of hybrid manufacturing research and commercial machines

<table>
<thead>
<tr>
<th>Time</th>
<th>Institute or Company</th>
<th>AM Process &amp; Machining type</th>
<th>Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Fraunhofer Institute of Production Technology,</td>
<td>Selective laser sintering &amp; Directed energy Deposition</td>
<td>Metal, ceramic [1]</td>
</tr>
<tr>
<td></td>
<td>Fraunhofer Institute of Laser Technology</td>
<td>(Controlled Metal Build up), no machining process</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>University of Missouri</td>
<td>Directed Laser Deposition (DED) and five-axis CNC</td>
<td>Metal [2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>milling</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>National Taiwan University of Science and Technology</td>
<td>Selective laser cladding (SLC) and 3-axis milling</td>
<td>Metal [20]</td>
</tr>
<tr>
<td>2003</td>
<td>Matsuura</td>
<td>Powder bed Fusion (PBF) / Laser sintering and 3-axis milling</td>
<td>Metal</td>
</tr>
<tr>
<td>2005</td>
<td>Joanneum Research Forschungsgesellschaft mbH, Austria</td>
<td>Directed Laser Deposition (DED) and five-axis CNC</td>
<td>Metal [3]</td>
</tr>
<tr>
<td>2006</td>
<td>Southern Methodist University</td>
<td>Welding, DED and plasma cladding processes with multi-axis milling machine</td>
<td>Metal [4]</td>
</tr>
<tr>
<td>Year</td>
<td>Institution/Project Details</td>
<td>Technology Details</td>
<td>Material(s)</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------</td>
<td>--------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>2008</td>
<td>De Montfort University &amp; The Manufacturing Technology Centre</td>
<td>Laser cladding/welding and 5-axis CNC machining/ grinding and five-axis on machine inspection</td>
<td>Metal [7]</td>
</tr>
<tr>
<td>2013</td>
<td>DMG MORI</td>
<td>Laser metal Deposition (LMD) and five-axis milling</td>
<td>Multi-metal material [11]</td>
</tr>
<tr>
<td>2014</td>
<td>Sodick</td>
<td>Powder bed Fusion (PBF) / Laser sintering and 3-axis milling</td>
<td>Metal, creating injection mold</td>
</tr>
<tr>
<td>2014</td>
<td>YAMAZAKI MAZAK (Integrex i AM)</td>
<td>Laser cladding and five-axis machining</td>
<td>Metal [10]</td>
</tr>
<tr>
<td>2015</td>
<td>Hermle, German</td>
<td>Thermal spray process based on lower-energy kinetic compacting, or micro-forging and five-axis machining (C 40 U) with heater and water quenching</td>
<td>Metal [19]</td>
</tr>
<tr>
<td>2015</td>
<td>Optomec</td>
<td>Directed Laser Deposition (DED) and five-axis CNC milling, lathes,</td>
<td>Metal [8]</td>
</tr>
<tr>
<td>2015</td>
<td>ELB &amp; Hybrid Manufacturing Technologies</td>
<td>Laser cladding and five-axis CNC machining (side spindle)/ robotic platform</td>
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<td>2015</td>
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<td>Directed energy deposition (DED) five-axis vertical machining (Hardinge G325)</td>
<td>Metal or ceramic [18]</td>
</tr>
<tr>
<td>2016</td>
<td>Enomoto Kogyo, Shizuoka University of Art and Culture &amp; C&amp;G Systems</td>
<td>Fused filament fabrication (FFF) and five-axis CNC milling</td>
<td>Multi-material, Plastic [6]</td>
</tr>
<tr>
<td>2016</td>
<td>Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University</td>
<td>Digital light projection (DLP) stereolithography (SL) and 3D micro-dispensing</td>
<td>3D electronic systems [5]</td>
</tr>
<tr>
<td>2016</td>
<td>Mitsui Seiki USA, Vertex 55X-H</td>
<td>Laser direct-energy and CNC Vertical Machining Center (VMC)</td>
<td>Metal [17]</td>
</tr>
<tr>
<td>2016</td>
<td>Elb-Schliff MillGrind</td>
<td>Laser deposition welding and grinding, milling</td>
<td>Metal [16]</td>
</tr>
<tr>
<td>2016</td>
<td>Trumpf’s TruLaser</td>
<td>Laser metal deposition (LMD) and five-axis laser cutting or precision welding</td>
<td>Metal [15]</td>
</tr>
<tr>
<td>2017</td>
<td>Manufacturing Technology Center in Coventry, UK</td>
<td>Directed Energy Deposition (AMBIT™ deposition system) and five-axis machining (Hamuel HSTM1000 CNC machine)</td>
<td>Metal [12]</td>
</tr>
</tbody>
</table>
Based on the review of these hybrid manufacturing systems, the most popular method for integrating AM and machining on a multi-axis platform is the use of Directed Energy Deposition (DED) to create the additive component, and five-axis CNC machining as the subtractive component. This dissertation is focused on a five-axis HM process that combines DED and CNC processes into one system. An example of such a configuration is the DMG MORI LASERTEC 65 3D Hybrid, shown in Figure 1.2 below. From this figure, we can see the AM process in this hybrid machine is the DED process with the five-axis CNC milling capabilities.

The HM process provides a more extensive design space not only in the geometric space but also in the material composition. Figure 1.3 shows some example parts that exhibit the capabilities of a five-axis HM machine. Figures 1.3a and 1.3b, show that some of the surfaces are machined, and the other surfaces are left as they were deposited. With this machining capability, parts can be finished in a relatively short time with precise holes and surfaces. Figure 1.3c shows

<table>
<thead>
<tr>
<th>2017</th>
<th>3D Hybrid Solutions and MultiAX</th>
<th>Wire-arc welding/DED/cold spray and large-format five-axis CNC machining/ lathes</th>
<th>Multi-metal with large scale [13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Okuma</td>
<td>Laser metal deposition (LMD) and milling, turning and grinding operations</td>
<td>Multi-material [14]</td>
</tr>
</tbody>
</table>
the capability of using multiple materials that allows the creation of heterogeneous material parts selected to fulfill the functional requirements of the part.

Figure 1-3. Parts manufactured on the DMG MORI HM machine [11].

There are several advantages to utilizing such a hybrid system:

1. Being able to utilize machining as an intermediate and alternating step allows for improved surface finish and dimensional control
2. The use of a single platform to add and subtract material removes the need for re-fixturing and relocating the part for post-deposition machining
3. The ability to deposit material on a five-axis platform allows for the creation of parts that do not need extensive support structures
4. Complex geometries can be created that are not otherwise possible, allowing for more sophisticated designs and functionality in a single part
5. The use of multiple materials (Figure 1-3.c) within a single part allows for the creation of functionally graded materials and multi-material parts

However, these advantages create a set of new challenges when planning the build of the part on such machines. Some of these are listed below:

1. Deciding what portions of the part should be additively manufactured and which should be machined
2. Sequencing the additive and subtractive portions to allow for accessibility of tools for machining and subsequent deposition
3. Generating five-axis toolpaths for both additive and machining features
The workflow for five-axis HM systems is shown in Figure 1.4. Notice that it is dominated by manual processing and decision making up until the actual generation of the tool path which still requires manual input to populate the parameters for the tool path generation. This is precisely what the work in this dissertation seeks to avoid. The steps are marked in green are fully automated in this study.

Figure 1-4. Workflow of Five-axis Additive and Hybrid Systems

Although Figure 1.4 represents the workflow of a five-axis HM system, if there only exists AM processes in the red dashed box, this would be the equivalent of a five-axis AM system workflow. Before the part can be physically printed, the process planning steps shown in the black dashed box must be executed first. Currently, the process of carrying out these steps is dominated by trial and error and requires substantial manual work by an HM expert. However, if this process can be automated, the benefits of multi-axis deposition and continuous switching between two processes can be achieved more readily.

A multi-axis additive/hybrid process allows for a wide range of possibilities in determining how a part could be manufactured, along with allowing for geometries that cannot be created without using support structures. For example, consider the part shown in Figure 1.5 that
is to be processed on a five-axis HM machine. The user must make several process planning decisions such as determining the build orientation, what form the part will begin processing as (i.e. the initial substrate, either a raw material blank or a clean slate where the part will be built starting with an additive process), which volumes will be deposited and which will be machined, and what sequence the volumes will be processed in to avoid local and global collision (see Figure 1.4 for the definitions of each type of collision). A fully automated process planning program should enable the automation of all the process planning decisions. Once the initial decisions are made regarding build orientation and starting characteristics of the initial substrate, the next step is the decomposition of the part into additive and machining volumes. Each of the decisions influences how the geometry should be decomposed, sequenced, and built to enable manufacturing. Figure 1.5 shows the result of one such decomposition sequence. The additive and machining volumes for a part were created using the Siemens NX [11] software for tool path generation with settings prescribed for the LASERTEC 65 3D hybrid. The decomposition and sequencing shown in the figure is manually generated. Automating this function will further advance automated process planning systems.

Figure 1-5. Decomposition into Additive and subtractive manufacturing features [11]
The goal of this dissertation is to develop algorithms to automate the process of
decomposition and sequencing of the decomposed volumes for HM systems. To further narrow
the scope of the dissertation, the following assumptions are made:

1. The initial build direction is known
2. Constraints (maximum overhang angle, rotatability, material deposition nozzle size...) on
   machine capabilities are known
3. The initial build preform geometry (the model which is sent to the machine with the
tolerancing requirements and substrate decisions) is provided as a 3D CAD model
4. Only local collision between the deposition nozzle and previous built geometry is
   considered
5. Machining tool size is not taken into consideration when preventing collision

Three different approaches to decomposition were developed in this thesis and are
discussed in detail in Chapters 2, 3, and 4. The 3 different approaches are briefly described as
follows:

1. 3+2 Axis decomposition of AM
   In this approach, the five-axis machine is treated as a 3+2 axis machine, where the 2
   rotational axes of the machine are only used for part orientation. Only additive operations are
   considered. The decomposed volumes are limited to be volumes that can be deposited only by
   planar layers such that they do not require support structures. The sequence of the
   decomposed volumes is free of local collision, and each decomposed volume is defined by
   the geometry and build orientation defined by the position of the rotational axis.
2. Five-Axis decomposition for hybrid (AM and SM)
   In this approach, the limitation that tool paths are planar is relaxed, and allows for
decomposed volumes that accommodate true 3-axis tool paths. The input CAD model is
   decomposed into single body volumes, where each single body volume is a swept volume and
there exists a corresponding tool path generation strategy in the CAM software library. Additionally, machined features are inserted and identified to enable building of the additive volumes in a support-free manner. These additive and machining volumes are sequenced in such a way to avoid all local collisions.

3. Direct five-axis slicing

In this approach, rather than creating volumetric decompositions that map to predefined tool path strategies, the part is directly sliced into five-axis printable layers that are self-supporting and satisfy the conditions for local collision avoidance. This eliminates the need for decomposition and does not rely on pre-defined tool path strategies.

Figure 1-6. Example using different approaches on the same part

Figure 1.6 shows a simple example illustrating the different approaches on the same part. Figure 1.6b and 1.6c shows the decomposition results by approaches 1 and 2 which segment the input geometry into support-free volumes. These volumes use 2D planar or 3D freeform toolpaths to build the geometry, thus resulting in different decomposed volumes. Figure 1.6d directly slices the geometry into printable layers which are support-free and can be continuously deposited upon the previous layers.

The remainder of the dissertation is organized as three separate standalone working papers each addressing the three problems. First, Chapter 2 presents the 3+2 axis approach, next Chapter 3 presents the five-axis approach, and then Chapter 4 presents the direct five-axis slicing
approach. Chapter 5 presents a comparison of the 3 approaches and Chapter 6 presents the conclusions and future work.
Reference:


[14] https://www.additivemanufacturing.media/suppliers/OKUMA


[17] https://www.additivemanufacturing.media/products/3d-printer-for-additive-subtractive-processes(2)


Chapter 2
Process Planning for Five-Axis Support-Free Additive Manufacturing

Abstract:

Traditionally, Additive Manufacturing (AM) is a two-dimensional layer by layer material deposition process which requires building the support structures along with the build of the desired model. Removal of the support structures is costly and time-consuming, especially for metal parts. Using a five-axis deposition machine has the potential to build structures without the need for supports. However, there is a lack of automated process planning software to support the full use of five-axis machines. This paper introduces an automated method that allows reorientation of the part during the build using a five-axis machine. The reorientations still allow the part to be built using traditional planar deposition but without the use of supports. This requires that the part be decomposed into sub-volumes, such that each sub-volume has an associated build direction and can be built with planar layers without the need for support structures. This paper presents the algorithms to determine the sub-volumes, their orientations, and building sequence: the major components of the process plan for manufacturing. The process plan is generated by sequencing the deposition of decomposed volumes in such a way to avoid collision between previously deposited volumes and the deposition nozzle. An added benefit of this automated process is the ability to evaluate the feasibility of building the part in a support-free manner. This can provide feedback to the designer on the support-free manufacturability of the part. Examples illustrating the methodology and establishing the viability of the decomposition strategy are presented to verify the effectiveness of the algorithms.
Introduction:

Traditional additive manufacturing (AM) builds parts layer by layer by determining a fixed build orientation, aligning the build orientation with the z-axis of the machine, and slicing the parts in the x-y plane to create the geometry for each layer. This approach is widely popular in the current generation of AM machines. It creates limitations on geometry that can be built without addressing the overhang issue that has to be resolved by the addition of support structures that have to be built simultaneously with the part. These support structures have to be subsequently removed and, in many cases, add significantly to the cost of the final part [26]. Several approaches have been used to reduce the need for support structures such as determining the optimal build orientation [28], optimizing the support structure geometry [27], using dissolvable supports [29], and manual part decomposition and stitching [9]. For more versatility of reducing/eliminating support structures, one can consider a five-axis machine platform that allows typical three-axis cartesian positioning while using the two additional axes to reposition the part during material deposition all while still retaining the ability to build the part using planar layer by layer in a z-orientation. This five-axis configuration is referred to as a 3+2 five-axis machine. In a 3+2 axes configuration, the two rotational axes are used to orient the part, and the translational axes are used to perform the positioning motions for the deposition in the x-y plane and the layers incremented in the z-direction. During the material deposition, the orientation is held fixed, thus allowing for the layers to be built in the traditional planar method.

Figure 2.1 shows the typical workflow for processing 3D models using a 3+2 five-axis AM process. Starting with a 3D CAD model, the following steps are taken:

1. Decompose the given input model into printable volumes based on 2D toolpath fabrication technique, where each printable volume is defined by a geometric volume and an associated build direction.
2. Sequence the decomposed volumes in a non-collision manner.

Two types of planar 2D tool paths are considered, one where the planar tool path is built along an axis, and another where the 2D tool path is deposited on a rotating axis. Additionally, manufacturability constraints such as allowable overhang angles, and collision detection between the deposition nozzle and deposited volumes must be considered to generate a feasible process plan. This approach has also been called support-free additive manufacturing [21-25]. The goal of this paper is to eliminate the manual decomposition and sequencing to create a seamless automated workflow to eliminate support structure while minimizing the number of reorientations needed. As a side benefit, the automated algorithm can be used as a tool to evaluate the feasibility of building a support-free part on the 3+2 axis machine for any input model.

![Diagram](image)

Figure 2-1. Example using different approaches on the same part

As an example, consider the geometry to be built in Figure 2.2a; this part cannot be built using traditional AM process without requiring many support structures, as shown in Figure 2.2b. If the part is to be built via a 3+2 five-axis AM process, there exists a decomposition of the part into sub-volumes with each volume having a build orientation that has no overhangs that need support structures. Figure 2.2c shows what these volumes look like.
The use of decomposition and chopping the part into smaller volumes has been proposed by a few researchers as a strategy to minimize or eliminate support structures using five-axis AM [21,25]. Recent results by Wu [21] and Xu [25] establish the usefulness of decompositions in eliminating or reducing support structures. However, there are still limitations in these approaches, and improvements can be made in decomposition strategies to address these limitations. Some of the limitations of these two approaches are listed:

1. During decomposition, restrictions are imposed on the allowable overhang angle which may cause it to be less than the true maximum overhang angle achievable with the given build parameters. These restrictions result in more decomposition planes as well as more decomposed volumes.

2. The algorithms are limited to planar cuts and hence still require support structures in some cases.

3. Some of the decomposed volumes, such as single curved sweeping features [11, 25], require the use of Ruan’s [11] non-uniform slicing method to further decompose into manufacturable volumes. Ruan’s technique is used to fabricate single sweeping features (e.g. curved geometry) by segmenting the geometry into nearly straight segments.

4. The algorithms presented in [11,21,22,25,33] require that the decomposed volume has only one building orientation. This constraint unnecessarily restricts the decomposition.
5. The algorithms are relatively time-consuming due to the search for cutting planes in 3-dimensional space [22].

The approach proposed in this paper addresses the limitations of the existing algorithms. Figure 2.3 illustrates the decomposition results from the algorithms proposed by Wu [21] and Xu [25] along with the decomposition generated by the algorithm proposed in this dissertation. An allowable overhang angle of 45 degrees was used. As shown in the figure, the proposed algorithm creates fewer volumes and hence requires fewer re-orientations.

Figure 2-3. Decomposition results of different models based on different algorithms

As for the goal of eliminating support structures, the proposed algorithm holds manufacturability as a significant concern among the other criteria when decomposing the geometry. The proposed algorithms focus on the following criteria:

1. Always search the **maximum volume** that fits within the buildable zone that is constrained by the machine manufacturability

2. Decomposed volumes can have **multiple slicing directions/building orientations** that would lead to reduce the number of decomposed volumes (detailed explanation in Figure 2.4)
3. Ensure there is no previously built volume above the building face to prevent collisions

Figure 2.4 is an example of a decomposed volume with multiple building faces. Having multiple is something no other existing decomposition method can do and improves the efficiency of cutting as well as reducing the number of decomposed volumes. The buildable volume based on the building face can be calculated based on the machine constraints on allowable overhang angle, details can be found in the Problem Statement and Out Approach sections. In this example, we illustrate how the use of multiple building faces can be used to reduce the decomposition and how tool paths can be generated to exploit the repositioning capability of the five-axis machine. As seen in Figure 2.4, there are 2 building faces, each of which can be used to generate a buildable volume by taking into account the allowable overhang (in this example 45 degrees). Each of these buildable volumes generated can be built without the use of support structures. If the decomposed volume lies entirely within this zone, this volume can be built under the machine manufacturing constraints and does not need further decomposition. Furthermore, the slicing directions which are parallel with the building faces can be defined for generating the buildable toolpath. A single layer tool path while still being planar but would require a reorientation of the part during the generation of the tool path.
Figure 2-4. Decomposed volume satisfying criteria and its slicing method

In Figure 2.4c, all sliced layers are presented, and the highlighted two layers are representing one path that contains two directional layers which require re-orienting of the geometry. The sliced layers are processed in a sequence of ascending orders of the maximum height along Z axis.

**Background and Literature Review**

Algorithms to decompose the input part as well as multi-direction slicing algorithms are essential to fully automating process planning. Since the development of CAD, much attention has been paid to 3D model decomposition and segmentation [1] for various applications. Based on the application of 3D segmentation, the aims of decomposition can be categorized into two main categories: first, the creation of sub-volumes from mechanical 3D objects for additive manufacturing, and second, segmentation for feature recognition of organically shaped parts.
The algorithms for segmentation and decomposition use approaches based on feature recognition [2], the centroid axis [3], curvature-based volume decomposition [4], the detection of overhang features [5,6]; and the partitioning of a part into assembly parts [7]. These methods are used for manufacturing mechanically shaped parts through either additive manufacturing or the assembly of additive manufacturing parts. Chlebus et al. [6] described feature recognition algorithms and the structure of a technological features database for giving the manufacturing plan for a part which share similar geometry and parameters. By using geometrical relationships between the lines and arcs in a sketch and checking the connections against the database, a design tree table was produced. Although this method gives us a hierarchical tree of all the features and patterns of objects, it only considers the subtractive manufacturing capabilities. Foskey et al. [3] suggested using the centroid axis that runs through the centers of all the slices in a feasible build direction. The weakness of this methodology is that it is difficult to ensure precision because precision is related to layer thickness. In addition, when the surface has sharp corners, the centroid axis will deviate from the skeleton of the part. Ding et al. [5] decomposed STL meshes into simple curvature-based volumes. By identifying the relationship between adjacent triangles, the intersecting curvature loops and holes can be determined. This algorithm is particularly useful for components with large numbers of holes, but it is not valid for complex parts that contain open concave loops and non-sharp edges. Sundaram et al. [8] identified overhang features using a surface interrogation method [6], which requires analyzing the overhang angles. The overhang angle is defined by the surface’s normal angle and building direction. Combining all points that have overhang angles larger than the threshold, the overhang features can be defined. The overhang parts are subtracted from the solid body to accomplish the decomposition. Luo et al. [9] introduced the chopper method to segment a 3D object into small printable pieces, which can be assembled with feasible joints. This methodology adopts multiple types of connectors and picks the most suitable one for cutting the cross-section. Although this method is user-friendly with the capability to adjust
the cutting plane position so that does not interfere with the process, the sub-volumes may still need support structures that require significant building time. This method may be more time-consuming because it requires printing and assembling small pieces. Moreover, the cutting plane is the hindrance for some features with curved surfaces. Chen et al. [10] built a benchmark for mesh segmentation based on human-generated disassembly. This algorithm makes the cut more similar to what a human would create; it combines manual segmentation with machine-generated cuts, making it preferable when using organic shaped models. However, this algorithm needs significant human involvement to collect enough data to produce better results; furthermore, it is not very suitable for model segmentation in metal additive manufacturing, since significant skill is needed for the assembly of the sub-set of the parts.

In addition to all the methods mentioned above, several metrics for dividing 3D models into meaningful parts [18-20] have been proposed. Liu et al. [18] developed two metrics: Similarity Hamming Distance (SHD) and Adaptive Entropy Increment (AEI). Both metrics are used to segment meshes by considering the diversity and disorder of different segmentations of the same shapes. These two methods require human perception and hierarchical segmentations. Jain et al. [19] determined how to re-group parts to form new hierarchies. The input model’s symmetry is a methodological constraint; however, this constraint can produce more sub-parts. Golovinsky et al. [20] presented a method in which the meshes are the input and produces several consistent segmentations. Taking into account convex and concave faces as well as connected faces, Golovinsky defined the segments by experimental input parameters but did not reach optimal solutions. The final addition of sub-meshes generated does not match the input mesh when using this algorithm.

Several research works have been focused on dealing with decomposition on multi-axis AM for targeting fabrication of support-free geometries. Wu et al. [21] presented a volume decomposition for minimizing the support structure under overhanging volumes. A beam-guided
search is used for handling models with multiple loops and handles. Wu et al. [22] provides a fundamental method which is combining the mesh from extraction of the skeleton and the distribution of the shape diameter metric. In this article, the sequencing planning has been emphasized for combining features which may cause collision. Wei et al. [23] uses a similar skeletal approach to partition models but collision detection is not tackled. The parts are decomposed into pieces without considering a continuous print.

Overall, these approaches illustrate how to segment a freeform design while overlooking the additive manufacturing machine’s capabilities. However, approaches such as medial axis transformation [3] and feature recognition [2] only provide roughly prescribed boundaries for sub-volumes, and these are not useful for manufacturing. Based on the current state of the art and the literature review, the automated decomposition methods are currently limited to a small set of parts.

In addition, there are several process planning strategies for multi-axis additive manufacturing which combine DED (Directed Energy Deposition) and CNC machining [11,12,13,14]. There are three major approaches taken in planning for hybrid manufacturing, which are: adaptive slicing method [11,14], non-planar conformal slicing [12] and generation of static operation sequences when considering building directions [15]. Adaptive slicing method and non-planar conformal slicing methods are aimed towards toolpath generation of planar or non-planar features. Human interaction is required to identify these features. Static operation sequencing involves sequencing all the manually identified and decomposed features and searching for a non-collision building sequence.

Ruan et al. [11] developed an adaptive slicing method to achieve non-uniform layer thickness geometry (Figure 2.5) and was able to generate toolpaths and the building sequence for the geometry. However, this method can only be applied to single-feature geometry. By segmenting the curved feature into several nearly straight features and applying a 2D planar toolpath to each of them, the single-feature curved geometry can be built based on multi-axis AM techniques. For
complicated geometry, the medial axis transformation was used to extract the skeleton of the model. Centroidal/medial axis extraction method detects the change of each centroid of the sliced layers. The accurate medial axis for the complex CAD model is difficult to extract, and sometimes cannot indicate the geometry change when two features’ sizes differ but share same medial axis.

![Image](image.png)

Figure 2-5. Non-Unifom layer based decomposition method [11]

Liou et al. [16] later extended Ruan’s work to provide a specific sequence of operations by considering the additive and machining sub-volume directions. This approach still cannot solve the complex geometry problem which includes organic shaped parts coupled with the collision problem. Similarly, Murtezaoglu et al. [32] developed a half-space cutting plane for the curved geometry, however, this cannot be applied to more complicated geometries which are required for multi-cutting planes. Kapil et al. [12] adopts a non-planar slicing method by using intermediate intersecting contours to generate a slicing method for multi-feature parts. This process planning method only covers a five-axis additive process without considering possible collisions between deposition volume and deposition nozzle. Zhang et al. [15] proposed a full process planning method for a hybrid manufacturing process which starts from decomposition of the 3D model. This process also contains the building/machining direction for each volume with collision detection. In contrast to the process planning approach proposed by Liou et al. [17], the sequence of the features do not consider the real building process which starts from the substrate. Furthermore, the decomposition method is not universal and cannot be applied to all 3D objects. There is no robust and automatic
feature recognition from the 3D CAD model and decomposition of complex geometries by searching skeletons of the objects. In contrast, Dai et al. [24] considers creating freeform surfaces that allows for material deposition without the need to decompose the model. The voxelization is first applied to the objects, then the curvature layers are calculated by counting shadowed voxels based on building accessibility. The existing problem in this research is the discretization of the printed objects for depositing materials in the unit of voxel instead of continuous path. The surface roughness is also a critical disadvantage of this approach.

In summary, the various multi-axis AM limitation and fabrication techniques reviewed here employ a multitude of decomposition methods looking to either to decompose the geometries into support-free volumes or to design the toolpath that can be applied on to the decomposed geometries. However, limited research has explored the manufacturability and geometrical concerns on the 3+2 five-axis AM outcomes.

Methodology:

Problem Statement

The geometric problem of decomposition that is addressed here can be formally stated as follows: given a CAD representation model \( M \), (such as step, igs format), fabricated in a layer by layer manner on varied building faces \( (S_i) \) with a fixed building orientation \( (N_i) \) separately, establish an approach to ensure the face \( (F_j) \) on the model M can be self-supported when located inside of the swept volume which is defined by building face \( (S_i) \) and building orientation \( (N_i) \).

\[
V_{(F_j, S_i)} = \begin{cases} 
1 & F_j \in \text{sweep}(S_i, R(\theta) \cdot N_i) \\
0 & \text{Otherwise}
\end{cases}
\]  

(1)
Where $\theta$ is the maximum allowable overhang angle when building in orientation $N_i$, $R(\theta)$ represents the rotational matrix. Face $(F_j)$ can be built without support structure when $V_{(F_j,S_i)} = 1$, otherwise it requires another building face $(S_i)$ and building orientation $(N_i)$. Support structures are a necessity for complicated geometries in traditional 2.5D printing where the building face and building orientation are not varied. Five-axis AM provides ease of switching building orientations during printing to reduce or eliminate support structures.

To conduct 3+2 five-axis AM, the model $M$ is required to be decomposed into $N$ buildable volumes, where:

- $M = \bigcup_{k=1}^{N} (M_k)$ (2)
- $\forall (F_j) \in (M_k)$ satisfy: $V_{(F_j,S_i)} = 1$ under $(N_i)$
- $M_k \cap M_{k+1} = S_{k+1}$ (3)
- All $(M_k)$ are ordered in a non-collision fabrication sequence

The problem can be solved by searching for decomposing planes/surfaces $(D_{i,j})$ when $\exists V_{(F_j,S_i)} = 0$ that create building faces which can be used to ensure that the faces are self-supported, where $i$ represents chosen building faces and direction and $j$ represents the surface on $M$:

$$s_{i,j} = D_{i,j} \cap M$$ (4)

Building faces $(s_{i,j})$ located at the intersection of decomposing planes/surfaces $(D_{i,j})$ and model $M$. $D_{i,j}$ needs to satisfy:

$$D_{i,j} = \perp tangent(F_j)|_{p_m}$$ (5)

Decomposed planes/surfaces $(D_{i,j})$ need to be perpendicular with the overhang faces $(F_j)$ at their lowest points.
Where \( p_m = \text{sweep}(S_{i-1}, \frac{N_{i-1}}{\cos(\theta)}) \cap F_j \), which is the intersecting curve between the self-supported volume and the remaining volume on \( M \). One example of constructing the decomposing planes/surfaces is shown in Figure 2.6.

![Figure 2-6. Workflow for constructing decomposing planes/surfaces](image)

As shown in Figure 2.6, the overhang surfaces (\( F_2 \)) can be defined based on \( S_1 \) and \( N_1 \), the decomposing plane/surface is required to be constructed to allow \( F_2 \) to be support-free. No overhang surfaces are allowed to be built without support structures. In this case, the decomposing plane \( D_{1,2} \) needs to be constructed perpendicular to \( F_2 \).

When constructing the decomposing planes/surfaces (\( D_{i,j} \)), we need to ensure the manufacturing sequence allows for the collision-free fabrication of all \( M_k \). All \( (M_k) \) are adjacent to \( S_1 \), which is further used to develop a hierarchy tree of all decomposed volumes used to generate a manufacturing sequence.
Our Approach

3+2 five-axis AM requires decomposing the input model $M$ determined by decomposing planes/surfaces ($D_{i,j}$) into printable volumes under manufacturing constraints, and these volumes need to be sequenced in an order that avoids collision. We define the volume made by $F_j$ under $V_{(F_j, S_i)} = 1$ to be $B_i$ along with the direction $N_i$, the remaining volumes contains $F_j$ that $V_{(F_j, S_i)} = 0$ to be $RB_{i,j}$. The volume “above” the $D_{i,j}$ is denoted by $D^+_{i,j}$, and the volume “below” the decomposing planes/surfaces is denoted by $D^-_{i,j}$. Each decomposed volume should satisfy the manufacturability criteria:

**Criterion I:** $\forall M_k \in B_k$, which is supported by $S_k$

Every decomposed volume is self-supported, ensuring the manufacturability of the region above $S_k$.

**Criterion II:** $\forall (F_j) \in (M_k)$ should be at an angle with $S_k$ that equals to maximum overhang angle $\theta$

**Criterion III:** $\forall M_k \cap D^-_{k} = \emptyset$

This criterion satisfies the collision avoidance constraint by ensuring the volume created is always below the build planes.

**Criterion IV:** $\forall (D_{i,j})$ only pass through $\forall face \in RB_{i,j} \parallel F_j \in B_i$ if $\exists V_{(F_j, S_i)} = 0$

When decomposing surfaces/planes ($D_{i,j}$) intersect other non-associated overhang surfaces they prevent unnecessary cuts (Figure 2.7). The faces where $V_{(F_j, S_i)} = 1$ or belongs to other Remaining Bodies (RBs) do not need to be decomposed. In Figure 2.7, $D_{1,2}$ should only intersect with $RB_{1,2}$ and $D_{1,3}$ should only pass through $RB_{1,3}$ for the purpose of generating the decomposition.
Figure 2.7. Workflow for constructing decomposing planes/surfaces

Figure 2.7 presents the workflow of applying decomposing planes to the sample geometry in Figure 2.7a. The decomposing planes should only pass its associated RB such that it does not create extra cuts, shown in Figure 2.7c.

**Criterion V**: $\forall (D_i)$ only pass through $\forall$face $\in B_i \cap \max (p_m | n_i)$

In general, in order to prevent collision between the printed geometry and the deposition nozzle, the volumes which have different building orientations need to satisfy the condition that there exists a coincident point in between. Therefore, we generally prefer a coincident point at the maximum height of $p_m$ along the building orientation of the $B_i$ volume.

**Criterion VI**: $\forall (S_i)$ is a 2D surface

This criterion ensures every building face meets the manufacturability of the 3+2 five-axis AM process.

In summary, the decomposed volumes of $M$ are created under all the above criteria. The scheme of the decomposition process and the two associated algorithms for creating the decomposing planes/surfaces are developed in the next section.
Schemes for Creating Decomposing Planes/Surfaces ($D_i$)

We introduce the overall workflow (Figure 2.8) for generating decomposing planes/surfaces for the input model $M$ for determining the corresponding decomposition.

1. **Input CAD model, initial build direction and machine constraints**
2. **Create buildable volumes, remaining volumes and intersecting curves in between based on defined build direction**
   - Algorithm 1

3. **Create decomposing planes/surfaces ($D_i$) for the buildable volumes and remaining volumes based on intersecting curves ($p_m$)**
   - Algorithm 2

4. **Sequence all decomposed volumes ($M_k$)**
   - Algorithm 3

Figure 2-8. Overall workflow of generating decomposing surfaces/planes for an input model

Algorithm 1, shown in Figure 2.9, starts from slice profiles of the CAD model along with the first input building orientation, which is used to define maximum building volume (Buildable Body $B_i$) and the volume that cannot be built in this direction (Remaining Bodies $RB_{i,j}$). By using Algorithm 1, overhang surfaces can be extracted with specified building orientation which are then applied to Algorithm 2 for the sake of calculating the decomposing surfaces/planes.
Algorithm 1: Generation of Buildable Body and intersecting curve with Remaining Bodies

**Input:** CAD Model $M$ (such as .stp, .prt...), Overhang angle $\theta$, normal $n_1$ of one building orientation, layer height $LH$ of machine capability

**Output:** Buildable Body ($B_i$) and intersecting curve ($intersecting\ curve_{i,j}$) with Remaining Bodies ($RB_{i,j}$)

1. **Define** Cross section profile based on $M$ with $n_1$ and $LH$, layer profile, $\forall i \in [1,...N]$
2. **for** $i = 1$: **all layers**
   3. $layer\ boundary_{i+1} = sweep(layer\ profile_i, R(\theta) \cdot n_i)$
   4. $layer\ profile_{i+1} = layer\ boundary_{i+1} \cap layer\ profile_{i+1}$
   5. **end**

6. $B_i = \bigcup_{i=1}^{N} layer\ profile_i$
7. **Do:** $M \setminus B_i = RB_{i,j}, i = 1,... \#Buildable\ bodies, j = 1,... \#remaining\ bodies\ with\ Bi$
8. $V_{overhang\ surface_{i,j}, layer\ boundary_{i+1}} = 0 \mid overhang\ surface_{i,j} \in RB_{i,j}$
9. **Set** $intersecting\ curve_{i,j} = B_i \cap overhang\ surface_{i,j}$
10. **Export** $B_i, RB_{i,j}, intersecting\ curve_{i,j}$

Figure 2-9. Algorithm 1 - for generating the buildable body and remaining bodies

Figure 2-10. Workflow of applying Algorithm 1 into example geometry shown in Figure 2-10 a)

Figure 2.10 shows the workflow for determining the buildable body (BB) and remaining body (RB) based on specified building orientation from Algorithm 1. The BB is determined by the intersection between the union of the layer profiles and the input model, the RB is the remaining portion of the body in the input model $M$. Each RB corresponds to a BB that requires further
decomposition. The decomposing surfaces/planes are decided by Algorithm 2, which can be seen in Figure 2.11.

**Algorithm 2**: Generation of Remaining Bodies and associated building orientations

**Input**: $B_0$, $RB_{i,j}$, intersecting curve$_{i,j}$

**Output**: decomposing surface$_{m,[i,j]}$ and decomposing plane$_{m,[i,j]}$

1. for $i = 1: \#B$,
2. for $j = 1: \#RB_{i,j}$
   3. $p_m \in$ intersecting curve$_{i,j}$
   4. if $m \geq 2$ || $\exists$ spline$_{i,j}$ @minimum along $n$,
   5. Do: tangent plane$_{m,[i,j]}$ = // overhang surface$_{m,[i,j]}$ @ any point on spline$_{i,j}$
   6. Build: iso-parametric curve $u_{m,[i,j]}, v_{m,[i,j]}$ of overhang surface$_{m,[i,j]}$
   7. $u_{m,[i,j]} = \text{directional profile of overhang surface}_{m,[i,j]}$
   8. Build: axis$_{m,[i,j]} \perp u_{m,[i,j]}$ on tangent plane$_{m,[i,j]}$
   9. cutting plane$_{m,[i,j]} = \perp$ tangent plane$_{m,[i,j]}$ @ axis$_{m,[i,j]}$
   10. curve$_{m,[i,j]} = \text{axis}_m \perp \text{cutting plane}_{m,[i,j]}$
   11. decomposing surface$_{m,[i,j]} =$ swept($R(\vartheta) \cdot$ curve$_{m,[i,j]}$, spline$_{i,j}$)
   12. else
   13. Do: tangent plane$_{m,[i,j]}$ = // overhang surface$_{m,[i,j]}$ @ $p_m$
   14. Build: iso-parametric curve $u_{m,[i,j]}, v_{m,[i,j]}$ of overhang surface$_{m,[i,j]}$
   15. $u_{m,[i,j]} = \text{directional profile of overhang surface}_{m,[i,j]}$
   16. Build: axis$_{m,[i,j]} \perp u_{m,[i,j]}$ on tangent plane$_{m,[i,j]}$
   17. decomposing plane$_{m,[i,j]} =$ ($\perp + \vartheta$) tangent plane$_{m,[i,j]}$ @ axis$_{m,[i,j]}$
   18. endif

19. Export decomposing surface$_{m,[i,j]}$ and decomposing plane$_{m,[i,j]}$

Figure 2-11. Algorithm 2 - for generating the decomposing surfaces/planes

![Tangent plane and directional profile](image1)

a) Input: $RB_{1,2}$

![Generation of decomposed volumes](image2)

b) Generation of $D_{1,2}$

c) Decomposed Results

Figure 2-12. Generation of decomposed volumes by Algorithm 2
The decomposed volumes $M_1$ and $M_2$, shown in Figure 2.12, which can be defined based on the application of the decomposed plane generated by Algorithm 2 on the example geometry found in Figure 2.10a. Decomposing surfaces/planes in algorithm 2 are used to obtain all decomposed volumes; the next step is to sequence all the volumes in an order that avoids collisions. Since one of our criterion ensures there is no overlapping volume under the same building orientation among the decomposed volumes, the sequence needs to justify the building hierarchy for these decomposed geometries. The process planning for developing a building sequence from the decomposed volumes is shown in Figure 2.13 as Algorithm 3.

**Algorithm 3: Process planning ($M_k, n_k$)**

<table>
<thead>
<tr>
<th>Input: $M_k$ with $n_k$</th>
<th>Output: Sequence of all $M_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deposition Nozzle Scheme</td>
</tr>
<tr>
<td>1. Set $M_k$ as nodes</td>
<td></td>
</tr>
<tr>
<td>2. if $RB_{ij} \subset M_p, M_q \subset B_i$</td>
<td></td>
</tr>
<tr>
<td>3. link $M_q \rightarrow M_p$</td>
<td></td>
</tr>
<tr>
<td>4. endif</td>
<td></td>
</tr>
<tr>
<td>5. if $\min(\text{euclidean}(\forall \text{point on } M_i &amp; \forall \text{point on } M_j)) &lt; 2 \times R$</td>
<td></td>
</tr>
<tr>
<td>6. $M_{i \cup j} = M_i \cup M_j$</td>
<td></td>
</tr>
<tr>
<td>7. end</td>
<td></td>
</tr>
<tr>
<td>8. Update the nodes and paths</td>
<td></td>
</tr>
<tr>
<td>9. Start from $M_i$, find open-path loop which go through all features by path directions</td>
<td></td>
</tr>
<tr>
<td>10. if: open-path loop cannot be formed</td>
<td></td>
</tr>
<tr>
<td>11. exit: the part cannot be built on $3+2$ axis AM process</td>
<td></td>
</tr>
<tr>
<td>12. elseif $\theta_{n_p, n_f} \leq 90 + 2 \times \theta$</td>
<td></td>
</tr>
<tr>
<td>13. exit: the part cannot be built on $3+2$ axis AM process</td>
<td></td>
</tr>
<tr>
<td>14. elseif: export the open-loop path with all $M_k$ with $n_k$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-13. Algorithm 3 - generating the overall process planning for a given geometry

Algorithm 3 (Figure 2.13) provides the sequencing method for the decomposed volumes. The decomposed volumes will be merged if a potential collision is detected between the deposition
nozzle and the existing geometry while still maintaining their associated building orientation. If the correct sequence cannot be found, the given model cannot be processed via 3+2 five-axis AM.

After the volumes and the build directions are established, the uniform layer-based slicing method can be applied to each decomposed volume along the normal of the decomposing planes/surfaces. Based on the sequencing algorithm in Figure 2.13, multiple decomposed volumes may be combined into one printing volume. The slicing methodology should follow their associated building orientations from Algorithm 2.

**Results and Discussion**

The algorithms presented in the previous sections have been implemented in SolidWorks using SolidWorks Visual Basic, using an Intel® Core™ i5-6600 CPU @3.30GHz 3.31GHz computer.

Several example parts (Figure 2.14) were processed through the implemented software to illustrate the resulting decomposition and sequencing. These seven example parts are derived from test examples in the literature review and can be built on 3+2 five-axis machines, but they all either need human involvement for decomposition or they cannot be processed successfully by current automatic decomposition methods. The collision detection in this result section assume the infinite small size of the nozzle.
Figure 2-14. Sample parts and their associated processing time

Figure 2.14 shows that these models all require a large number of support structures when built using traditional 2.5-axis AM machines. Some of the supports are even located inside of the geometry, such as those in model 12.14b, d, and e which cannot be removed after the print unless the material can be dissolved. The figure also shows the results of the decomposition using the algorithm proposed in the paper. The decomposed models (decomposition shown in different colors) can be printed in a sequence without requiring supports while using planar tool paths. The execution time for processing the decomposition of these parts is also shown in Figure 2.14.

For the purpose of demonstrating the proposed approach for 3+2 five-axis additive manufacturing process planning, example decompositions with overhang angles set to 0 are used. Figures 2.15-20 show the sequenced decomposition result of each of the five parts from Figure 2.14.
Figure 2-15. Model 2.14a’s process planning

Figure 2-16. Model 2.14b’s process planning

Figure 2-17. Model 2.14c’s process planning
Figure 2-18. Model 2.14d’s process planning

Figure 2-19. Model 2.14e’s process planning
Figure 2-20. Model 2.14e’s process planning

Our algorithms provide sequenced volumes with their building orientations, which are calculated by Algorithm 2. The building orientations are provided as a vector that is used to orient the part such that the vector is aligned with the z-axis of the machine. Figure 2.21 shows the toolpath generated based on each sub-volume and its building orientation.
To verify the capability of handling these geometries via the 3+2 five-axis AM process, each decomposed volume can be printed on a traditional 3D printer without using support structures. Model 2.14e’s assembly process is shown in Figure 2.22 to illustrate the sequencing of the decomposed volumes.
The experimental results are shown in Figure 2.23. Each decomposed volume is printed separately due to the lack of availability of a 3+2 five-axis machine, then glued together for indicating the effectiveness of the proposed algorithm.
A different decomposition results based on different machine capability, overhang angle in this case, is shown in Figure 2.24. If the 3+2 five-axis AM process requires no support structures for overhang angles less than 45°, then the decomposed volumes changes. Thus different manufacturing constraints can be easily accounted for during decomposition.

![Diagram](image)

**Figure 2-24. Decomposition results comparison based on different manufacturability**

The results from the approach presented in this paper are also compared to the 3+2 five-axis decomposition method by Wu [21], Xu [25], and Gao [33] as seen in the Figure 2.25. Since the decomposed volumes, as generated by [21,25,33], do not always use the maximum allowable overhang angle they potentially result in a greater number of volumes. Besides, all the decomposition methods mentioned above provide the decomposed volumes with one fixed building orientation which may generate more volumes. In addition, Wu’s [21] decomposition method is based on the shape-diameter analysis. It can only decompose the geometry that can be abstracted by a skeleton structure and may fail for ring-like models [33]. Meanwhile, Xu’s [25] method is
only applicable to the tree-shape structure which cannot decompose geometry that has a merging zone.

In contrast, our proposed algorithm attempts to maximize the volume by utilizing the maximum overhang angle, thus reducing the number of decomposed volumes. Furthermore, the proposed method generates the decomposed volumes which can have multiple building faces which associate with multiple slicing directions. This allows for multi-directional material deposition that more effectively utilizes the capability of multi-axis additive manufacturing.

<table>
<thead>
<tr>
<th>Original Model</th>
<th>Decomposition 1</th>
<th>Decomposition 2</th>
<th>Decomposition with Overhang = 0</th>
<th>Decomposition with Overhang = 45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xu [25]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wu [21]</td>
<td></td>
<td>Gao [33]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xu [25]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-25. Decomposition results comparison based on different manufacturability

Our results are decomposed by planar or revolved surfaces and sliced into 2D planar layers so that the model can be built without support structures. The maximum overhang angle can be adjusted based on the machine capability. As seen from the examples, the number of decomposed volumes from our proposed method is less than the number of decomposed geometries from the other existing methods under the allowable overhang angle of 45°. In addition, Wu’s [21] and Gao’s [33] algorithm can generate particularly small volumes, as can be seen in the second example of Figure 2.25. These small volumes may not be manufacturable due to the machine constraints.
Furthermore, Xu’s [25] algorithm mainly focuses on decomposition of tree-branch structures, which cannot be used to decompose other geometries, such as models 2.14b, d, and e.

Our approach assumes that a starting build direction is given. However, it is quite possible that a support-free decomposition may not exist using this build direction. In this case the algorithm returns infeasible solution as the result. This information could be used to choose another build direction and recomputate the decomposition. There are certain geometries that cannot be handled given an initial build direction. Geometries such as long bridging models (Figure 2.26) will result in decomposition failure through our 3+2 five-axis AM decomposition and sequencing. If the part is processed based on the starting building orientation as shown in Figure 2.26, the middle bridging geometry cannot be built since there exists collision between the deposition nozzle and the existing geometries. The collision detection only eliminates the collision between the sub-volumes and deposition nozzles, any potential collision between the building substrate and the building trajectory is not considered due to the size of the building substrate being a variable for the 3+2 five-axis AM process. There may also be hard limits on the orientations of rotary axis that in practice may create additional manufacturability limits.

Figure 2-26. Decomposition results comparison based on different manufacturability
Future Work and Conclusions

3+2 five-axis AM adds versatility to the traditional 2.5-axis-based AM systems, and allows for the capability to produce parts without support structures. Current limitations in automated processing planning are the main roadblocks to the widespread adoption of the 3+2 five-axis AM technologies. The algorithms presented in this paper demonstrate that this process can be automated, and process plans for 3+2 axis systems can be generated without additional human effort. The promising results of the decomposition of parts with complex shapes shows that the algorithms developed are successful in automatically generating feasible volumetric decompositions and building sequences for 3+2 five-axis additive manufacturing. The proposed approach addresses the limitations of the existing methods and extends the state of the art as well as the quality of the decompositions produced.

The results presented here are limited to additive 3+2 five-axis capabilities, which only allows for depositing on 2D surfaces. Further research is needed to develop decomposition and slicing strategies for five-axis hybrid manufacturing (subtractive and additive) and five-axis hybrid manufacturing with non-uniform layer thicknesses, as this requires different segmentation for the single-body volumes (sweep feature) during the process. Research in the field of hybrid manufacturing has the potential to extend and combine the possibilities of various machining technologies in the future.

Reference:


Chapter 3

Automatic Process Planning for a 5-axis Hybrid Manufacturing System

Abstract:

Hybrid Manufacturing (HM) combining Additive Manufacturing (AM) and Subtractive Manufacturing (machining) technologies have recently been introduced and have the potential to address some of the shortcomings of AM, such as poor surface finish and inadequate dimensional tolerance. One such example of a HM machine is the DMG Mori Lasertec 65. These 5-axis HM machines allow for rapid deposition of material through additive manufacturing and address the aforementioned issues by subtractive machining. Additionally, the ability to machine intermittently with the deposition process enables HM processes to produce complex geometries that are not possible with standard 5-axis machining. Currently, process planning for HM is a complex task that relies heavily on manual formulation by experienced operators, and therefore widespread use of the technology is hampered by the lack of automation tools. Critical steps in HM process planning are; decomposition of the part into individual additive and subtractive volumes, proper sequencing all volumes, and assigning the toolpaths for these volumes. When there exists no feasible building sequence for the decomposed geometries, additional AM building volumes are needed to provide a solution, sometimes requiring further decomposition. This paper presents algorithms which decompose any input part geometry and sequences the additive and subtractive volumes in an automated manner, paving the way for a fully automated system for HM. A supplementary algorithm for generating “supports” compatible with a locally collision-free building plan on a 5-axis Hybrid Manufacturing platform is also provided. Examples of a wide range of geometries demonstrating the capability of the algorithm are presented.
Introduction:

Traditionally, AM is a layer-by-layer material deposition process along a fixed layering direction. This strategy significantly increases the fabrication complexity of parts compared to the traditional machining process. While the machining process is a faster, more cost-effective, and more accurate production process in the usual way that can accommodate a broader range of materials, recent advances in manufacturing tools have enabled five or more axis hybrid manufacturing (HM) platforms which merge AM and machining and allow switching between these two processes throughout fabrication. These HM machines utilize AM to build near net shape parts, and machining to provide the required surface finish and accuracy, thereby exploiting the mutual benefits of both technologies. Machines such as the DMG Mori Lasertec 65 3D Hybrid [2], Hybrid Manufacturing Technology [3], and 3D 5X- [27] provide the hardware capability to fulfill the 5-axis HM process. These machines allow the creation of innovative geometries that are unable to be manufactured using just one technology alone, yet they add another level of complexity to process planning. Manufacturing is no longer restricted to a traditional planning sequence, involving AM first followed by machining. However, with the current state of the art, planning this complex fabrication process requires substantial manual activities performed by experts in HM, as described below.

A HM process allows for a wide range of process sequences to manufacture parts, involving decisions regarding whether the geometries should be created entirely by machining or AM. Parts can be manufactured by an additive process followed by a machining process, or conversely they could also be produced from machining of a block of raw material followed by creation of other volumes by the AM process. In this manuscript, we only consider a 5-axis HM process that starts by depositing material on an initial substrate that does not become part of the final component and is intended to be removed later. A strategy to automate the geometry
decomposition and process sequencing to enable the AM and machining is developed. Since the 5-axis HM process enables 5-axis AM, it is different from the traditional AM fabrication method where 3D layering occurs along a single axis. Determining the volumes to be additively manufactured and specifying the sequence of these AM volumes are necessary for 5-axis HM process planning. *The decomposition and sequencing of AM and machining volumes on a multi-axis HM machine have been largely under an unexplored domain.*

Though the determination of machining volumes in a traditional machining process has been solved by Han [1], in a 5-axis HM process some of the traditional “machining volumes” can be fabricated through an AM process. For geometric volumes that require tight dimensional tolerance, there exists a volumetric difference between the Preform CAD model and desired final part model, which requires calculation of additional machining volumes for subsequent machining processing. The Preform CAD model requires the consideration of the substrate dimensions, initial building orientation, and the other pre-processing conditions in order to add/remove the materials from the desired final model. Behandish [36] provides a solution to generate a cost-effective machining technique from the desired final part model to the preform CAD model. *However, too little work has been devoted to considering all AM and Machining volumes in a feasible building sequence that accounts for AM manufacturability, and potential for interference between the machine tools and the build volume.*

Figure 3-1 shows a current workflow for the 5-axis HM process, typically a manual operation performed by an expert. The first type of machining volume that accounts for the volumetric difference between the Desired Final part model and Preform CAD Model must be calculated, and the decomposition, including detection of all AM and machining volumes on the Desired Final part model, must be processed in parallel. Following these steps, the sequencing and toolpath generation on these AM and machining volumes can be performed. A process planning strategy that includes both decomposition and sequencing needs to be developed to enable process
automation. Since there exist machining volumes (Volumetric Difference) on some AM volumes that may be inaccessible to machining tools later, the automated sequencing of AM and machining actions are developed in this paper to avoid this situation.

The additive building strategies on a 5-axis AM can be defined as two types: 2D toolpaths and 3D toolpaths (shown in Figure 3-2). 2D toolpaths allow material deposition in parallel planes along with one fixed direction, which can be found in Figure 3-2 a). The 3D toolpaths have non-planer layers and have been created on the multi-axis AM process from the work performed in [29-33], depositing material on a freeform surface where the deposition happens during the geometry is being oriented. Both toolpaths strategies can only be applied onto a \textit{single-body volume}, which refers to a swept feature that is defined by a profile contour and guided curved in CAD modeling systems. \textit{There exists a strong need for decomposing the given model into single-body volumes so that existing toolpath strategies can be readily applied.}
From Figure 3-2 a, based on the parallel plane deposition strategy, the formed geometry can only be built along one fixed direction, in this case a sweep feature that follows one fixed vector (in Cartesian or cylindrical coordinates). The 3D curved toolpaths, shown in Figure 3-2 b, can be classified into two categories: (1) a 2D planar toolpath deposition with orientations based on the guided curved on the single-body volume (a swept feature that follows a changeable vector), or (2) 3D depositions parallel to a freeform surface (sweep feature that sweeps from a 3D freeform surface but follows a fixed straight/curved line). Practically, all the toolpaths mentioned above can only build volumes that are constructed from a closed contour 2D/3D geometry (profile contour) with a single straight/curved sweeping direction (guided curve).

Typical strategy for a 5-axis HM process include identification of multiple volumes that could be deposited along different directions defined by one or few profile contours. With undefined separation of the profile contours and unmatched guide curves, an arbitrary CAD model cannot be automatically interrogated, and an AM and machining strategy cannot be calculated. In order to successfully fabricate parts on a 5-axis HM machine, an experienced operator is required to manually separate the single model into multiple single-body volumes and combine AM and machining volumes into a workable processing sequence, as shown by example in Figure 3-1. Even
though 5-axis HM offers unprecedented capability, planning and fabrication remain manual activities that require expertise in HM.

To automate portions of this process, simple decomposition based on planar cuts from existing concave edges in triangulation CAD representation models is proposed by Ding [35]. However, only closed loop concave edges (Figure 3-3a) are adopted to decompose the model. Also, not every closed loop concave edge can form a planar/freeform surface due to the different tangential curvature. In addition, collision problems and 3D freeform deposition is not considered as well. Meanwhile, the complicated model which contains such concave edges (Figure 3.b) cannot be decomposed through the existing methods.

In Figure 3-3, concave edges are extracted from CAD models in order to decompose the model into individual input geometries. The situation can be categorized into (1) concave edges that form a closed-loop and are all located on the same surface (Figure 3-3a), and (2) concave edges that can/cannot form a closed-loop on a single model surface but rather are located on different surfaces in the model (Figure 3-3b). In the second case, due to the curvature difference between the created surface and the connecting surfaces on the model, the surface (Figure 3-3d) that is created by a closed-loop concave edges cannot be used to decompose the model.

Figure 3-3. Concave edge loops on models

To provide a solution to automating the 5-axis HM process, we have to identify the following tasks:

- Volumetric Decomposition of input model
• Support Material Machining Volume Generation

• Sequencing the Decomposed volumes

• Slicing and Toolpath Generation

In this paper, we will demonstrate the first three tasks and the last step will be performed in CAM software to slice the geometry and identify the associated toolpath. The key challenge in multi-axis HM is to develop a robust and efficient decomposition algorithm capable of all sets of models. And the decomposition results should satisfy support-free and collision-free condition. Existing part decomposition methods for multi-axis AM and HM are evaluated and compared in Figure 3-4.

<table>
<thead>
<tr>
<th>Decomposition Method</th>
<th>Strategy</th>
<th>Disadvantages</th>
<th>Decomposition by 3+2 axis AM</th>
</tr>
</thead>
</table>
| silhouette-edge based method [37] | Project silhouette-edge along with specified building orientation to decompose the part | • Detection of machining volumes (holes) takes long iterations  
• Collision detection is not taken into consideration  
• Extensive amount of decomposed volumes | Decomposition based on the maximum buildable volume  
• Cannot detect machining volumes (holes)  
• Not fully utilizing of 5-axis |
| Transition wall [38] | Deposition a thin-wall by turn the machine 90 degree | • Only efficient to revolving geometry  
• Extensive amount of decomposed volumes | |
| Centroid axis extraction [26] | Decomposition based on the medial axis (skeleton) | |

Figure 3-4. Existing Decomposition Methods and associated results, defects

Figure 3-4 shows results of decomposition by existing methods. Each method is only suitable for small groups of geometries. In addition, these methods cannot efficiently compute both AM and machining volumes that both utilizing 5-axis rotatability.
To address these challenges, a set of algorithms are developed in this paper to extract and recognize single-body volumes from either a B-Rep or IGES representation model. In these types of models, a workpiece is usually represented with faces and edges that define closed 3D volumes. *The decomposition algorithm mainly relies on the extraction of the concave edges and clustering them into groups that can form a surface to split the solid model.* As shown in Figure 3-3b, the indicated concave loops are used to split geometries with merged volumes that are difficult to decompose using current algorithms. This manuscript provides an automatic approach for decomposing the complex geometries into single body volumes, to which existing 2D and 3D toolpaths can readily be applied. It provides the prerequisites to automatically process the model into a sequence that prevents collision in a 5-axis HM process.

Within the context of the development of automated process planning systems for HM, the overall goals of this research are to develop algorithms to automate the geometric decomposition and processing sequence for the two different manufacturing techniques on a single platform HM machine. The problem can be stated as follows: given a 3D representation of an object, automatically compute the object’s AM and machining volumes and associated building/machining directions, and define feasible building sequence so that the object can be built via the 5-axis hybrid manufacturing process without collisions. Two specific problems that are addressed in this work are:

1. **Volumetric decomposition of an arbitrary CAD model for a 5-axis hybrid process.** A true 5-axis hybrid machine can move all axes simultaneously for both additive and subtractive operations. Volumetric decomposition will separate an arbitrary CAD model into individual sub-volumes (for processing via AM or MACHINING) that can used as input to an automated process sequencing algorithm

2. **Construction of a manufacturing sequence of all the decomposed geometries, from Desired Final part model input to the final Preform CAD geometry.** All the machining
volumes and the post-processing geometries to achieve geometric tolerance are considered into this manufacturing sequence. Automatic collision detection between the material deposition nozzle and the building geometry is addressed, as well. If there exist no feasible building sequence of decomposed AM and MACHINING volumes due to the potential collision between the deposition nozzle/machining tool with the previously built geometries, a substantial AM building volume will be added to the Desired Final part model which enables manufacturability (thus creating a new Preform CAD Model). This newly added AM volume will be removed by the machining process within the overall manufacturing sequence to realize the final design component geometry.

Background and Literature Review

This section reviews the state of art in the HM process automation, focusing mainly on the proposed research objectives. The automation strategies are classified into two sections: (1) decomposition of 3D objects and (2) path planning and toolpath generation based on the decomposition volumes for hybrid manufacturing.

Decomposition of 3D objects

Decomposing an arbitrary CAD model into feasible volumes is essential to automate the hybrid process. There are various strategies to segment the CAD geometry, but not all practical due to potential for collisions in downstream fabrication processes.

Demir [6] introduced a divide-and-conquer approach for AM, which can reduce material consumption and decrease printing time. The input object is segmented into near-convex shapes for packing the components efficiently in fused deposition process (FDM) and stereolithography
(SLA). However, the parts are decomposed without considering the collisions that could occur if performing the build in one continuous process. Besides, the combination of all decomposed components is not equal to the input model due to the convex decomposition gives all resultant volumes into convex-hull shapes. Lien [8] divides the input geometry by separating concave surface volumes, but this does not provide clear boundary information for the divided components. Hu [7] provides a solution to define the boundary characterization by separating part into approximate pyramidal shapes that are optimal for building in AM. This technique requires that components are “glued” back to the original input. Zhou [13] measures the cylindricity defined by the skeletal and cross-section profiles of the parts in order to decompose the geometries. This reduced the number of parts compared to results from [10-12], though the results do not adapt well to geometries with machining all volumes, and such volumes may be missing in the resulting decomposition. Luo [9] proposed a “Chopper” method to decompose large parts into manufacturable size components that can fit in a given printing volume. Each sub-component is embedded with a customized connector to enable assembly of the parts. Jadoon [15] improved the “Chopper” [9] work by enabling the user to define the union segments employed during decomposition. This method provides fewer chopped parts with quicker time response, but it cannot be applied to 5-axis hybrid manufacturing decomposition due to the fact that it does not consider potential for collisions in downstream manufacturing processes. Recently, Hao [10] provided a curvature-based method by introducing planes to segment the STL models. The decomposition is restricted from using planar cuts from the model and relies instead on the dihedral angle and perimeter ratio of triangles in the .STL files to determine segmentation planes. Medellin [11] uses a regular lattice subdivision method to partition the 3D models, though this constrains cuts to the common grid size and ignores the object volumes. Zhou [12] converts models into large voxel-like-box and sequence the boxes into a continuous folding sequence. The printed boxes can be later folded back to the shape as required, though the shape is not equal to the input as well. Wu [14]
presents a multi-axis AM technique to fabricate parts with the minimum amount of support. A beam-guided search that accounts for manufacturing options present in a specific machine, such as the rotatability of the multi-axis machines, is considered. However, the connection between the adjacent volumes are weak which results the summation of all sub-volumes cannot map back to the original geometry. Yi [16] efficiently segments polygonal domains by using the part’s medial axis. This technique cannot efficiently decompose parts in the case of a symmetric or patterned model.

Ren [17] discussed integrated process planning for multi-axis hybrid manufacturing process that: decomposes the CAD model; designs a scanning pattern; and detects collisions. The models are decomposed by extracting the medial axis the arrangement dictated from the relationship graph. However, the decomposition algorithm is not capable for revolved geometry and the other complicated models.

Path planning and toolpath generation of decomposed 3D objects

Once CAD models are decomposed, the toolpath generation and sequencing must be considered. Multi-axis deposition processes provide the opportunity to build on a curved surface, though the curved layers could be conformal uniform thickness or non-uniform thickness.

Llewellyn-Jones [18] provides a 5-axis deposition solution for concave and convex surfaces, and showed that this strategy results in a better surface finish than that created when employing traditional 3-axis AM. The input geometry can only be single-body volume which starts with a 3D freeform surface. Zhao [19] extracts concave edges to create closed-loop edges to construct the splitting surfaces. The 5-axis AM toolpath is created based on offsetting the curved layers to build up 3D components. The curved splitting surface can only be generated from sets of closed loop concave edges which share same curvatures. Isa [20] develops the toolpath while considering the surface profiles for the freeform shapes. In this case, transition surfaces are created
to serve as the “base” of the upper curved layers. The initial build orientation, which is defined in a manual operation, serves as the first step in generating path to produce the component in a 5-axis AM process. Shen [21] proposed the similar offsetting curved surface with proposed work in [19], the ideal input models start with non-planar surfaces which should be manually prescribed beforehand. Le [22] integrates the additive and subtractive into one scheme to build a hybrid manufacturing hardware platform which is promising since it benefits from both processes. The capability of using multi-axis hybrid manufacturing is provided in this paper, while the process still uses planar toolpath for building the sub-components and requires for manual specification of decomposition process. Dai [23] presents a novel fabrication method on 6-axis robotic printing system. By converting the models into voxel and discretized them along with the surfaces of convex hulls for avoiding collisions, the author successfully prints the models within one continuous process without support structures. Due to the printing toolpath followed by the moves of the voxel locations, the final parts lack connectivity between the voxel-based layers. Pan [24] developed a similar toolpath for CNC machining by depositing material on the existing model. This requires a starting geometry/surface for creating 3D layers, and it only handles simple geometries. Huang [25] tackles the sequencing problem for fabricating frame shapes. Collision detection is considered when building the sequence loop in this work. Ruan [26] developed an adaptive slicing method to build non-uniform 3D layers and was able to sequence the layers for generating the toolpath. However, this methodology only applies to the single body volume. For complicated models that contain multiple volumes, medial axis is adopted for splitting the geometry. When the model is either symmetry or revolving, the method cannot separate the body which further requires manual decomposition.

Five-axis DEDAM processing can be used to extend the design complexity accessible to AM. Combining AM with subtracting manufacturing process enables parts to be manufactured with tight geometric and dimensional constraints in a shorter production time compared with normal
DED process. However, specifying the AM and subtractive volumes and correctly sequencing these volumes often requires intensive manual work. This research aims to automate the decomposition and sequencing process for 5-axis hybrid manufacturing on general models.

Methodology

Problem Statement

In the existing 5-axis hybrid manufacturing process, decomposition and collision detection are performed manually by an experienced operator using trial and error. Process planning for 5-axis HM starts with a given arbitrary model $M$ (Desired Final part model - “comprising a one or more connected single body volumes”), (such as step, igs), from which it is possible to fabricate AM volumes in a layer by layer manner on varied foundation surfaces ($S_i$) with guided curves ($C_i$). The machining volumes are associated with corresponding AM volumes and follow the sweeping feature criteria (Figure 3-5, Figure 3-6).

A single body volume can be defined by a foundation surface and an associated guided curve along which the foundation surface is swept, which is represented in Figure 3-5 and Figure 3-6. The type 1 of single-body volume starts with 2D planar surface and swept through single straight guided curve. The type 2 of single-body volume starts with 3D freeform surface and swept through multiple curved guided curves.
In this work, the goal is to establish an approach to decompose the input into single-body volumes that ensures the individual AM and machining piece is a volume which is swept from foundation surface \((S_i)\) by guided curve \((C_i)\).

\[
M = \sum_{AM \ features} - \sum_{SM \ features} \\
= \sum_{i=1}^{i} \text{sweep}(S_i, R(\theta) \cdot C_i) - \sum_{j=1}^{j} \text{sweep}(S_j, R(\theta) \cdot C_j)
\]

Where \(i \ [j]\) is the number of composed AM [machining] volumes, \(\theta\) is the maximum allowable overhang angle along with the guided curve \(C_i\), and \(R(\theta) \cdot C_i\) represents the guided curve rotated based on \(\theta\). HM using a 5-axis system provides ease of switching building orientations.
along with the guided curve on each sweep feature during the deposition to reduce or eliminate the need for ancillary support structures.

To conduct the 5-axis AM process, the model M must be decomposed into buildable AM (or machining) volumes in a continuous manner, where:

\[
M_{AM(i)} = \text{sweep}(S_i, R(\theta) \cdot C_i) \tag{1}
\]

\[
M_{AM(i)} \cap M_{AM(i+1)} = S_{i+1} \tag{2}
\]

• All \( (M_{AM(i)}) \) are ordered in a non-collision fabrication sequence

When there exist multiple single body volumes (or sub-volumes) in one model, the concave edges represent the intersecting lines of these volumes. The problem can be simplified by splitting the model into splittable sub-volumes from intersecting curves & concave edges \( (e_k, e_q) \). The guidelines for creating splitting surfaces \( (D_i) \) by intersecting curves need to follow:

\[
\text{loop}_{m,n} = \bigcup e_k, \text{ if } \forall e_k, e_q \text{ share the same surface on M}, \tag{3}
\]

\[
\text{loop}_{m,n} = \bigcup e_k + AB, \text{ if } A, B \text{ are the unconnected nodes in } \text{loop}_{m,n} \tag{4}
\]

Here, \( m: \) number of \( \bigcup e_k \) groups, \( n: \) individual \( e_k \) in the group

\[
D_i = \bigcup_{n=1}^{n} \text{surface}(\text{loop}_{m,n}) \tag{5}
\]

\[
S_i = D_i \cap M \tag{6}
\]

Here \( \text{loop}_{m,n} \) represents concave edges loops in model M, which are intersecting curves loops between sets of merged volumes. Figure 3-7 illustrate the grouping of concave edges for part decomposition.
Figure 3-7. Example of grouped concave edges and splitting surfaces

From Figure 3-7, the model M contains five loops of concave edges which can be used for constructing the splitting surfaces ($D_i$). The individual concave edges loop constructs the splitting surfaces separately, then knit into $D_i$ for decomposing.
Our Approach

5-axis HM requires decomposing the input model into AM and machining volumes as single-body volumes. In doing so, these volumes will be able to use existing 2D planar/3D freeform toolpath strategies for fabrication. Nonetheless, these volumes need to be sequenced to prevent collision throughout the fabrication sequence. The overall workflow which starts from the input CAD model is presented in Figure 3-8. It comprises three main algorithms that are used for decomposing and sequencing the geometries for a general 5-axis HM process.

![Figure 3-8. Overall Workflow of a 5-axis HM Process Planning](image-url)
The details of this approach provided in this section. Algorithm 1 in Figure 3-9 starts from the input Desired Final part model which contains edges and surfaces information. The splitting surfaces are created by extracting and grouping concave edges from the input Desired Final part model. The decomposed sub-volumes will be processed through Algorithm 2 to construct the machining volumes. After obtaining the AM volumes and machining volumes in all sub-volumes, a hierarchy tree can be formulated to create the build sequence for all volumes without collision, and ensure there is no building volume that is out-of-reach by Algorithm 3, which sequences the AM and machining volumes.

**Algorithm 1: Decomposing into sub-volumes**

In this section, the automatic decomposition algorithm is presented for decomposing the input CAD models into sub-volumes that can utilize the toolpaths already provided in most 5-axis hybrid manufacturing systems, such as the DMG-Mori Lasertec 65 via Siemens NX.
Algorithm 1: Decomposition CAD models into sub-volumes

**Input:** CAD Model $M$ (such as: .stp, .prt…)

**Output:** Sub-volumes

1. Extract all concave edge loops in CAD model: $e_i$
2. Every $e_i$ has two connecting surfaces on $M$, name $face(i)_1, face(i)_2$
3. $loop_m = \cup e_i (m = 1, … \#of\ edge\ loops)$
4. $loop_{m,n} = \cup e_i e_j, if\ e_i & e_j; face(i)_{1or2} = face(j)_{1or2}$ or\ $tangent(face(i)_{1or2}@edge_i) = tangent(face(j)_{1or2}@edge_j)$,\ $(n=1, … \#of\ sub\ edge\ loops)$
5. if $loop_{m,n}$ is not a closed loop
6. Start and end points on $loop_{m,n}$ to be: $A_{m,n}, B_{m,n}$
7. $fill_{m,n} = A_{m,n}, B_{m,n}$
8. **endif**
9. $loopsurface_{m,n} = surface(loop_{m,n} + fill_{m,n})$
10. if $\forall fill_{m,n}$ inside of $M$
11. $surface_{\bot_{m,n}} = \bot fill_{m,n}$, until it reach $\forall face$ on CAD model surface
12. **endif**
13. **knit** all $loopsurface_{m,n}$ if they share a edge, $D_i$
14. Decompose the $M$ by $D_i$ into $M_i(sub-volumes)$

Figure 3-9. Creating splitting surfaces ($D_i$) algorithm

If the sub-volumes created by using the splitting surfaces ($D_i$) produced in Algorithm 1 cannot be built using 5-axis (AM), further decomposition is required. Algorithm 2 provides a method for automatically finding machining volumes for the sub-volumes.

Algorithm 2: Detecting machining volumes and create AM volumes in sub-volumes

There are two types of machining volumes which are determined in this section. The first type is the difference between Desired Final part model and Preform CAD Model models which are designated to be stock machining volumes (Volumetric Difference) by using Algorithm 2 in Figure 3-11. The stock machining volumes (Volumetric Difference) are processed along with
algorithm 1 in order to further separate stock machining volumes (Volumetric Difference) and link them with a specific sub-volume from the input (Preform CAD Model). The second type of machining volume (support material machining volume) is the volume that cannot be processed by the AM process alone that require for fill with support. This type of machining volume is represented in Figure 3-10.

Figure 3-10. Support material Machining volume representation
Obtaining all the machining volumes and their associated AM volumes from Algorithm 1&2, the methods to decide build sequence is discussed in later section. The primary assumption in the sequencing algorithm is that all sub-volumes only require AM processes, since all AM volumes have associated building orientations from Algorithm 1 (decomposing surfaces). It is more straightforward to determine the building sequence of all AM volumes first, then put in the machining features into the sequence based on assessment of tool access requirements. Correctly assigning the machining features into the AM building sequence is addressed in algorithm 3.

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**Algorithm 2: Detecting machining features in sub-volume**

**Input:** $M_i(sub - volumes)$ from Algorithm 1  
**Output:** Machining Volumes

1. Collect all $Face_i$ from all $M_i(sub - volumes)$
2. Extract all $closetop(i)_m$ on $Face_i$
3. if ∃ multiple $closetop(i)_m$, choose outer surface boundary  
   Pass
4. else
5. Do: $Newface_i = surf(closetop(i)_m)$
6. endif
7. $AM Volume_i = Knit(all\ visible(Newface_i, Face_i))$
8. remaining bodies = $AM Volume_i - M_i(sub - volumes)$
9. if remaining bodies = Ø
10. Print: there is no necessary machining features in sub – feature
11. elseif
12. machining$_{i,k}$ = remaining bodies
13. endif
14. if $\forall$ machining$_{i,k}$: machining feed direction = normal (geometric center at $D_i$ on $M_i(sub - volumes)$)
15. delete: machining$_{i,k}$
16. endif
17. export all machining$_{i,k}$ with their associated $M_i(sub - volumes)$ and $AM Volume_i$

---

Figure 3-11. Decomposition Algorithm for detecting machining volumes from Algorithm 1
Algorithm 3: Sequencing all AM and Machining Volumes

In this section, algorithm 3 assigns each AM and machining volume into a sequence which is achievable without local and global collision (Figure 3-12). Collision detection between the deposition nozzle and previously built geometry is incorporated into the sequencing operation to ensure built feasibility. If it is determined that the sequenced hierarchy tree developed using Algorithm 3 results in a global collision where the print part collide with the machine rotary table, several volumes will be combined, and an added machining volume will be created. This machining volume will be merged into the newly combined AM volume, and then removed by subtracting process after the build of combined AM volume (shown in Figure 3-13). Overall, Algorithm 3 automatically specifies building sequence for all AM and machining volumes avoiding local and global collision.
Algorithm 3: Sequencing and creation of Added Machining Volume Algorithm

**Input:** machining$_{j,k}$ with their associated AM Volume$_i$

**Output:** Sequence

1. **Set up a hierarchy tree** of the AM Volume$_i$, set them as node$_i$. **Extract** all D$_i$ or AM Volume$_i$. **Obtain** each normal$_i$ on geometric center point of the D$_i$.

2. **Set** the node$_i$ has the largest amount of paths to be Rank 1 and **set all path** to be outward. The remaining bodies follow the same path direction.

3. **when** $\exists$node$_i$ has the largest amount of outward path

4. **Set** node$_i$ as starting **feature**, the starting building plane & direction is given

5. **if** $\exists$node$_j$ has the largest amount of outward path that is connected with node$_i$

6. **Set** node$_j$ as next building feature

7. **endif**

8. **end** until iterate all node

9. **if**: node$_i$ & node$_j$ are same rank, and node$_i$ $\cap$ node$_j$ $\neq$ $\emptyset$

10. node$_{i,j}$ = node$_i$ $\cup$ node$_j$

11. **endif**

12. **if**: $\forall$ normal$_i$ & normal$_j$ $\geq$ 180° $\parallel$ node$_i$ & node$_j$ sit on two sides of the D$_k$ on node$_k$

13. **Print**: Collision Detected

14. **Merge** normal$_k$ with lowest part between node$_i$ & node$_j$ along D$_k$, e.g. node$_j$

15. **endif**

16. **Create** the building surface of the updated node$_i$ & node$_k$ based on D$_i$

17. **Swept** = Swept$_D_j$ ($\prod$ node$_{i,j,k}$)

18. **Added Machining Volume**$_{j,k}$ = Volume(Swept$_D_j$) - node$_j$ - node$_k$

19. D$_{j,k}$ = D$_j$ + D$_k$ + Added Machining Volume$_{j,k}$

20. Sequence AM Volume$_i$ by hierarchy tree from highest rank to lowest rank

21. **Insert** machining$_{j,k}$ after associated AM Volume$_i$ in the sequence

22. **Output**: Sequence of all AM and machining volumes

Figure 3-12. Sequencing Algorithm

An example of applying Algorithm 3 for creating Added Machining Volume is shown in Figure 3-13. If AM Volume 3 is built after AM volume 1&2, AM Volume 3 will collide with the machine table. The added machining volume eliminates the collision by merging the “conflict” AM volumes and create an extra volume to satisfy the building condition. This process automatically
avoids the global collision when the corrected building sequence still generate the collision between the part and the machine.

Figure 3-13. Example of creating Added Machining Volume

**Results and Discussion**

The examples used to demonstrate the decomposition and toolpath generation strategies defined above start with **Desired Final part model**, which can differ from **Preform CAD Model** if additional material must be “added” to the Preform CAD model to allow for post-build machining to achieve required dimensions and are currently done manually. Since splitting planes shown in Figure 3-14 are not usually provide, the models cannot be automatically decomposed into AM and machining volumes using existing algorithms or commercial software.

The algorithms presented in the previous section have been implemented using SolidWorks Visual Basic, Rhino Grasshopper, and Python running on an Intel® Core™ i7-4790 CPU 3.31GHz computer. Three models (Figure 3-14) have been processed using these algorithms to illustrate the resulting decomposition results. Without using the algorithms defined in the previous section, these seven parts would all require manual human interaction and tribal knowledge in order to determine and define the splitting planes & surfaces necessary to decompose into the individual AM and machining build volumes and volumes.
The decomposition results and time for the models are shown in Figure 3-14 by running the implemented algorithm. The models range from simple models to complex shapes for demonstrating the capability of the automatic decomposition software. With current commercial technology, these examples either cannot be automatically decomposed and therefore require heavy manual work by experienced engineers to decompose the component, define AM & machine volumes, and generate a practical, collision-free sequence of operations.

Model (a) starts from the user defined Preform CAD Model which requires extra machining to achieve the Desired Final part model. The algorithm automatically performs a Boolean subtraction to determine the required machining volume (volumetric difference). The result of this volumetric difference is shown in Figure 3-15.
Figure 3-15. Machining volumes from volumetric difference of model a

The decomposition results by utilizing Algorithm 1 is shown in Figure 3-16. The part has been decomposed into five sub-volumes some of which require further processing through Algorithm 2 to detect machining volumes and create associated AM volumes.

Figure 3-16. Output of Algorithm 1: Decomposition Result of model (a). Note the numbering does not yet reflect processing sequence
All resultant sub-volumes from Algorithm 1 will be processed through Algorithm 2 to detect the support material machining volumes and associated AM volumes, the results are shown in Figure 3-17.

These are automatically detected and generated by Algorithm 2.

The hierarchy tree of all AM volumes is shown in Figure 3-18. The Rank 1 volumes will be built first and then Rank 2, Rank 3.

Figure 3-18. Hierarchy Tree of model (a). This sequence is determined by Algorithm 3.
The Rank 1 volume is chosen based on the maximum number of the connected volumes of each AM volume based on the connectivity from Algorithm 1. The building sequence of all AM and machining volumes of model (a) is shown in Figure 3-19. The associated machining volumes (volumetric difference and support material type) will be proceed after the build of the associated AM volumes follow the hierarchy rank.

Figure 3-19. Building Sequence of model (a), VD – Volumetric Difference
Model (b) has no preform CAD model, and so the processing can directly start with decomposition of the final desired CAD model. The decomposition results of model (b) by utilizing Algorithm 1 is shown in Figure 3-20.

Figure 3-20. Decomposition of model (b) using Algorithm 1

The machining volumes that need to be added to two sub-volumes from Figure 3-20 in order to be manufacturable are obtained through Algorithm 2. Their associated AM volumes are shown in Figure 3-21 as well.
Figure 3-21. Machining Volume and its associated AM volumes in model (b) sub-volume 2&3, as generated by Algorithm 2

Here, a hierarchy tree is defined by Algorithm 3 to specify the processing sequence. The hierarchy tree is shown in Figure 3-22.
Figure 3-22. Hierarchy Tree of model (b), as generated by Algorithm 3

The building directions for each AM sub-volume are shown in blue dashed lines in Figure 3-22. AM volume 2 & (5, 6) building directions are in conflict due to collision with deposition head while processing. In addition, AM volume 1, 2 and 4 share the same building direction. Overall, the AM volume 1, 2, 4, 5 and 6 should be merged into the one building volume. Since there exists controversy of these AM building volumes’ building directions, the “adding machining volume” is created using Algorithm 3 for providing a feasible building sequence. The detailed building sequencing and adding machining volume are shown in Figure 3-23.

Figure 3-23. Sequence of all AM volumes and machining volumes of model b).

The adding machining volume created from the combination process of sub-volume 1, 2, 4, 5 and 6 should be removed in the last step.

Decomposition results of model (c) is shown in Figure 3-24 by using Algorithm 1. The part has been decomposed into eight sub-volumes. Here it is assumed that no preform is required, though in practice that would need to be addressed.
Figure 3-24. Decomposition of model (c) using Algorithm 1

Associated machining volumes and related AM volumes are shown in Figure 3-25.
Figure 3-25. Machining Volume and its associated AM volumes in model (c) sub-volume 1&6 and determine using Algorithm 2

The hierarchy tree for constructing the correct building sequence is shown in Figure 3-26.
The processing sequencing for model d is shown in Figure 3-27.

Model c) has been implemented on DMG MORI LASERTEC 65 Hybrid. Its sequenced toolpath and final printed parts are shown in Figure 3-28.
Figure 3-28. Decomposed volumes in the correct sequence and simulated toolpath and final printed part.
As we can see from Figure 3-28, the part has been successfully built with the consideration of avoiding collision between the material deposition nozzle and the previously built part. Several opportunities to improve the algorithms were uncovered during the physical experimentation:

- Process parameters stay constant on one freeform layer, which leads to overbuilding in corner regions.
- Some geometries do not require 3D freeform conformal toolpath, such as volume #6. The layered geometries due to the freeform generation creates a more significant geometrical inaccuracy.
- The AM volume is sequenced and built without consideration of thermal impacts, there exists lack of built and overbuilt zone throughout the whole geometry.
- Volume #8 is not be able to be deposited due to the global collision detection from Algorithm 3.

**Summary and Future Work**

Combining additive and subtract manufacturing processes extends the design space for manufacturing complex geometries. Compared with traditional powder bed fusion process, DED is much more cost-effective and practical for larger components. The 5-axis DED and machining provides a larger design space and faster manufacturing process than the traditional DED process as well. However, the lack of comprehensive and automatic process planning tools limits the ease of use of the hybrid additive manufacturing process. At present, CAD models must be manually decomposed into AM and machining volumes and the process plan is mapped out by hand using operator experience and trial-and-error. This is inefficient and time-consuming. This work demonstrates algorithms that automatically decompose a CAD model into AM volumes and
machining volumes from arbitrary shapes, determines and defines and machining volumes that must be generate to enable fabrication, and then automatically specifies the process path type that enables the 5-axis hybrid manufacturing to build the component without interference (locally and globally). Three case studies were used to demonstrate the effectiveness of the proposed decomposition algorithm for improving the process planning of the 5-axis hybrid manufacturing process. For portions of the process that currently require manual interventions, e.g. creating Preform CAD model, decision on substrate dimensions are defined for future development of required automation tools.

The generation of the specific toolpaths required to produce the AM sub-volumes will be discussed in a future study. In addition, non-uniform thickness 3D layers can be obtained through the 5-axis continuous rotary table, and so the toolpath for creating non-uniform thickness layers on 5-axis HM will also be discussed.

In the present work, “accessibility” is assessed in an simplistic manner, and overall manufacturability (such as machining tool accessibility, deposition head accessibility, machining tool size, etc.) is not yet taken into consideration in these automated process planning algorithms. Automated selection of substrate, substrate dimension, initial build item can be considered a future work to fully automate the HM process. In addition, based on different optimization objectives, such as the minimizing overall building time, minimizing the material waste, the proposed process planning can later be optimized towards different targets.

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of the author(s) and do not necessarily reflect the views of the CCDC Army Research Laboratory nor the Naval Sea Systems Command (NAVSEA).

Reference:


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Chapter 4

Direct Five-Axis Slicing and Support-Free Toolpath Generation on a Five-Axis Additive Manufacturing System

Abstract:

Five-axis additive manufacturing allows for deposition of material along a planar or curved toolpath. This can reduce the need for support structures by means of a continuous multi-axis material deposition. Traditional planar toolpaths can only be deposited along a fixed building orientation, while curved toolpaths require specification of the guided curves for orienting the building geometry. In practice, parts with multiple growing directions cannot be built without decomposing the geometries into volumes and specifying the correct toolpath strategy to each decomposed volume. In this manuscript, a toolpath generation algorithm is proposed to avoid the volumetric decomposition problem by directly computing 3-axis tool paths and their associated 3-axis slice volumes, called printable layers. The 3D printable layers are computed based on the geometric consideration of the existing layers to allow for a support-free build, while taking into account the manufacturability considerations of the five-axis machine. The algorithms for computing the printable layers are presented. Example parts processed using these algorithms are presented. A wide range of part geometries that traditionally require a large number of support structures can be manufactured support-free using this approach.
**Introduction:**

Additive manufacturing (AM) allows parts to be printed with increased geometric complexity, functioning as a deposition process along the z-direction that requires support structures underneath the overhang surfaces. For metal parts, removal of support structures adds to the effort required during post processing. Since different build orientations will require different amounts of support structures, much research has been done to optimize build orientations by minimizing the amount of support material necessary [1-3]. Multi-axis AM processes, such as five-axis AM and robotic deposition machines, have the potential to reduce or eliminate the need for support structures [9]. Multi-axis AM processes allow for additional rotational axes which can be used to build non-planar layers. The flexibility to deposit material on a curved surface while rotating the deposition head leads to the ability to create support-free geometry, even in the presence of overhangs. Process planning for multi-axis AM machines requires the development of algorithms for tool path planning that are capable of fully exploiting the machine capabilities. Current approaches are not without limitations, and the proposed research addresses some of the limitations of generating support-free tool paths.

As shown in Figure 4.1, the approach currently implemented in industry software, such as Siemens NX, is based on a manual approach. The user manually decomposes a part into additive volumes. These volumes are manually mapped on to existing tool path strategies, available in the software library, that can be used to manufacture the decomposed volumes.
Embedded within the tool path strategies are the individual layers needed to build the decomposed volume and the tool path along with the processing parameters. In the case where there is no direct mapping between the decomposed volumes and available toolpaths, further decomposition or new decompositions may be necessary. While performing these decompositions, the user must also consider the manufacturability constraints imposed by physical constraints of the machine. The overall workflow of building given geometries is shown in Figure 4.2. The manufacturability constraints depend on the machine, and include the following: overhang angle, the maximum angle that can be built without the need for support structures; available tool-path strategies; limits on the rotation angles of the rotational axes; and collision between the already built part and the tool. The manual approach is tedious and time consuming and not suitable for automation in a digital environment.
Figure 4-2. Workflow of building a geometry on a five-axis AM process

Three main strategies have been used in multi-axis AM for automation of the process.

**Method 1:** Using the additional axes for orientation such that it allows changes in build direction during the fabrication process, while the layers built are still planar. This approach requires decomposition of the part into volumes, such that each volume is built in a different orientation while still using planar layers and planar tool path strategies. The decomposition of the part into the sub-volumes is typically performed manually. This approach does not exploit the full capability of the five-axis machine and only uses the rotatability to orient the part that allows each volume to be built with planar tool paths. Using this approach makes it possible to create support-free parts [11-12, 28], provided there is full accessibility throughout the build process. Instead of constraining the 2D planar toolpath, the full 5-axis system can provide the capability of continuous rotation during the material deposition process to achieve 3D freeform surface deposition.

**Method 2:** Another approach allows for use of 3D tool paths instead of planar tool paths, but the 3D tool paths are restricted to conformal surfaces, and decomposition of the part into sub-volumes is still required. Decomposing a part and developing slicing algorithms for 3D conformal tool paths is an area of recent research interest [32]. The degree of complexity in the tool paths is much higher than that of planar tool paths. The conformal tool paths are still limited since they are generated by offsetting an existing surface, and still require manual decomposition into planar and
conformal tool path volumes. Collision with deposition head, machine, part are significant concerns that haven’t been addressed.

**Method 3**: Instead of decomposing the part into large sub-volumes that can be filled in with the existing 2D/3D toolpath strategies, directly generate 3D curved printable layers that exploit the continuous positioning capability of the five-axis (or multiple axis) machine to facilitate support-free printing. Adding orientation changes and more degrees of freedom to the toolpath makes the problem more complicated. Support-free printing also requires algorithms for generating toolpaths. These tool paths can potentially be automatically generated using different strategies from the generated curved layers. Two approaches used in recent literature are:

a. development of curved layers based on iso-geodesic contours [20] and generating curved tool paths. This can potentially cause collision between the deposition nozzle and concave regions of the part.

b. build using voxel-based decomposition and classification into “allowable voxels” based on the defined overhang angle and aggregation of voxels into tool paths [13]. This approach is not computationally efficient and has the potential to miss print voxels.

Figure 4.3 illustrates the three different approaches (mentioned above) in the literature using Method 1 and 3 and our proposed method to automatically generating support-free toolpaths using five-axis machines.
Figure 4-3. An example illustrating current and proposed algorithms applied to a “C-shape”. Colors are used to indicate different layers.

The first toolpath generation method (Figure 4.3a) is adopted from Ruan [12]. As we can see from Figure 4.3a, the “C-shape” volume is first implicitly decomposed into “straight” sections that each can be filled up using a layered 2D planar toolpath strategy (as shown in different colors). This result in a stair-case surface at the interface between the two adjacent “straight” sections. Moreover, the decomposition into such single feature geometry is the prerequisite. This toolpath strategy can only apply to the tree-shape geometries or single-body volume – sweep feature that is constructed by a combination of foundation surface and one or more guided curves. Currently, the decomposition still requires heavy manual work. Figure 4.3b illustrates a voxel-based toolpath which is generated by searching for printable nearby voxels that are computed by the maximum overhang angle and allowable rotary table positioning angles for multi-axis AM processes [Dai 13].
However, the toolpath is not vector-like and non-continuous which further leads to issues with skipping voxels (e.g. single voxel in one toolpath) and poor surface finish.

The 3D curved toolpath utilizing iso-distance surfaces created using Geodesics is proposed by Xu [20] is shown in Figure 4.3c. The curved layers’ boundaries only use the iso-geodesic contours on the part’s surface which lacks insurance of the convexity of the curved layer that further creates collision between the part and deposition nozzle.

Geometries such as the one shown in Figure 4.4 when adopting such techniques would lead to the collision between the material deposition nozzle and the printed geometries.

Figure 4-4. Collision cases while applying current methods

Figure 4.4 shows a geometry that fails to generate a feasible building plan when applying Method 1 (Figure 4.3a) and Method 3a (Figure 4.3c). When method 1 is applied to this geometry, the part is decomposed into volumes that would fill up with 2D planar toolpath strategies. The volume that is marked in yellow (Figure 4.4a) has two starting surfaces where the material deposition nozzle (shown by the arrows) will collide with printed geometries (red/blue volume in Figure 4.4a). There exists no feasible building strategy if using this method. Similarly, Figure 4.4b
depicts the iso-geodesic contours which measures the distance along shortest and straightest curves through the 3D volume [48] on the same structure. These curves cannot be used for constructing curved printable volumes that satisfy the manufacturability concerns of collision due to the same reason as mentioned above.

Another problem that arises when using iso-geodesic curves is that the generated 3D freeform layers still create overhang areas that cannot be deposited with the nozzle in perpendicular position to the curve. When the upper layer is overhanging over the one below, the nozzle requires a specific modification (Figure 4.5) on the deposition orientation and processing parameters, such as the deposition rate and speed.

Figure 4-5. Deposition technique for adjusted zone [20].

In Figure 4.5, the re-adjusted deposition orientation is applied to the volumes which are marked by arrows. The black arrow in Figure 4.5 represents the perpendicular vector of the deposition surface (upper surface of the existing geometry) which is the theoretical nozzle orientation based on the computed freeform layer. However, the rectified material deposition nozzle needs to be oriented (red arrow) based on the vector which is defined by the edge of upper and bottom surface of this freeform layer. It is not equal to the perpendicular vector (black arrow) which aims to create the extra deposition volume for the non-uniform-thickness volume (red arrow). This rectification will increase the overall toolpath generation computational complexity as well.
A curved model is processed through four different building strategies as shown in Figure 4.6. Figure 4.6a represents the traditional layer by layer material deposition method which requires support structure where the surfaces exceed the overhang limitation. Since all layers are planar, this building process is the fastest among the four building strategies, however, it consumes extra materials. Figure 4.6b shows non-uniform layer creation by segmenting the geometry based on the curvature of the medial axis. However, this building strategy mainly applies to tree-shape structure since it causes collisions at the merging point of two features. Since all layer’s creation are planar, the building time is fast, however, the rotation for positioning the geometry requires extra building time but can provide additional building directions for eliminating the overhanging volume. Figure 4.6c adopts Xu’s method [20] which utilizes the iso-geodesics to create freeform surfaces. This method is similar to the method in Figure 4.6b but with curved surfaces. However, it always uses curvature layers which induce the longest building time. For example, the volume which is in the green dashed box does not require the nozzle to be re-oriented since there is no overhanging volume. This method would eventually induce a longer building time. Our proposed method aims to re-orient the nozzle to allow overhang volumes that require no support, the other volume persist the 2D planar toolpath. This method can effectively construct support-less layer and with a much shorter building time. Figure 4.6d shows the building strategy created by our proposed algorithm. Notice rotation only happens as needed – when there exists an overhang (defined by the starting building orientation). Compared with Figure 4.6a, the layers follow the same pattern, except the edges of the constructed layers are curved to satisfy the support-free condition. This proposed method avoids the unnecessary curved surfaces which can cut down on the build time.
Figure 4-6. Illustration of the volume building methods: (a) parallel planar layer decomposition of traditional 3D printing, support is needed; (b) medial axis based decomposition with parallel 2D planar layers; (c) curved layer decomposition of multi-axis printing; (d) proposed curved layers decomposition multi-axis printing.

In this paper, a new approach to developing support-free tool-path strategy that utilizes the abilities of the five-axis machine is proposed. The goal is to automatically generate printable layers ($V_i$) that are either planar (2D) or curved (3D). Each printable layer is associated with the tool path for a single layer.

These printable layers are required to satisfy the following condition (Figure 4.7):

1) The printable layer $V_{i+1}$ can be fully deposited on top of $V_i$ (no such situation shows up in Figure 4.4)

2) The $V_i$ should be perpendicular with the overhang surface

Figure 4-7. Condition of the printable layers
From Figure 4.7, we can see that the projection from the nozzle orientation does not exceed the previously built volume. There will not be any material deposited on air which will satisfy condition 1. Besides, the surface which marked in blue in Figure 4.7 is perpendicular to the overhang surface. This will ensure the success of support-less build of this overhang area (condition 2).

Compared to the existing techniques for multi-axis AM, our proposed technique generates smoother layers that can be fully covered by the 3D vectorized toolpath. The proposed method does not cause voids or skipping in the toolpath due to the surface/volume-based layer.

The problem can be stated as follows: given any 3D CAD model, automatically compute the 3D printable layer so that the object can be built via a five-axis AM process without collision occurring between the previously build geometry and the deposition head. The three specific contributions that are addressed are:

1. 3D printable layer is constructed by i) previous build geometry; ii) allowable overhang angle; iii) overall input geometry, for ensuring the model can be printed support and collision-free.
2. Decomposition for avoiding collision due to the geometric and building orientation constraints (such as, machine tool/build platform/substrate collisions) if necessary.
3. 3D vectorized toolpath generation on the freeform surfaces to build up the 3D freeform layers.

A variety of complicated geometries, such as multi-features and bridging structures that originally required support structures in traditional 3D metal AM processes, have been processed through the proposed approach to calculate the sequenced 3D printable layers and toolpaths. Along with the fabrication results from our methodology using an overhang angle of zero degrees, this new method eliminates the need for support structures by utilizing the capability of continuously
reorienting the building geometry while the material is being deposited. This new method can be used to pave the road for automating the whole process in five-axis hybrid manufacturing.

**Literature Review:**

This section presents the existing multi-axis AM fabrication techniques focusing mainly on the proposed research objectives. Current research in process planning in multi-axis AM can be classified into two main categories: volumetric decomposition for multi-axis AM and multi-axis AM toolpath generation.

**Volumetric decomposition for multi-axis AM**

Model decomposition has been used in printing large scale geometry in industry for years [29,30]. Recently, it has been applied to multi-axis AM fabrication for reducing material usage and decreasing the inaccessibility of support structures for the purpose of removing them after the AM process is completed.

All the multi-axis based deposition strategies [10,11] are based on 2D layer deposition when fabricating each decomposed volume. There exists a variety of ways of segmenting the 3D models. One example comes from Zhang et al. [10] who used the part’s skeleton to represent the topology of the part. The partitioning process is based on cutting the equivalent topological skeleton into line or curvature segments. Luo et al. [11] designed a framework for chopping the large-scale model into printable sub-volumes with the associated assembly features. The printability, connector feasibility, and ease of assembly for each sub-volume must be considered all while minimizing the overall number of sub-volumes. Jadoon et al. [29] propose a similar segmentation method based on the user’s interaction and constrained tree algorithm splitting. With the intention of improving
surface finish, Wang et al. [30] provide a decomposition method for the 3D model where each segment has the best surface finish under its own building direction. A novel decomposition method for building up the geometry by stacking the sub-volumes is proposed by Chen et al. [26]. In terms of feature-based decomposition, Lee et al. [27] successfully partitioned the geometry that has overhanging surfaces into prismatic shapes. With a similar goal in mind, Wu et al. [28] used a beam-guided search to find the clipping plane for each segment. Hergolz et al. [30] searched the building geometry along the \( z \)-direction to find the volume that satisfied the manufacturability constraints. Gao et al. [21] developed a decomposition method by using a genetic algorithm to find cutting planes which further lead to the minimum numbers of cuts. Human involvement is required to specify the numbers of cutting planes and the computation of the cutting plane can take a significant amount of time. Doherty et al. [24] provides a scheme of decomposing the 3D model into feature-based geometries through the STL representation. The emphasis in this paper is to stiffen the joint between two features.

All the above-mentioned decomposition strategies result in planar cuts that allow fabrication on 2D surfaces. With the change of building orientation, 2D material deposition method is applied on multi-surfaces which allows the generation of a wider range of the geometry without the need for supports.

Unlike the above planar decomposition method, Ding et al. [37] introduced a process planning system for robotic AM systems which integrates the decomposition based on the overhang surfaces and the multi-axis slicing technique. Similarly, Zhao et al. [36] provided a feature-based decomposition based on concave edges. This decomposition methodology can only be applied to models which have closed-concave edges loops. Moreover, Ding et al. [40] applied the same concave edge decomposition to the mesh geometries in order to do multi-direction deposition. The proposed algorithm cannot be applied to geometries which have two or more features merged into same point. More recently, Nguyen et al. [45] decomposed CAD models by using the centroidal
axes which navigate the slicing and building directions of the sub-features. However, this method is only applicable to tree-shape geometries.

**Multi-axis AM toolpath Generation**

Chen et al. [22] developed a toolpath based on CNC accumulation which can have multi-axis motions to build more complex geometry, such as the curved geometries used when repairing parts. However, this technique requires the use of support structures if the geometry is not supported at a certain location. Similarly, Pan et al. [25] developed a CNC-based accumulation method on a five-axis AM platform, which successfully built geometry on existing geometries. Moreover, Ruan et al. [12] developed a method to build non-uniform thickness layers that utilize the built-up geometry surface. The process of filling up the non-uniform thickness layer with toolpaths parallel to the building plane and then rotating this non-uniform layer geometry, thereby letting its upper layer be the second building plane, is illustrated in Figure 4.6b. Still, this method can only be used for fabricating the geometry after decomposition and not for the multi-feature input model. In the meantime, Keating and Oxman [33] built a hybrid platform, includes robotic fabrication and milling, turning 6-axis printing from a concept to a practical solution.

To fully exploit the multi-axis capability, some researchers came up with fabrication strategies utilizing multi-axis continuous material deposition combined with the repositioning of the building geometry [13,20,22,25]. Xu et al. [20] proposed the method of constructing freeform surfaces along with iso-geodesic contours, which differs from voxel deposition [13]. An adaptive slicing method is used in slicing the decomposed 3D layers but, the convexity of the decomposed layers is not guaranteed, and collision may not be avoided.

Similarly, Chalvin et al. [34] proposed a non-planar layered 3D path strategy in which the layers are defined two points on medial axis with the same normal. This path can minimize process
parameter variation which could potentially reduce the building time compared with the Xu’s [20] method. On the other hand, this method cannot compute the toolpath in multi-feature complex geometries. Recently, Dai et al. [13] presented a voxel-based fabrication method for filling up the advancing fields for material accumulation under a convex-hull constraint. Searching for available voxels is time-consuming for complex geometries and skipping voxels in some overhanging regions is a possibility. Flores et al. [23] uses the normal from the points on the curved geometry (STL model) to generate curved layers which are perpendicular to the curved geometry. Then, the zigzag and contour toolpath are applied onto the adaptive sliced layers. The adaptive curved layer cannot be applied onto concave geometry due to inaccessibility of the deposition nozzle. Additionally, Isa et al. [38] came up with building up transitional layers for curved geometries. This technique can improve the surface roughness, especially for the geometries with a freeform top surface. The constraint for this algorithm is that it is only applicable to geometry with only a single feature. Besides, Coupek et al. [39] focus on reducing the printing time conformal 3D freeform layer up. By transforming the conventional 2.5D slicing technique to the cylindrical coordinates, the building time and surface finish can be improved. Li et al. [42] implemented an additive-subtractive manufacturing process to achieve higher surface quality by utilizing the multi-axis additive and machining capabilities at the same time. In addition, Bhatt et al. [41] computed the axis of symmetry in thin shell parts for the purpose of constructing non-parallel planar slices. The varied layer thickness and collision detection are considered during computation as well. Furthermore, Zhao et al. [32] provided two nonplanar slicing strategies for the after-decomposed curved geometries. The two methods are capable of using STEP models and mesh models separately. However, without decomposition of the input geometry the developed slicing strategies cannot be directly applied to the input. Kubalak et al. [43] utilized the multi-building direction by depositing material along a part’s surface, improving the mechanical properties. There are
limitations on the input geometries because of concerns regarding collisions between the tool head and the printed part.

All the above toolpath generation strategies are providing a non-parallel planar/curved slicing method for the curved single-feature geometry. The decomposition which is mentioned in the previous section is a necessity in conjunction with applying these toolpaths.

Plakhotnik et al. [35] presented a CAM planning method for 3D freeform surfaces in laser AM processes that also considers collisions between the deposition nozzle and the surface on the workpiece. However, this path planning only considering coating material on the convex/concave surface with collision avoidance and cannot be apply to the 3D model build up process. Ding et al. [44] were able to achieve similar results when they optimized the layer toolpath using medial axis transformation for void-free deposition with reduced post-processing. Another layer-wise toolpath strategy in 5-axis polymer AM is proposed by Tam and Mueller [46], they filled in the 3D freeform layer along with principle stress lines, improving the potential strength and stiffness gain. Alsharhan et al. [47] also developed a dome-shaped toolpath which leaded to higher stiffness and peak load due to the toolpath follows the stress distribution. All these 3D freeform layer-wise toolpaths are developed to fill the slices after the non-parallel and non-planar slicing.

**Methodology**

**Problem Statement**

Given a 3D solid model \( M \), we aim to find a sequenced series of printable layers \( \{ V_i \}_{i=1,...,n} \) which can be accumulated to form \( M \). We establish an approach to ensure the upper surfaces
\((F_j : F_j \in V_i \| \notin V_{i-1})\) on \(V_i\) can be supported by \(V_{i-1}\) under the condition that the layer can be fully deposited based on the previous layer

\[
O_{(F_j, n_j)} = \begin{cases} 
1 & \sum_{j=1}^{V_i} F_j + \sum_{j=1}^{V_{i+1}} FV_k = \sum_{j=1}^{V_{i+1}} F_j \cdot n_j \\
0 & \text{Otherwise}
\end{cases}
\]

Where \(n_j\) represents the perpendicular vector of the associated surface \((F_j)\) on \(V_i\), and \(FV_k\) is the upper surface on the volume which is constructed by \(\bigcup\{F_j \mid V_i \cdot (F_j \mid V_i) \cdot n_j \mid V_{i+1}\}\). If every \(F_j\) satisfies \(O_{(F_j, n_j)} = 1\) on \(V_{i+1}\), \(V_{i+1}\) does not require support structure since it can be fully projected onto \(V_i\).

Each \(V_i\) represents the volume that can be built upon the upper surfaces of \(V_{i-1}\) under the support-free condition. As shown in Figure 4.8, \(V_{i+1}\) is a volume that is constructed under the following conditions: i) an available building volume that is calculated from \(V_i\); ii) formed by the building constraints from remaining body \((M - V_i)\).

We name the face down surfaces in \(V_i\) to be \(DF_{i,j}\) (\(i: \) index of the layer, \(j: \) index of the face down surface), upper surfaces to be \(UF_{i,j}\) (\(i: \) index of the layer, \(j: \) index of the upper surface), overhang surface that is connected with \(UF_{i,j}\) to be \(OH_{i,k}\) (\(i: \) index of the layer, \(k: \) index of the overhang surface). Since \(V_i\) and \(V_{i+1}\) are adjacent, the \(UF_{i,j} = DF_{i+1,j}\). The creation of the \(UF_{i,j}\) requires following the subsequent conditions (Figure 4.8):

1) \(Partial (UF_{i+1,j}) \parallel UF_{i,j}\)

2) \(UF_{i+1,j} = UF_{i,j} + Surface \perp OH_{i,k}\)

3) \(V_{i+1} = UF_{i+1,j} \cap (M - \sum_{m=1}^{l} V_m)\)
In Figure 4.8, we can see all the conditions are satisfied to construct such a printable layer.

To conduct five-axis AM in a continuous process, the input $M$ needs to be decomposed into $N$ consecutive printable layers, where:

- $M = \bigcup_i (V_i) \parallel V_i \cap V_j = \emptyset$, with $i, j$ represent random sub volumes in the sequence
- $V_i = \text{convex hull} (V_{i-1})$
- $F_j \mid_{V_{i-1}} + FV_k \mid_{V_i} = \text{proj}_{n_i} F_i \mid_{V_i}$, so, every $V_i$ can be supported by upper surfaces on $V_{i-1}$
- $\{V_i\}$ are in a collision-free sequence, ensuring there is no interference between the deposition nozzle and existing printed geometry

**Our approach**

Five-axis AM provides the capability of re-orienting the building geometry while material is being deposited which further allows multiple building orientation within one build. In addition, the decomposition surfaces can be freeform surfaces or a combination of several 2D surfaces. We define the cross-sectional area between the solid model $M$ and its foundations surface ($S$) to be the first working zone ($w_0$), denoting the volumetric representation of a printable layer based on working zone ($w_i$) to be $V_i$. The decomposition operation gives the printable layer by:
• \( w_0 = S \cap M \)

• \( V_i = \text{Volume}(w_{i-1}, w_i) \)

• \( V_i = w_{i+1} \cap (M - V_{i-1}) \)

We also define that the printable layer can be built without using support structures which should satisfy the manufacturability:

**Criterion I:** \( \forall F_j \in V_i, \forall F_k \in V_{i+1} \) \( > \frac{\pi}{2} \| F_j \& F_k \) are adjacent

This criterion ensures that there exists no gap between the two consecutive printable volumes.

**Criterion II:** \( \| (\forall P \in V_{i+1} \notin V_i, V_i) \|_1 < d \)

\( d \) represents the maximum allowable printable volume height which can affect the as-built surface finish. Normally \( d \) is larger than the minimum layer thickness defined by the machine. Here, \( \| . \|_1 \) denotes the \( L^2 \) norm from any point on \( V_{i+1} \) to \( V_i \). The criterion set a printable zone from the existing \( V_i \). The interference of the printable zone and the solid model is considered to be an allowable deposition zone.

**Criterion III:** When adding a \( V_{i+1} \) to a set of \( \{ V_{1..i} \} \), the deposition nozzle should not collide with \( \{ V_{1..i} \} \)

This criterion set the geometric constraint for avoiding collisions and depends on multiple factors, including: i) input solid model \( M \) geometry; ii) \( \{ V_{1..i} \} \) geometry; iii) \( V_{i+1} \) working zone. The challenge will mostly happen at the “merging” point on “bridging” geometries. When designing the volume of the printable layers, both the support-free and collision-free conditions have to be verified at the same time. This criterion will be verified by Algorithm 3.

**Criterion IV:** Sequencing all \( V_i \) is based on constructing an adjacent surface into a tree-shape hierarchy. Processing \( V_i \) is based on an ascending order of \( \max(V_i|N_i) \).

\( \exists \) multiple \( V_i \) have same \( \max(V_i|N_i) \), these \( V_i \) share the same rank in the hierarchy.
$N_1$ represents the first chosen building orientation on model $M$. In order to avoid collision between the existing building geometry and the deposition nozzle, $\{V_i\}$ are sequenced into a hierarchy based on their adjacent surfaces.

**Schemes of Creating Printable Volumes ($V_i$)**

In this section, a scheme for the overall workflow is presented in Figure 4.9. Algorithm 1 (Volumetric Layer Creation - VLC) and Algorithm 2 (Geometric Layer Creation - GLC) are used to calculate the printable layers under the condition that Algorithm 1 calculates all printable layers it is able to and Algorithm 2 generates the layers that cannot be constructed using Algorithm 1. For example, when $UF_{i+1}$ is not cut ($M - V_i$) due to the constraints from $OH_i$, Algorithm 1 cannot generate a valid printable layer. The supplementary algorithm (layer generation by GLC, in Figure 4.11) will generate a series of printable layers which ignores the geometric constraints and only consider the previous build volumes geometric information and the manufacturability.
Intuitively, Algorithm 1 (in Figure 4.10) helps to achieve the maximum zone for allowing depositing material within the machine manufacturability under the constraints of the overall geometry, existing build geometry and the overhang angle constraints. The generation of the upper surface on the printable layer is mostly decided by offsetting the upper surface on the existing build volumes. The computation only requires calculating the perpendicular surface of the adjacent overhang surface which can significantly reduce the computational time compared to the existing multi-axis AM techniques.
**Algorithm 1**: Generation of 3D printable layers by Volumetric Layer Creation method

**Input**: CAD Model $M$ (such as: .stp, .stl ...)

**Output**: Continuous 3D printable layers $\{V_i\}$

1. Set a 3D layers’ height = $d$
2. $\text{manufactured}_i = \bot (\text{edge@} w_i) \cap M \text{ at length} = d$
3. $\text{manufactured}_i = \text{manufactured}_i + w_i$
4. Move $\text{manufactured}_i$ along $N_i$ at distance = $d$
5. $V_{i+1} = M \cap \text{Moved} \text{manufactured}_i$
6. **Repeat** step 2 – 5, **until** $V_{i+1} = \emptyset$

Figure 4-10. Algorithm for generating printable layers by VLC

Here, an illustration of constructing printable volume ($V_{i+1}$) based on $V_i$ using VLC is shown in Figure 4.11. VLC gets its name from the way it creates subsequent volumes based on the geometric constraints of the build geometry.

![Diagram of Algorithm 1](image)

Figure 4-11. Creation of $V_i$ method (Volumetric Layer Creation - VLC)

In Figure 4.11, lines that share a color represent the offsetting surfaces. The unique colored line on every $V_i$ that does not match any other color on $V_{i-1}$ represent the perpendicular surface on
\( V_{i-1} \). Offsetting this surface to \( V_i \) can ensure the overhang surface on \( V_{i-1} \) can be built in a perpendicular manner.

Algorithm 2 (Figure 4.12) provides a substitution method of generating the allowable deposition layer based on the existing geometry. The condition under which Algorithm 1 cannot generate the valid printable layer is illustrated in Figure 4.9.

**Algorithm 2:** Generation of 3D printable layers by Geometric Layer Creation method

| Input: | CAD Model \( M \) (such as: .stp, .stl...), \( V_{i-1} \) when \( V_i = \emptyset \) |
| Output: | Continuous 3D printable volumes \( \{ V_i \} \) |

1. Set a 3D layers’ height = \( d \), \( w_{i-1} = V_{i-1} \cap M \)
2. \( \text{working}_\text{plane}_{i-1} = \text{tangent plane } @ (\text{geometric center } @ w_{i-1}) \)
3. \( W_{i-1} = \text{proj}(w_{i-1} \cap M)_{\text{working}_\text{plane}_{i-1}} \)
4. \( W_i = W_{i-1} + u_{i-1} \cdot d \) (\( u_{i-1} \): normal of \( \text{working}_\text{plane}_{i-1} \))
5. \( W'_i = \text{Offset}(W_{i-1}, d) \)
6. \( \text{surface}_{i-1,i} = \text{sweep}(W'_i, W_i) \)
7. \( \text{sweep}_i = \text{sweep}(W'_i, -u_i) | @ d \)
8. \( V_{i+1} = M \cap \text{knit}(W_i, \text{surface}_{i-1,i}, \text{sweep}_i) \)
9. **Go** Algorithm 1, **until** \( V_i(\text{Algorithm 1}) = \emptyset \)

Figure 4-12. Algorithm for generating 3D printable layers by GLC

In Figure 4.13, we provide a visualization of Algorithm 2 to assist in providing a detailed explanation.

Figure 4-13. Visualization of printable layer creation by Geometric Layer Creation (GLC).
Notice that the later volume, $V_{i+1}$, is created by using the upper surface on previous volume, $V_i$, and a pre-defined sweep surface. Generating $V_{i+1}$ this way allows for tilting the material deposition nozzle within the machine’s capability.

After creating a series of the printable layers by Algorithms 1 & 2, the collision detection should be executed before beginning to generate the uniform layers. Algorithm 3, provided in Figure 4.14, creates a secondary volumetric decomposition when a collision is detected between the deposition nozzle and the existing geometry (Criterion III). This algorithm is applied to avoid collision specifically for the bridging/joining geometry. Algorithm 3 is capable of segmenting the bridging/joining geometry into non-collision volumes from the given deposition nozzle geometry and the input model.

**Algorithm 3:** Decomposition for collision avoidance

**Input:** $M, V_i, w_i, N_i$, deposition nozzle radius $R$, height $H$

**Output:** Decomposed bodies $M_k$

1. if $\exists \angle N_{i_{V_m}}, N_{i_{V_n}} \leq \frac{\pi}{2} || \sum w_m, w_n = concave$
2. $N = \|N_i + N_j\|$, plane = $\perp N$|minimum$(w_m, w_n)$
3. $P =$ Geometric Center @[$\exists$ single contour $(plane \cap M)$]
4. $\text{curve} = \text{spline} \left( P, P + \frac{\bar{N}}{\cos(\arctan(\frac{\bar{H}}{R})+\theta)} \right), \theta: \text{tolerance angle} \in [0, 20°]$
5. $\text{decompose surface} = \text{revolve} (\text{curve}, \bar{N})|_{\@P}$
6. end
7. $V_i = \text{decompose surface outer surface} (-\bar{N}) \cap V_i$
8. $M_k = \text{decompose surface inner surface} (\bar{N}) \cap M$

Figure 4-14. Decomposition algorithm for avoiding collision between the deposition nozzle and built geometry

A collision occurs when the minimum distance between two printable layers is smaller than the size of the deposition nozzle and the upper surfaces on these two volumes creates a concave hull. In this situation, Algorithm 3 creates a concave decomposition for the overall geometry based
on the size constraints of the deposition nozzle to ensure there is nothing above the deposition surfaces.

Figure 4.15 gives an example of detecting possible collision by using Algorithm 3. Figure 4.15a gives a series of printable layers which will cause volumes 7 & 8 to force a collision between the nozzle and the previously built layers. Figure 4.15b gives a decomposition which takes into account the nozzle size; a concave surface is constructed to segment the geometry to further ensure there exists nothing above the building surface of one printable layer. The printable layers (V1-V8) are decomposed from the Figure 14a to Figure 15c. Thus, the remaining layer above the decomposing surface from Algorithm 3 can be calculated by Algorithms 1 & 2, as shown in Figure 4.15.d.

Figure 4-15. Illustration of applying Algorithm 3 to the 3D solid model to avoiding collision

Note that the layers shown in red in Figure 4.14d are concave due to Algorithm 3. Although the decomposition surface is concave it does not cause collision between nozzle and previously built geometry. The subsequent layers after the decomposition will start with concave surfaces and process through Algorithms 1 & 2. These layers are concave but follow the concavity constraints therefore avoiding any potential collisions.
Each printable layer needs to fulfill the requirement of reasonable layer thickness. However, since the printable layers are non-uniform thickness, there is a chance that the layer thickness exceed the maximum allowance layer thickness which is defined by the machine. Since the process parameters (laser scanning speed, material deposition rate…) stay constant and cannot be adjustable when depositing one layer, the final shape of the layer is hard to be controlled into such non-uniform shape. To cope with this issue, we further rectified such non-uniform thickness layer by dividing into uniform-thickness sub-layers, as depicted in Figure 15. The example in Figure 15, we can see that the printable layer is divided into multiple sub-layers whose thickness satisfy the machine requirements.

![Figure 4-16](image)

**Figure 4-16.** Rectified printable layer with non-uniform layer thickness > maximum allowance layer thickness

The larger the variation of the layer thickness between the bottom and top surface on one printable layer, the more noticeable the stair-stepping effect which is marked by red dashed line in Figure 15.

By applying these algorithms, every individual printable layer is designed to be a convex shape or a concave surface that can be process in a collision-free manner. Therefore, these surfaces can be reached by the deposition head while not colliding with previous layers. As the last step, the vectorized linear toolpath is applied on the printable layer.
Result and Discussion:

The algorithms presented in the previous sections have been implemented in SolidWorks using SolidWorks Visual Basic and were executed using an Intel® Core™ i5-6600 CPU @3.30GHz 3.31GHz computer.

Five example parts (Figure 4.17) were processed through the implemented software to illustrate the resulting printable layer formation. These five examples are derived from the literature review and all can be built on five-axis AM machines. However, using current methods, they all need human input to be fully decomposed into volumes which can utilize current toolpath strategies. The printable layers presented in Figure 4.16 appear thicker than they are in actuality to make it easier to see the layers.
<table>
<thead>
<tr>
<th>Input Models</th>
<th>Printable layers</th>
<th>Computing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td><img src="image" alt="Model A" /></td>
<td>43s</td>
</tr>
<tr>
<td>Model B</td>
<td><img src="image" alt="Model B" /></td>
<td>28s</td>
</tr>
<tr>
<td>Model C</td>
<td><img src="image" alt="Model C" /></td>
<td>56s</td>
</tr>
<tr>
<td>Model D</td>
<td><img src="image" alt="Model D" /></td>
<td>42s</td>
</tr>
<tr>
<td>Model E</td>
<td><img src="image" alt="Model E" /></td>
<td>60s</td>
</tr>
</tbody>
</table>

Figure 4-17. Printable layers visualization and computation time of five models. Layer thickness is enhanced to aid with the visualization of individual layers.
As we can see from Figure 4.17, geometries of varying complexity can be successfully decomposed into printable layers without collision.

Figure 4.18 provides the layer generation results for another example model. In this simulation, our proposed 3D toolpath generation method successfully built up the geometry in such a way that avoided the need for any supports. The 3D printable layers shown in Figure 4.18b are generated using Algorithm 1. These layers satisfy the geometric condition and manufacturability on a five-axis AM machine. The final G-code was then generated and sent to the self-built five-axis AM machine from (Lulzbot Taz6). The final printable model is shown in Figure 4.18c. All the layers are deposited correctly with tight bonds; however, the deposition rate could be adjusted to improve the surface roughness.

Figure 4-18. Simulation results of a curved model: (a) the model; (b) the accumulated printable layers; and (c) final printed model
**Future Work and Conclusions:**

A new deposition strategy is proposed which utilizes the five-axis AM technique. Printing on a five-axis machine is a continuous process which allows for variable building orientations and avoids the need for support structures. Current techniques of building geometry for a multi-axis AM process require decomposition of the model into single-body volumes as a prerequisite. 3D layers are computed for each individual single-body volume along with the medial axis. Bridging geometry can still not be successfully solved for continuous layers without collision. Efficiently computing the 3D layer for the whole geometry so that the part can be fabricated under collision and support-free mode is a necessity.

We propose a technique to calculate the printable layers by accumulating material based on the existing printed geometry within the bounds of the machine’s printing capabilities. The printable layers are convex-shaped layers, which ensure that the deposition nozzle is able to access the entire layer without any collisions. Our process first creates the layers that can be successfully built based on the previous build volumes and then by rotates the geometry to make the overhang volume an allowable printing zone. After that, the surface-based linear toolpaths for covering the layers can be calculated.

The proposed algorithm has been verified by virtual modeling and simulated toolpath generation. Five-axis toolpaths of models with large overhangs and complex geometries were successfully computed through the use of our algorithm. The future work will implement and experimentally validate the proposed process and improve the performance of the algorithm. Since the computation time depends on the part geometric size and the printable layer height, the larger the printable layer height that the user chooses, the lower the computation will be, but at the cost of a more significant stair-case effect shown on part surfaces. The sub-decomposing of such thick printable layers can be further discussed to reduce the computational complexity for large and
complex geometries. Furthermore, we will conduct more experimental analysis based on our proposed printing strategy on a five-axis AM machine to discover the optimized processing parameters.
Reference:


Chapter 5
Contribution and Comparison

Contribution

Based on the previously presented work, three different process planning strategies on multi-axis AM/HM systems were proposed, as follows:

1. Automatic process planning for five-axis AM, which is restricted to only 2D toolpath strategies. The rotation of the build table is only used for orienting the building geometry to adjust the build orientation. Each decomposed volume is support-free and can be correctly sequenced in such a way to avoid collision between the previously built geometry and the deposition nozzle.

2. Automatic process planning on five-axis HM, which combines five-axis AM and five-axis CNC machining into one system that can switch between two processes. Five-axis additive capability has been fully utilized in this system, which allows material deposition while orientating the geometry. The critical issue in this research is to decompose the input into the AM volumes, which can utilize the 2D/3D toolpaths in the existing library. Additionally, algorithms were developed to provide a feasible sequence for all AM and machining volumes, thus paving the path to automating this complicated process and reduce the manual work.

3. A direct slicing and toolpath generation on a five-axis AM system is also provided as a continuous work from the previous process planning. Instead of processing the decomposed volumes into CAM software for generating the toolpath, we provide a direct
five-axis slicing method that allows straightforward, non-uniform slicing of any input geometry into 2D planar or 3D freeform layers.

These three strategies all serve to limit human mistakes and save time and labor in the process planning of complicated geometries on five-axis AM/HM systems.

**Comparison**

Since three different process planning strategies have been proposed and developed, in this section we:

- Develop a holistic set of comparison metrics for comparing the performance and effectiveness of the three strategies.
- Use the developed metrics to evaluate the three strategies and attempt to identify their underlying strengths and weaknesses, including their decomposition results’ effectiveness and efficiency.

The number of final decomposed volume/layers for each of three examples are shown in Figure 5.1.

<table>
<thead>
<tr>
<th>Original Model</th>
<th>3+2 5-axis AM</th>
<th>5-axis HM</th>
<th>Direct 5-axis Slicing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Model 1" /></td>
<td>#18 12s</td>
<td>#13 2s</td>
<td>#26 60s</td>
</tr>
<tr>
<td><img src="image2.png" alt="Model 2" /></td>
<td>#2 4s</td>
<td>#2 1s</td>
<td>#45 42s</td>
</tr>
<tr>
<td><img src="image3.png" alt="Model 3" /></td>
<td>#3 2s</td>
<td>#3 1s</td>
<td>#17 28s</td>
</tr>
</tbody>
</table>

Figure 5-1. Simulated decomposition results of three models
Beyond comparing the number of decomposed volumes from the three strategies, we provided other metrics (Table 5.1) that can fully capture the advantages and disadvantages of each process planning strategy.

Table 5-1. Evaluation metrics for the three process planning strategies

<table>
<thead>
<tr>
<th></th>
<th>3+2 5-axis AM</th>
<th>5-axis HM</th>
<th>Direct 5-axis Slicing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capability</strong></td>
<td>Decompose the model into additively manufacturing Volumes</td>
<td>Decompose the model into additively/machining Volumes</td>
<td>Decompose the model into additively manufacturing layers</td>
</tr>
<tr>
<td><strong>Input Model</strong></td>
<td>Solid Model without void</td>
<td>Any Solid Model</td>
<td>Any Solid Model</td>
</tr>
<tr>
<td><strong>Number of decomposed volumes</strong></td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Decomposed volumes require further processing (layer generation) or not</strong></td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td><strong>Building Method – Toolpath (2D/3D)</strong></td>
<td>2D</td>
<td>2D/3D</td>
<td>2D/3D</td>
</tr>
</tbody>
</table>

From Table 5.1, we can see that the direct five-axis slicing method provides the greatest number of decomposed layers when compared to the other two methods. This is because it directly generates layers rather than generating volumes which required further slicing.

Furthermore, the five-axis HM strategy can generate fewer decomposed volumes than the 3+2 five-axis AM strategy. This is because five-axis HM allows using 3D freeform toolpath, which increases building flexibility compared to the 3+2 five-axis AM system.

Below, a case study utilizing the three process planning strategies is presented and compared with traditional AM method in Table 5.2.
Table 5-2. Case study of three process planning methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Computational Time (s)</th>
<th>Material Waste (Removal Supports) mm²</th>
<th>Estimated Building Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional AM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3+2 5-axis AM</td>
<td>12s</td>
<td>58304.351</td>
<td>8hr50min</td>
</tr>
<tr>
<td>5-axis HM</td>
<td>3s</td>
<td>523.25</td>
<td>4hr 51min</td>
</tr>
<tr>
<td>Direct 5-axis Slicing</td>
<td>57s</td>
<td>288.7</td>
<td>3hr 30min</td>
</tr>
</tbody>
</table>

The model is processed through Materialise Magics with Optomec LENS850 set up with 1200 W laser power and 500 um layer thickness. The building time using traditional DED can be calculated. The decomposed volumes in 3+2 5-axis are sent to Magics to calculate the building time estimate. The estimated building time for 5-axis HM is calculated from Siemens NX. Since there exists no commercial software can directly calculate building time based on direct 5-axis slicing method. Two layers (one 2D planar and one 3D freeform) which have same surface area are sent to Autodesk Powermill software to estimate the simulated “building time” of depositing freeform layer and the planar layer. The ratio of the simulated “building time” can be estimated and based on the 3+2 5-axis building time, the building time of the direct 5-axis slicing can be estimated.

The advantages and disadvantages of using these three methods are shown in Table 5.2 below.
Table 5-3. Advantages and disadvantages of the three process planning strategies

<table>
<thead>
<tr>
<th></th>
<th>3+2 5-axis AM</th>
<th>5-axis HM</th>
<th>Direct Slicing on 5-axis AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>1. All 2D planar toolpaths</td>
<td>1. Fully utilizes 5-axis rotatability</td>
<td>1. Fully utilizes 5-axis rotatability</td>
</tr>
<tr>
<td></td>
<td>2. Cheaper process</td>
<td>2. Fewest number of decomposed volumes</td>
<td>2. Always provides a feasible slicing strategy without using any supports</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>1. Connectivity between adjacent volumes</td>
<td>1. No control over the choice between planar or freeform deposition</td>
<td>1. Non-uniform layer thickness</td>
</tr>
<tr>
<td></td>
<td>2. Requires some supporting machining volumes</td>
<td>2. Requires some supporting machining volumes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Requires manual specification on toolpath decision and selection</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 6

Future Work and Conclusions

Future Work

This research has demonstrated the direct use of CAD data to automate process planning on the five-axis additive and hybrid systems. Part geometry and overall geometrical relationships are also presented for providing feasible building solutions on these novel systems within the capabilities of the five-axis machines. However, the process is not yet automated for the full scope of multi-axis AM and HM processes. Further research and development are needed to increase the scope and directly generate the final model based on the final desired CAD model.

A full workflow of the five-axis HM system is presented in Figure 6.1. The boxes which are marked green have already been implemented. The five-axis AM system workflow is embedded in the workflow of five-axis HM, which does not consider the machining processes.
Each of the collision conditions included in Figure 6.1 are shown in detail in Figure 6.2.

In this dissertation, we only consider avoiding local collisions, shown in Figure 6.2a. Collision detection and avoidance algorithms can be more sophisticated and take into account the other two types of the collisions by incorporating more global information into the calculations. Global information, such as substrate dimensions and the relative positioning of the part to the
machine table, can be used to assist in the selection of optimal first building volume, and constraints on rotatability. The substrate geometry can also be optimized to provide a better solution for avoiding the global collision. It can also be used to make a global reference about the whole part. If the optimized substrate is chosen to be the global reference, it is attached to the machine rotary table which needs to be considered into the global collision detection. The global collision problem can be simplified by considering the build geometry and the global reference.

The current research can be extended in several ways. Based on the comparison and evaluation results in Chapter 5, we are not able to discover the microstructural and mechanical property differences when the same geometry was built using each of the three strategies. The build plan is sure to impact the thermal history, which will have an impact on microstructure and properties. This thermal variation can also change the melt pool size and shape, and real-time feedback control may be required. The relationship between the final measurements (microstructural and mechanical properties) and the three processing techniques can be used to better inform decision making in the future. As we can see from Figure 6.1, the starting point for automated process planning is the preform CAD model, however, the steps for automatically constructing such models are still manual. This manual work, which includes the initial process decision (AM/SM), initial part orientation, and substrate geometry, must be performed by an expert. Furthermore, the classification of the toolpath is not well-defined. The “most likely toolpath” concept can be developed to automatically map to the corresponding toolpath to the decomposed volumes with its associated process parameters (guided curve, foundation surfaces, laser parameters…).

After the part is built on a multi-axis AM and HM machine, the geometric information should be extracted so it can be compared with the desired final part CAD model. Currently, the reverse engineering process, which includes the extraction of the CAD model from the build geometry and modeling it into the feature-based part, is not an automated process. Additionally,
the creation of the preform CAD model for indicating the overbuilding/underbuilding volumes still lacks automation.

The current generation of automated process planning on multi-axis AM and HM does not provide quality assessment and control. However, the material and mechanical qualities are expected to be different than those produced by the traditional AM process due to the multi-directional building and non-uniform thickness freeform layering. In order to ensure the functionality of the final build, in-situ monitoring and control systems should be set up to maintain the quality of the build to maximize the chances of a successful build.

One of the main challenges of multi-axis material deposition is that the fusion between the two adjacent layers/volumes cannot be ensured. While a solution to this was not addressed during this research, it provides another area for future research. This problem can be stated as follow: given the decomposed volumes/freeform layers, determine the change of the processing parameters necessary to maintain the bond between two adjacent volumes/freeform layers. One way of approaching this problem is to extend the process map, which includes all relevant processing parameters and the material characterization (grain growth/size), to get the optimal processing parameters while depositing on a non-planar surface.

The automatically generated toolpath from the multi-axis AM can be directly fed to a multi-axis robotic system for depositing materials in a freeform and support-free manner. The toolpath, which is provided by work #3, has been directly fed to a remodeled five axis Lulzbot machine, which allows us to deposit material continuously along with a variable z-axis position. The resultant accumulated freeform layers are shown in Figure 6.3.
Here, we can see that the rectified printable layers with non-uniform layer thickness > maximum allowance layer thickness are successfully printed. We process the layer with a fixed set of process parameters at the maximum thickness location, the lack of melting issue could be ignored. In the meantime, there will be a re-melting zone in the previous layers. This re-melting effect material and mechanical properties cannot be stated without first performing an implementation on a five-axis metal AM system.

**Conclusions**

This research aims at developing automated process planning strategies for five-axis AM and HM systems. The input CAD model has been either decomposed into support-free volumes that adopt current planar/freeform toolpath strategies or has been directly sliced into printable layers under the manufacturability constraints. Three hierarchical structures are formulated for correctly sequencing all decomposed volumes/layers in such a way that collisions are avoided.
Two volumetric decomposition methods based on the support-free concept has been developed. The methods were based on buildable volume calculations per one fixed orientation and concave edge extraction methods. These methods provide the means to decompose the geometries based on the constraints from the toolpath feasibility of the machines, ensuring robust and reliable decompositions. Another direct five-axis slicing, and toolpath generation method focused on the non-planar and non-uniform slicing technique that can be directly fed to the machine is also provided. These techniques of decomposing the input geometries into support-free volumes pave the path to automating the full scope of process planning for multi-axis AM and HM systems.

By far, the most critical application of this research is to serve as an automated bridge between the input CAD model to the machine code. The proposed algorithms have been demonstrated through physical implementation and testify to the effectiveness of the automating multi-axis AM and HM systems.
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