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Automated process planning for metal hybrid additive and subtractive manufacturing

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Automated process planning for metal hybrid additive and subtractive manufacturing

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

This dissertation is dedicated to my family and friends. Thanks to my parents who gave life to me and provided everything they can for my education. Thanks to my wife who spend four of her best years with me in the US during my graduate study. Thanks to my daughter who made my Ph.D. study more adventurous and livelier. This dissertation work is impossible to be completed without supports from my families.

I also dedicate this dissertation to my friend Ashish Joshi who is more like a brother to me. Ashish not only led me start my research work but also helped me start my life in US.

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ABSTRACT

The manufacturing industry is currently evolving from mass production to mass customization and ultimately towards mass personalization. Direct Digital Manufacturing (DDM) is deemed as a key to the future of manufacturing, and Hybrid Additive and Subtractive Manufacturing (Hybrid AM/SM) can be a path to realize it. While Hybrid AM/SM equipment are being developed, automated process planning for them is far from being integrated. Enabling automated process planning for Hybrid AM/SM will bring the integration of AM and SM to an unprecedented level. This research problem spans multiple aspects of Computer Aided Design (CAD), Computer Aided Process Planning (CAPP) and Computer Aided Manufacturing (CAM). This presentation introduces several proposed methods for AM/SM automated process planning, including an out-of-envelope method, Design-for-Hybrid systems and future integration modes for Hybrid AM/SM. The results of this work will enable integration of the extraordinary geometric capabilities of Additive Manufacturing with the precision of subtractive methods.

CHAPTER 1. INTRODUCTION

As manufacturing industry evolves, the available technologies have vastly changed paradigms in different directions. As Figure 1-1 shows, modern manufacturing started from what is referred as "craft production" before the first industrial revolution. At that stage, the crafter would manually create the product according to the request of the customer. This manufacturing process is the most customized, but at a very high cost. Then through the first and second industrial revolutions, with the introduction of machines, the invention of the production line and the steam and electrical power, mass production was made possible. At this stage, products were made in large volume and at low cost, however, at the expense of sacrificing the product variety. In the last four decades, the demand for customization arises

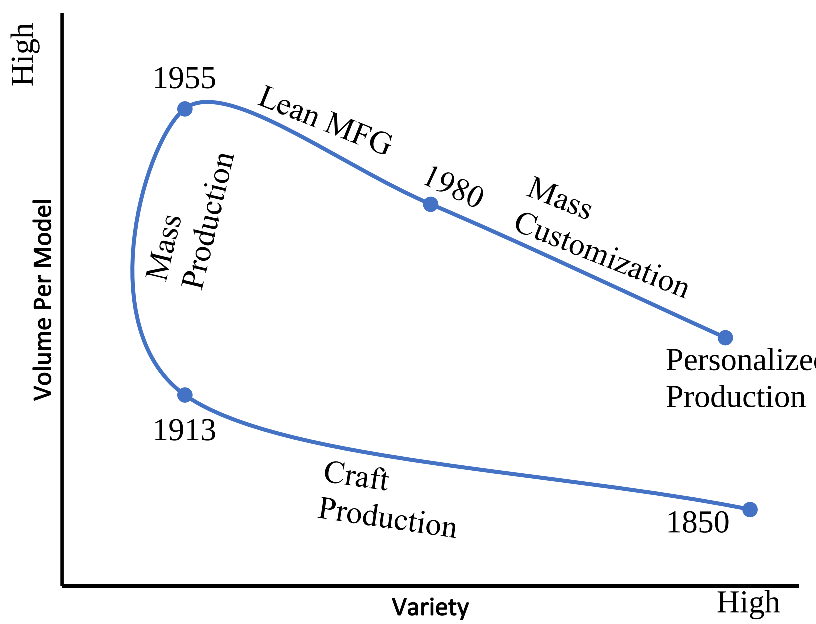


Figure 1-1 Changes in manufacturing Paradigms (Hu et al. 2011)

and has resulted in the trend toward a "mass customization" paradigm with highly customized requirements. This was made possible through modularized design that deliver the products with a variety of selected combinations. The changes in manufacturing paradigms can be better conveyed with the automobile manufacturing history; a luxury item before 1908. Automobile production in the early days was indeed craft production. Then after Henry Ford invented the first production line for the Model T, automobiles for the first time become affordable for millions of people(Ford 2017). However, at that time, the customers have no choice of their car configuration. Nowadays, customers can "build" their own customized car by selecting paint color, powertrain, drive types, and different equipment. In the next level of manufacturing, "personalized production" would have even more variety with having the customer participating the product design process.

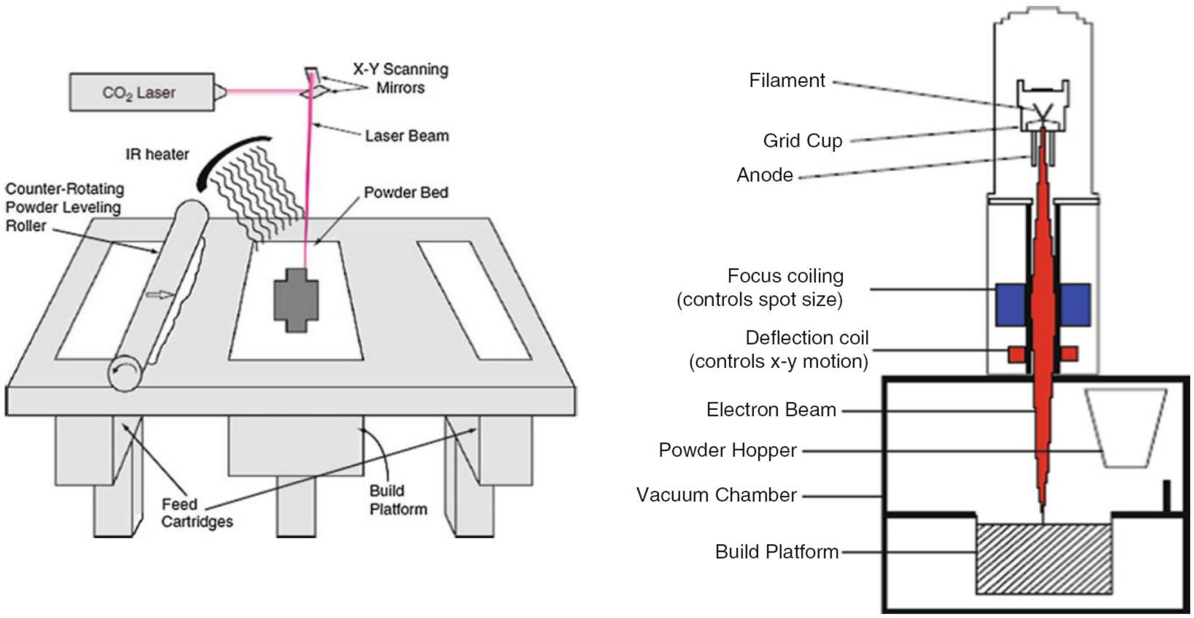
The manufacturing evolving map demonstrates how manufacturing technologies lead market changes, and how the market competition in turn promote manufacturing technologies. This map also points out the future manufacturing trend as "personalized production" which is already happening in recent years. As Hu et. al (Hu et al. 2011) pointed out, one of the technologies that enables the "personalized production" is on-demand manufacturing systems that can quickly respond, fabricates the components and assembles the final product. Taking a further look at purely the manufacturing portion of on-demand manufacturing systems, it can be easily seen that a perfect solution would be Direct Digital Manufacturing(DDM) which can directly turn a digital design into a physical part with the use of advanced manufacturing technologies such as Additive Manufacturing(AM)(Chen et al. 2015). AM works by depositing materials point by point/line by line to the shape of the cross sections of a geometry with a small thickness, and then accumulatively builds up the part layer by layer. The deposition tool path for AM can be generated from creating paths that fill series of polygons that represent the cross sections of the geometry. The layer by layer manufacturing characteristic allows vastly automated process planning as compared to traditional manufacturing processes. It did not take long for researchers to develop algorithms for automatically generating the tool paths for AM. Due to this advantage of AM, it has been considered a perfect solution for creating complex geometries rapidly, ever since it was invented. The ease of automated process planning is what makes AM different from other manufacturing processes, and what makes DDM superior to conventional manufacturing methods in short turnaround production.

Representative metal Additive Manufacturing processes

Currently, AM is able to build parts using various raw materials such as polymers, waxes, paper, metals, and even live cells (Gibson et al. 2010). Out of all available AM materials, metal is the most heavily used material in industrial production. This dissertation is focused on manufacturing with metal.

Metal AM, as an important area in the whole AM industry, has attracted huge investment in research and production in aerospace, automotive, agricultural and medical equipment manufacturing. Representative AM technologies for metal printing includes Selective Laser Melting (SLM), Electron Beam Melting (EBM), Laser Engineered Net Shaping (LENS), and welding arc additive manufacturing (WAAM).

Both SLM and EBM are categorized as powder bed fusion (PBF) processes as illustrated in Figure 1-2. The entire process can be summarized into three major steps: 1. Material feeding on to the building platform as a layer, 2. Fusion energy source selectively melting the layer of the material, 3. Building platform moving to be ready for building the next layer. The major difference between SLM and EBM is the energy source. SLM uses a laser as the fusion energy source whilst EBM uses electron beams. EBM is generally faster in the building process and capable of melting higher melt point metal, and results in lower residual stress. In contrast, SLM builds with higher surface quality and unlike EBM is able to print non-conductive materials.



(a) (b)

Figure 1-2 Representative Powder Bed Fusion AM processes a. Selective Laser Melting, b. Electron Beam Melting (Gibson et al. 2010)

LENS and WAAM are both directed energy deposition (DED) processes as Figure 1-3 shows. Different from PBF processes, DED melts and deposits material at the same time. The material used in the DED processes is often in the form of metal powder or wire. DED uses a laser, electron beam or electric arc as a focused heat source. In a DED process, the material is directly delivered to the desired location through the deposition head, and at the same time the heating source melts the material on the fly. Due to its flexibility in material feeding, DED is often used in 4- or 5-axis systems, providing more degree of freedom for manufacturing. However, at the same time it has less building accuracy as compared to PBF processes. Also, DED processes are less preferable for making complex geometries than PBF processes because the support structure is difficult to create without the powder bed, and the resolution is lower than PBF processes. DED processes are difficult to achieve better than 0.25 mm accuracy and less than 25 µm surface roughness(Gibson et al. 2010).

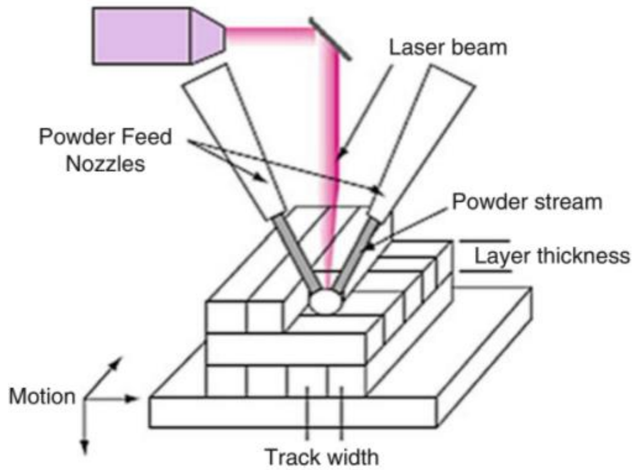


Figure 1-3 Representative Directed Energy Deposition AM processes: Laser Engineered Net Shaping (Gibson et al. 2010)

Motivation for Hybrid Additive and Subtractive manufacturing

DDM envisions a future of an affordable, fast, highly customized process from design to product. As the mechanical component design trends are moving towards topology optimization to achieve light weight and strong mechanical property, more complex freeform features will be part of the design. At the same time, functional features remain on the design for assembly. The functional features are in relatively simpler geometry but requires higher GD&T requirements, while the freeform surfaces are designed less stringent requirements but in complex shapes. In addition to the increasing geometric complexity of industrial mechanical designs, on-site on-demand manufacturing is becoming a need for defense manufacturing (Frazier 2010). However, the currently available manufacturing technologies are not yet ready to fully support DDM to meet such needs for the future of industrial and defense manufacturing. Up to today, although AM has competitive advantages in manufacturing flexibility over other traditional manufacture processes, it lacks the ability to create parts with stringent requirements. The nature of AM, building geometries in layers, has provided AM the convenience of automated process planning and at the same time limited the accuracy of AM process. Also, AM commonly requires support structures to ensure a successful build. The supports can be difficult to remove, especially for metal AM parts. In practice, AM parts will need to go through tedious post processing to remove the support structures and allowances to get to the final shape; which makes the AM process not as “rapid” and “effort free” as it seems to be.

One approach to solve this problem is through Hybrid Manufacturing. Hybrid Manufacturing, is defined as the integration of AM with one or multiple manufacturing processes such as machining, surface treatment, heat treatment, etc. Hybrid Additive and Subtractive (Hybrid AM/SM), has shown great potential to produce AM parts with GD&T requirements (Stucker & Qu 2003). In traditional manufacturing, a subtractive process such as machining, is often planned as a secondary process after the primary formative processes such as casting or forging. When transiting the primary process produced part to the machining station for the secondary process, costly locating and fixturing devices need to be designed and manufactured for each design. For both the primary and secondary processes in traditional manufacturing, the fixturing cost is 10-20% of the total manufacturing system cost no matter how many parts will be produced(Bi & Zhang 2001). For mold tooling for the formative processes and the fixture for the machining process, the same tooling or fixture can be used for multiple thousands of production cycles which splits the cost on each individual part to lower the average cost. However, in the future “personalized production” paradigm, the traditional manufacturing processes are not able to well balance the design variety and the cost. AM offers a new flexible material addition process that allows selectively adding material in the 3D space. In the machining process, milling offers a more flexible material removal process in the 3D space as compared to turning and drilling. Based on these key characteristics of AM and milling, combining AM and milling could provide the best flexibility of both material adding and removal. Moreover, AM and milling can be integrated into one computer numerically controlled (CNC) system to provide a more compact manufacturing station to create high surface quality parts. In this dissertation, Hybrid AM/SM is more precisely defined as the hybridization of additive manufacturing and CNC milling.

Currently developed Hybrid AM/SM manufacturing systems have shown great potential to produce higher surface quality additive manufactured metal parts. However, there is no evidence showing that these hybrid manufacturing systems can avoid tedious manual process planning to achieve a successful build; which makes the hybrid manufacturing not yet a rapid manufacturing process. The key characteristic of DDM is, to some extent, effortless process planning regardless of the complexity of the geometry. Hybrid AM/SM, based off additive manufacturing and CNC milling, would not be attractive without maintaining the key characteristic of DDM. Therefore, automated process planning for Hybrid AM/SM manufacturing is critically needed in order to mature this technology.

Research objectives

When additive and subtractive processes are integrated, there are different challenges that need to be considered than conducting each process independently. Potential challenges in Hybrid AM/SM manufacturing includes, but is not limited to passing manufacturing information through AM and subtractive process, adding machining allowances, designing the fixture across AM/SM, locating the part for AM to subtractive transition, subtractive process planning, designing for Hybrid AM/SM, etc. Out of all these challenges, this dissertation research focuses on developing automated process planning methods for Hybrid AM/SM.

As such, the sub-objectives of this dissertation research are summarized in the following three topics:

1) **Automated post machining process planning for hybrid additive and subtractive manufacturing.**

   AM process enables the creation of overall high quality near net shape stocks for the subtractive process. Only functional surfaces with high GD&T requirements needs to be machined. A method needs to be developed to selectively machine those functional surfaces to allow less volume of material removal, less machining time and consequently less cost.

2) **Support structure removal for hybrid additive and subtractive manufacturing.**

   In subtractive process other than the machining allowance, another type of volume needs to be removed is the support structure. Support structure is commonly required in metal AM processes, and it needs to be removed before finishing the functional surfaces. Conventional support structure removal for metal AM requires tedious planning and manual work. A method needs to be developed to automate the support structure removal process.

3) **Process planning for hybrid additive and subtractive manufacturing to integrate machining and direct energy deposition.**

Hybrid additive and subtractive manufacturing (Hybrid AM/SM) offers a new integrated process with more manufacturing capability. Although the initial purpose of integrating subtractive process with the additive process is to create better surface quality for additively manufactured parts, more advantages can be expected from this hybrid process. This research proposed a new process planning strategy for Hybrid AM/SM considering both manufacturability limitation and the economic efficiency factors of each individual process, and a method is developed automated process planning for Hybrid AM/SM with the consideration of the two factors.

Thesis Organization

A general introduction, research motivation and objectives are presented in Chapter 1. A more detailed literature review about subtractive manufacturing and current stage of hybrid additive and subtractive systems development is presented in Chapter 2. In Chapter 3, a research study about automated post machining process planning for AM parts is presented in a journal publication format. In Chapter 4, a research on support structure removal for AM parts is presented in a journal publication format. Chapter 5 will be about the third research work on process planning for Hybrid AM/SM to integrate machining and directed energy deposition. In Chapter 6, the contribution of this dissertation work is summarized and furthermore planning for the future work.

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CHAPTER 2. LITERATURE REVIEW

In this section, representative subtractive manufacturing process, CNC-RP is introduced. A review of the currently developed hybrid manufacturing systems is also presented in this section.

Toolpath planning for Subtractive Manufacturing

Subtractive manufacturing or material removal processes can be categorized as mechanical (machining, water jet cutting, etc.), electrical (electrical discharge machining), thermal (laser cutting), and chemical (chemical milling) (Ramsdale 2006). Out of all the subtractive processes, CNC milling is most advantageous in terms of producing complex geometry and compatibility with AM processes. Multi-axes CNC milling so far is still the only manufacturing option for many geometrically complex designs with high surface quality requirements. Although, CNC milling has the capability of creating complex geometries it was not commonly considered as a rapid prototyping/manufacturing process. Because, CNC milling requires tedious fixturing design and process planning to ensure a successful build, and the same fixture and process planning method cannot be duplicated for different designs. As compared to AM, CNC milling is never a low human effort requirement process to just load material, CAD model, and push the start to build the part. The CNC-RP well addresses the pain points of traditional CNC milling.

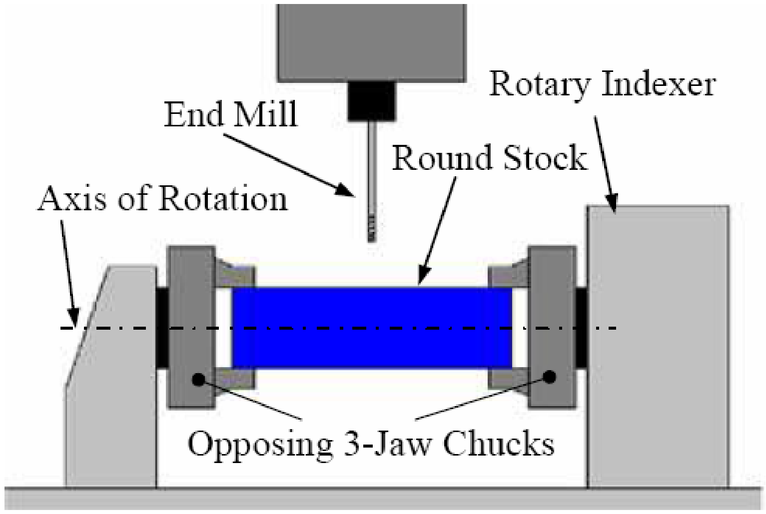

Figure 2-1 CNC-RP machine configuration

CNC-RP manufacturing process starts with a cylindrical stock that bounds the design as Figure 2-1 shows (Frank et al. 2004). The stock is fixed on a rotary axis to provide convenience for switching from one setup to another setup for the consequential milling processes.

CNC-RP solves the fixturing problem by creating sacrificial support structures for a CAD design as Figure 2-2 shows (Boonsuk & Frank 2009). 2-4 cylindrical support will be

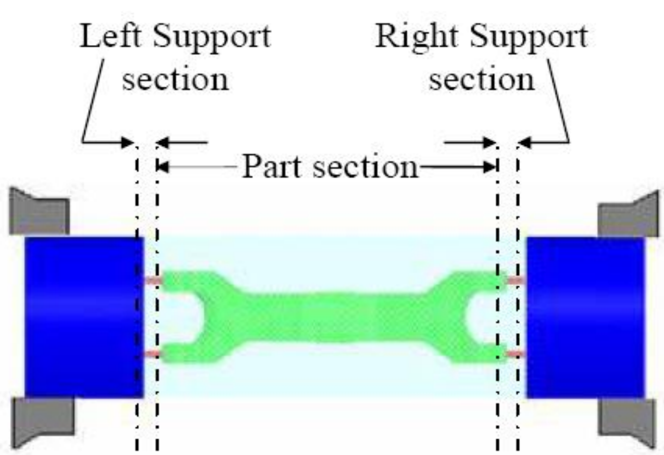

Figure 2-2 CNC-RP sacrificial support

created during the machining process. The support number, diameter, and location is generated according to the part geometry and the maximum bending and torsion condition. After the part is finished, the support structure will be removed to harvest the part from the building envelope. Algorithms are created to calculate the principle parameters of process planning for CNC milling: Setup planning (what are the A axis orientations to machine the part), tools selection (what are the tools to choose), and cut depths (the Z axis depth range for each machining operation) in CNC-RP (Frank et al. 2006).

CNC-RP offers a new approach of automated process planning for CNC milling; which makes CNC machining based rapid prototyping/manufacturing a possible approach for DDM. It offers a solution for creating higher surface quality according to the GD&T requirements of the design in a rapid manner.

Hybrid additive and subtractive manufacturing

There are currently several representative Hybrid AM/SM manufacturing systems that have been developed. Shape Deposition Manufacturing(SDM)(Merz 1994), first introduced machining to an AM process. In SDM, the part geometry is divided into layers with and without undercut features. The layer without undercut will be deposited first with the primary material, then milling the layer to a more accurate shape. Next, the process adds a support material to fill the void of that layer and then milling down the support material to achieve an accurate top surface of that layer. In contrast, the layer with undercuts will be first deposited with support material, milling down to a mold, then will use the primary material to fill the mold and milling down to an accurate top surface. In this manner, the part geometry will either be accurately machined or be "cast" from an accurately machined "mold" surface build with the support material. SDM had seen considerable development, however, due to the high demand for the support material and high residual stress in the as built part, SDM cannot readily be applied to metal mechanical component printing.

Later, a Hybrid Layer Manufacturing(HLM) method that integrated a MIG/MAG welding head with a three-axis machining process was developed for direct metal tooling (Akula & Karunakaran 2006). In the HLM method, layers are created with MIG/MAG depositing the metal beads, then it used face milling to create an accurate Z height for each layer. In the later research, multi-axis milling was introduced to the HLM process to achieve better surface quality.

The Laser Aided Manufacturing Process(LAMP) is another representative hybrid manufacturing method that integrates Laser-Engineered Net Shaping(LENS) and multi-axis CNC machining (Liou et al. 2001). In this research, multi-axis DED and CNC machining are incorporated. This work well addressed the support structure issue for DED processes. A part decomposition method is developed so the part can be additively built in several subparts, and each subpart can be built with a proper orientation with the least requirement of support structures. Moreover, an adaptive non-uniform slicing method is developed to ensure the successful build for multi-axis DED. In this research, CNC milling is also considered for integrating with the AM processes for surface finishing.

In both HLM and LAMP method, a single building station hybrid AM and CNC milling system was developed to improve the manufacturability of two different DED processes. Related algorithms for AM tool path generation are developed. However, the other important aspect of Hybrid AM/SM, the machining process is not well addressed in both hybrid systems. When machining is considered as a secondary process with AM, machining allowances need to be added to functional surfaces for later post machining to achieve GD&T requirements. In this dissertation, an automated process planning method for machining prismatic/cylindrical functional surfaces is developed to address the subtractive aspect of Hybrid AM/SM.

In more recent years, there are also several commercialized Hybrid AM/SM manufacturing systems developed. LUMEX series developed by Matsuura and OPM series developed by Sodick are representative PBF based hybrid systems as Figure 2-3 illustrates. A micro milling process and the selective laser sintering process take actions alternatively to create a more precise layer contour. The PBF based hybrid systems takes full advantage of

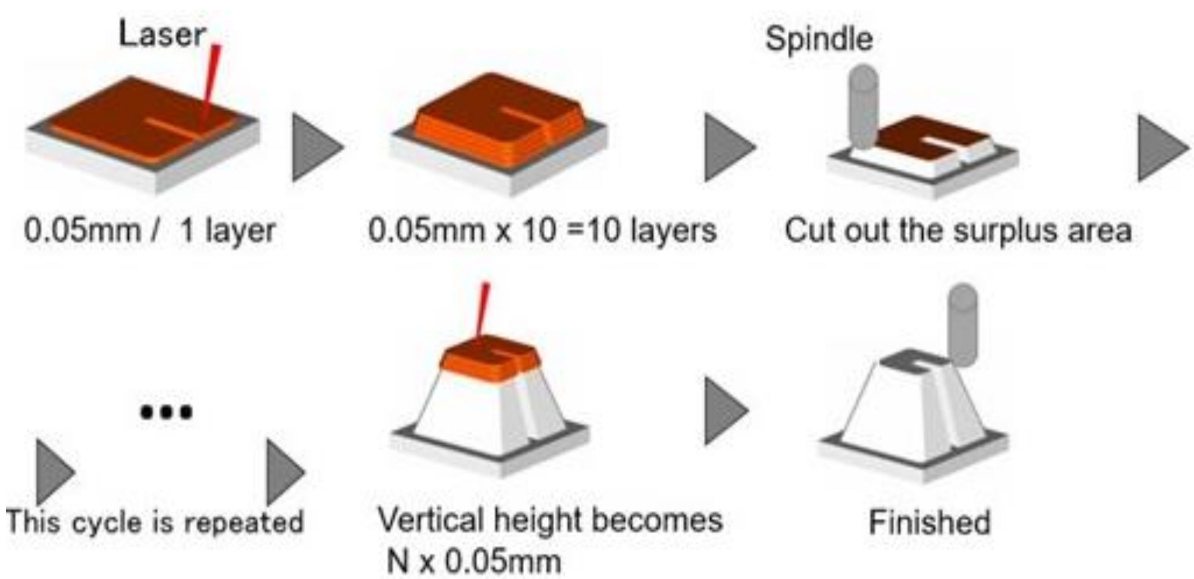

Figure 2-3 PBF hybrid process (Matsuura 2017)

layer based manufacturing, by incorporating the milling process right after each layer is sintered. It brings convenience in toolpath generation for the milling process. However, at this current stage, residual stress is still a big challenge in AM processes that require melting temperature or good thermal and electrical conductivity (introduced in CHAPTTER FOUR). This problem can only be solved through adding support structures. This alternative layer by layer AM and milling process in PBF based hybrid will not be able to build support structure since every layer is machined. Thus, PBF based hybrid as these systems are designed can only be working with lower temperature laser sintering AM process.

The LASERTEC series developed by DMG MORI and the AMBIT system developed by Hybrid Manufacturing Technologies are representative DED based hybrid systems. The material adding and removing process are as Figure 2-4 shows. DED hybrid systems offers high manufacturing freedom by having 5-Axis CNC configuration for both the AM and the machining process. However, manual process planning is required for the toolpath planning for AM and the machining process.

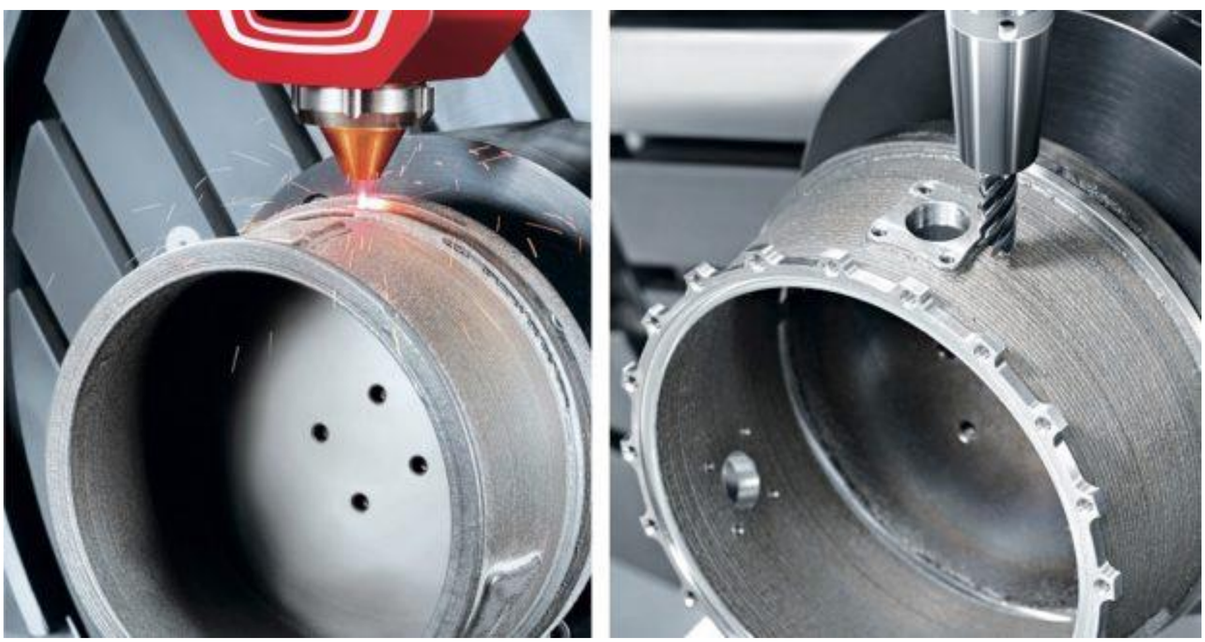

Figure 2-4 DED hybrid process (DMGMORI 2017)

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CHAPTER 3. AUTOMATED POST MACHINING PROCESS PLANNING FOR A NEW HYBRID MANUFACTURING METHOD OF ADDITIVE MANUFACTURING AND RAPID MACHINING

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Abstract

Purpose – The purpose of this paper is to present a new method for automated post machining process planning for a hybrid manufacturing process. The manufacturing process is expected to generate complex functional parts by taking advantage of free form surface creation from additive manufacturing and high-quality surface finishing from CNC milling.

Design/Methodology/Approach – This hybrid process starts with additive manufacturing to generate a near net shape part with pre-defined machining allowances on surfaces requiring high quality surface or tight tolerances, along with integrated fixture geometry. The next step is to conduct automated machining process planning to determine critical parameters such as setup angle, tool selection, depth, tool containment and consequently the NC code to machine the part.

Findings –This method is shown to be a feasible solution for rapidly creating functional parts. Tests have been conducted to validate the method developed in this paper.

Originality/Value – This paper introduces a new automated post machining process planning method for integrating additive manufacturing with a rapid milling process.

Keywords – Additive manufacturing, Hybrid manufacturing, CNC milling

Paper type – Research Paper

Introduction

Manufacturing processes can be categorized into three main types: material adding (additive) processes, material removal (subtractive) processes and material shaping (formative) processes. Additive processes include binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (Gibson et al., 2010), while subtractive processes include milling, turning, and grinding, to name a few. Formative processes include traditional manufacturing processes such as casting, forging and powder metallurgy. Among the three, Additive Manufacturing (AM) has a clear advantage in producing free-form and complex geometries. However, this approach sometimes struggles to meet dimensional and surface requirements, especially for high-end metal components. Subtractive manufacturing, on the other hand, often fails to produce free-form and complex geometries easily or at all, but when possible, it excels in dimensional accuracy and surface finish. It stands to reason that combining additive and subtractive processes could take advantages from both. Research on integrating additive manufacturing and machining to achieve better manufacturing flexibility has been conducted for many years. Arguably, machining was first introduced to an AM process in a process called Shape Deposition Manufacturing(Merz, 1994). Later, a Hybrid Layer Manufacturing(HLM) method that integrated a MIG/MAG welding head with a three axis machining process was developed for direct metal tooling(Akula & Karunakaran, 2006). The Laser Aided Manufacturing Process(LAMP) is another representative hybrid manufacturing method that integrates Laser-Engineered Net Shaping(LENS) and 5-axis CNC machining(Ruan et al., 2005). Also, related research on developing machining strategies for enhancing surface finish for parts after printing has been conducted(Stucker & Qu, 2003). When AM is used in a hybrid additive/subtractive process, extra material called machining allowance can be added through offsetting slice contours for the layer-based AM process(Akula & Karunakaran, 2006). However, most hybrid AM and CNC machining approaches treat all surfaces the same for the machining process (not selectively), which can lead to material waste, tool wear and generally long machining times since most of the part surfaces may not have required finishing. The requirements for machining AM parts can be likened to the requirements for machining metal castings or forgings. For most components, the initial process can produce the majority of the features, leaving a smaller set of features that need to be machined. A review of casting applications featured in the Steel Casting Handbook (Blair & Stevens, 1995) support this premise that a casting process can achieve the majority of the features for most components. If the world of metal casting has been successful whilst having post processing, a similar process might be applied for additively manufactured metal components.

Rapid process planning for CNC milling called CNC-RP (Frank et al., 2006) illustrated a new method for calculating process parameters and enabling a highly automated rapid machining process (Figure 3-1). With 3 axes (x,y,z) plus an asynchronous rotation axis (A-

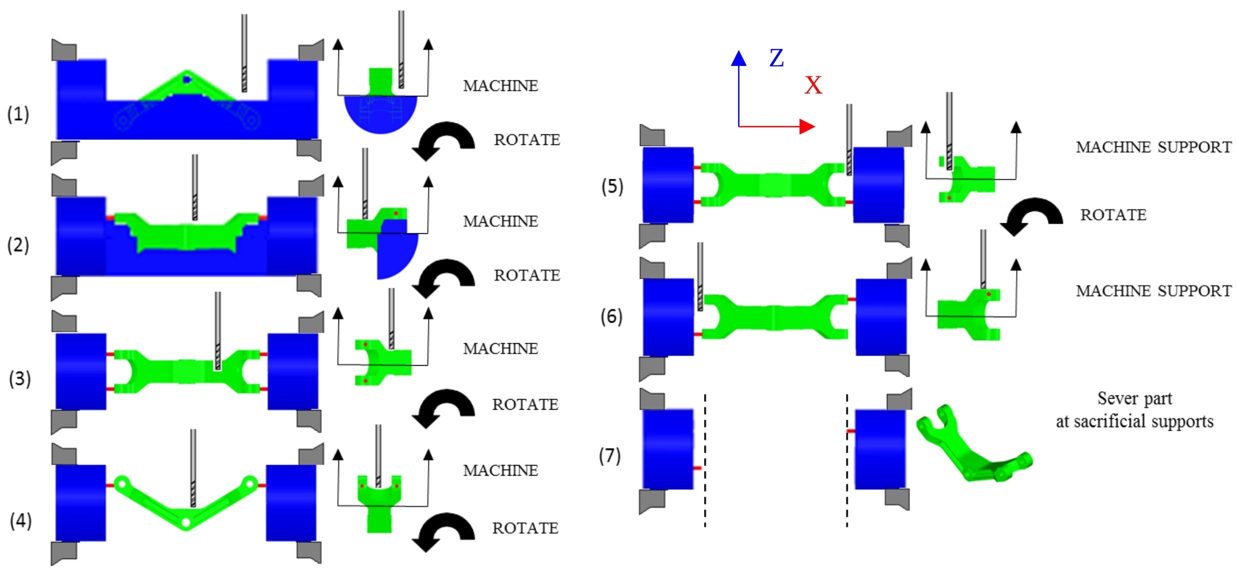


Figure 3-1 CNC-RP machining process steps, showing rotated part about a-axis and machining operations

axis) configuration, parts can be rapidly machined from round stock. In this system, setup angles are selected according to a visibility analysis of the sliced model along a calculated rotation axis. Machining depths are calculated from the visible segments from each setup angle. In addition, remaining stock for each setup angle is calculated through a "Slice shadowing" process (Petrzelka & Frank, 2010). As shown in Figure 3-1, CNC-RP executes 3-axis machining across steps 1-6, where a set of fixture elements (sacrificial supports) keep the part secured to stock until step 7 where the part is cut away at the supports. Whereas AM adds material along on "build" direction, CNC-RP simply removes material about a plurality of orientations.

The 3+ axis setup for a machine running CNC-RP is illustrated in Figure 3-2. Of course, since CNC-RP is subtractive only, it is still limited at creating intricate, complex, or undercut shapes, and freeform geometry is very expensive in general. The process uses a minimum

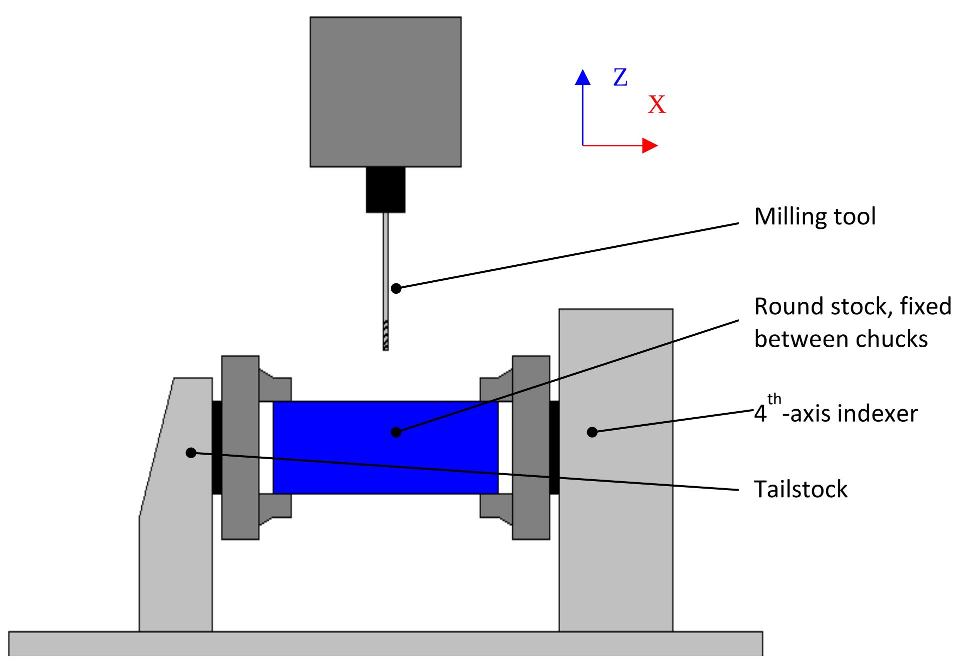


Figure 3-2 CNC-RP machine setup (Frank et al., 2006)

bounding standard cylindrical stock regardless of part geometry; which can lead to long machining times and tool wear. When it comes to super-alloys such as Ti6Al4V, this drawback might eliminate CNC-RP from consideration. That is, it could be argued that the difficulty and cost of machining super alloys is one of the drivers to use metal AM instead. Another limitation is that CNC-RP treats all surfaces the same, machining 100% of the surfaces, and lacks the ability to differentiate a flat surface from a free-form, for example. These limitations are the accepted cost of automated process planning and NC code generation; CNC-RP may make sense for one or several parts, but perhaps not for long production runs.

In this paper, CNC-RP is extended to work with an additive manufacturing process, aptly renamed CNC-RP_{Hybrid}. The hybrid approach will enable the ability of customized machining of each individual functional surface. In this new approach, setup angles, tools, depth and tool containment boundaries will be individually calculated for each functional surface. As such, each functional surface can have a more optimal toolpath strategy, and since each surface is selectively machined we can avoid redundant toolpaths that over-machine a surface. Non-critical surfaces, free form surfaces or internal geometries that cannot be manufactured through machining will be left as-additively-manufactured. The resultant of the process will be a functional part with complex free-form additively manufactured surfaces, of which some are CNC-machined as needed. One could argue that this is akin to a high performance machined metal casting, but with exceedingly more complexity possible.

Methodology

It should be noted that CNC-RP_{Hybrid} is intended for a *sequential* hybrid manufacturing process, where additive manufacturing is first and then the part moves on to post-process machining. We can refer to this as an out-of-envelope approach, unlike the integrated in-envelope systems like the DMG lasertec 65, Mazak i400am, or AMBIT systems where AM occurs within the machining center. CNC-RP_{hybrid} is intended to follow a powder bed fusion AM process such as Selective Laser Melting (SLM) or Electron Beam Melting (EBM), and the machining process can be done on nearly any 3-axis (x,y,z) CNC machine with a rotary axis (A-axis). The two-phase process begins with a CAD model as input, where pre-AM process planning has been conducted to provide a model for AM in a suitable building orientation, machining allowance on critical surfaces and with integrated fixture geometry. In the second phase, post-AM machining process planning is conducted to provide NC code for automated critical feature machining. Machining features of the part geometry represent the functional surfaces, which can be categorized as holes, pockets, open pockets, faces and bosses (Yan et al., 2000). From a geometrical perspective, the majority of machining features are composed of planar or cylindrical surfaces or a combination of both. The method proposed in this paper focuses on planar and cylindrical machining features. The overall steps include; 1) segmentation, 2) machining feature recognition, 3) model generation for AM, 4) additive manufacturing, and 5) customized machining, an integrated process called "Direct Additive Subtractive Hybrid"(DASH) manufacturing (Srinivasan et. al., 2015). A flow diagram is shown in Figure 3-3 to illustrate the two major phases of the overall process; from initial part design to final machined AM component. The specific focus of this paper is on the second phase, customized machining process planning, for which CNC-RP_{Hybrid} is proposed.

CAD geometry can be represented by a triangle mesh model such as the STL (STereoLithography) format. An STL model can conveniently represent any geometric feature of varying complexity (Grimm 2004). Many existing computational geometry algorithms are designed to run efficiently on such triangular mesh representations (Frank et al., 2006; Liu & Wang, 2011; Stucker & Qu, 2003; Kim et al., 2004). Algorithms for offsetting, segmentation,

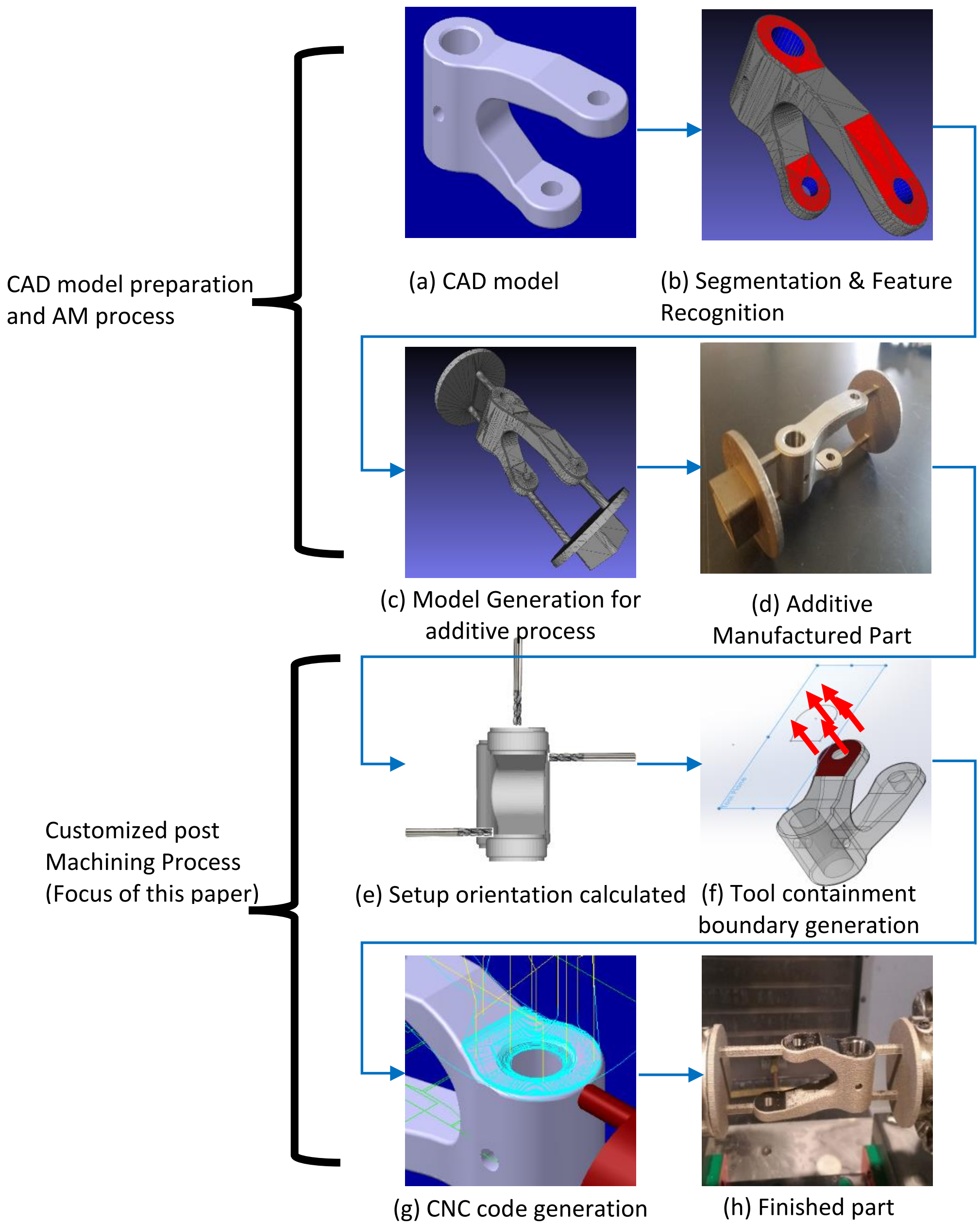
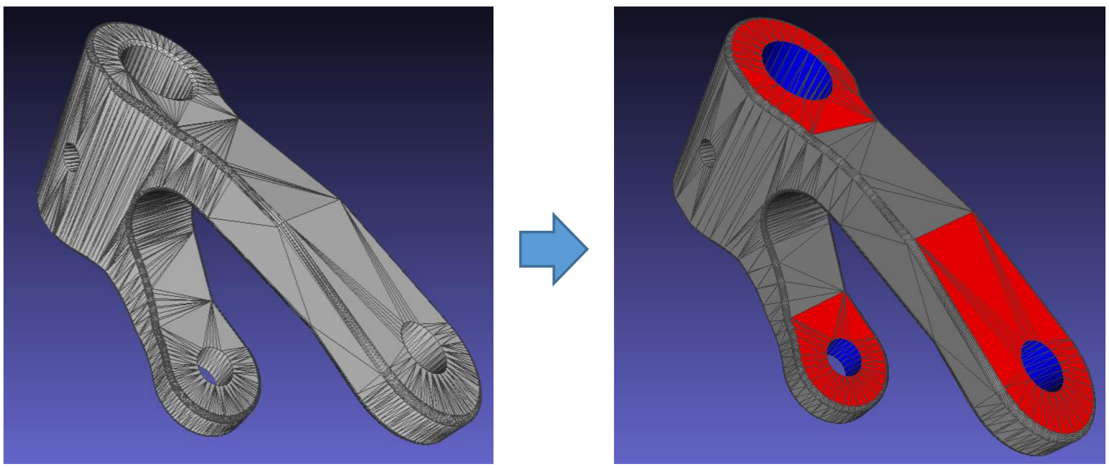


Figure 3-3 Hybrid Manufacturing Method Overview

feature recognition, visibility calculation, etc. have already been developed for triangle mesh models. In this paper, all analysis is based on triangle mesh and new algorithms are developed that take advantage of existing algorithms. In this work, the original free-form surface model has been modified to provide information about functional surfaces in a parametrized machining feature form. That is, the use of facet color and metadata can inform CNC-RP_{hybrid} that a “flat” or “hole” feature exists. Then, new algorithms and methods developed in this research automatically determines critical milling parameters such as setup orientation, cutting depth, tools and tool containment boundaries for the milling process on each feature. Although more advanced file formats such as Additive Manufacturing Format (AMF) and 3D Manufacturing Format (3MF) offer more capabilities such as providing material, color, feature information, etc. , the basic geometric structure is still simply triangles and vertices. The method developed in this research is based on triangle meshes and can be easily transformed to work with either STL, AMF or 3MF formats; however, the authors used STL for this work.

Segmentation

Segmentation has always been an important and challenging process for handling mesh models. It basically takes a mesh model and turns it into multiple “clusters” of meshes where each “cluster” could be a meaningful representation of a portion of the geometry. Since pure triangular mesh geometry does not contain any feature information, segmentation may allow identify machining features that can be isolated from other free-form surfaces (ones that will likely remain As-Additively-Manufactured). Triangle meshes can be segmented based on dihedral angles along with the enhancement of adding feature vertices. When the normal vectors of two neighbor facets are greater than a threshold, the shared edge of these two neighbor facets can be defined as a feature edge. A combination of feature edges will form the entire feature boundary. Then, feature vertices are added to create a hard feature boundary (Razdan 2003). In this paper, triangle models are segmented as shown in Figure 3-4, where machining features are isolated and marked by different colors for feature recognition. With AMF or 3MF format, instead, this segmentation process can be replaced with marking machining features in AMF- or 3MF-supported CAD tools initially.



(a) Feature Free triangle mesh model without feature marking

(b) Color indicated model, holes(blue), flats(red) and as-AM surfaces(grey)

Figure 3-4 Triangle mesh model segmentation

Machining feature recognition

After the segmentation process, the triangle mesh model is divided into multiple clusters and each cluster would represent a design feature. In an industrial design, we expect a combination of both free-form surfaces and prismatic/analytical surfaces; where one might expect the prismatic/analytical surfaces to have more specific functional purposes (bolt holes, mounting flanges, etc.). Furthermore, we can suggest that free-form surfaces are perhaps more easily created by additive or solidification processes, while prismatic/analytical surfaces are better handled by machining processes. So, it is perhaps both reasonable and convenient to focus on recognizing prismatic/analytical geometries for post-process machining of AM parts. In this work we simply identify the marked clusters by fitting primitive geometries such as

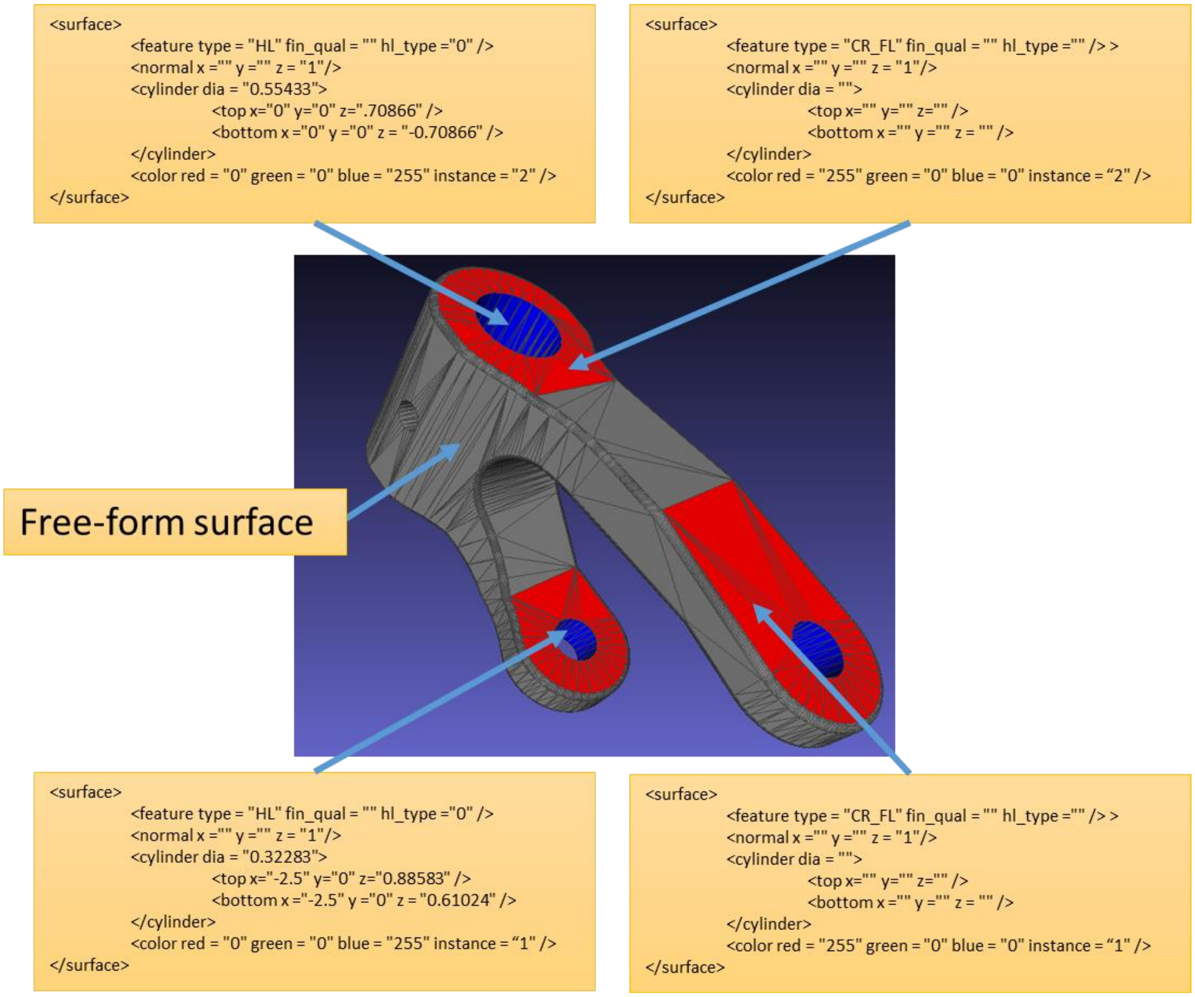


Figure 3-5 Combined model of free-form surface and parametrized prismatic/analytical surfaces

planes and cylinders (Attene et al. 2006). From this feature recognition process, both the feature type (planar or cylindrical feature) and parameters for each are obtained. For example, planar features have a surface normal associated with them, while cylindrical features have a radius, center, and end points defining the axis of the cylinder. After the feature recognition process, the part model has clearly delineated and parametrized prismatic/analytical geometry among the free-form surfaces, as shown in Figure 3-5.

The triangle meshes with colored features and information can be carried on through the AMF or 3MF formats as textures and metadata for each individual facet. Existing software packages such as *Materialise Magics* and *Solidworks (v2015 and above)* are example CAD tools that can create, edit and export AMF models. The process of generating an AMF model that contains machining feature metadata from a triangle mesh model can be efficiently executed by “AMF Creator”, a software package developed by Srinivasan in the aforementioned DASH process development (Srinivasan, 2016).

Model generation for additive process

In the next step of the hybrid approach, near net shape parts with machining allowance and required machining fixture geometries are created using AM. This requires a new model by offsetting the identified prismatic/analytical surfaces that require post process machining. Machining allowance can be added on the model through triangle mesh model offset based on previous methods (Kim et al., 2004; Liu & Wang, 2011). The amount of machining allowance required is generally based on shrinkage and other geometric variation from AM, but also on the machining process requirements and setup accuracy (Manogharan, 2014). In this work, with EBM printed Ti6Al4V parts, a 0.05 (1.27mm) allowance was proven to be sufficient; but may not be applicable for other materials or AM processes. In addition to machining allowance, support structures for fixturing are added to the model (Boonsuk & Frank, 2009). These fixture support structures are intended to be clamped by the dual opposing rotary jaw chucks in the 4th axis setup. The original and modified models for additive manufacturing are illustrated in

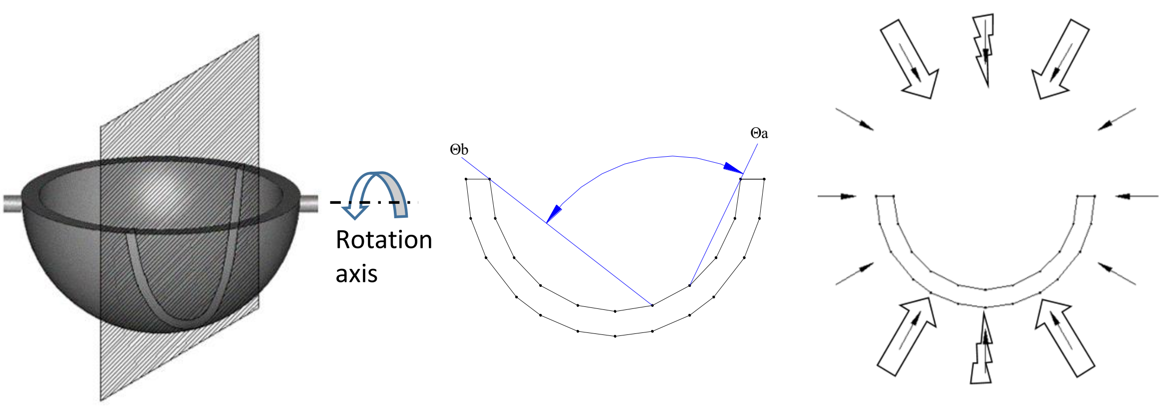
Figures 3-6a and 3-6b, while the Figure 3-6c shows the as-printed metal AM component with fixture support and machining allowance.

Customized machining process

In the process planning of CNC-RP, cross sectional slices along the rotation axis of the model are used for determining the required setup orientations (Figure 3-7). From each slice, the visible range of each segment can be calculated and then a series of setup orientations can be determined that will cover all segments across all slices.

(a) Original Mesh model (b) Mesh model for additive process (c) Additive manufactured part

Figure 3-6 Model generation for additive process



(a) Slice along the rotation axis (b) Visibility analysis for a segment on the slice (c) Set up orientations selected through the visibility of all segments

Figure 3-7 CNC-RP visibility analysis (Frank et al., 2006)

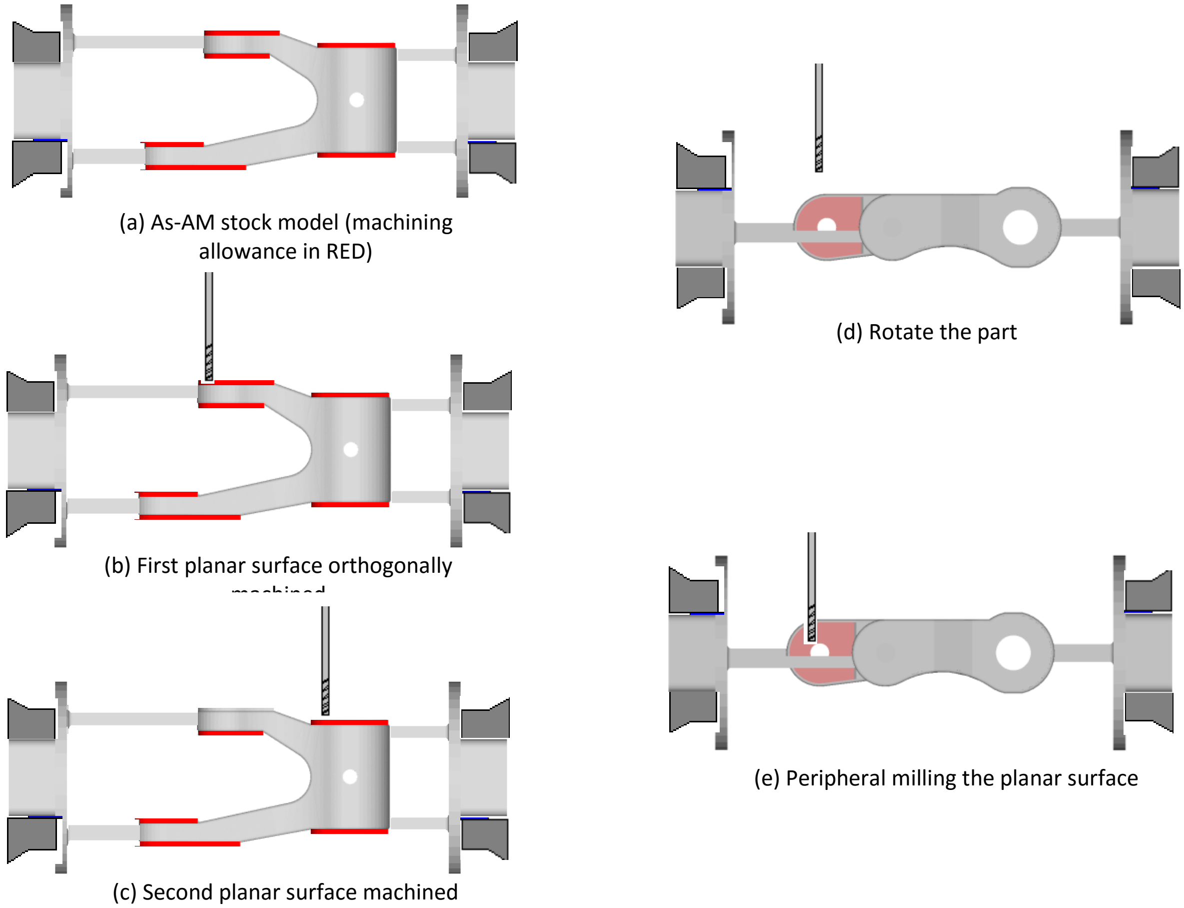


Figure_3-8 CNC-RPHybrid machining process for planar surfaces using both orthogonal and peripheral milling

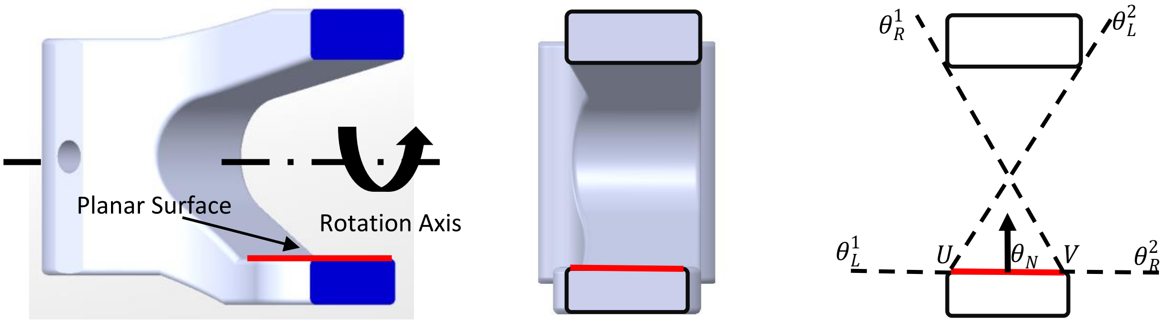
In the original CNC RP process (Figure 3-1), no assumptions for feature information as input is made for process planning since all the surfaces are considered equally pocket milled. CNC-RP$_{\text{Hybrid}}$ however, accepts a combined model of free form geometry and machining feature information for critical surfaces and each machining feature is individually identified and analyzed so that it can have its own specific toolpath strategy as Figure 3-8 shows. It should be noted; however, that a roughing operation precedes all feature based cutting, wherein any remaining AM support materials are removed. This paper only focuses on the process planning of critical features, which is detailed in the following sections.

Available setup angles calculation

Under the 3+ axes machine setup, the setup orientation is composed of two parts: a setup *axis* and a number of setup *angles*. Although it could be one of many, the setup axis is assumed to be one of the three standard orthogonal axes (X, Y, Z axis) from the model's design coordinate system. Then, for a selected setup axis, setup angles about that axis are calculated for machining the critical features.

Practically, planar surfaces can only be orthogonally or peripherally machined by a milling tool. If the planar surface is not parallel to the selected axis, this surface can only be potentially machined peripherally. To analyze which angle or angles a planar surface can be machined, the visibility of the planar surface is calculated to determine setup orientations (Frank et al. 2006). Sliced along the selected axis, a portion of the planar surface can be represented as Figure 3-9a indicates.

The red segment U-V in Figure 3-9c represents the slice segment of the planar surface. $\Theta_{visi-segment}$ denotes the angle range for a slice segment, and $\Theta_{visi-surface}$ for the entire surface. The angles Θ_L and Θ_R are the left visible bound and the right visible bound, respectively in the range of ($0^{\circ}\sim360^{\circ}$). The angle $\Theta_{visi-segment} = \{(\Theta_L^1, \Theta_R^1), (\Theta_L^2, \Theta_R^2), \ldots, (\Theta_L^n, \Theta_R^n)\}$. Θ_N denotes the angle of the normal of the planar surface. If the facet is parallel to the rotation axis and the normal direction $\Theta_N \in \Theta_{visi-surface}$, then this planar surface can be machined orthogonally. If $\Theta_N - 90^{\circ}\ or\ \Theta_N + 90^{\circ} \in \Theta_{visi-surface}$, then this surface can be machined peripherally. As the example in Figure 3-9c shows, $\Theta_N \notin \Theta_{visi-surface}, \Theta_N - 90^{\circ}\ and\ \Theta_N + 90^{\circ} \in \Theta_{visi-surface}$. This planar surface can only be peripheral milled. We can now decide the machining angle(s) of the planar surface Θ_{setup}



(a) Cross section of CAD model with planar surface marked as red.

(b) Slice representation, red line segment corresponding to the planar surface.

(c) Visibility analysis of the red line segment.

Figure 3-8 Planar surface slice segment visibility.

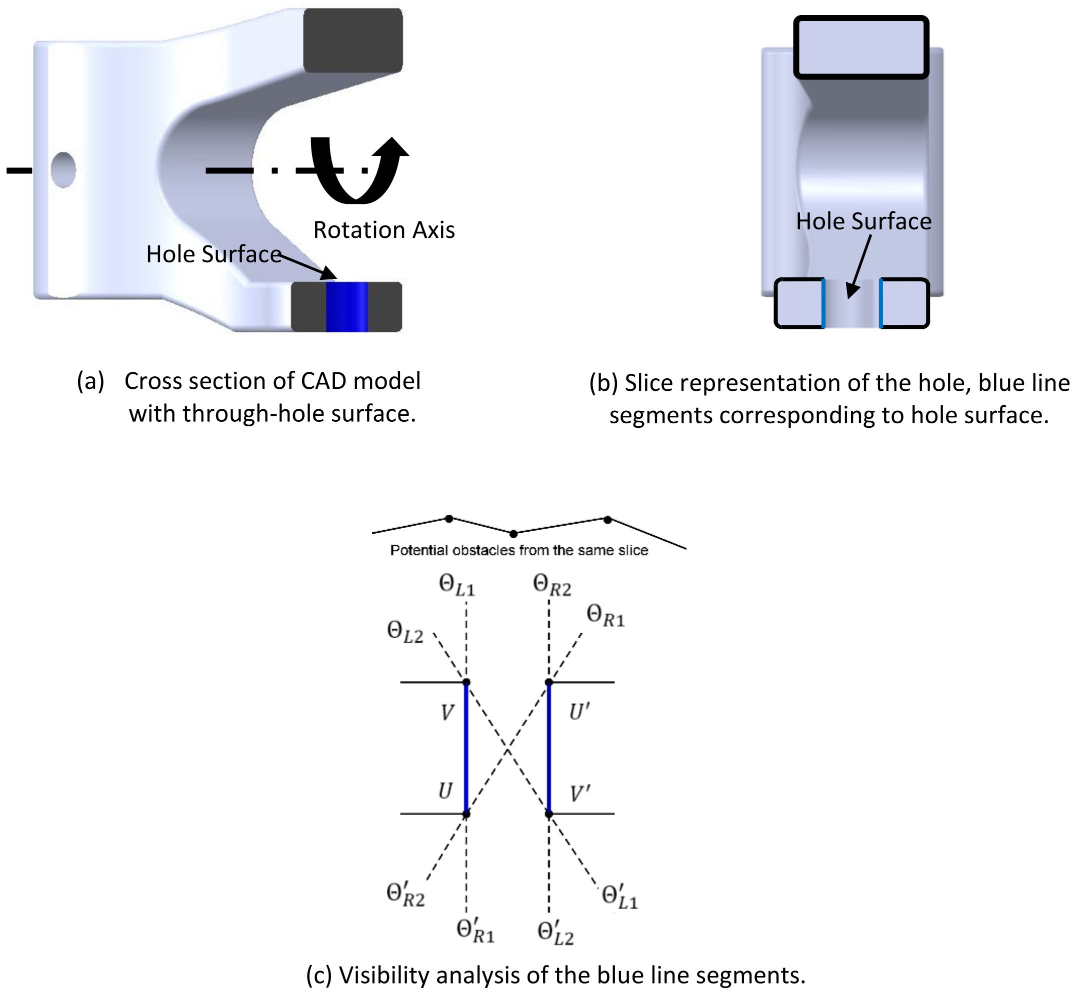
using the algorithm described in Algorithm 1.

Algorithm 3-1 Calculating the setup angle(s) for a planar surface

---

Input: Triangle mesh model with machining feature marked, facet normal angle Θ_N
Output: Setup angle(s) Θ_{setup}
Get the slices of the planar surface along the selected axis(SliceGroup)
FOR each slice in SliceGroup:
    Calculate the visible angle range set $\Theta_{visi-segment}$ for the planar surface segment (Algorithm1 Frank, 2006)
END FOR
Intersecting all the visible angle range sets $\Theta_{visi-segment}$ to get the surface visible angle range set $\Theta_{visi-surface}$.
IF $\Theta_N \in \Theta_{visi-surface}$:
    IF facet parallel to the selected axis:
        Add Θ_N to Θ_{setup}
    END IF
END IF
IF $\Theta_N - 90^{\circ} \in \Theta_{visi-surface}$:
    Add $\Theta_N - 90^{\circ}$ to Θ_{setup}
END IF
IF $\Theta_N + 90^{\circ} \in \Theta_{visi-surface}$:
    Add $\Theta_N + 90^{\circ}$ to Θ_{setup}
END IF

For a cylindrical hole, the machining orientation must obviously be along the axis of the hole. If it is a blind hole, then it can only be machined from the opening direction while a through-hole can potentially be machined from one of two oppposing directions. However, if the hole axis is not perpendicular to the selected setup axis, then the hole cannot be machined. Slicing along the setup axis, the hole surface can be represented as shown Figure 3-10b, where the segments of the surface of the hole in the slice are represented in blue.



(a) Cross section of CAD model with through-hole surface.

(b) Slice representation of the hole, blue line segments corresponding to hole surface.

(c) Visibility analysis of the blue line segments.

Figure 3-9 Cylindrical hole surface visibility

Algorithm 3-2 Calculate the setup angle(s) for cylindrical hole surface

---

Input: Triangle mesh model with machining feature recognized, axis angle $\boldsymbol{\Theta}_{Axis}$
Output: Setup angle(s) $\boldsymbol{\Theta}_{setup}$
Get the slices of the planar surface along the selected axis(SliceGroup)
FOR each slice in SliceGroup:
    Calculate the visible angle range set $\boldsymbol{\Theta}_{visi-segment}$ for the cylindrical hole surface segment (Algorithm1 Frank 2006)
END FOR
Intersecting all the visible angle range sets $\boldsymbol{\Theta}_{visi-segment}$ to get the surface visible angle range set $\boldsymbol{\Theta}_{visi-surface}$.
IF hole axis perpendicular to the selected axis:
    IF $\boldsymbol{\Theta}_{Axis} \in \boldsymbol{\Theta}_{visi-surface}$:
        Add $\boldsymbol{\Theta}_{Axis}$ to $\boldsymbol{\Theta}_{setup}$
    END IF
    IF $\boldsymbol{\Theta}_{Axis} + \mathbf{180}^{\circ} \in \boldsymbol{\Theta}_{visi-surface}$:
        Add $\boldsymbol{\Theta}_{Axis} + \mathbf{180}^{\circ}$ to $\boldsymbol{\Theta}_{setup}$
    END IF
ELSE
    Hole not accessible
END IF

For either blind or through-holes, the same approach can be applied to calculate the setup angle(s). The visible range of each hole segment can be calculated first, and then the intersection of all visible ranges of the segments and of all slices of the cylindrical hole surface will be the available setup angle of the hole. A hole can only be machined from two directions along its axis, denoted by Θ_{Axis} *and* $\Theta_{Axis} + 180^{\circ}$, and only if the hole axis is perpendicular to the selected rotation axis. Next, one can check if Θ_{Axis} *or* $\Theta_{Axis} + 180^{\circ} \in \Theta_{visi-surface}$, to decide the set of directions the hole can be machined, if any. As the example in Figure 3-10c shows, Θ_{Axis} is perpendicular to the rotation axis; however, it is blocked by other portions of the model from the top direction. So, this cylindrical hole surface can only be machined from the bottom direction along the axis. The setup angle(s) of the cylindrical hole surface Θ_{setup} can be calculated as Algorithm 2 describes.

Depth calculation

Depth is another parameter required for CNC milling. It defines the required tool movement range in the Z axis. The depth of a machining feature can be obtained through the facets of the machining feature. The algorithm traverses over all facets that belong to this machining feature, finding the maximum and minimum z value that correspond to the max and min cutting depths. Figure 3-11 indicates the depth for a peripheral milled planar surface. In the case of a cylindrical hole surface, the depth can be calculated based on the recognized cylinder information; two end points and setup orientation, as Figure 3-12 indicates.

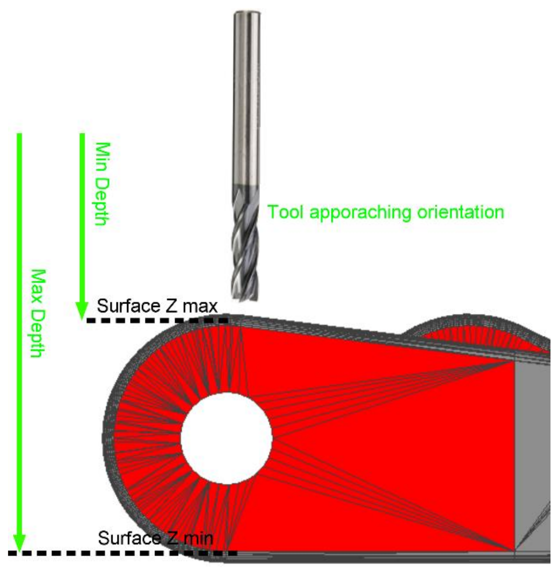
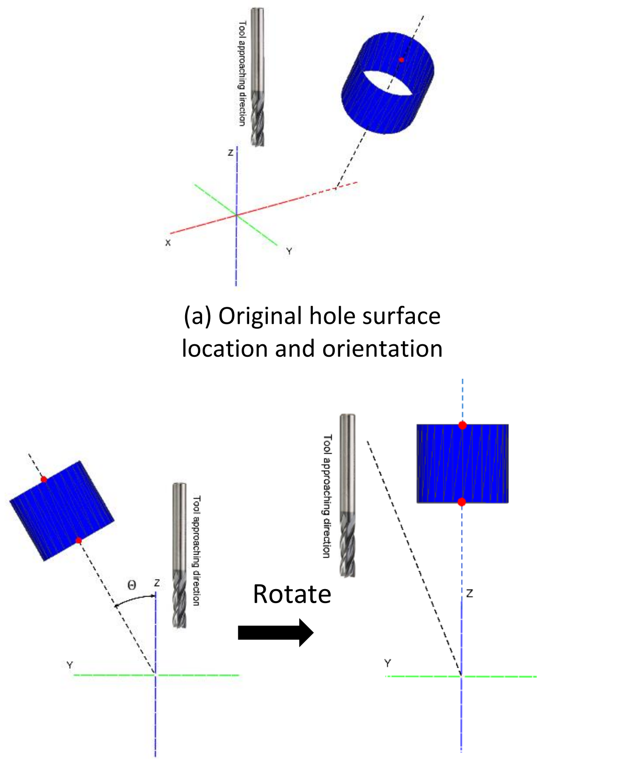


Figure 3-10 Planar surface depth



(a) Original hole surface location and orientation

(b) View along the X-axis

(c) Rotate hole surface to setup angle

Figure 3-11 Cylinder Hole surface depth

$$Depth\_1 = Z\ coordinates\ of\left(\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\Theta & -\sin\Theta\\ 0 & \sin\Theta & \cos\Theta\end{bmatrix}\begin{bmatrix}Top\ Point_x\\ Top\ Point_y\\ Top\ Point_z\end{bmatrix}\right)$$

$$Depth\_2 = Z\ coordinates\ of\left(\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\Theta & -\sin\Theta\\ 0 & \sin\Theta & \cos\Theta\end{bmatrix}\begin{bmatrix}Bot\ Point_x\\ Bot\ Point_y\\ Bot\ Point_z\end{bmatrix}\right)$$

$$Min\ depth = max\{Depth\_1, Depth\_2\}$$

$$Max\ depth = min\{Depth\_1, Depth\_2\}$$

In this work, a basic tool selection metric for filtering out unsuitable tools is applied. The depth parameter is the criteria for choosing the length of the tool. For planar surfaces, tool diameter is not restricted by it geometry, unlike for holes which require equal to, or smaller diameter tools. In this work, there are additional assumptions/conditions for the the tool geometries with respect to cutting length and diameter. For one, this approach assumes that the shank diameter is equal to or less than the flute diameter. In fact, most tools in the library are of a “neck style” configuration with reduced shank diameter from the holder to the beginning of flutes. The diameter assumption allows tools to have reach and access to the full *stick-out* length outside of the holder. Also, it is assumes that machining depths, in general for this process, are well within the commercially available flute lengths. That is, since this is an auto-generated NC programming approach, the callouts for machining depths are rather shallow and conervative. In practice, machining depths prescribed in CNC-RP are often an order-of-magnitude below commerically available flute lengths in the library.

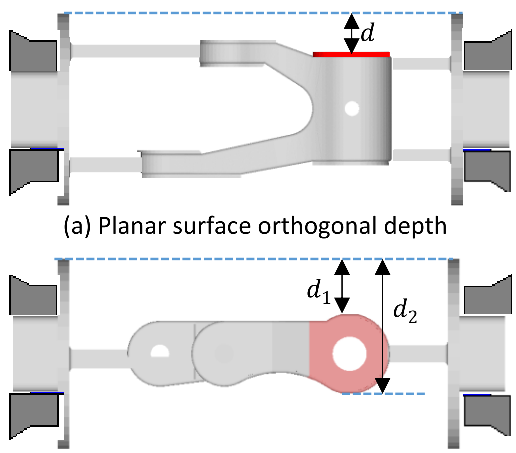


Figure 3-12 Planar surface depth

Setup angle optimization

From visibility analysis, a set of available setup angles can be calculated. For a planar surface, there can be three possible setup angles, one orthogonal and two peripheral angles (+/-90^0), while a hole can have two possible setup angles aligned with the hole axis. From all possible angles, a better decision can be made if consideration for the depth is made. A larger depth requires a tool with longer cantilevered length (distance from tool holder to the tool end) and consequently leads to more deflection δ_m (Kops & Vo, 1990).

$$\delta_m = \frac{l_e^2(3l - l_e)\varepsilon}{6th}$$

Where: l is the tool overhang length, l_e is the effective overhang length, t is the distance from the force to the center of strain gauge and h is the distance from the neutral axis to the surface on which the strain gauge is mounted, and ε is the strain.

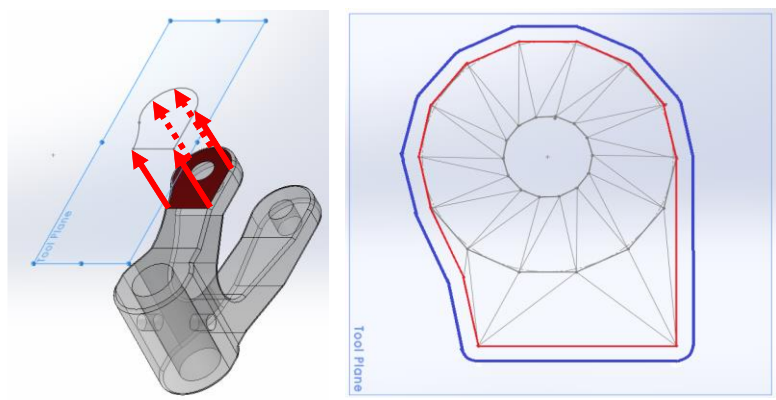
As Figure 3-13 illustrates, the planar surface marked in red has a depth of d for orthogonal milling, but has a min depth of d_1 and max depth of d_2 for peripheral milling. With $d < d_2$, the orthogonal milling setup angle is selected. The same setup angle optimization strategies are similarly applied to each of the cylindrical hole surfaces.

Tool containment boundary calculation

Tool containment boundaries are often used in CAM programs to restrict the toolpaths to a particular region; a task typically done manually by the user, but automically in this work. With the new color model approach of this work, feature information is passed along and therefore machining toolpath strategies can be separately designed for planar surfaces and cylindrical holes. If for example, we wish to machine a planar surface, either orthogonally or peripherally, the appropriate containment boundary is needed. For planar surfaces orthogonal milling, the tool containment boundary needs to be calculated according to the projection of the target surface onto the tool plane(Heidrich 2005), as shown in Figure 3-16a.

First, all the triangles of planar surface will be projected to the tool plane and the outer loop boundary of the projection can be found (red polygon in Figure 3-14b). Since the triangle mesh model is just an approximation of the surface, the size of the boundary may be smaller than the actual geometry, therefore we offset the red polygon to the maximum chord value of the triangle mesh model for compensation, generating a new loop (blue). In the case of orthogonal milling, this new offset polygonal loop will be the tool containment boundary for the center of the tool.

If peripheral milling; however, the tool containment boundary must be calculated differently. For peripheral milling, the projection of the planar surface to the cutting plane will degenerate to a zero-area polygonal line. In this case, a line fitting through the projected vertices is first calculated, from which a rectangular tool containment boundary will be generated. We assume that the fitted line is defined by two points *Pa*, *Pb*, the normal of this planar surface is *N*, the machining allowance on this surface is *t* and the diameter of the selected tool is *D*. The four points of the rectangular tool containment boundary is shown in Figure 3-15 and calculated as the follows:



(a) Projecting target surface onto tool plane

(b) Finding the outer loop boundary and offsetting

Figure 3-14 Tool containment boundary for orthogonal milling of plane

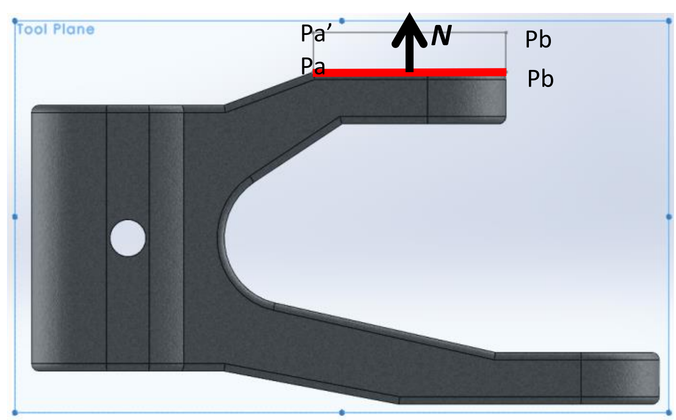


Figure 3-13 Containment boundary peripherally milled plane

$$P_a{}' = P_a + \boldsymbol{N} \cdot (t + \frac{D}{2} + \Delta)$$

$$P_b{}' = P_b + \boldsymbol{N} \cdot (t + \frac{D}{2} + \Delta)$$

Note that theoretically, Δ should be zero. In practice Δ is set to a constant small value obtained from trial and error (0.01 inches in the practice) to compensate for any inaccuracy of the data in this process. The influence of value of Δ on the machining process for CNC-RP_{Hybrid} is trivial, as it simply ensures adequate access of the tool to the surface, even in the presence of small errors in tessellation.

Similar to planar surface features, tool path planning for cylindrical holes depends on the parametric information that is extracted from the color model approach. Parametric information for cylindrical holes includes a pair of center points (PointA, PointB) and a radius (R). Drilling toolpaths and helical milling finishing toolpaths can be created from the parametric information directly, with no need for tool containment boundaries. Either a canned drilling or helical milling process is deployed in the current software.

After the aforementioned steps, beginning with model coloring and axis selection through containment boundaries, all CNC process planning parameters (setup orientation, depth, tool containment boundary) are calculated. In a manual machining process planning session, this is where the user would be finished with decision making and parameter selection, and it would be time to execute the actual cutter location data calculation within the CAM system. In CNC-RP_{Hybrid}, the entirety of the process is automated from CAD input to NC code posting for machining. The following section will provide implementation and testing examples.

Implementation and Tests

The methods presented are implemented in a C++ program which is available as an installable toolbar within the MasterCAM software package and has been tested on metal AM components. The part in Figure 3-16 was manufactured through Electron Beam Melting (EBM) in Ti-6Al-4V with a machining allowance of 0.05 inches (1.27 millimeter), while CNC milling was conducted on a HAAS VF2ss.

Example toolpaths for planar and cylindrical surfaces within MasterCAM are shown in Figure 3-17. Recall, the colored feature mesh model is used extensively for analysis and

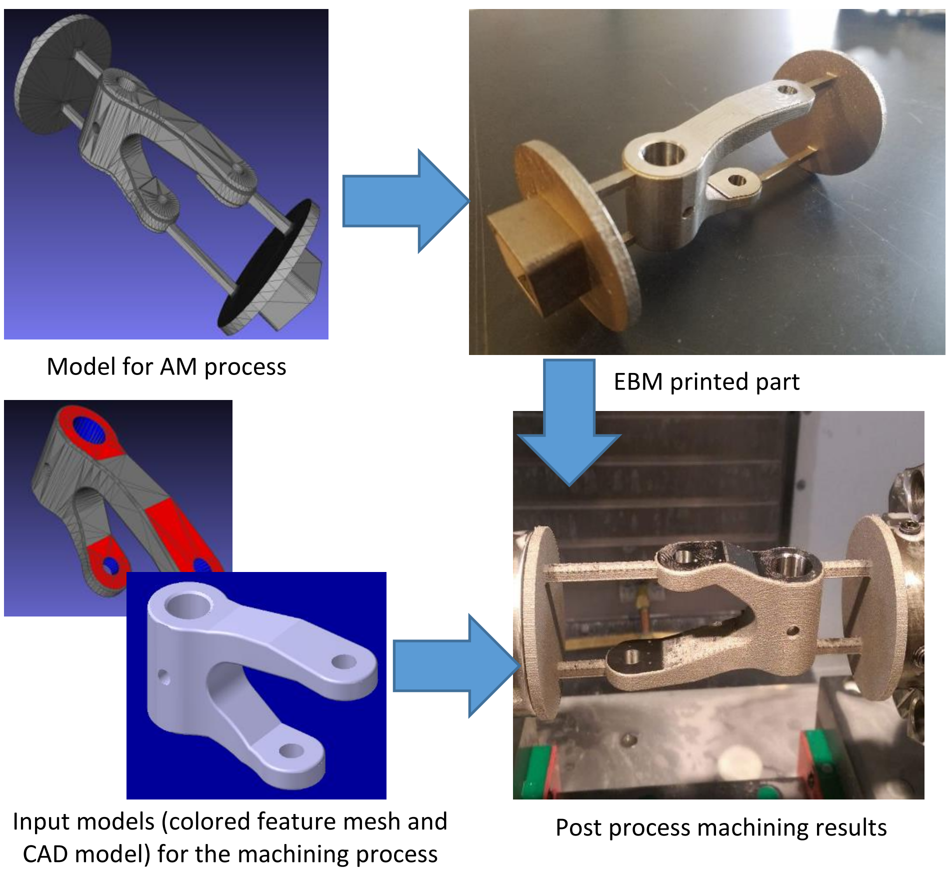
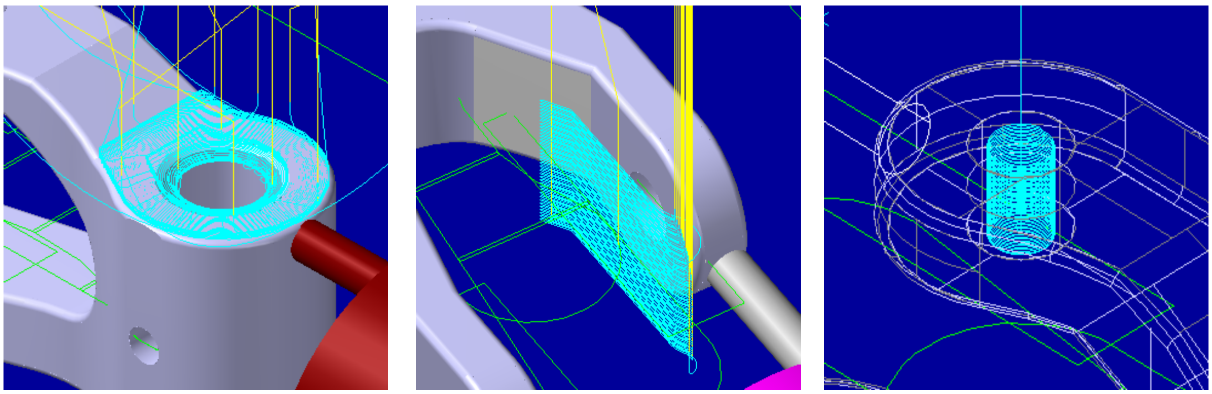


Figure 3-15 Test part, showing model for AM with supports and fixtures, as printed part, color feature-indicating model, and final machined part between centers

process planning; however, all toolpath generation is done on the native CAD file in the CAM package. Hence, the accuracy of the machining process is not inherently different than conventional NC programming; at least not due to model input.



(a) Orthogonal milling toolpath (b) Peripheral milling toolpath (c) Helical milling toolpath

Figure 3-16 Machining toolpath for surface finishing

Dimensional Analysis

A dimensional inspection was conducted for the machined example part using a ZEISS Calypso™ CMM. The as-designed dimensions are given in Figure 3-18 and inspection results for a selected set of features are provided in Table 3-1. The results show reasonable accuracy for a machining process, with maximum deviation on the order of 0.0038 inch (0.09mm).

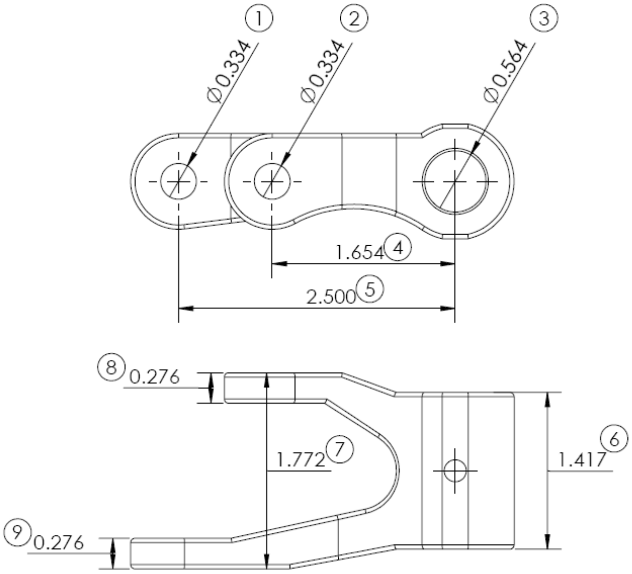


Figure 3-17 Example part basic dimensions (inches)

Table 3-1 Inspected Dimensions (Unit: inches)

Features	Inspected Dimension	Deviation
1	0.3378	0.0038
2	0.3374	0.0034
3	0.5646	0.0006
4	1.6529	0.0011
5	2.4992	0.0008
6	1.4184	0.0014
7	1.7723	0.0003
8	0.2767	0.0007
9	0.2758	0.0002

Process performance comparison

The proposed method takes the advantages of an AM process to create a near net shape model, greatly reducing the volume of material removed, as compared to machining alone. In the previous example part, the material removal volume is reduced from ~8 $inch^3$ (from round stock) to less than 0.4 $inch^3$ (Table 3-2).

Table 3-2 . Material removal volume comparison (Unit: inch3)

Original Part volume	Bounding Cylinder Stock (2-inch diameter)		Bounding Box Stock		Hybrid AM Stock (0.05 machining allowance)	
	Stock Volume	Material Removal volume	Stock Volume	Material Removal volume	Stock Volume	Material Removal volume
1.898	10.884	8.405	6.361	4.463	2.215	0.317

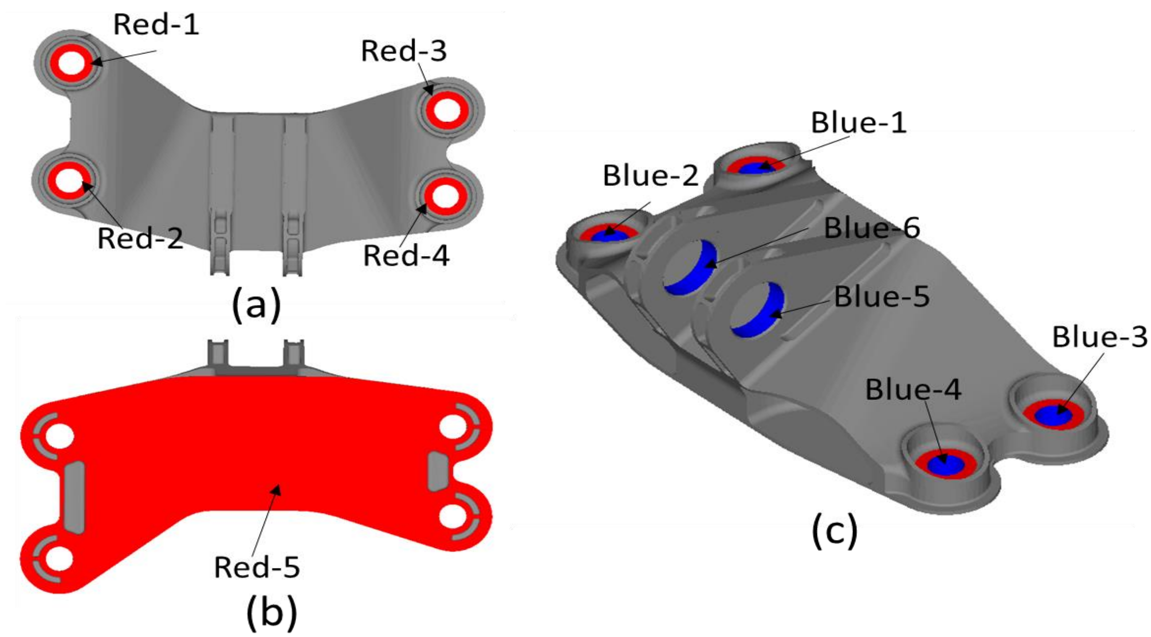


Figure 3-18 GE engine bracket with critical features; (a) Top view, (b) Bottom view, (c) Isometric view.

An additional example is a GE bracket challenge component; a part designed for additive manufacturing, but also including critical features that would likely require post process machining. For example purposes, the colored surfaces are proposed as critical for this trial (Figure 3-19).

The calculated rotation axis for complete coverage of features is shown in Figure 3-20. Given this axis, the calculated orientations with minimum cutting depths at selected orientations is given in Table 3-3.

Table 3-3 GE bracket machining orientations (angle about a-axis) and max depth calculated (Unit: inch)

Feature	Angle	Visible	Max depth	Angle	Visible	Max depth	Angle	Visible	Max depth
Red_1	270	Yes	2.15	180	No	NA	0	No	NA
Red_2	270	Yes	2.15	180	No	NA	0	No	NA
Red_3	270	Yes	2.15	180	No	NA	0	No	NA
Red_4	270	Yes	2.15	180	No	NA	0	No	NA
Red_5	90	Yes	0.02	0	Yes	7.00	180	Yes	7.00
Blue_1	90	Yes	0.31	270	Yes	2.46	NA	NA	NA
Blue_2	90	Yes	0.31	270	Yes	2.46	NA	NA	NA
Blue_3	90	Yes	0.31	270	Yes	2.46	NA	NA	NA
Blue_4	90	Yes	0.31	270	Yes	2.46	NA	NA	NA
Blue_5	0	Yes	3.06	180	Yes	4.19	NA	NA	NA
Blue_6	180	Yes	3.06	0	Yes	4.19	NA	NA	NA

In this example, the material removal volume is reduced from ~208 inch^3(from round stock) to less than 1 inch^3, as shown in Table 3-4. Similarly, the machined surface area reduced from 121 inch^2 to 19 inch^2, which is only the area of the critical machining features.

Table 3-4 Table 4. Material removal volume comparison (Unit: inch3)

<table>
<tr><th rowspan="2">Original Part volume</th><th>Round Stock (8-inch dia.)</th><th>Bounding Box Stock</th><th colspan="5">Hybrid AM Stock
(0.05 machining allowance)</th></tr>
<tr><td colspan="2">Stock Volume</td><td>Material Removal volume</td><td>Stock Volume</td><td>Material Removal volume</td><td>Stock Volume</td><td>Material Removal volume</td></tr>
<tr><td>4.681</td><td colspan="2">213.628</td><td>208.947</td><td>73.215</td><td>68.534</td><td>5.631</td><td>0.950</td></tr>
</table>

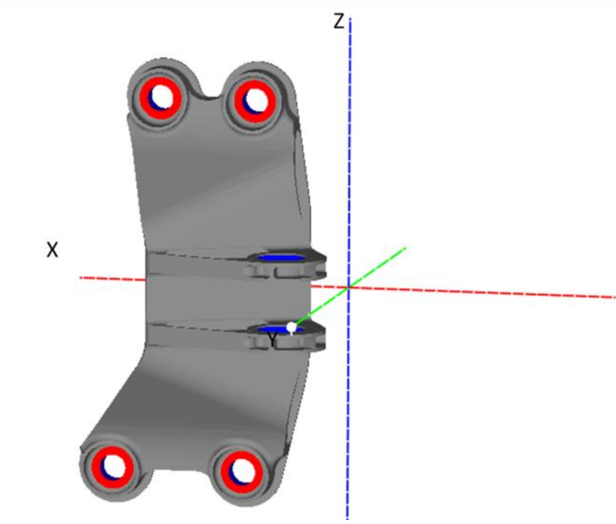


Figure 3-19 GE bracket CNC-RPhybrid machining orientation

Conclusions and future work

This paper presented a new automated post machining process planning method for hybrid additive and subtractive manufacturing. This method targets the production of functional parts that take advantage of additive manufacturing to create complex free form surfaces and CNC milling to improve dimensional accuracy and surface finish on critical features. This approach is advantageous and novel since it uses color triangle mesh model information such that toolpaths will only be created for machining features that have been identified by the user. The process is shown to be largely automated with limited to no human intervention or skill required. The benefit of automation for any CNC process planning would be clear; however it may be more relevant for metal AM part machining. The problem with one-off parts, prototyping or short run production is that one cannot easily absorb the time and expense of creating the NC code, fixtures and stock/setup plans. Initial dimensional analysis is showing accuracy on the order of conventional machining. Satisfying critical GD&T callouts on AM parts truly closes the loop on integrating the capability of AM with machining. Also, compared to previous work on rapid machining of the original CNC-RP, the hybrid approach drastically reduces machined volume overall. This will pay for itself in subsequent time and cost reductions, less waste and tool wear. This paper only details the CAM portion of the process chain, but it also illustrated the entire DASH method through the successful creation of hybrid manufactured steel and titanium industrial components.

CNC-RP_{Hybrid} is based on a typical 3½-axis machining configuration. This configuration provides the convenience from both an algorithmic standpoint in automating the process plan and is also a relatively low cost machine configuration in practice. However, when it comes to increasingly complex machining features, especially those not aligned parallel/perpendicular to machine axes, this configuration would be limited. Having a 5-axis configuration in the future would be beneficial for those non-regular cases, but could still be downwards compatible with 3½-axis configurations. Also, machining feature types considered in this paper are planar surfaces and cylindrical holes. Although planar surfaces and cylindrical holes are some of the most commonly machined surface types, the software and method would need to be expanded to handle freeform geometries, or other analytical surfaces.

The method developed in this paper is targeted at additive and subtractive manufacturing; however, the approach could be extended and applied to other hybrid combinations with machining. Most notably, a similar problem is found in low volume metal castings. One difference would be that we would need to consider draft on part surfaces if conventional pattern tooling (i.e. for sand casting) is used, making it less straightforward to simply add machining allowance. The methods of CNC-RPhybrid presented in this work could allow for this extension to metal castings, but also to other combinations of near-net shape and final finishing operations.

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CHAPTER 4. SUPPORT STRUCTURE REMOVAL FOR HYBRID ADDITIVE AND SUBTRACTIVE MANUFACTURING

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Abstract

For powder bed metal additive manufacturing (AM), additional post-processing for support structure removal is required. However, this removal process is not formally considered during the design of support structures. Therefore, when either manual or CNC milling is required, some support structures may not be easily removed due to tool accessibility. In this research, with STL model as input, tool accessibility is calculated and used to map onto the facets to grow supports that are more amenable to machined removal. It provides a way to combine previous analysis on support layout with additional information to guide suitable setups; ones that consider not only critical angles requiring support but also removability. This work could enable better support designs that will lead to higher throughput of metal AM by reducing effort and expense in post-process machining.

Keywords – Additive manufacturing, Hybrid additive and subtractive manufacturing, tool accessibility, support structure, removal

Literature Review

Support structures are needed in different Additive Manufacturing(AM) processes for a variety of different purposes. In all AM processes, support structures are required for keeping the features in position during fabrication (Gibson et al. 2010). Support structures are required when the critical inclination angle is reached for overhanging geometries (Allen 1994). In powder bed fusion processes, Selective Laser Melting(SLM) for example, support structures are needed for fixing the features to prevent potential warping caused by residual stresses from the rapid solidification of molten metal (Mumtaz et al. 2011). As for Electron Beam Melting(EBM), the support structures also improve thermal and electrical conductivity (Gibson et al. 2010; Harryson & Cormier 2003; Dinwiddie et al. 2013). Since support structures are not part of the final geometry to be created, they need to be removed; a process that requires significant extra time and effort. Even when removal is easy, the surface quality of the part at support attachments can be diminished.

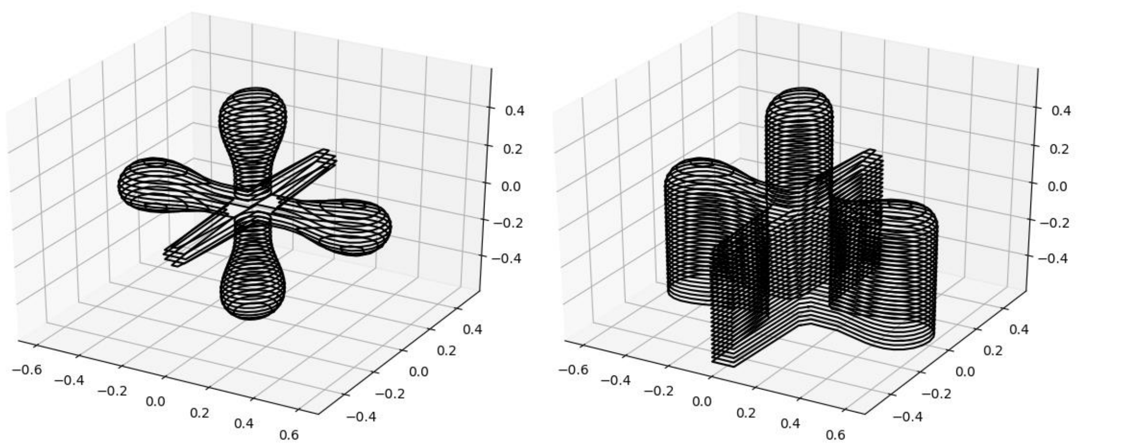
Researchers have developed many methods to alleviate this support structure issue, and some of the methods are widely used in commercial AM systems. One approach is using a secondary dissolvable material for building the support structure. After the part is fully printed, the part is removed from the building tray and moved to a bath and sometimes mechanical vibration and heating to accelerate the dissolving process. A representative example would be the *WaterWorks*™ solutions developed by *Stratasys*. A similar dissolving approach has been proposed for directed energy deposition(DED) systems(Hildreth et al. 2016). From the same research, it can be observed that, with DED printing, multi material metal printing is applicable, but the boundary between the base metal and support metal cannot be controlled well which leads to poor surface quality after the metal support is dissolved. Moreover, with stronger materials like metals, the support removal effort increases dramatically over polymer. However, in full melt metal powder bed fusion processes, support structures cannot be readily built with a secondary material. To overcome this challenge, a recent research has shown an approach to dissolve support structures after a carburization process(Lefky et al. 2017). This approach is promising but it still faces various challenges such as long etching time, partially etched geometry, environmental issue, and application to multiple materials. Another common approach is to optimize the build orientation and design of the support structures in order to minimize the volume of supports (Strano et al. 2013; Cloots et al. 2013; Vanek et al. 2014). Although minimizing the volume of the supports is important for AM process planning, none of the previous research has taken support removal into consideration, which can potentially lead to difficulties in post processing.

In this research, a geometric analysis method is proposed in order to optimize the build orientation for AM processes to facilitate support structure removal. This method can be further utilized for hybrid additive and subtractive process planning for automated support removal.

Methods

For an AM process, the building orientation determines which surfaces the support structures need to be grown on. In this work, considering the removability of the support structure geometry is essentially considering tool accessibility of the surface that the support structure is grown on. For example, a surface that has low tool accessibility will need a small diameter tool to access the surface, making it less desirable to have supports attached. Tool accessibility is calculated for each facet, and the optimal AM building orientation for support structure removal is calculated based on the tool accessibility. In this research, an STereoLithography(STL) file is used as input data to represents the part geometry, the AM processes considered are SLM and EBM, post processing is assumed to be via CNC milling with a flat end milling tool.

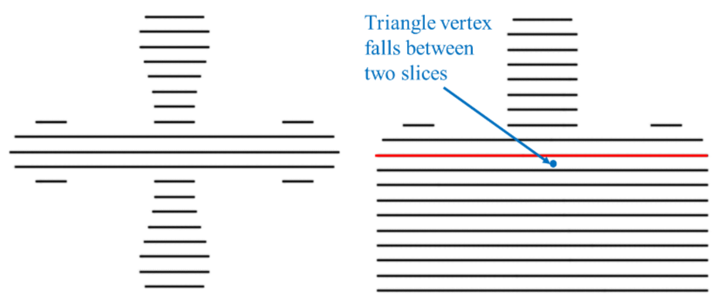
Tool accessibility calculation



(a) (b)

Figure 4-2 Tool orientation consideration (a) Slice Model and (b) Effective Slice Model

The tool diameter in a milling operation affects the machining time and cost. The larger the diameter of the tool used in a milling operation, the shorter the machining time tends to be (Chang & Wysk 1997; Yang & Han 1999). In CNC milling, the tool accessibility of a design determines if the surface can be machined with the available tools and the maximum diameter tool that can machine the surface. Tool accessibility can be calculated based on the selection of a set of tool approach orientations and tool diameters. Existing research used different geometry models for calculating the tool accessibility. Non-Uniform Rational B-Splines(NURBS) surfaces were



(a) (b)

Figure 4-1 Effective slice for accessibility calculation (side view) a. slice model, b. Effective slice model utilized by Lee and Chang in their research to calculate global tool interference for its control polygon convex hull property (Lee & Chang 1995). Slice models were used in D'Souza's tool sequence selection research for approximating free-form pocket geometries(D'Souza et al. 2004). Voxel model based geometries were employed in Balabokhin and Tarbutton's research to represent part and tools (Balabokhin & Tarbutton 2017). In this research, the STereoLithography(STL) file is used as input for the part geometry for the convenience of calculation.

For a facet on the model, any other facets that are above the facet have the potential interfere with its accessibility.

The tool accessible bound (TAB) is a set of simple polygons on the same plane that bounds the non-accessible area for a tool; the outside of the TAB is accessible for the tool. In the method developed in this research, the model is first sliced along a given tool approach orientation to obtain the slice model as Figure 4-1(a). Then, accumulatively union each slice of the slice in slice model from top to bottom to calculate the effective slice model as Figure 4-1(b). When calculating accessibility, the vertices of the facets are used; where, first, the accessibility of each vertex of the entire model is first calculated. Then, for each facet, its accessibility is set as the lowest accessibility among its three

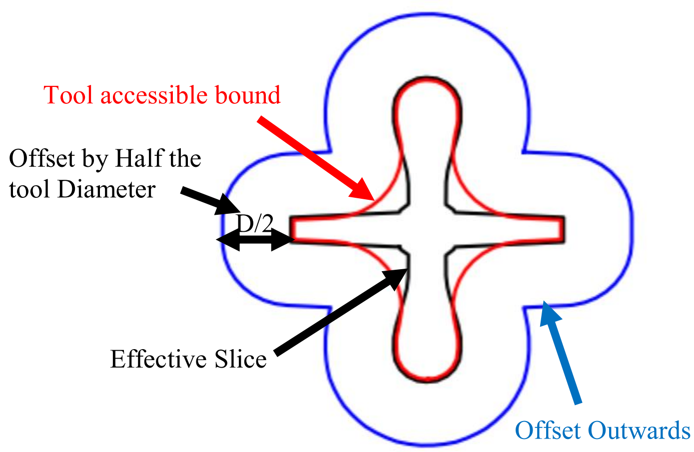


Figure 4-3 Tool diameter consideration Slice(Black), Offset Outwards(Blue), Tool Accessible Boundary(Red)

vertices. For each vertex, the effective slice that is immediately above or passes it will be used for the consequential TAB calculation (Figure 4-2).

By offsetting the effective slice by the tool radius and then offsetting it inward by the radius of the tool, the tool diameter can be taken into consideration (Yang & Han 1999; Lim & Corney 2000) to calculate the tool accessible bound. The effective tool accessible bound for the calculated tool radius would be the area outside the red slice polygon of Figure 4-3. The following sections will present the key steps of tool accessibility calculation.

Slice plane selection

As mentioned, the geometry is sliced along the tool approaching orientation to acquire the geometry sampled for later TAB calculation. Similar to the stair case issues in AM, the choice of slice planes can sometimes affect the quality of the final result. In AM slice strategy, there are many research developed different adaptive slicing method to reduce the error caused by the stair case effect. The slicing method is not the focus of this research.

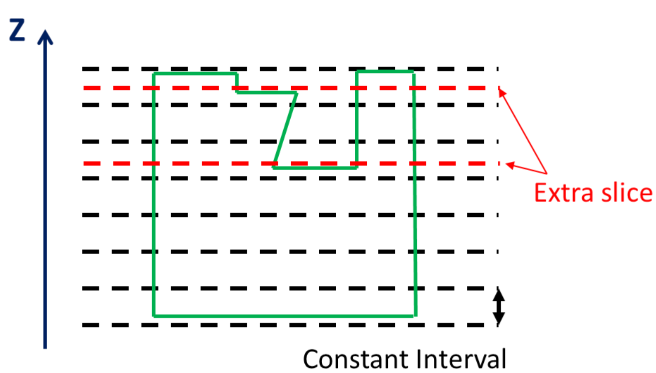


Figure 4-4 Slice plane strategy

In this research, slice planes are selected according to a simple rule which uses the combination of constant interval slicing and extra slices for surfaces that are perpendicular to the Z axis as Figure 4-4 shows. For a surface that is perpendicular to the Z axis, an extra slice at the height that is right above the Z coordinate of the surface at a small value to better sample the geometry for the accessibility calculation. The constant interval in this research is set to 0.5mm.

2D tool configuration space calculation

Once slice planes have been determined for a tool approach orientation, the model geometry can be approximated with the slice model. When considering the accessibility for a vertex, all slices above the vertex will be the potential obstacles that hinder accessibility since CNC milling is a top to bottom process for each setup. The following calculation which takes the intersection of all the TABs calculated from each slice above the vertex can be conducted to calculate the TAB for the vertex.

$$TAB_v = \bigcap_{i=0}^{n} TAB_v(\, S_i) \qquad (1)$$

In which, TAB_v represents the overall TAB for a vertex, $S = \{S_0, S_1, \dots, S_{n-1}, S_n\}$ represents the slices that are above this vertex, $TAB_v(\, S_i)$ represents the TAB for a vertex if only slice S_i is considered.

The next step is to calculate $TAB_v(\, S_i)$. For a given slice geometry, the calculation of the TAB for a milling tool can be regarded as a 3 degree of freedom(DOF) Configuration Space(C-Space) calculation problem, which considers X-Y motion and a rotation. In this case, since the cross section of the milling tool is a circle, this C-Space calculation problem can be further brought down to a 2 DOF problem with only X - Y motion. The C-Obstacle represents the infeasible motion region of the milling tool. This infeasible motion region of the center of the milling tool can be calculated through Minkowski sum of the slice geometry and a circle (Tl) centered at the original coordinate point with a diameter of half that of the milling tool as Figure 4-5 shows. Next, considering the region that the cutting flute of the milling tool can touch, the infeasible region of the tool can be calculated through Minkowski difference between the previously calculated region and Tl as Figure 4-6 shows. The infeasible region is bounded by TAB. The entire calculation can be written in the form:

$$TAB_v(S_i) = (S_i \oplus Tl) \ominus Tl \qquad (2)$$

Substituting $TAB_v(S_i)$ in equation (1) with equation (2), the following is used to calculate TAB_v :

$$TAB_v = \bigcap_{i=0}^{n} ((S_i \oplus Tl) \ominus Tl) \qquad (3)$$

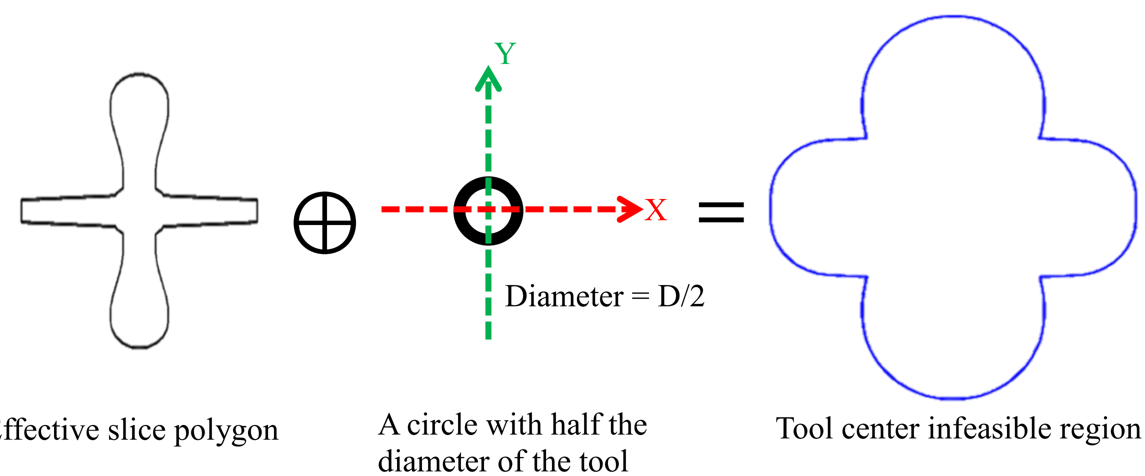
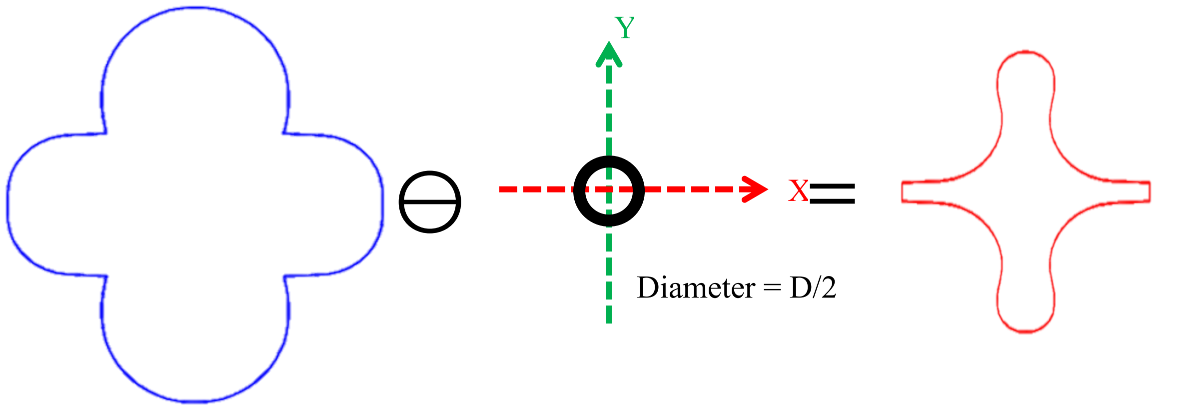


Figure 4-5 Tool center infeasible region calculation



Tool center infeasible region

A circle with half the diameter of the tool

Tool accessible boundary

Figure 4-6 Tool accessible boundary calculation

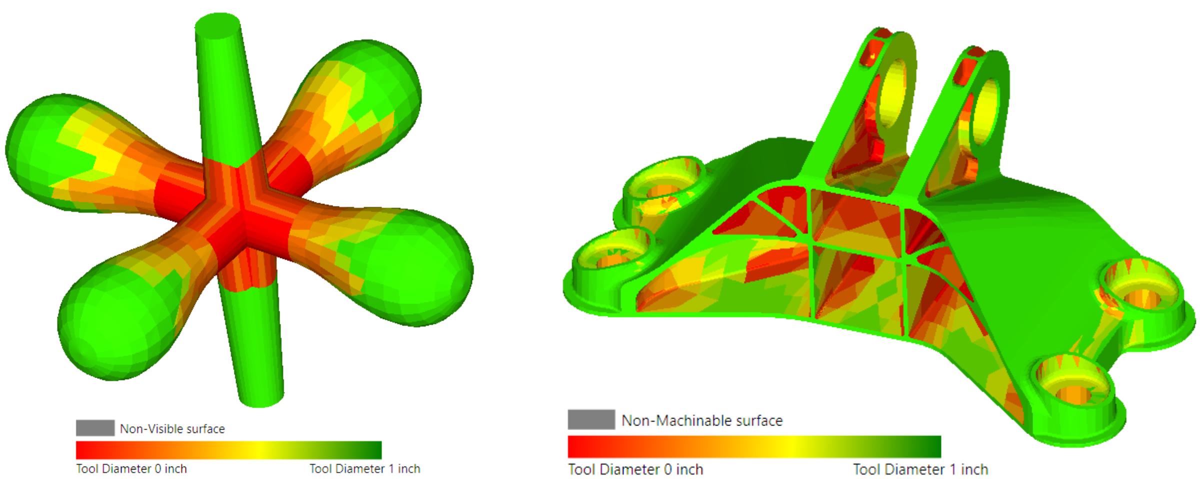
Furthermore, equation (3) can be written as:

$$TAB_v = \left(\bigcap_{i=0}^{n}(S_i) \oplus Tl\right) \ominus Tl \qquad (4)$$

Equation (4) provides theoretical support for the accumulative union of slices from top to bottom to calculate the effective slice, and to use the effective slice to calculate the tool center infeasible region and further, the tool accessible region.

Tool accessibility calculation and mapping for each facet

The tool accessible bound ($TAB_{z,d}$) is calculated for all sampled z-heights(z) and for all tool diameters(d) that are taken into consideration. The tool accessibility for each facet can be calculated by comparing the projection of the facet and the $TAB_{z,d}$. The tool accessibility mapping results for a toy Jack and GE engine bracket example are given in Figure 4-7 (a) and (b), respectively. These maps show a tool diameter range from 0 to 25.4 mm with an interval of 3.175 mm.

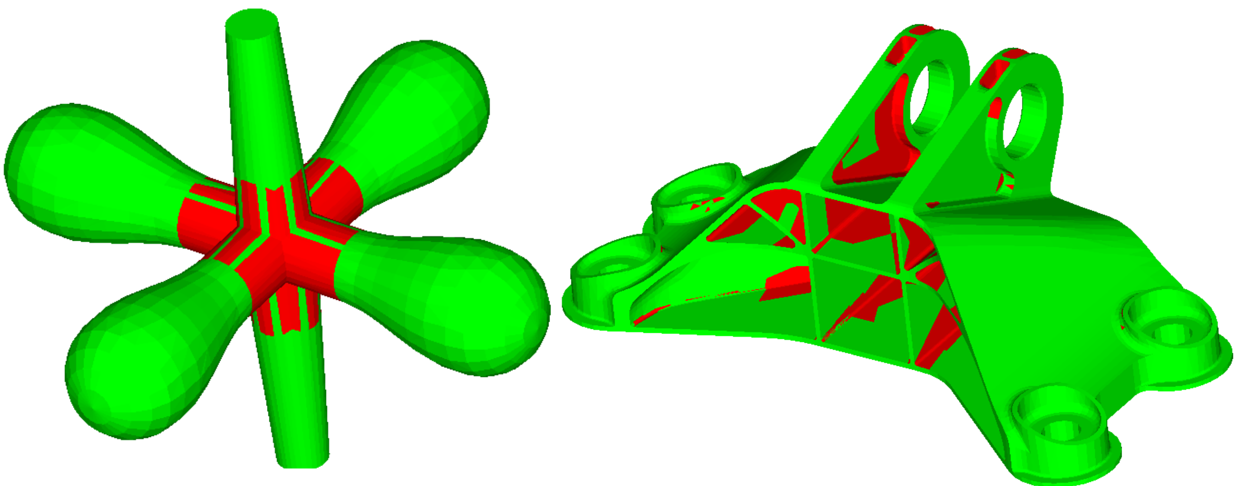


(a) (b)

Figure 4-7 Tool accessibility map (a) Jack and (b) GE Engine Bracket

AM orientation optimization for support removal

For facets that require a tool diameter deemed too small, that diameter threshold can be set for a given part map. For example, when the threshold is set to be 6.35mm tool diameter, the tool accessibility map can be converted to a binary color map as shown in Figure 4-8.



(a) (b)

Figure 4-8 Non-accessible map (6.35 mm tool diameter) (a) Jack and (b) GE Engine Bracket

The surface of a part can be categorized into three types as Figure 4-9 indicates; 1) surfaces that require support structures, 2) surfaces that act as the base for a support structure to grow on, and 3) surfaces that have no support structure contact. In this work, both type 1 and type 2 surfaces are considered equally. By comparing the Non-accessible map and the support surface map, the surface area that both requires supports and at the same time is non-accessible by a machining tool can be calculated and minimized through selecting a proper additive manufacturing set up orientation.

Support surface calculation

The calculation for Type 1 support surfaces is straightforward. The criterion for determining which facets require support structures is the critical inclination angle. For a facet, if the angle between the surface normal and gravity direction is smaller than a presumed critical angle, then it is considered needing support (Allen 1994). As Figure 4-10 indicates, if the angle θ between the normal of the facet and the –Z direction is less than a predefined critical angle, this facet should be marked as a Type 1 support surface.

Type 2 support surfaces are facets that act as the base for support structure growth. There are three characteristics that can be concluded for Type 2 surfaces; 1) that Type 2 surfaces must be facing up (the normal of the surface must have positive Z value), 2) that Type 2 surfaces should be located below the Type 1 surface it is supporting, 3) that Type 2 surfaces overlap with the projection of the Type 1 surface it is supporting. According to these three characteristics, the Type 2 surfaces can be located for each Type 1 surface. However, there is possibility that multiple sets of Type 2 surfaces will be calculated for the same Type

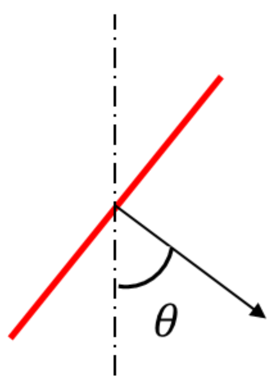


Figure 4-10 Angle between facet normal and -Z direction. (Red line segment represents facet)

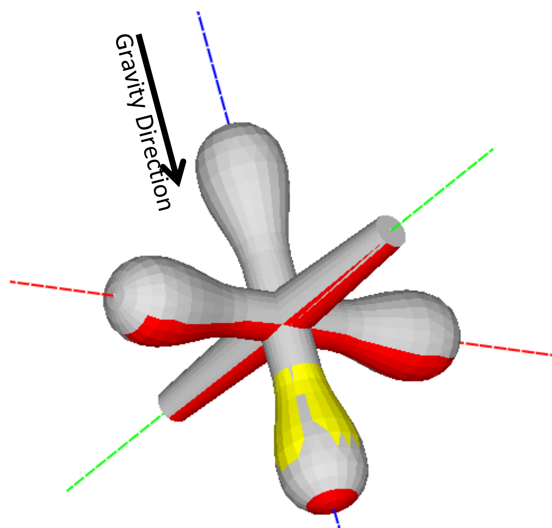


Figure 4-9 Type 1 surface (red), Type 2 surface (yellow), Type 3 surface

1 surface, while only one set of the Type 2 surface is correct. As Figure 4-11 illustrates, the model is represented in 2D side view. For Type 1 surface S_{11}, both Type 2 S_{21} and Type 2

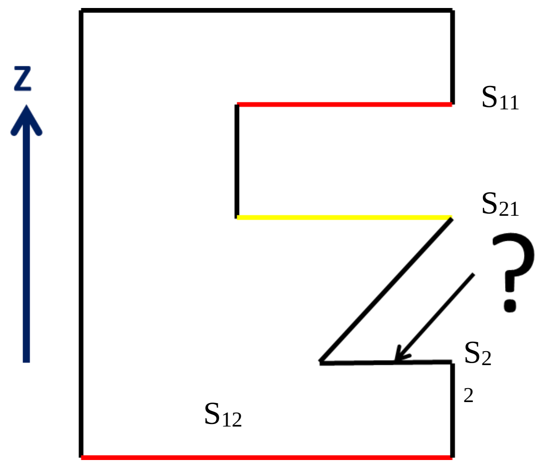


Figure 4-11 Type 2 surface according to Type 1 surface

Algorithm 4-1 FindAMSupportFacets(T, CriticalAngle)

Input: Type 1 Facets(*Type1Facet*) and all facets of the model (*T*)
Output: Type 2 Facets(*Type2Facet*)

```
FOREACH Type1Facet in Type1SupportFacets,
|   FOREACH facet in T
|  |    IF (facet normal z > 0)
|  |   |   IF(facet is below and overlaps with Type1Facet)
|  |   |   |   Mark this facet  checked, and Type2Facet. Initialize an empty eventQue,
    and all the three neighbors of facet to the eventQue.
|  |   |   |    WHILE(eventQue is not empty)
|  |   |   |   |   Set f as last element of eventQue, mark it as checked and delete it
    from the eventQue
|  |   |   |   |   IF(f overlaps with Type1Facet)
|  |   |   |   |   |  Mark f as Type2Facet
|  |   |   |   |   |  FOREACH neighbor_facet of f
|  |   |   |   |   |  |  IF( neighbor_facet is not marked checked AND normal z >
    0)
|  |   |   |   |   |  |       Add neighbor_facet  to the eventQue
|  |   |   |   |   |  |  ENDIF
|  |   |   |   |   |  ENDFOR
|  |   |   |   |   ENDIF
|  |   |   |   END WHILE and Break the FOREACH facet in T loop
|  |   |   ENDIF
|  |   ENDIF
|   ENDFOR
ENDFOR
```

S_{22} will be calculated as support surfaces for Type 1 S_{11}. However, in fact, only Type 2 S_{21} should be the support surface for Type 1 S_{11} surface.

In this research, to avoid cases such a Type 2 S_{22} being calculated as a Type 2 surface, a search algorithm is designed as Algorithm 1 states. First of all, all facets are sorted according to its maximum Z coordinate from top to bottom. Then, for each Type 1 facet, search all facets from top to bottom to find the first facets that is below and up facing; mark as a Type 2 facet. Find all the facets around the first found Type 2 facet that in total would fully cover the Type 1 facet. Mark all of them as Type 2 facet. Proceed to the next Type 1 facet, and repeat the searching steps.

AM orientation calculation

The surfaces that will have support structure grown on change when the build orientation changes. The objective of optimizing the AM build orientation is to minimize the surface area of those regions that both need support AND are deemed non-accessible.

$$Minimize: OverlapArea(\theta) = \sum_{i=1}^{n} Area(facet_i) \cdot \alpha_i \cdot \beta_i$$

Where:

$\boldsymbol{\theta}$: *AM build orientation*
$\boldsymbol{i}$: *facet index*
$\boldsymbol{\alpha_i}$: *A binary indicator for tool accessibility, set to* 1 *if the facet is not accessible,* 0 *if it is accessible*
$\boldsymbol{\beta_i}$: *A binary indicator for support structure, set to* 1 *if the facet has support structure,* 0 *if the facet has no support structure*

With a recalculated non-accessible map, the α_i can be obtained for each facet. For any given AM building orientation, β_i can be obtained through the algorithm described in section 3.2.1. Given a set of AM building orientation candidates, the OverlapArea for each orientation can be calculated and compared. The best AM building orientation with the most removable support structures can be found.

Results and Discussion

Two example parts are used to illustrate the method developed in this work. The bounding box of the Jack is $30.480 \times 30.480 \times 25.400\ mm$ and the GE Engine Bracket is $178.000 \times 62.500 \times 108.000\ mm$; as measured in X-0 orientation. The critical inclination angle used to calculate support-requiring surfaces was 39°, and a total of 18 build orientations were evaluated. The results for the Jack and GE Engine bracket are given in Tables 4-1 and 4-2, respectively.

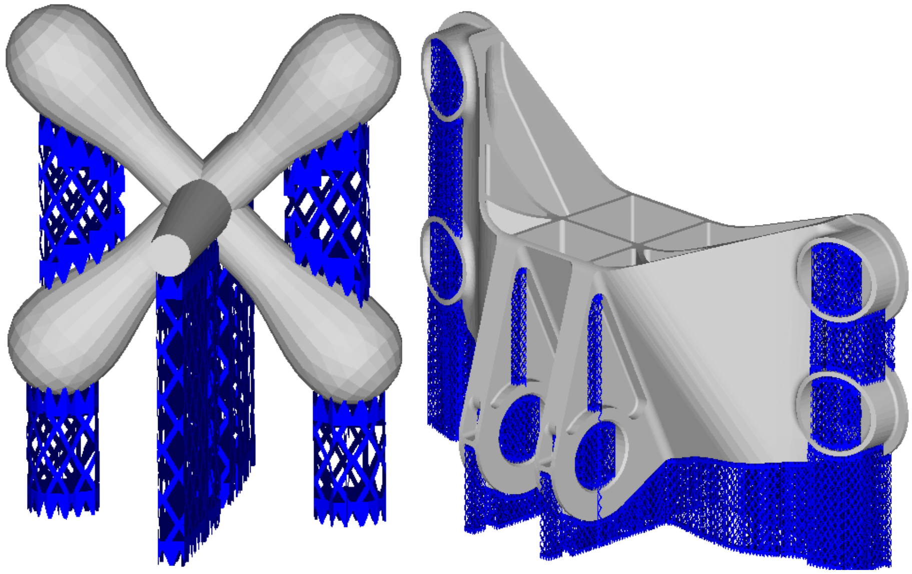
Table 4-1 Overlap areas for Jack model (red colored rows are redundant)

ORIENTATIONS	AREA(MM^2)	ORIENTATIONS	AREA(MM^2)
X-0	8.115	**y-180**	11.454
X-45	9.504	**y-225**	9.488
X-90	20.746	**y-270**	20.736
X-135	10.383	**y-315**	9.503
X-180	11.454	**z-0**	20.746
X-225	9.963	**z-45**	4.578
X-270	21.082	**z-90**	20.794
X-315	9.504	**z-135**	5.592
Y-0	8.115	**z-180**	21.082
Y-45	9.507	**z-225**	4.874
Y-90	20.794	**z-270**	20.736
Y-135	9.316	**z-315**	5.596

Table 4-2 Overlap areas for GE Engine Bracket model (red colored rows are redundant)

ORIENTATIONS	AREA(MM^2)	ORIENTATIONS	AREA(MM^2)
X-0	1229.069	**y-180**	2215.912
X-45	2861.059	**y-225**	3608.825
X-90	8047.597	**y-270**	8624.499
X-135	5422.118	**y-315**	2504.137
X-180	2215.912	**z-0**	8047.597
X-225	2344.834	**z-45**	6552.568
X-270	8648.692	**z-90**	7625.146
X-315	1402.075	**z-135**	4887.713
Y-0	1229.069	**z-180**	8648.692
Y-45	2208.854	**z-225**	4996.274
Y-90	7625.146	**z-270**	8624.499
Y-135	4082.334	**z-315**	6735.083

Across the 18 tested building orientations, the optimal orientation to facilitate support removal for the Jack model and the GE Engine Bracket model is a rotation about Z axis 45° with a minimum overlap area of 4.578 mm^2 and about X axis 0° with a minimum overlap area of 1291.268 mm^2. The two parts in the suggested building orientations are shown in Figure 4-12.



(a) (b)

Figure 4-12 Optimized build orientation (a) Jack and (b) GE Engine

Finally, an additional v-block part example is tested to demonstrate how the proposed tool accessibility criterion can be considered as compared to other build criterion, namely, for minimizing build height and for minimizing overall support structure volume. For this example, the best case (Case 1) for minimizing overall support volume is shown in Figure 4-13. However, if minimizing z-height has the highest priority, the part could be given either of the two orientations in Figure 4-14. Data for all 3 cases are given in Table 4-3. In all cases, minimum inclination angle was 39 degrees and the part bottom was set to 3mm above the build plate for calculating the support volume.

For Case 1, since there is no support, it will also be optimum for the tool accessibility for support removal criterion; making the proposed calculations moot. However, for the latter 2 cases, the proposed tool accessibility provides a clear choice of orientation 3 for tool accessibility, even though support structure volume for Case 2 is less (2590 mm^3 versus 4740mm^3). That is, assuming a minimum tool diameter of 6.35 mm, all the support structure in Case 3 can be removed, but Case 2 has a total of 1239.630 mm^2 non-accessible area. Regardless, the selection of build orientation is complex, and there is perhaps not a clear choice across all factors; however, the proposed method provides yet another criterion to factor into the decision.

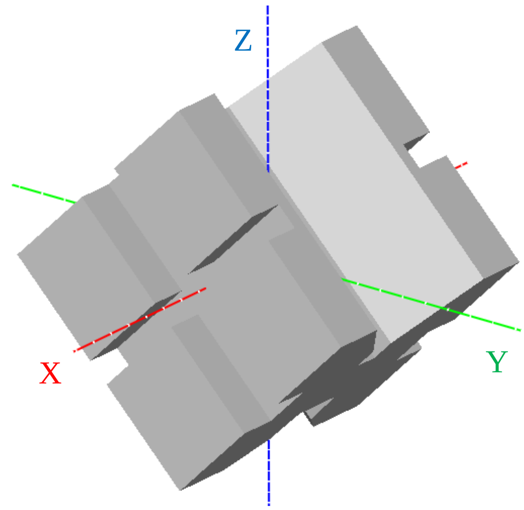


Figure 4-13 Best case for minimum support volume (Case 1)

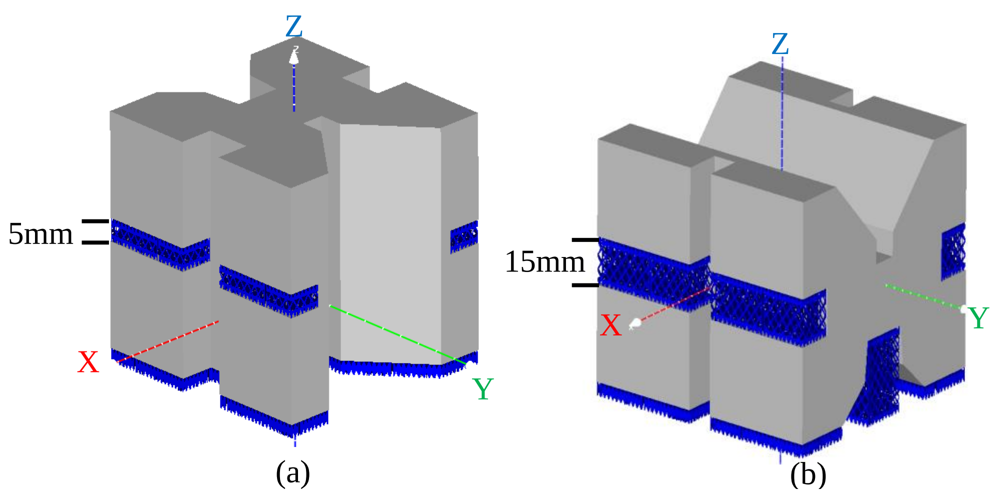


Figure 4-14 Two possible orientations with Z-height as priority

Table 4-3 AM building orientation selection comparison (red colored as optimum case)

DATA OF COMPARISON	CASE1	CASE2	CASE3
Z-HEIGHT(MM)	71.842	50.800	50.800
SUPPORT STRUCTURE VOLUME(MM^3)	0.000	2590.000	4740.000
OVERLAP AREA FOR TOOL ACCESSIBILITY(MM^2)	0.000	1239.630	0.000

In closure, the results calculated using the proposed method provides a new consideration to the idea of an optimized choice of build orientation. This method may offer a new perspective of designing for hybrid additive/subtractive manufacturing that allows for considering the challenging post-processing required for most metal AM technologies today.

Taking a further step from this research, support structure removal planning can be conducted. The largest tool diameter, a proper setup or tool approach orientation, tool length and tool containment boundaries can be calculated based on the tool accessibility map and the support-requiring surfaces. Subsequent research problems such as fixturing design under a multi-axis machine configuration, and a mixed design for both AM support structures and machining fixturing will be topics of future research.

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CHAPTER 5. PROCESS PLANNING FOR HYBRID ADDITIVE AND SUBTRACTIVE MANUFACTURING TO INTEGRATE MACHINING AND DIRECT ENERGY DEPOSITION

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Abstract

This paper presents a new hybrid additive and subtractive manufacturing method to integrate process planning considerations. This method could offer a new solution to deliver parts in a timely manner, minimizing inventory and material waste. The method essentially incorporates the base plate of additive manufacture into a final additive/subtractive manufactured product. Manufacturing begins with a base plate, where a set of subtractive steps will first create a portion of the design geometry. Next, the additive manufacturing process will be planned to create geometry on the machined base plate in two opposite directions, to minimize support structure and build height. Finally, a secondary machining process is planned to produce finished surfaces on the additively manufactured near net shape geometry. The work is implemented in the form of planning algorithms that integrate the aforementioned subtractive and additive process planning stages.

Keywords – Additive manufacturing, Hybrid additive and subtractive manufacturing, Direct Digital Manufacturing, process planning

Introduction

As the paradigm for manufacturing evolves toward customization and personalization, custom and spare part supply is becoming a more critical business challenge (Suomala et al. 2002). Considering a set of situations that may require spare parts; agricultural equipment used for time-critical harvest or that is far from its service location, a navy vessel on the open ocean, or even a spacecraft or station, having an inventory of spare part is strictly limited by volume, weight and/or cost to maintain. There could be thousands of parts that may require replacement during the system's lifetime, and it would be both costly and unrealistic to have an inventory of all spare parts on site, and to deliver the part from a warehouse to the site could be days, weeks or longer.

There are different approaches to reduce the cost of spare part inventory such as improving management (Gajpal et al. 1994; Government Accountability Office 2008) or optimizing the logistics (Huiskonen 2001), etc. Other than optimizing the spare part supply through supply chain and logistics management, another promising approach is on-demand manufacturing. In on-demand manufacturing, Additive Manufacturing(AM) has shown great potential of producing parts in low volume at low cost, and the flexibility for manufacturing different parts (Khajavi et al. 2014). AM is deemed as the manufacturing method that is closest to Direct Digital Manufacturing (DDM); the terms AM and DDM are often intermixed. DDM has been envisioned to be the solution for parts-on-demand for the maintenance of broken or worn parts for the Navy (Frazier 2010) and is considered a technology that will revolutionize the aerospace industry by improving the spare parts supply chain (Liu et al. 2014).

In most AM processes, the build plate is a critical component where all material is deposited. The functions of the build plate span a variety of purposes, from fixturing and support to heat and electric conduction for a successful AM build. It can be argued that an analog of the AM build plate in CNC machining would be the starting stock material. However, unlike the machining stock, the AM build plate is not part of the final geometry. Since AM is a costly process, less AM volume per build may be more economical in some cases. Generally, in metal manufacturing, the raw material per weight for AM (water or gas atomized metal powder) is much more expensive than that for machining (bar stock) and the processing (deposition) times are generally long. Hybrid additive and subtractive manufacturing (Hybrid AM/SM) processes are usually designed to utilize a machining process to post-process finish the additive manufactured part features to achieve better surface quality, which genuinely is a critical aspect of Hybrid AM/SM. However, additive and subtractive can be better integrated such that the advantage of each can be better utilized. Rather than using AM to build the entire near net shape, a more economical approach may be to start with a bar material, then machine it to partially create the final design geometry. This partially made geometry will actually act as the "base plate" for the AM process. As such, an additive step based on the machined geometry at that phase can be use complete the near net shape reminder of the design. Finally, one can machine the AM near net shape geometry to remove support structures and create critical features to achieve designed GD&T. In this manner the advantages of AM and SM can be better exploited. From the AM perspective, the total volume of deposition is reduced by the geometry partially created "in" the base plate. From the SM perspective, since part of the geometry will be created by AM, a relatively smaller size of stock will be required and there will be less volume of material removed. This hybrid approach may be challenging to implement on a current Powder Bed Fusion type AM system. However, with Directed Energy Deposition type AM systems, either Laser Engineered Net Shaping (LENS) or Wire Arc Additive Manufacturing (WAAM), the material can be deposited with a high degree of freedom under 5-axis control, which will be a better initial fit for this approach.

In this research, a new hybrid AM/SM method that better incorporates SM with AM for better manufacturability and economic efficiency is developed for a 5-axis milling and DED type AM hybrid machine configuration. This effort could provide a new approach to automated process planning to deliver custom/spare parts with minimum inventory requirement, material waste, and lead time.

Related Work

This section provides an overview of current Hybrid AM/SM methods, design for Hybrid AM/SM with manufacturability analysis, and approaches for optimizing Hybrid AM/SM process planning.

Hybrid AM/SM methods

New manufacturing processes and equipment have been developed to integrate SM with AM to achieve better manufacturing capability. Shape Deposition Manufacturing was one of the first processes that integrated a machining process with AM (Merz 1994). Later, a Hybrid Layer Manufacturing (HLM) method that retrofitted a MIG/MAG welding head to a three-axis machining center was developed for direct metal tooling (Akula & Karunakaran

2006). The Laser Aided Manufacturing Process (LAMP) is another representative hybrid manufacturing method that integrates Laser-Engineered Net Shaping(LENS) and 5-axis CNC machining (Ruan et al. 2005). Also, related research on developing machining strategies for enhancing surface finish for parts after printing has been conducted (Stucker & Qu 2003).

Manufacturability analysis for Hybrid AM/SM

One major advantage of Hybrid AM/SM over traditional individual manufacturing processes is that it increases the manufacturability of a design by incorporating multiple manufacturing processes. AM has some manufacturing limitations; challenges with sharp corners, thin geometries, need for support structures, and managing accurate build height. At the same time, machining also has limitations, such as internal corners that lead to tool accessibility issues, and significant material removal volumes (Joshi & Anand 2017). Design for Manufacturing (DFM) provides a plausible approach for the planning of Hybrid AM/SM by assisting decisions on the proper manufacturing process for a specific geometry features. In DFM approaches, the part design is divided into multiple modules, and then the manufacturability of each module can be evaluated, so the best manufacturing process can be chosen for each (Kerbrat et al. 2010; Kerbrat et al. 2011).

Process planning for Hybrid AM/SM

In AM process planning, there are multiple parameters such as part orientation, layer thickness, bead overlap, toolpath strategy, temperature, scanning speed, etc. Different parameters will lead to different building capabilities and qualities. One critical parameter that is widely studied for various AM processes is part orientation. Part orientation largely determines parameters such as the build height, part projection area and support structure and it has great influence on surface quality and cost. New methods and algorithms are being developed to optimize part orientation for minimizing support volume, reducing cusp height error, reducing overall cost, and improving geometry tolerance (Alexander et al. 1998; Paul & Anand 2015; Ezair et al. 2015; Zwier & Wits 2016). There are also approaches to more advanced build orientation optimization by using multi-axis (4 and above) control. In those approaches, the part is separated into multiple 3D layers. With 5-axis capability, each 3D layer can be built with an optimized orientation to avoid overhang geometries, and then machining operations are planned for each 3D layer to create a better surface finish (Wu et al. 2017; Ruan et al. 2005).

Methodology

The proposed Hybrid AM/SM process is generally envisioned as shown in Figure 5-1. It starts with a machining setup on a specified size of stock. Then the first set of machining operations will be conducted to partially create the part geometry. After the first set of machining operations, the partially created part will act as the “build plate” for the AM operations. The AM material will be deposited onto the build plate from two orientations to create the remainder of the part geometry in near net shape. Finally, the part is finished with a secondary set of machining operations.

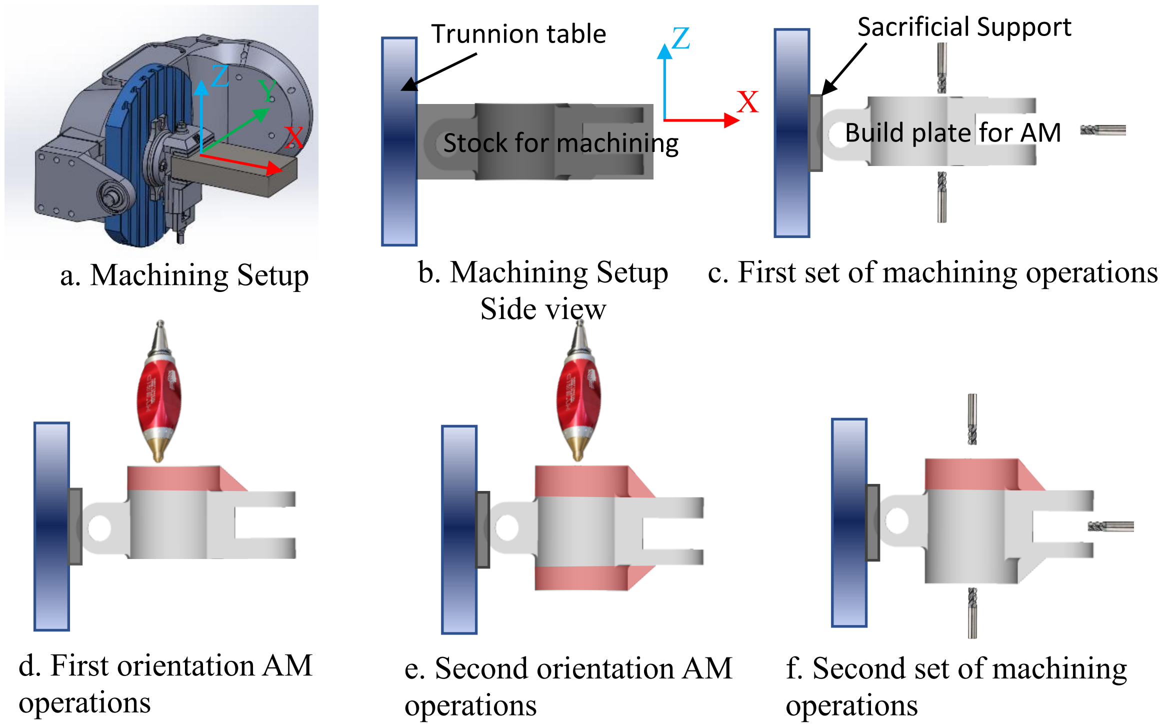
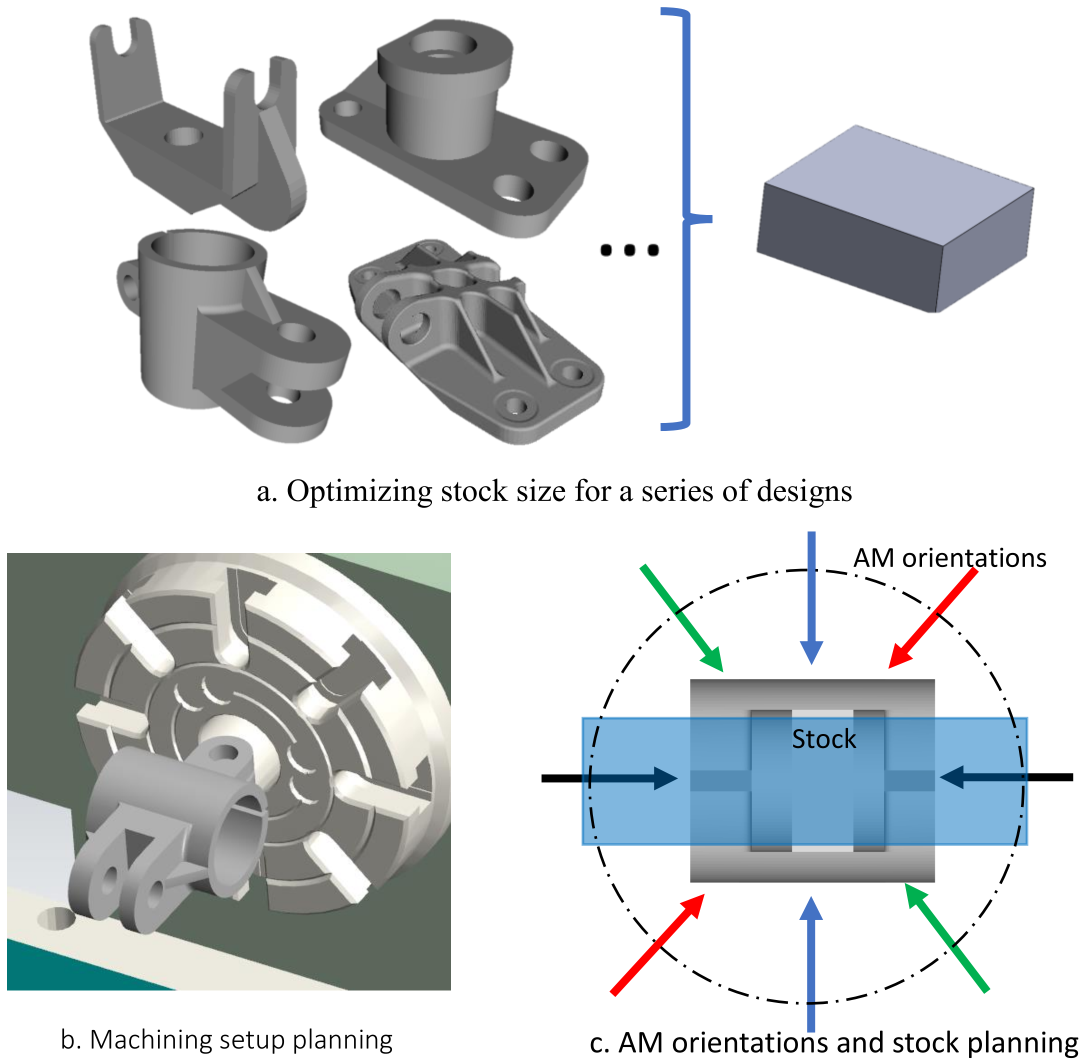


Figure 5-1 Hybrid AM/SM process overview

Note that in this work, the term "stock" is used for all machining operations, and "build plate" is used for all AM operations. "Stock" is commonly used in machining, representing the raw stock material that encloses the final machining geometry. While "build plate" is commonly used in AM, representing the flat plate-shaped geometry that the material is deposited on, which usually is not part of the final geometry. In this proposed Hybrid AM/SM process the "build plate" also represents the geometry that the material is deposited on, but is also the partially created part geometry from the first set of machining operation rather than a conventional flat build plate.

The high level process planning can be summarized in three steps as Figure 5-2 illustrates. The first step is deciding the stock size. For a series of designs that are of similar sizes or share similar features, deciding one size of the stock model that best suits the entire design series (part family), might be an economical advantage. In the second step, planning for the machine setup is conducted. For an individual design from a part family, with a given



a. Optimizing stock size for a series of designs

b. Machining setup planning

c. AM orientations and stock planning

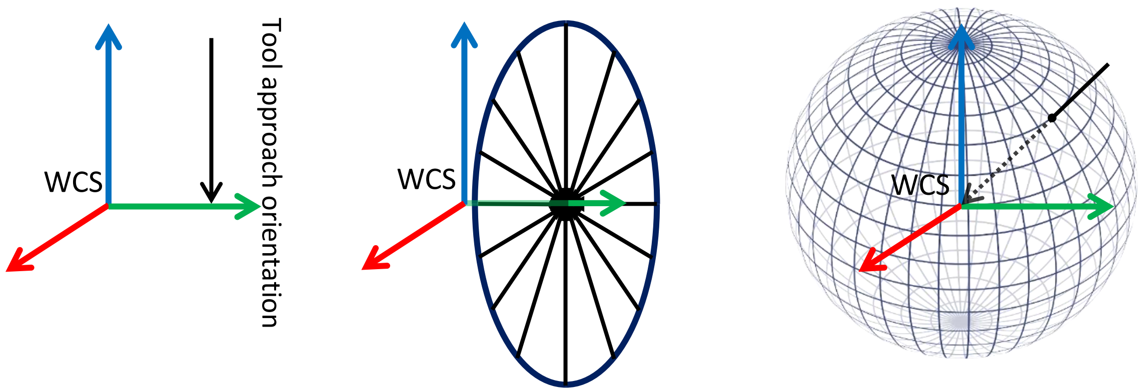
Figure 5-2 Overview of Hybrid AM/SM planning

size of stock, determining a feasible orientation that the part should be placed is critical. In the third step, we need to decide the AM printing orientation(s) and stock location with consideration of AM support structures, overall AM volume, and build height. The first step could be considered more of a production planning problem, and will not be addressed; the second and third manufacturing process planning steps are the focus of this paper. In AM planning, the build orientation(s) could be designed to minimize or even eliminate the need for supports. In the approach proposed here, only two AM orientations that are 180 degrees apart are considered. This two-sided AM approach can potentially reduce the AM height by half. Also, two-sided AM builds could achieve better balance on residual stresses to counter warping and provide better overall heat management (Williams et al. 2016).

Machining setup planning

In CNC milling, the axis number limits the possible orientations the machining tool can access the surface of the part within one fixture setup. As Figure 5-3 illustrates, in a 3-axis machine configuration, the machining tool can only access the part from one orientation. In a 4-axis configuration an additional rotation is added, which enables tool approach angles about a unit circle. Finally, a 5-axis CNC machine configuration technically allows machining tools to approach the part from any orientation from a unit sphere; with fixture collision limits that often reduce it to a hemisphere.

In this research, the approach is based on a 5-axis machine. To be more specific, a 3+2 axes machine configuration is considered, which uses 3 synchronized X,Y,Z axis motion with two asynchronous rotation axes (A and B) to allow more tool approach orientations. When planning for the machine setup, tool accessibility is the essential factor. Tool accessibility can be measured from two aspects, the maximum diameter of the tool that can reach the surface and the minimum tool length required to reach the surface.



a.3-axis b. 4-axis c. 5-axis

Figure 5-3 Tool approach orientation in machines with increasing controllable axes

For a given design, the machining tool accessibility of the surface is determined by two factors: the geometry itself, and the setup orientation for fixturing. In a typical 5 axis configuration with a trunnion table (Figure 5-4), if only considering the fixture setup as obstacles, the trunnion table would block the conical area indicated between the two red dashed lines. If only the part geometry itself is considered, a different accessible range can be obtained as the green dashed lines illustrate. When both factors are considered, if there is overlap between the two accessible ranges then the surface can be accessed in this setup. Otherwise, the surface will not be able to be accessed. When deciding the part setup orientation for fixturing, the most feasible machine setup should ensure better accessibility considering both the fixture and the part geometry itself.

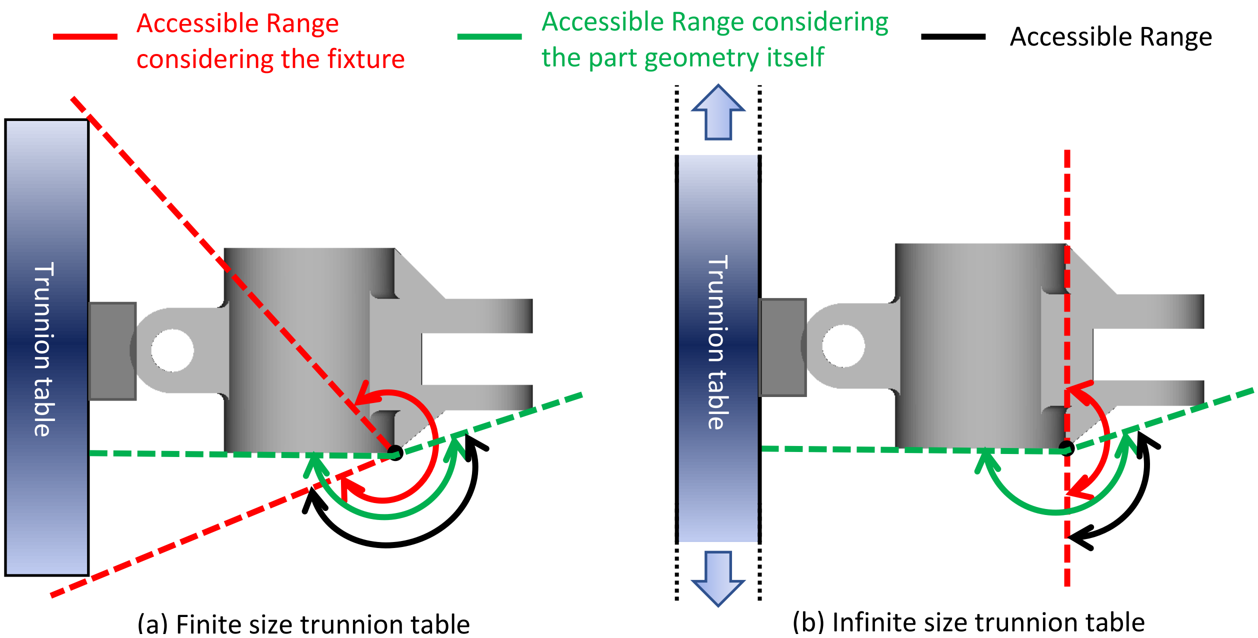


Figure 5-4 Machining setup and tool accessible range

To find a feasible machining setup, one approach is to examine a given set of orientations for accessibility and determine preferred orientation(s) among the given set. In previous research, a tool diameter accessibility measure has been developed for a set of tool sizes and tool approach orientations. When calculating the tool accessibility for a design, the entire spherical space is considered. In machining setup planning, the non-accessible cone created by the fixture (the clamp, trunnion table, etc.) need to be considered. When calculating the accessibility of a point on the part surface, *n* orientations $Orientation_{sphere\ set} = \{\theta_1, \theta_2, \dots, \theta_n\}$ sampled from spererical space, *m* tool diameters $\{d_1, d_2, \dots, d_m\}$, and *k* tool lengths $\{l_1, l_2, \dots, l_k\}$ are considered. For each orientation, the accessible tool sizes can be calculated for this point. The tool diameter accessibility for a point P_i can be represented as $d_i(\theta_j)$, which marks the largest tool that can access this point from orientation θ_j.

As for tool length calculation (Figure 5-5), for a point P_i (green colored dot) on the part surface, the minimum tool length required for accessing this point for a given tool approach orientation is the distance from this point to the 3D convex hull of the part along the approaching orientation. Taking an infinite size trunnion table into consideration, the 3D convex hull needs to be replaced with a waterfall model of the 3D convex hull onto the trunnion table. For each $\theta_j \in \{\theta_1, \theta_2, \ldots, \theta_n\}$, there is a tool length $l_i(\theta_j)$ can be calculated accordingly.

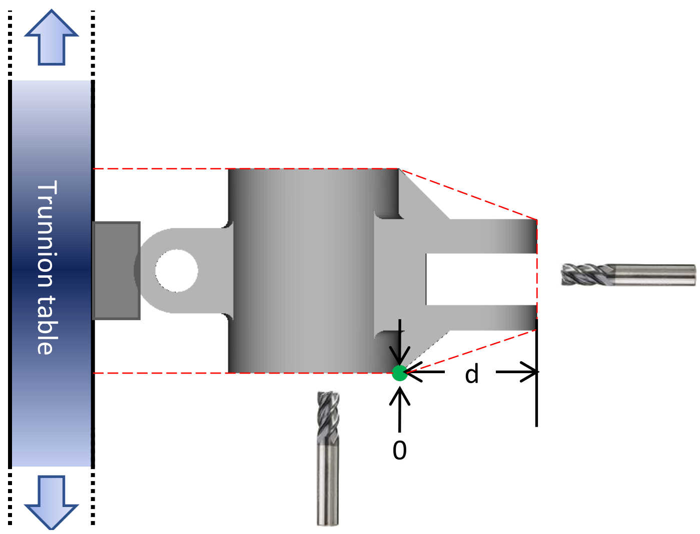


Figure 5-5 Minimum tool length and tool approach orientation

Now, if the non-accessible cone created by the fixture is considered, for a point P_i, the orientations in this non-accessible cone is a subset of the complete orientation set $Orientation_{cone\ set}(P_i) \subset Orientation_{sphere\ set}$. It can be noted that $Orientation_{cone\ set}(P_i)$ is different for each point. In this research, the trunnion table is assumed to be infinite, so the non-accessible cone becomes a fixed hemispherical space for a setup orientation. That case becomes: for each point $Orientation_{cone\ set}(P_i) = Orientation_{hemisphere\ set}$. Now, the tool accessibility measure for all the points on the part surface can be calculated with the same set of orientations. The diameter accessibility measure can be updated as $d_i(\theta_j) : \theta_j \in \{\theta_1, \theta_2, \dots, \theta_n\}, \theta_j \notin Orientation_{hemisphere\ set}$. The length accessibility measure can be updated as $l_i(\theta_j) : \theta_j \in \{\theta_1, \theta_2, \dots, \theta_n\}, \theta_j \notin Orientation_{hemisphere\ set}$.

Having both tool diameter and length accessibility calculated, the machine setup can be evaluated based on tool accessibility. In a milling process, tool deflection is a complex result of tool dimension, shape, flute count, flute shape, RPM, etc. The maximum tool deflection can be modeled as (Kops & Vo 1990; Khorasani et al. 2016).

$$\delta_m = \frac{Fl_e^2(3l - l_e)}{6EI}$$

Where: F is the force applied at l_e distance from the fixed end, l is the tool overhang length, l_e is the effective overhang length, E is the Young's modulus of the tool material, and I is the moment of inertia of the geometry. Here, for a solid cylindrical geometry $I = \pi d^4/64$, where d is the diameter of the tool. If only the tool dimensions, which is determined by tool diameter and length, are considered, the function can be simplified as:

$$\delta_m \propto \frac{l}{d^4}$$

To minimize the tool deflection, ld^{-4} needs to be minimized. From the accessibility point of view, d^4l^{-1} can be used for the tool accessibility measure, and it needs to be maximized.

For any point P_i at a given machine setup, the tool diameter and length accessibility are $d_i(\theta_j) and\ l_i(\theta_j) : \theta_j \in \{\theta_1, \theta_2, \dots, \theta_n\}, \theta_j \notin Orientation_{hemisphere\ set}$. To get an overall accessibility for all of the surface, the facet accessibility can be approximated as the average of the three vertices (points) that make up each triangular facet on a mesh model representation. Thus, the tool diameter and length accessibility for a facet F_i can also be represented as $d_i(\theta_j) and\ l_i(\theta_j)$. The tool access measure of this facet can be represented by:

$$ToolAccess(F_i) = \max(\frac{d_i(\theta_j)^4}{l_i(\theta_j)} : \theta_j \in \{\theta_1, \theta_2, \dots, \theta_n\}, \theta_j \notin Orientation_{hemisphere\ set}).$$

Note that, the minimum diameter is 0 inch, which represents complete non-accessibility. In the length range, the minimum length should always be positive, even though the theoretical required length might be zero.

To evaluate the overall tool accessibility of the model for a machine setup the overall accessibility for the part can be calculated, weighted by area, as:

$$PartAccessibility(Setup) = \frac{\sum(ToolAccess(F_i) \cdot A_i)}{\sum A_i}$$

Where: A_i is the area of the facet i.

AM Setup planning and Stock locating for Hybrid AM/SM

Once the machining setup is decided, the two AM orientations that are 180 degrees apart need to be determined. This basically a decision on the orientation of two parallel planes for AM building in two directions. In AM printing, there are many aspects to consider such as build height, support structure volume, support structure area, projection area on the build plate, etc. The two important factors for AM set up planning considered in this research are build height and support structure area. In the proposed Hybrid AM/SM method of this paper, the AM orientations are 180 degrees apart, the selection of the orientations decides the support structure area, and together with the location of the build plate decides the build height, as Figure 5-6 indicates.

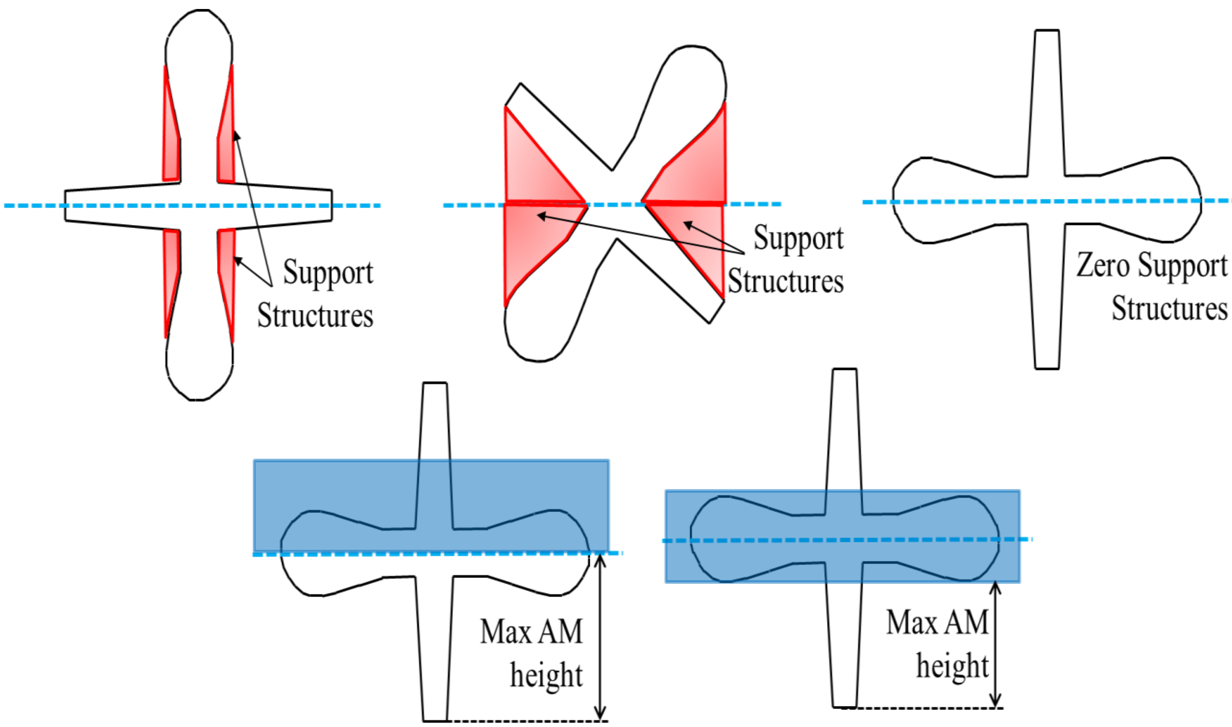


Figure 5-6 AM build orientations planning

The AM setup planning, in fact, is effectively deciding the build plate location and orientation. The location and the orientation of the build plate together determine the AM height and the support structure for a design. From the sampled combinations of locations and orientations, a feasible planning that gives the overall minimum AM build height, as well as a minimum support structure, can be calculated:

$$Minimize: f(z,\theta) = \alpha \cdot AM_{height} + \beta \cdot Support_{area}$$

Subject to:

$$\begin{cases} Part\_zmin \leq z \leq Part\_zmax \\ 0^{\circ} \leq \theta \leq 180^{\circ} \end{cases}$$

In which,

z: The location of the build plate, distance from the plate center to part bottom.
θ: Represents the orientation, marked by rotation angle and axis from the original part orientation.
AM_{height}: The maximum AM building height for the given build plate location and orientation.
$Support_{area}$: The part surface area requiring support structures at this given build plate location and orientation.
α : The assigned weight of the AM_{height} for the objective function.
β : The assigned weight of the $Support_{area}$ for the objective function.
$Part\_zmin$, $Part\_zmax$: Represent the maximum and minimum z coordinate of the part orientation θ.

Implementation

Two example parts, a toy jack model (Jack), and an aerospace bracket (AE Bracket) are tested with the proposed Hybrid AM/SM planning method and process planning calculation results are presented in this section.

Determine the machine setup

In setup planning for machining tool accessibility, the size of the trunnion table in part decides the accessible angles. As mentioned, to simplify the calculation the size of the trunnion table is assumed to be infinite diameter, thus forcing part accessibility to be considered within a hemisphere. In this implementation, 13 tool approach orientations sampled from the hemisphere with 45° interval are used to calculate the tool accessibility for this part.

For both machining setup and AM orientations planning, orientations from the whole spherical space are considered. In the trial, 18 orientations with 45-degree interval of x,y,z axis rotation are calculated. The 18 setups are as follows marked by the rotation from the original setup around the axis, red colored ones are redundant: (x-0),(x-45),(x-90),(x-135),(x-180),(x-225),(x-270),(x-315),(y-0),(y-45),(y-90),(y-135),(y-180),(y-225),(y-270),(y-315),(x-90,y-0),(x-90,y-45),(x-90,y-90),(x-90,y-135),(x-90,y-180),(x-90,y-225),(x-90,y-270),(x-90,y-315). In the accessibility calculation, 9 tool diameters $\{0, 0.125, \dots, 1\}$, and 10 tool lengths $\{1, 2, \dots, 10\}$ are considered. The machining accessibility result for all the setups for the Jack, and AE Bracket are given in Tables 5-1 and 5-2, respectively.

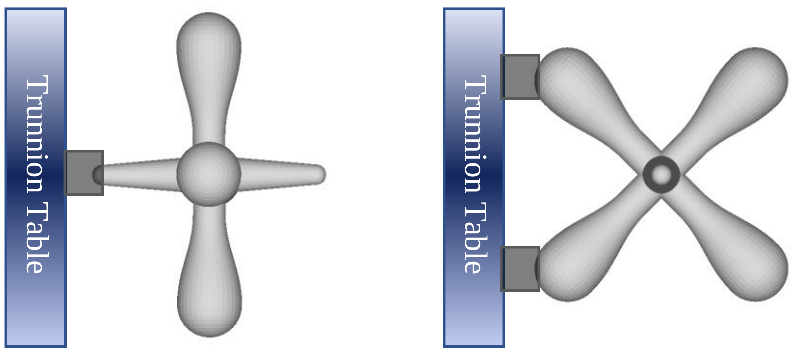
Table 5-1 Machining accessibility for Jack

Setup	Accessib-ility	Setup	Accessib-ility
X-0	0.8581	Y-90	0.8439
X-45	0.7964	Y-135	0.7971
X-90	0.8442	Y-225	0.7970
X-135	0.7970	Y-270	0.8438
X-180	0.8596	Y-315	0.7962
X-225	0.7969	Z-45	0.8551
X-270	0.8441	Z-135	0.8552
X-315	0.7961	Z-225	0.8552
Y-45	0.7963	Z-315	0.8551

Table 5-2 Machining accessibility for AE Bracket

Setup	Accessib-ility	Setup	Accessib-ility
X-0	0.6261	Y-90	0.6310
X-45	0.5589	Y-135	0.6186
X-90	0.6179	Y-225	0.6089
X-135	0.5771	Y-270	0.6457
X-180	0.6175	Y-315	0.6165
X-225	0.5811	Z-45	0.6032
X-270	0.6253	Z-135	0.6038
X-315	0.5633	Z-225	0.6311
Y-45	0.6061	Z-315	0.6154

For the Jack example, from the machining accessibility result, it can be found that setups X-0, X-180, Z-45, Z-135, Z-225, Z-315 all give a similar highest accessibility. Due to the symmetry of part geometry, all the setups can be represented in two setups X-0 and Z-45 as Figure 5-7 a and b show. Furthermore, if fixture planning is also considered, which will be studied future work, Z-45 orientation would provide a better fixture option with a stronger sacrificial support structure design.



a. X-0 b. Z-45

Figure 5-7 Jack setup X-0 and Z-45

For the AE Bracket example, the setup Y-270 gives the highest accessibility, as shown in Figure 5-8.

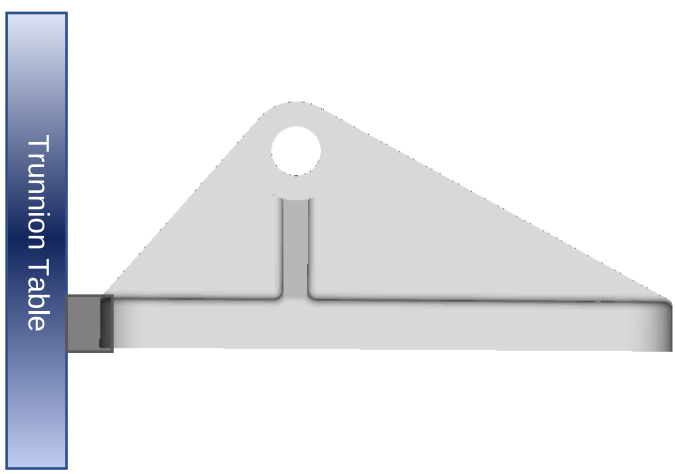


Figure 5-8 AE Bracket setup Z-270

Determine AM orientation and stock locating

Based on the calculated machining setup, the AM orientations and stock locating can be conducted. For a given thickness stock, different locations of the stock and orientations can be examined. In this test, locations are examined with 0.100-inch interval, and orientations with 45° interval. Stock thickness at 0.250 inches (thin), 1 inches (medium), and 1.500 inches (thick) are checked. For the Jack example, as mentioned in section 4.1, there are two candidate setups for machining accessibility. Other than the fixture design, it can be

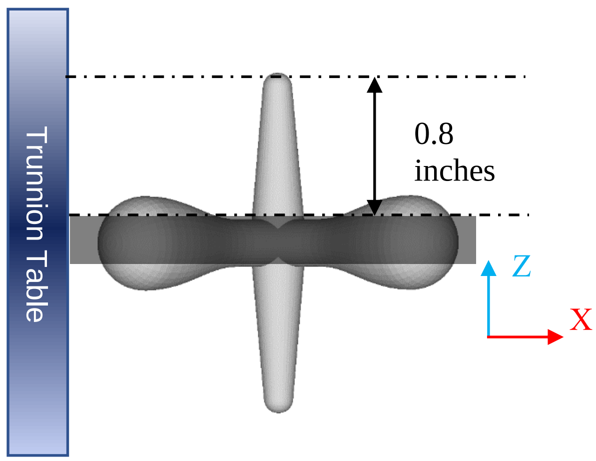
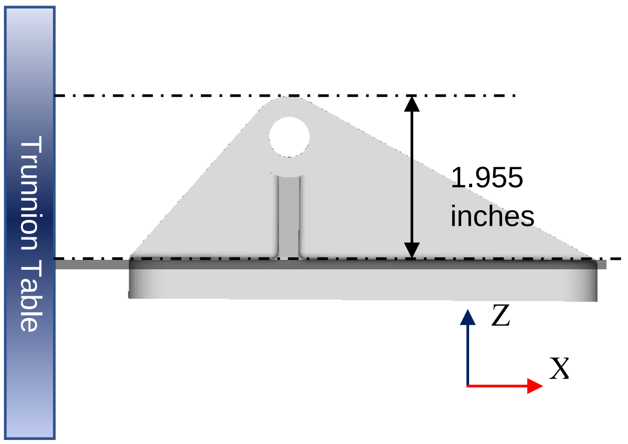
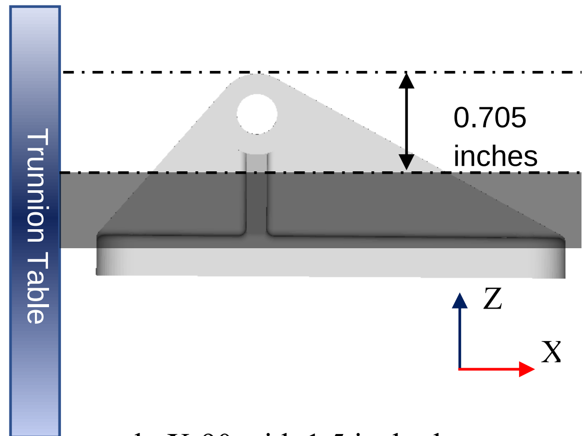


Figure 5-9 AM orientations and build plate location

found that from all AM orientations, the X-0 setup will need support structures. So considering both, Z-45 should be a better machine setup. In the test, only Z-45 orientation is calculated. From the results (APPENDIX A), it can be found that, for 0.250-inch plate, the best AM orientation is 0 angle rotation, and locating the build plate around the center of the part within a certain range (Figure 5-9). This AM orientation will bring the support area down to 0 $inch^2$ with minimum AM height of 0.800 inches. Furthermore, within this building plate locating range, it clear to see that the build plate is located at the center, and therefore the AM build height will be minimized. If given a 1.000-inch plate, both 0 and 90 degrees of rotation becomes possible candidates. Similarly for the 1.500-inch plate. If given a 2.000 or above inch plate, the part will be entirely bounded inside the build plate; and no AM is required.



a. X-90 with 0.25 inch plate



b. X-90 with 1.5 inch plate

Figure 5-10 AE Bracket Orientation X-90 and X-0

For the AE Bracket example, the best machining setup candidate is Y-270. From the result (APPENDIX B), it can be found that, for the 0.250-inch plate, the best AM orientation is 90 angle rotation, locating the build plate position as Figure 5-10a shows. With this AM setup, we can achieve a minimum support area 0.897 $inch^2$ with minimum AM height of 1.955 inches. If given a 1.000-inch thickness build plate, a similar result can be calculated, but with smaller minimum support area 0.841 $inch^2$and with minimum AM height of 1.205 inches, since part of the support-requiring surfaces will be inside the build plate. When given a 1.500-inch thickness plate, the best AM setup is still at 90 degree rotation, locating the build plate position as Figure 5-10b shows. With this AM setup, one can achieve a minimum support area 0.372 $inch^2$with minimum AM height of 0.705 inches.

Summary

In this paper, a new approach to process planning for a hybrid additive and subtractive manufacturing system is proposed. This method brings the current AM and rapid machining technologies one step closer to Direct Digital Manufacturing. In this method, algorithms are developed to find an optimal setup for both machining and AM. Two test parts are examined with the algorithms, and it is shown to generate feasible manufacture plans. This research solves the problem of process planning for this Hybrid AM/SM method with a given size build plate. However, for a series of parts, how to decide the most economical build plate size considering both manufacturing and inventory will be another critical issue. The result of this research can provide manufacturing plans, which can be applied for manufacturing cost estimation. It can be further extended for optimizing the build plate size. Fixture planning is not considered in this research. However, the planning of fixturing is an important part for multi-axis machining. An integrated planning algorithm, considering both fixturing and machining setups will be developed in the future. Also, in this proposed Hybrid AM/SM method, only two AM orientations that are 180 degrees apart are considered. This setup provides the convenience of AM process planning and geometry partitioning. In the future, this method could be extended to more AM orientations to take full use of the multi-axis capability.

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Appendix A. Test result for the Jack model

All areas in square inches, all length in inches.

Table A1. Jack, angle 0, plate thickness 0.250 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.775	1.190	1.550	0.000	1.550
-0.675	1.190	1.450	0.100	1.450
-0.575	1.190	1.350	0.200	1.350
-0.475	1.190	1.250	0.300	1.250
-0.375	1.190	1.150	0.400	1.150
-0.275	0.326	1.050	0.500	1.050
-0.175	0.000	0.950	0.600	0.950
-0.075	0.000	0.850	0.700	0.850
0.025	0.000	0.750	0.800	0.800
0.125	0.000	0.650	0.900	0.900
0.225	0.025	0.550	1.000	1.000
0.325	0.596	0.450	1.100	1.100
0.425	1.190	0.350	1.200	1.200
0.525	1.190	0.250	1.300	1.300
0.625	1.190	0.150	1.400	1.400
0.725	1.190	0.050	1.500	1.500

Table A2. Jack, angle 45, plate thickness 0.250 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.625	0.662	1.249	0.000	1.249
-0.525	0.634	1.149	0.100	1.149
-0.425	0.605	1.049	0.200	1.049
-0.325	0.509	0.949	0.300	0.949
-0.225	0.489	0.849	0.400	0.849
-0.125	0.520	0.749	0.500	0.749
-0.025	0.679	0.649	0.600	0.649
0.075	0.605	0.549	0.700	0.700
0.175	0.485	0.449	0.800	0.800
0.275	0.492	0.349	0.900	0.900
0.375	0.527	0.249	1.000	1.000
0.475	0.621	0.149	1.100	1.100
0.575	0.660	0.049	1.200	1.200

Table A3. Jack, angle 90, plate thickness 0.250 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.832	0.772	1.664	0.000	1.664
-0.732	0.772	1.564	0.100	1.564
-0.632	0.766	1.464	0.200	1.464
-0.532	0.696	1.364	0.300	1.364
-0.432	0.619	1.264	0.400	1.264
-0.332	0.595	1.164	0.500	1.164
-0.232	0.550	1.064	0.600	1.064
-0.132	0.528	0.964	0.700	0.964
-0.032	0.585	0.864	0.800	0.864
0.068	0.570	0.764	0.900	0.900
0.168	0.485	0.664	1.000	1.000
0.268	0.642	0.564	1.100	1.100
0.368	0.585	0.464	1.200	1.200
0.468	0.646	0.364	1.300	1.300
0.568	0.720	0.264	1.400	1.400
0.668	0.766	0.164	1.500	1.500
0.768	0.766	0.064	1.600	1.600

Table A4. Jack, angle 0, plate thickness 1.000 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.400	0.000	0.800	0.000	0.800
-0.300	0.000	0.700	0.100	0.700
-0.200	0.000	0.600	0.200	0.600
-0.100	0.000	0.500	0.300	0.500
0.000	0.000	0.400	0.400	0.400
0.100	0.000	0.300	0.500	0.500
0.200	0.000	0.200	0.600	0.600
0.300	0.000	0.100	0.700	0.700
0.400	0.000	0.000	0.800	0.800

Table A5. Jack, angle 45, plate thickness 1.000 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.250	0.089	0.499	0.000	0.499
-0.150	0.000	0.399	0.100	0.399
-0.050	0.000	0.299	0.200	0.299
0.050	0.000	0.199	0.300	0.300
0.150	0.000	0.099	0.400	0.400

Table A6. Jack, angle 90, plate thickness 1.000 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.457	0.297	0.914	0.000	0.914
-0.357	0.287	0.814	0.100	0.814
-0.257	0.243	0.714	0.200	0.714
-0.157	0.129	0.614	0.300	0.614
-0.057	0.048	0.514	0.400	0.514
0.043	0.022	0.414	0.500	0.500
0.143	0.121	0.314	0.600	0.600
0.243	0.229	0.214	0.700	0.700
0.343	0.287	0.114	0.800	0.800
0.443	0.297	0.014	0.900	0.900

Appendix B. Selected test result for the AE Bracket model

All areas in square inches, all length in inches.

Table B1. AE Bracket, angle 0, plate thickness 0.250 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-1.575	14.642	3.150	0.000	3.150
-1.475	14.642	3.050	0.100	3.050
-1.375	14.513	2.950	0.200	2.950
-1.275	14.611	2.850	0.300	2.850
-1.175	14.591	2.750	0.400	2.750
-1.075	14.573	2.650	0.500	2.650
-0.975	13.834	2.550	0.600	2.550
-0.875	9.074	2.450	0.700	2.450
-0.775	9.137	2.350	0.800	2.350
-0.675	7.293	2.250	0.900	2.250
-0.575	6.792	2.150	1.000	2.150
-0.475	6.792	2.050	1.100	2.050
-0.375	12.596	1.950	1.200	1.950
-0.275	12.589	1.850	1.300	1.850
-0.175	12.547	1.750	1.400	1.750
-0.075	12.596	1.650	1.500	1.650
0.025	12.586	1.550	1.600	1.600
0.125	12.577	1.450	1.700	1.700
0.225	12.547	1.350	1.800	1.800
0.325	12.579	1.250	1.900	1.900
0.425	11.990	1.150	2.000	2.000
0.525	6.781	1.050	2.100	2.100
0.625	7.249	0.950	2.200	2.200
0.725	9.093	0.850	2.300	2.300
0.825	9.046	0.750	2.400	2.400
0.925	9.022	0.650	2.500	2.500
1.025	14.505	0.550	2.600	2.600
1.125	14.614	0.450	2.700	2.700
1.225	14.594	0.350	2.800	2.800
1.325	14.575	0.250	2.900	2.900
1.425	14.516	0.150	3.000	3.000
1.525	14.621	0.050	3.100	3.100

Table B2. AE Bracket, angle 90, plate thickness 0.250 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-1.128	0.903	2.255	0.000	2.255
-1.028	0.903	2.155	0.100	2.155
-0.928	0.903	2.055	0.200	2.055
-0.828	0.897	1.955	0.300	1.955
-0.728	1.067	1.855	0.400	1.855
-0.628	5.512	1.755	0.500	1.755
-0.528	16.091	1.655	0.600	1.655
-0.428	16.091	1.555	0.700	1.555
-0.328	16.091	1.455	0.800	1.455
-0.228	16.091	1.355	0.900	1.355
-0.128	16.091	1.255	1.000	1.255
-0.028	16.575	1.155	1.100	1.155
0.072	16.575	1.055	1.200	1.200
0.172	16.477	0.955	1.300	1.300
0.272	16.385	0.855	1.400	1.400
0.372	16.385	0.755	1.500	1.500
0.472	16.577	0.655	1.600	1.600
0.572	16.581	0.555	1.700	1.700
0.672	16.813	0.455	1.800	1.800
0.772	16.910	0.355	1.900	1.900
0.872	17.115	0.255	2.000	2.000
0.972	17.068	0.155	2.100	2.100
1.072	17.185	0.055	2.200	2.200

Table B3. AE Bracket, angle 0, plate thickness 1.500 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.950	6.352	1.900	0.000	1.900
-0.850	6.310	1.800	0.100	1.800
-0.750	6.310	1.700	0.200	1.700
-0.650	6.397	1.600	0.300	1.600
-0.550	6.456	1.500	0.400	1.500
-0.450	6.427	1.400	0.500	1.400
-0.350	6.428	1.300	0.600	1.300
-0.250	6.550	1.200	0.700	1.200
-0.150	0.795	1.100	0.800	1.100
-0.050	0.795	1.000	0.900	1.000
0.050	0.795	0.900	1.000	1.000
0.150	0.795	0.800	1.100	1.100
0.250	5.956	0.700	1.200	1.200
0.350	6.471	0.600	1.300	1.300
0.450	6.471	0.500	1.400	1.400
0.550	6.499	0.400	1.500	1.500
0.650	6.441	0.300	1.600	1.600
0.750	6.353	0.200	1.700	1.700
0.850	6.353	0.100	1.800	1.800

Table B4. AE Bracket, angle 90, plate thickness 1.500 inches

Plate position	Support area	AM height 1	AM height 2	Max AM height
-0.503	0.841	1.005	0.000	1.005
-0.403	0.690	0.905	0.100	0.905
-0.303	0.651	0.805	0.200	0.805
-0.203	0.372	0.705	0.300	0.705
-0.103	0.552	0.605	0.400	0.605
-0.003	4.997	0.505	0.500	0.505
0.097	15.576	0.405	0.600	0.600
0.197	15.483	0.305	0.700	0.700
0.297	15.250	0.205	0.800	0.800
0.397	15.250	0.105	0.900	0.900
0.497	15.250	0.005	1.000	1.000

CHAPTER 6. SUMMARY AND FUTURE WORK

In this dissertation, automated process planning for hybrid additive/subtractive manufacturing has been studied for the purpose of achieving true DDM. The research was conducted in three aspects: feature-based functional surface finishing, support structure removal, and new manufacturing modes for in-envelope DED type hybrid manufacturing. In Chapter 3, a post-machining process planning method is developed to derive machining planning parameters from marked-up triangle mesh model. In this research, feature-based model is proven to be a feasible CAD model for hybrid AM/SM process planning. Higher surface finish was able to be created on AM parts through automatically generated machining tool path. Hybrid AM/SM is proven to be able to produce ready to use part as compared to pure AM process, and produce part at low material removal volume as compared to pure SM process. In Chapter 4, an AM planning method to facilitate support structure removal is developed. In this research, the AM support removal in hybrid AM/SM is further studied. The solution proposed in this research is to solve this problem is through AM process planning. From the method developed in this research, a better AM printing orientation can be calculated to minimize the total area of the surfaces that are both hard to access in SM and require support structure in AM. In Chapter 5, a new integration mode of DED type AM and 5-axis milling is proposed with the process planning methodology. This research targets at finding an approach to better incorporate AM and SM to take the best advantage from both manufacturing processes. In the proposed hybrid AM/SM mode, smaller AM volume, lower build height, and less support structure can be achieved, which could significantly reduce the failure rate, build time, and cost for AM. As for SM, less material removal, better tool accessibility can be achieved.

In summary, this dissertation research explores the macro process planning aspects of Hybrid AM/SM to bridge the gap between existing manufacturing AM/SM equipment and DDM. The macro process planning includes setup planning and AM/SM operation planning. These macro process planning in the past requires considerable efforts from experienced engineer to complete. With the methodology developed in this research, the process could be automatically planned; such the human intervention can be significantly reduced or even eliminated.

Future work

This dissertation used marked up triangle mesh model for feature-based model handling. Although new triangle mesh based AM CAD formats such as AMF and 3MF has been developed and is gradually being adopted in the 3D printing industry, it might not be a perfect solution for metal mechanical parts hybrid AM/SM manufacturing which requires a much tighter GD&T. At current stage, there is no CAD model standard developed for easily integrating Additive and Subtractive technologies. It is believed by the author that, the Standard Exchange Protocol (STEP) has great potential in being developed to the standard file format for hybrid AM/SM. STEP is already widely used in industrial production, it is capable of representing exact geometry shape in both tessellated shape and parametric shape. As the STEP is been continuously developed for aerospace and the automotive industry it has been integrated with more Product and Manufacturing Information (PMI), with which GD&T can be defined for the model. Although STEP format has such advantages, and there research to use STEP file in AM, it has never been widely used in AM. The major reason is STEP file in nature is far more complex than STL format and its further derived AMF and 3MF. Also, the triangle mesh based models was able to meet the requirement for AM. However, with the development of hybrid AM/SM, STEP file could show its advantage over the STL/AMF/3MF in industry production and precise geometry representation. The process planning of hybrid AM/SM in the future could be better implemented based on a more advanced CAD format like STEP.

In this research, the tool accessibility is calculated based on a sampled slice model and orientations. The accessibility and manufacturing plan is concluded within the sampled set. This calculated result is not guaranteed to be the globally optimized result. Future work could continue to improve on finding an optimized result in a broader range as well as maintaining high calculation efficiency.

Another worth further exploring work is fixture planning for hybrid AM/SM. Fixture planning plays an important part in the machine setup. Creating algorithms and manufacturing plans to automatically generate sacrificial support structuring for the SM process as well as the AM process is a must be solved problem before putting this method into industrial application. This fixture planning method needs to be universal and robust. It needs to be able to handle different types of geometries and able to generate support structures that provide strong enough fixturing to limit the deflection during the manufacturing process.

The author envisioned that, with the further development of automated process planning for hybrid AM/SM in the future 5-10 years, the CAM side of hybrid manufacturing would be able to keep up with the hybrid equipment development and realize true industrial level DDM in 15-20 years.