Robotic Off-Axis Fused Filament Fabrication

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Approval

The following thesis, **Robotic Off-Axis Fused Filament Fabrication**, developed at the **University of Wisconsin-Madison** has been approved by:

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Abstract

Yada Yada Yada

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Symbols and Acronyms

Acronyms

AM	Additive Manufacturing
CAD	Computer Aided Design
FDM	Fused Deposition Modeling^{TM}
FFF	Fused Filament Fabrication
RP	Rapid Prototyping
SLA	Stereolithography
SLS	Selective Laser Sintering

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Introduction

Additive Manufacturing (AM) is an umbrella term that encompasses all fabrication techniques where the final geometry of the part is obtained through superposition of material in a layer-by-layer basis [1]. Developed in the 1980s, this manufacturing technique permits immensely shorter part development cycles, since the transition from a 3D *Computer Aided Design* (CAD) to part fabrication only requires one intermediate step: the use of a slicing engine that converts the geometry of the object into machine instructions [1]. For this reason, AM technologies were initially employed exclusively for prototype development and were referred to as *Rapid Prototyping techniques* (RP). However, recent innovations in the field have caused AM to be perceived as a legitimate manufacturing technology since it is also capable of reproducing complex geometries unattainable through other means [1].

While offering great advantages over traditional part fabrication methods, AM comes with its own set of limitations and disadvantages: First and foremost, the use of a stratified build approach tends to produce extremely anisotropic parts. Secondly, the geometric accuracy of the object produced is highly dependent of process parameters, particularly of the thickness of the layers. Finally, as of the time of this writing, AM lacks the standardization and scrutiny that are associated to most traditional manufacturing techniques [1].

Fused Filament Fabrication (FFF), also known under the trademark *Fused Deposition Modeling* (FDM™), represents perhaps the most prevalent AM technique in the market due to the advent of low-cost, desktop 3D printers in the early 2010s [2]. Due to the broad availability of machines and relatively low costs of material, there's a surging interest in optimizing FFF to produce small batches of end-user grade parts. Success stories are varied, but examples include vacuum form molds, fixtures, jigs, and tools used to aid assembly lines in the automotive industry [3, 4, 5]. However, this technology still faces the challenges and limitations that currently affect the field of AM as a whole. Namely, anisotropy introduced through the layer-by-layer build approach makes it difficult to assess the expected mechanical behavior of FFF parts when subjected to important mechanical stresses [2]. For these reasons, multiple attempts have been made to characterize the anisotropy of FFF objects. Recent studies performed by Koch *et al.* [6] and Rankouhi *et al.* [7] show that the ultimate tensile strength of FFF coupons is sensitive to process parameters such as the layer thickness and, in particular, the orientation in which the plastic strands are laid during the build process

-henceforth referred to as the bead orientation. However, literature related to preventing failure through design is scarce, given the difficulty of using commercially available FFF machines to produce test coupons with unconventional bead orientations, as well as the limitations inherent to commonly used failure criteria that make it difficult to develop an accurate failure surface.

This research applies a novel criterion, tailored for anisotropic materials, to develop a failure surface for FFF parts through mechanical testing of coupons under various types of loading conditions. Certain test specimens were produced using a unique, in house developed off-axis 3D printer that allowed production of coupons in unconventional configurations. Such surface can be an invaluable tool in part design, since catastrophic failure can be prevented in the early stages of part development. This could potentially allow a broader embrace of FFF as a legitimate manufacturing technique in highly demanding engineering fields, such as the aerospace or automotive industries -where part failure is to be avoided at all costs.

This work offers a comprehensive overview of AM technologies and FFF in Chapter 1. Chapter 2 details the failure criterion used, as well as outlining its advantages over similar criteria. Chapters 3 through ? detail the experimental setup followed, as well as outlining noteworthy results. Finally, Conclusions and Recommendations are given in Chapter ?? in the hopes of guiding future work on the topic.

1 Background

1.1 Additive Manufacturing

Additive Manufacturing (AM) technologies had their beginnings in the decade of the 1980s. During this time, various independently developed patents were filed across the globe describing a process that would construct an object by selectively adding layers of material -as opposed to removing excess matter or deforming the material to obtain the desired shape. This represents the core definition of AM: any technology where the final geometry of the manufactured object is obtained through controlled addition of material qualifies as an Additive Manufacturing technique [1].

Advancements in the fields of computing, *Computer Aided Design* (CAD), and controllers, among other technological developments, were necessary to translate the patents into working prototypes that would eventually become the foundations of commercially successful companies such as 3D Systems in 1986 and Stratasys in 1989 [1, 8, 9]. Since then, the basic process of AM has remained largely unchanged : First, a computer model of the object is made using CAD software and exported under the *.stl* file format. Afterwards, the part geometry is stratified, or "sliced", and translated into machine instructions using a specialized software called *slicing engine*. An AM machine then follows said instructions, commonly referred to as the *toolpath*, to build the object in layers. Finally, the part is available to the user. Depending on either the requirements of the part, or the specifics of the AM technique used, some post-processing may be required [1]. A visual representation of the process is shown in Figure 1.1.

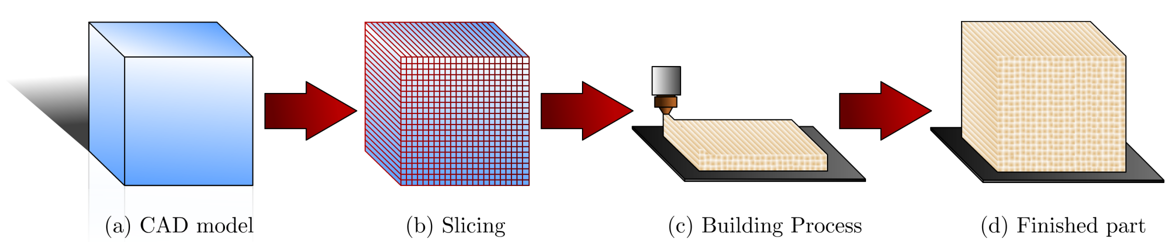

Figure 1.1: Process flow of AM

1.1.1 Fused Filament Fabrication

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