Robotic Deposition to Enable Multi-Axis Material Extrusion

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ABSTRACT

The layer-by-layer deposition of the material extrusion (ME) additive manufacturing process provides geometric freedom in part design, but its use in fabricating end-use components is limited. The mechanical properties of ME parts are anisotropic (i.e., weaker in the build direction) and therefore often require design compromises to maintain part strength (e.g., additional material in critical areas of the part). This issue stems from the three degree-of-freedom (DoF) tools used in ME, which restrict deposition to within the XY-plane. By incorporating additional DoF into the motion control system, the tool head and printed part can reorient relative to each other. This capability allows material deposition outside of the XY-plane, enabling more flexible deposition strategies and material alignment with load paths throughout the part geometry. In this paper, methods for improving mechanical strength by (i) selectively changing the build direction and (ii) depositing surface reinforcement are presented. The toolpath planning algorithm used in (i) is also shown to minimize support material usage with appropriately chosen build directions.

Keywords: material extrusion, additive manufacturing, robotic deposition, multi-axis deposition, degree of freedom

1 INTRODUCTION

Material extrusion (ME) additive manufacturing creates parts through the controlled deposition of material, often a heated thermoplastic, onto a substrate. This deposition occurs in planar layers stacked along a single build axis. As the depositions cool rapidly, there is only a short window of time (less than 2s for ABS) in which the material is at a suitable temperature for bonding [1]. This introduces layer interfaces that reduce mechanical performance along the build axis [2]. This same phenomenon occurs, to a lesser extent, between adjacent depositions (referred to as roads) within a single layer. The mechanical properties of ME parts are therefore anisotropic, weaker in the build direction and across inter-road bonds than in the road direction [3].

Due to this, design for AM guidelines often recommend that parts be printed in an orientation such that the printed roads are aligned with the anticipated load paths. Parts with simple loading conditions may have a build orientation in which loads travel solely within the printed layers, removing the inter-layer bonds from the load paths. However, more complex loading conditions, that are more common in end-use applications, often do not have such an orientation. As a result, parts might require additional material in high-stress areas to compensate for the mechanical property deficiency, or ME may be unsuitable as a manufacturing option.

As XY-planar deposition imposes constraints on part performance, researchers have explored other deposition strategies to improve the mechanical performance of ME parts. Curved layer slicing (CLS) stacks curved, rather than planar, layers along a single axis [4]. In doing so, some road alignment is obtained in the build direction, improving part performance [5]. CLS is not without issue though, as it requires material to be above the tool head at certain parts of the toolpath. This introduces collision concerns between the tool head and previously deposited material, limiting the amount of achievable curvature and therefore road alignment in the build direction [6].

High degree-of-freedom (DoF) systems, which integrate additional DoF (more than three) into the motion control system, allow the tool head and part to reorient relative to each other (e.g., tilt/turn build beds, robotic arms, etc.). These systems have been used for tasks including hybrid ME and subtractive manufacturing [7], conformal printing onto curved surfaces [8-10], support material minimization [11], and conformal wire embedding [12].

The additional flexibility allows for material deposition along multiple build axes throughout the part (referred to as multi-axis deposition). In effect, multi-axis deposition enables the selective variation of layering and road directions locally throughout the part. This variation can achieve deposition alignment with three dimensional stress contours and load paths, creating stronger and more efficient parts. For instance, a 5-DoF system, which integrated a delta bot and tip-tilt platform, has been used to print hemispherical pressure caps with roads following stress contours [13]. Topology optimized surface geometries have also been fabricated using a 6-DoF robotic arm [14]. In both cases, the roads were aligned with stress contours and principal stress lines to create curved layers. This improved part performance over geometrically similar parts fabricated by 3-DoF XY-planar deposition.

In this paper, the authors explore opportunities afforded by multi-axis ME for improving part quality. First, a demonstration of a multi-axis system's capability to eliminate the need for support material is demonstrated by fabricating a branched test specimen that requires seven different build directions (Section 2.1). Second, the impacts of multi-axis deposition on tensile strength and modulus are explored by comparing properties of specimens printed along a variety of build orientations using both 3-DoF and 6-DoF ME techniques (Section 2.2). Both of these demonstrations are supported by a toolpath planning algorithm that extends the capabilities of existing 3-DoF slicing software for multi-axis printing.

Finally, a deposition strategy inspired by composite layup is used to deposit surface-reinforced tensile specimens. These specimens are fabricated by first printing a part core using XY-planar deposition and then printing a conformal 'skin' onto the surface of the core (Section 2.3).

2 MULTI-AXIS DEPOSITION

The presented work used a ME platform built around a 6-DoF robotic arm, specifically an ABB IRB 7/0.7 [15] (shown in Figure 1). In the case of Sections 2.1 and 2.3, an E3D v6 [16] tool head was used. For Section 2.2, a custom-built tool head was used; more information on the design of the tool head can be found in [17].

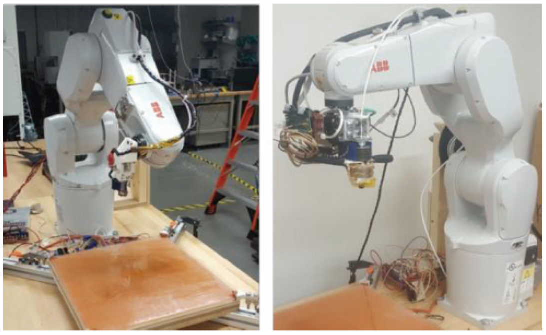

Figure 1: The robot platform used in (left) Sections 2.1 and 2.3 and (right) Section 2.2

Although the additional flexibility afforded by multi-axis systems enables novel deposition strategies, toolpath planning for such a system requires additional considerations beyond those for 3-DoF systems. Specifically, typical GCode used by 3-DoF ME systems does not fully constrain the tool head in multi-axis deposition, as the tool head has multiple orientations that can reach any given point in space. In order to fully constrain the tool head, additional rotation information is required at each point in the toolpath.

Two toolpath planning strategies are presented which generate the requisite orientation information: (i) an algorithm that reorients STL segments in order to utilize existing XY-planar slicers and (ii) a surface-following algorithm that generates a toolpath along the surface of the desired part geometry (details in [18]). There are a number of ways to represent tool head orientations, but in this work, a quaternion is used due to its prevalence in robotics.

2.1 Support Material Minimization

In contrast to additive manufacturing processes like powder bed fusion, overhanging structures in ME require the deposition of additional material for support. If left unsupported, these structures often deform or otherwise do not print properly. These supports must then be removed post-process, which can damage the part or reduce surface quality. While it is possible to fabricate self-supporting overhanging features, they are often limited to approximately 30° measured from the Z-axis due to the amount of unsupported material relative to the previous layer.

The amount of unsupported material deposited per layer is related to the angle between the build direction and the surface normal of the geometry [19]. As this angle approaches 90°, the amount of unsupported material is reduced. Using a multi-axis system, the build direction can be selectively changed to minimize this angle throughout the geometry, allowing steep overhangs to be printed without support material. The branching part shown in Figure 2 was fabricated using seven build directions, chosen such that support structure was not required. On a typical 3-DoF platform, the steep overhangs beneath build directions 2, 4, and 6 would have required support structure.

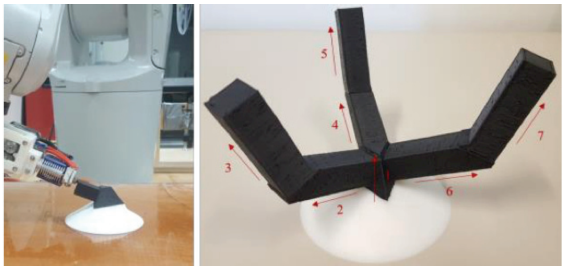

Figure 2: (left) A multi-axis part being fabricated without the use of support material. (right) The finished part with arrows denoting the build direction for each segment.

The toolpath for the part was generated using an off-the-shelf XY-planar slicer. In order to obtain layers in their desired relative orientations, the full part STL was decomposed into segments, each with its own unique build direction. Each segment was then rotated such that its desired build direction aligned with the slicing direction (i.e., the Z-axis). After slicing, each segment was then rotated back to its original orientation. This rotation was used to generate a corresponding quaternion that was paired with each Cartesian coordinate in the toolpath to maintain tool head perpendicularity with the layers. As a result, the layers comprising each segment were rotated out of the XY-plane, enabling support-free deposition.

There is a limit to this multi-axis deposition strategy, as large, steep overhangs (e.g., fully vertical layers) are still subject to gravity effects. Therefore, the stacking of multiple layers along a horizontal build axis could still produce a part that droops or otherwise does not have the desired resolution. Integrating additional DoF into the build stage (e.g., [11]) could allow the part to reorient relative to gravity, which would enable the fabrication of steeper overhangs without drooping.

2.2 Tensile Property Comparison

Multi-axis deposition strategies have been shown to improve mechanical properties relative to XY-planar deposition (e.g., [13,14]), but generalizable mechanical property evaluations are unavailable. These design criteria (e.g., yield tensile strength and tensile modulus) are necessary for multi-axis ME to be useful in producing end-use products. To address this gap, tensile specimens were printed using ABS on a 6-DoF ME platform at two different angles relative to the build platform: (i) flat on the bed (XYZ) and (ii) vertical (ZYX). The multi-axis toolpath planning algorithm aligned road deposition with the loading direction (i.e., all depositions travel along the long direction of the specimens). These multi-axis specimens were then compared to geometrically similar XY-planar specimens. In the case of the XYZ specimens, both deposition strategies used the same toolpath. Therefore, only one set of specimens was printed.

The results of the tensile tests are shown in Figure 3. The 3-DoF (XY-planar) specimens demonstrated a decrease in strength as more load was applied across the inter-layer bonds. This result agrees with existing material characterization literature for printed ABS [2,3]. Conversely, the 6-DoF specimens do not show the same decrease, instead exhibiting similar performance in both orientations. This is attributed to all of the multi-axis specimens having the same degree of road alignment with the loading condition. As a result, the tensile properties were found to be independent of the deposition angle, implying that roads deposited along any vector in space will have equivalent tensile properties to roads deposited in the XY-plane.

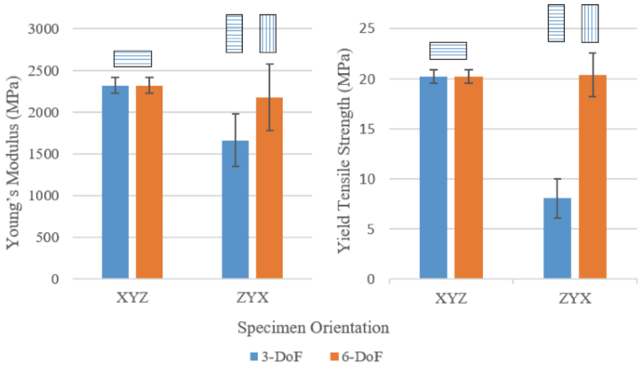

Figure 3: (left) Young's modulus and (right) Yield tensile strength of 3-DoF and 6-DoF tensile specimens. Part orientations and layering directions are shown above the corresponding bar.

2.3 Surface Reinforcement

By enabling relative reorientation between the tool head and the part, the tool head is able to remain perpendicular to the surface of the part at arbitrary orientations. This capability was used to fabricate a surface-reinforcing 'skin', inspired by the composite layup process. In that process, composite laminates are adhered to a part core to improve the performance characteristics of the overall part. This concept has been demonstrated in ME previously [20], but relies on multiple manufacturing steps to produce the final part. Using multi-axis deposition, the core and an analog to the composite laminates can be manufactured using the same system, as shown in Figure 4. This process can achieve strong road alignment with the initial build direction, which should improve mechanical performance.

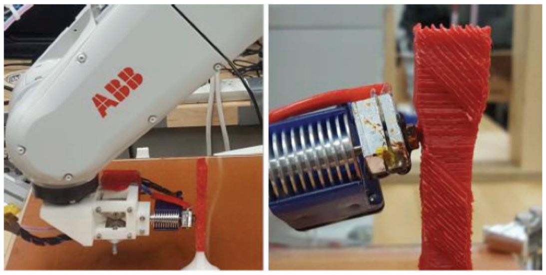

Figure 4: Material is deposited directly onto the surface of a printed part to reinforce layer interfaces.

The toolpaths for this skinning approach are generated using a surface-following algorithm that traces a vector at a user-defined angle along the surface of the input geometry [18]. Cartesian coordinate information is generated through the intersections of the vector with the STL facets. Tool head orientation can be extracted from the facet used to find the intersection, as the tool head should be kept perpendicular to that facet. The orientation is therefore related to the face normal of the facet.

In order to quantify the mechanical benefit of the skinning approach, reinforced specimens were compared to geometrically similar unreinforced specimens. The specimens were fabricated out of ABS with a skin pattern at 45° to the loading direction. The results, shown in Figure 5, demonstrate a 59% improvement to yield tensile strength with the skin [18].

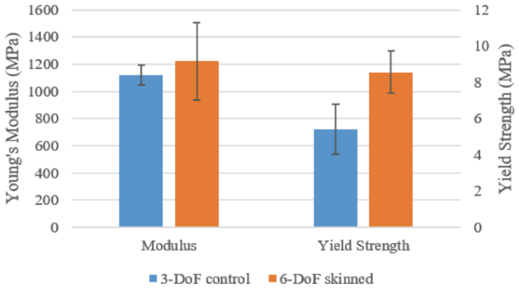

Figure 5: Skinned and unskinned tensile specimen mechanical property results.

3 CONCLUSIONS

ME is often challenged to produce parts for end-use applications due to anisotropic mechanical properties. These properties are the result of limitations in the deposition process that stem from the use of 3-DoF tools. By integrating more DoF into the deposition system, the tool head and part are able to reorient relative to each other. This enables new deposition strategies outside of XY-planar layer stacking; however, it also introduces additional tool head orientation information requirements during toolpath planning. This paper presented two toolpath planning methods: (i) a modification to off-the-shelf 3-DoF slicing software that rotates STL segments to enable multi-axis printing, and (ii) a surface-following algorithm that generates a toolpath that maintains perpendicularity between the tool head and the surface of the part geometry to enable the deposition of surface reinforcement.

The off-the-shelf modifications were used to eliminate the support material in a branching part (Figure 2) and investigate the effects of multi-axis deposition on tensile properties. From the experiment, it was evident that the tensile properties are independent of the deposition direction. As a consequence, the tensile properties of roads printed along any arbitrary vector will exhibit the same performance as though it were printed in the XY-plane.

The surface-following algorithm was used as an approach for depositing surface reinforcement onto ME parts, utilizing the conformal deposition capabilities of a multi-axis system. A single layer of the 45° skin improved yield tensile strength by 59%. This technique is expected to dramatically improve the efficiency of composite materials (e.g., carbon fiber filled ABS), as the long continuous surface depositions should enable continuous reinforcement along the entire surface.

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