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Reviewed Paper

ANALYSIS OF BUILD DIRECTION IN DEPOSITION-BASED ADDITIVE MANUFACTURING OF OVERHANG STRUCTURES

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Abstract

Additive manufacturing (AM) has gained repute as a direct method of fabrication of complex parts. However, the requirement for each layer to be structurally supported can make parts with overhangs hard to produce without alterations to the parts. This work proposes using multi-axis additive manufacturing to fabricate and analyze freeform overhangs such as bridge structures. Multi-axis AM allows reorientation of the build direction so that overhangs can be 3D printed. Consequently, decision on the build orientation is necessary and its result should be analyzed. The effect of the AM build direction with respect to the overhang's local surface directions will be studied. A Rhinoceros® plugin is designed to generate the path of the multi-axis AM for the unsupported components like roofs, bridges and protrusions. The effects of the build direction on the surface quality and deformation of the components are studied.

Introduction

Additive manufacturing (or 3D printing) became a popular rapid prototyping method since its beginning in the 1980s. It has since then expanded in application to various fields in engineering and sciences. It is now prevalent in the rapid prototyping, biomedical, construction and multi-functional applications. The most popular AM method is the fused filament fabrication (FFF) where molten material is deposited in layers to construct a part directly from a digital model. The layers are commonly extracted and filled from a tessellation model called StereoLithography (STL). This format represents an approximation of the actual analytical model using triangular surface meshes. The inaccuracy in STL files are usually negligible and do not affect the ability of AM to fabricate complex parts. Despite the complexity of parts obtainable by AM compared to other traditional manufacturing methods, the requirement for each layer to be supported limits the types of features realizable. Parts with overhanging structures like branch, roof and bridge components may not be directly manufacturable by AM. In such cases, preprocessing is commonly carried out by addition of support features to model. The additional support adversely affects production time, efficiency and quality of the part[1].

An alternative way of 3D printing overhanging features is by reorientation of the part. The reorientation is aimed at repositioning the part so that a feature can be 3D printed support-less. To evaluate the amount of tilting required, it is relevant to know the overhang angle. The overhang angle is the angle by which a layer contour deviates from the vertical build direction. Features that deviate from the vertical by an angle greater than a tentative angle of 45^0 are usually required to be supported [2–4]. This critical overhang angle serves as the criterion to use in deciding if a part can be additively manufactured. By reorienting a part, a new equivalent overhang angle below the critical angle can be obtained. However, such reconfiguration needs to be carried out on a multi-axis AM(MAAM) system because many complex parts do not have any orientation where overhangs can be eliminated. MAAM is not a new concept since it has been utilized in manufacturing. In machining, it improves machining efficiency of freeform parts. Even though AM is already compliable with freeform parts, multi-axis benefits has been demonstrated in overhang manufacturing [5]. By determination of part orientation for every overhanging portion in STL, partitioning method has developed to fabricated in stages at various suitable part orientation [6].

There are few studies on application of multi-axis positioning in additive manufacturing. A robot arm platform has been used for AM using multi-plane toolpaths [7]. Non-planar slicing paths has been developed for

MAAM robot to reduce need for supports and improve production time [8]. Recently, A new slicing method termed inclined layer printing has been developed to 3D print overhang features in uniaxial AM systems[9]. The use of an inclined surface allows AM of overhangs beyond the critical slant angle. However, the pressure of compaction during deposition is less when the deposition layer is not perpendicular to the build direction. To reposition the relative build direction normal to the sliced layer, MAAM can be introduced. Research on MAAM is multifaceted comprising of design, control, process planning, path planning and analysis of manufactured parts. Most of these categories occupy an entire scope of research. Hence this paper will focus on the analysis of overhang features produced by AM.

Multi-axis AM using 2D build platform

A 5-axis AM system has been developed to facilitate variable axis of fabrication. As stated in the previous section, MAAM can be used to change part orientation to avoid unsupported features in a model. Figure 1 shows the constructed system where a motorized build platform is attached to a 3D printer designed from Delta design concept[10]. The arms carry the print-head, which distributes material melted from the filament. The build table configuration is defined by the angles θ and ϕ.

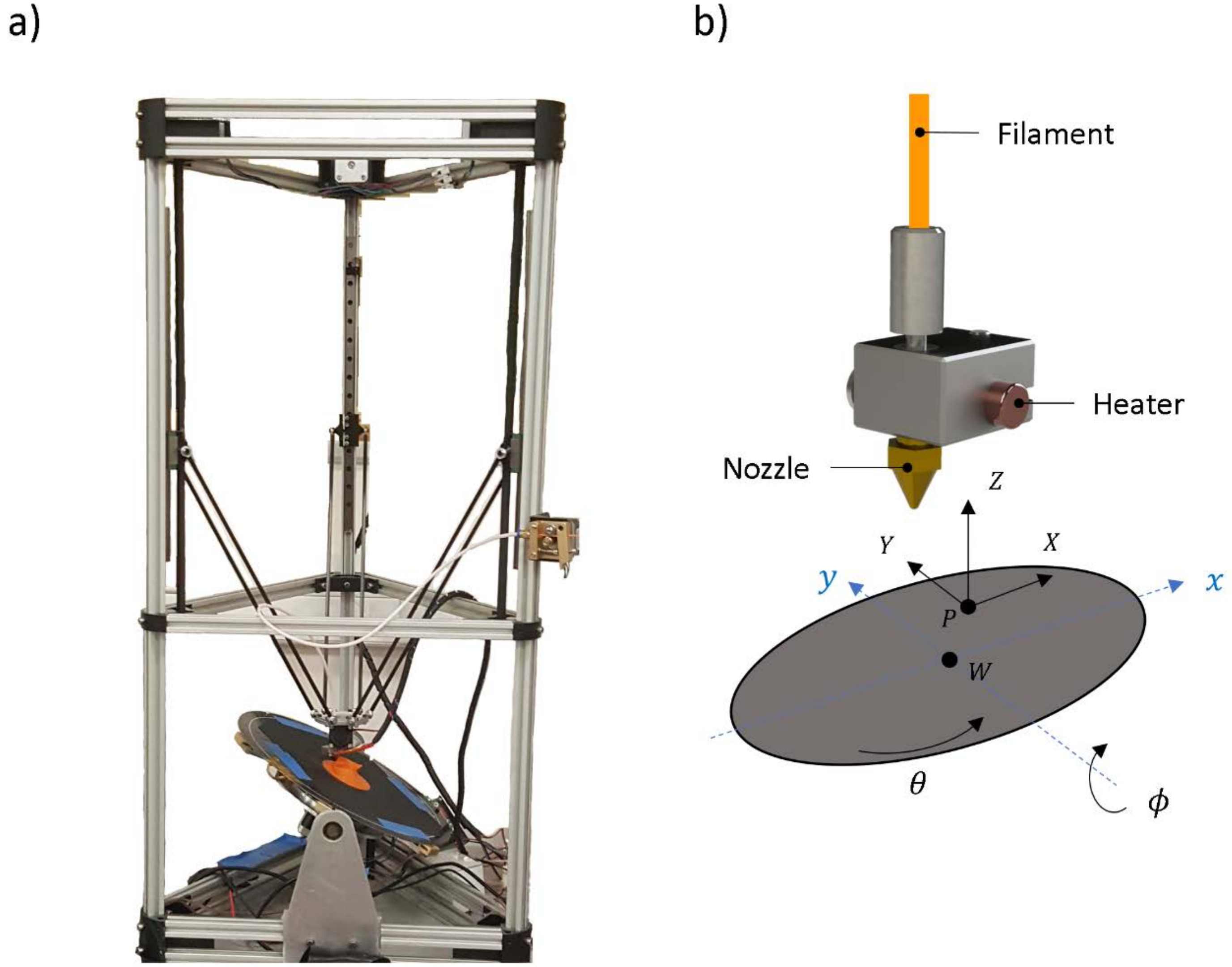

Figure 1:a) The designed 5-axis additive manufacturing system. b) Reference frames of the 3D printer and the 2D base platform where 5-Axis relative motion between the frames is facilitated

An initial stage in fabrication of a part is the 3D printing path planning. The path is planned within the workpiece frame of reference. Since the part manufactured moves with the build table, it is necessary to transform each point in the part's path to a fixed frame P. Equation 1 provides the transformation relation from the workpiece frame W to the 3D printer frame P. Where the relative position of workpiece origin O with respect to the printer origin P is $\langle w_x,\ w_y, w_z \rangle$.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_P = \begin{bmatrix} \cos(\phi) & 0 & -\sin(\phi) \\ 0 & 1 & 0 \\ \sin(\phi) & 0 & \cos(\phi) \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x - w_x \\ y - w_y \\ z - w_z \end{bmatrix}_W + \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} \quad (1)$$

The transformed path in P frame is send to the printer control system where actuation takes place. The control unit of the 5-axis 3D printer is designed to receive commands of positions X, Y, Z, rotations θ and ϕ and filament extrusion E.

Additive manufacturing of parts with overhangs

Complex parts used in various applications can have overhanging regions that necessitates the use of support in AM. The setbacks introduced by the supports has led to research in how the use of support structures can be minimized. Supports, commonly generated as vertical columns, patterns or tree-like structures, are usually minimized to improve AM productivity. Given a design model, usually in STL format, regions requiring supports are identified. Bounding regions (surfaces and edges for meshes), that incline by an angle greater a critical overhang angle, are considered for support generation. Vanek et. al[11] and Mao et.al[12] sampled points at such regions to generate support structures. In horizontal AM case where build direction remains fixed, studies have been carried out to either modify the desired part to reduce support structure or optimize the needed support structures.

By changing general designed model orientation, using multi-objective optimization, Jibin [13] and Pandey et. al.[14] obtained improved part orientation with respect to surface quality, support volume and production time. Optimal direction for simple models has also been studied to minimize geometric dimensioning and tolerancing errors[15]. Recent studies in design for AM have suggested inclusion of support minimization constraint at part design stage using topology optimization[16,17]. Hu et. al. investigated shape optimization and transformation of models to reduce supports. The design of support structure itself has also been studied. The goal is to use the best part orientation and generate the minimum amount of support since fully self-supporting part cannot be guaranteed on a uniaxial AM system.

Manufacturing and analysis of overhang structures

With the ability to change part orientation in the making, several types of overhang structures are fabricated and analyzed in this section. The instances where the outlines of a model slants significantly away from the build direction usually results in rough surface. This is attributed to the fact that the new line of deposited material on the outline may be entirely or partially unsupported. Figure 2 shows the overhang angle θ_0, slicing angle θ_s, and the print platform tilt angle. Free overhangs (Figure 2b), bridges (Figure 2c) and roof components are studied in this paper.

The lack of research and tools in non-planar slicing has been acknowledged[18,19]. Hence most MAAM systems are used to fabricated parts using planer slicers at different build orientation. The overhangs need to be identified as explained in the previous section. Moreover, for MAAM, the model is required to be partitioned after identification of support requirement. Lee et. al.[20] used adjacent layer features classification to label features and partition them into buildable and unbuildable regions. In this study, the overhang features are predesigned separately to investigate them. A common two-pass printing path is used to fabricate the overhang structures. The path obtained directly from the analytical model of an overhang part using a developed Rhino plugin. A solid overhang model, in STEP or IGES file format, is first selected. After the starting layer is specified, the plugin generates the 3D printing paths.

The three types of overhang parts considered can be constructed in similar matter. It is observed that fabrication of bridge components is harder than roof components because roofs are supported at the sides. The side supports on roofs makes deposition of each raster easier due to the supports on both ends. Also, the free hanging component can be manufactured using similar design with the bridge, with elimination of the end wall. Hence, the analysis of overhang structures is carried out using the model in Figure 2a. Small variation in the design is used to study roof and free-hanging parts. The free-hanging part does not require collision check like the bridge component. The filament used is Colorfabb PETG filament of diameter 1.75. Fabrication of the base region of the designed model that holds the overhang structures is fabricated using normal horizontal AM using Simplify3D® for g-code generation.

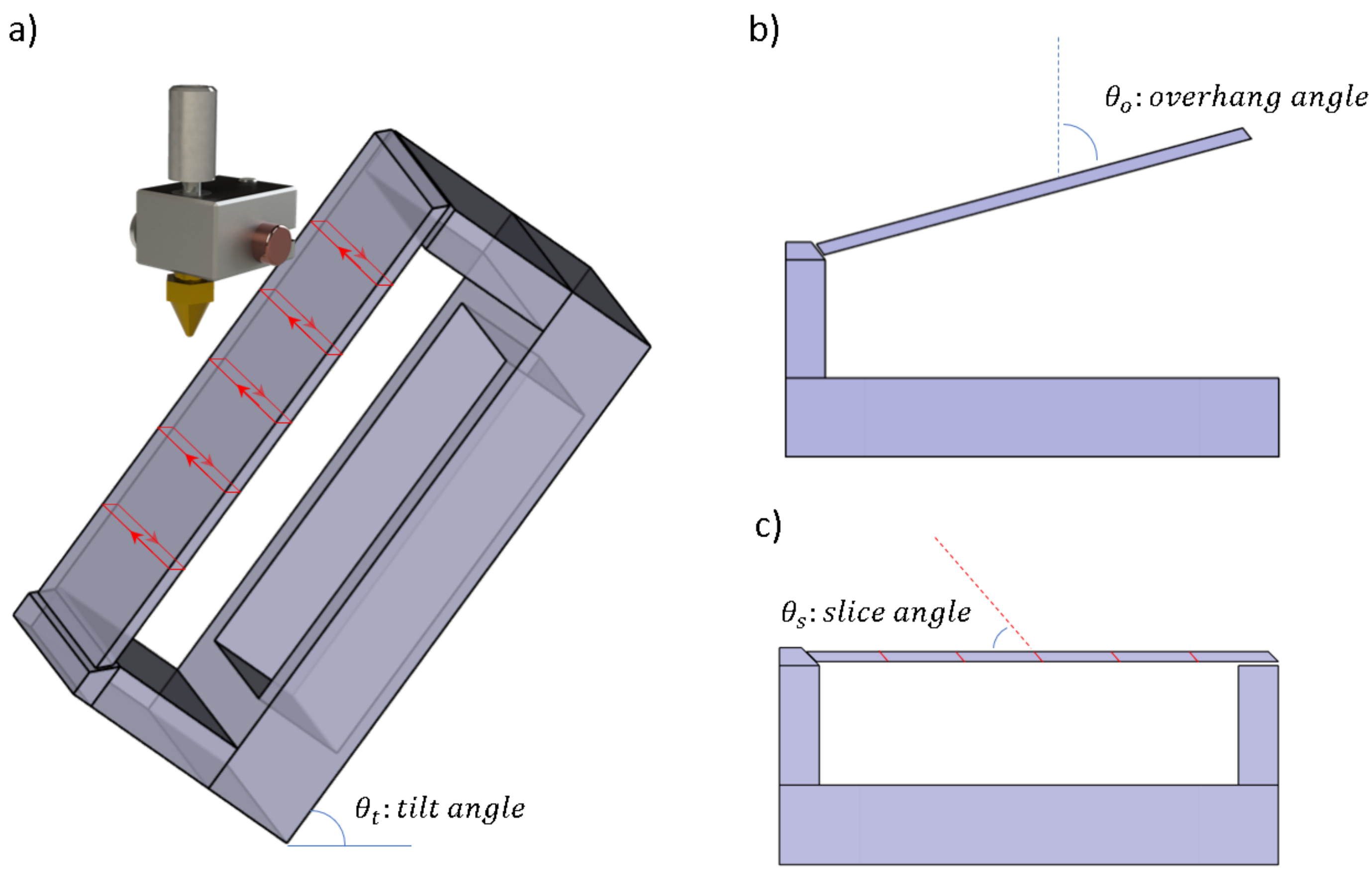

Figure 2:Demonstration of a) the slice path and tilt angle used in manufacturing thin overhang components, b) overhang angle definition for an overhang, c) slice angle which is equated with the tilt angle

The bridge component introduced has an overhang angle of 90^0. For bridge length greater than 10mm[21], there should be added supports to prevent deposition on air. Upon tilting the bridge, the effective overhang (θ_e) can be decreased $\theta_e = \theta_0 - \theta_t$. The tilt angle is chosen to be equal to the slice angle. For slice angles ranging from 25^0 to 70^0, the bridge component is manufactured.

Figures 3a and 3b shows an overhang fabrication with high and low slice angles respectively. While deposited material in Figure 3a rests on a rigid layer, the one in Figure 3b hardly touches the bridge with insufficient support. Another issue with low slice angle is the blade-like ends. The sharp end of the low slice angle bridge makes the supporting structure less rigid and less heat dissipative. Hence, for small slice angles, the tip of the bridge during fabrication is fragile and neither supports the deposited material nor dissipate the heat away from the nozzle. The top surface of the component is analyzed using contact type CMM with Renishaw MH 20 probe of 1mm diameter, as shown in Figure 3c. It is used to study the form of the bridge surface at various slice angle.

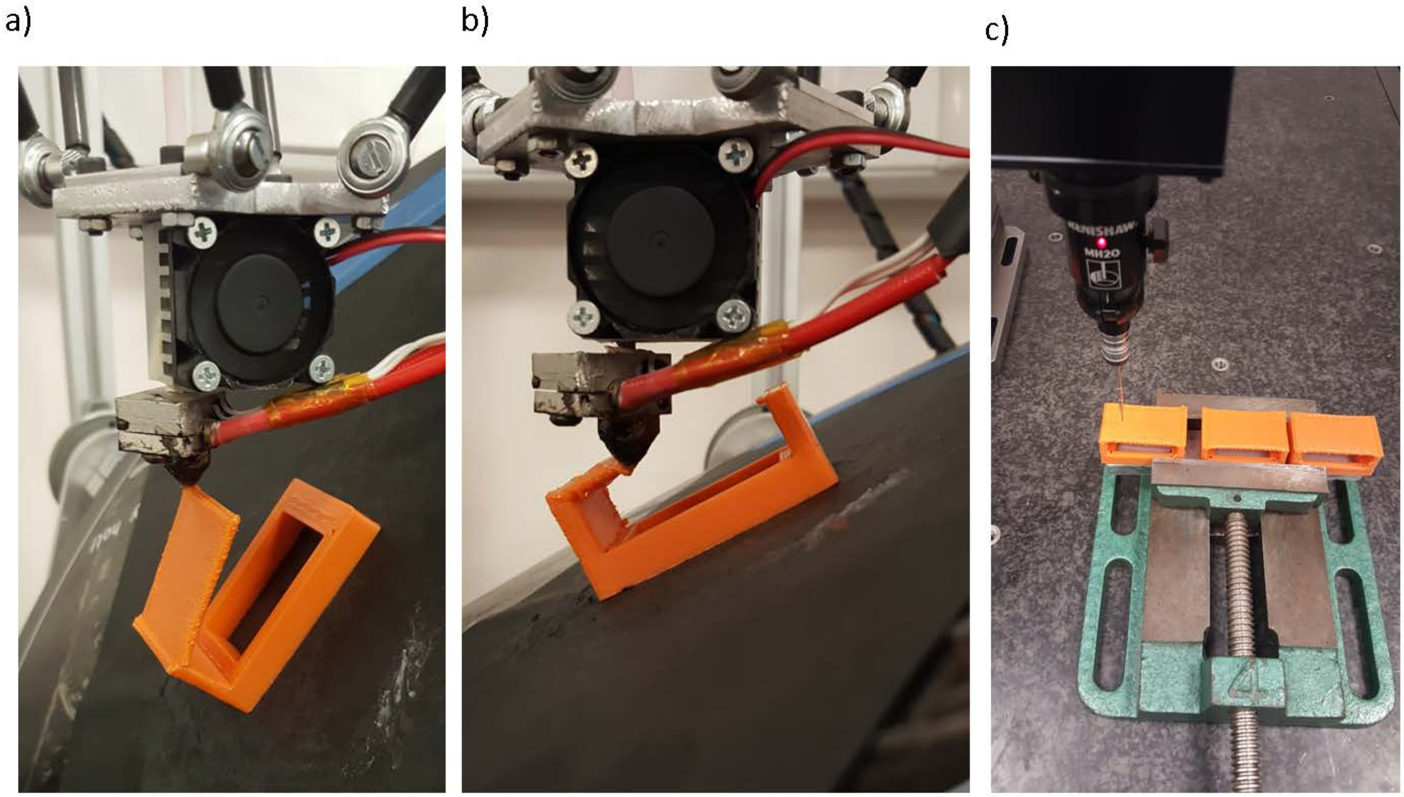

Figure 3:Fabrication of a) part with high slice angle, b) low slice angle using 5-Axis AM 3D printer. c) CMM measurement of surface deviation of sample parts

The CMM results of four slice angles are shown in Figure 4. Around 150 points are sampled from each surface and the deviations from the expected planar surface are analyzed. From the results found, it is observed that it is not only the surface roughness that is affected by slice angle[9], but also the overall shape of the surface. The complete results of average deviations from the plane at different slice angle is given in Figure 5.

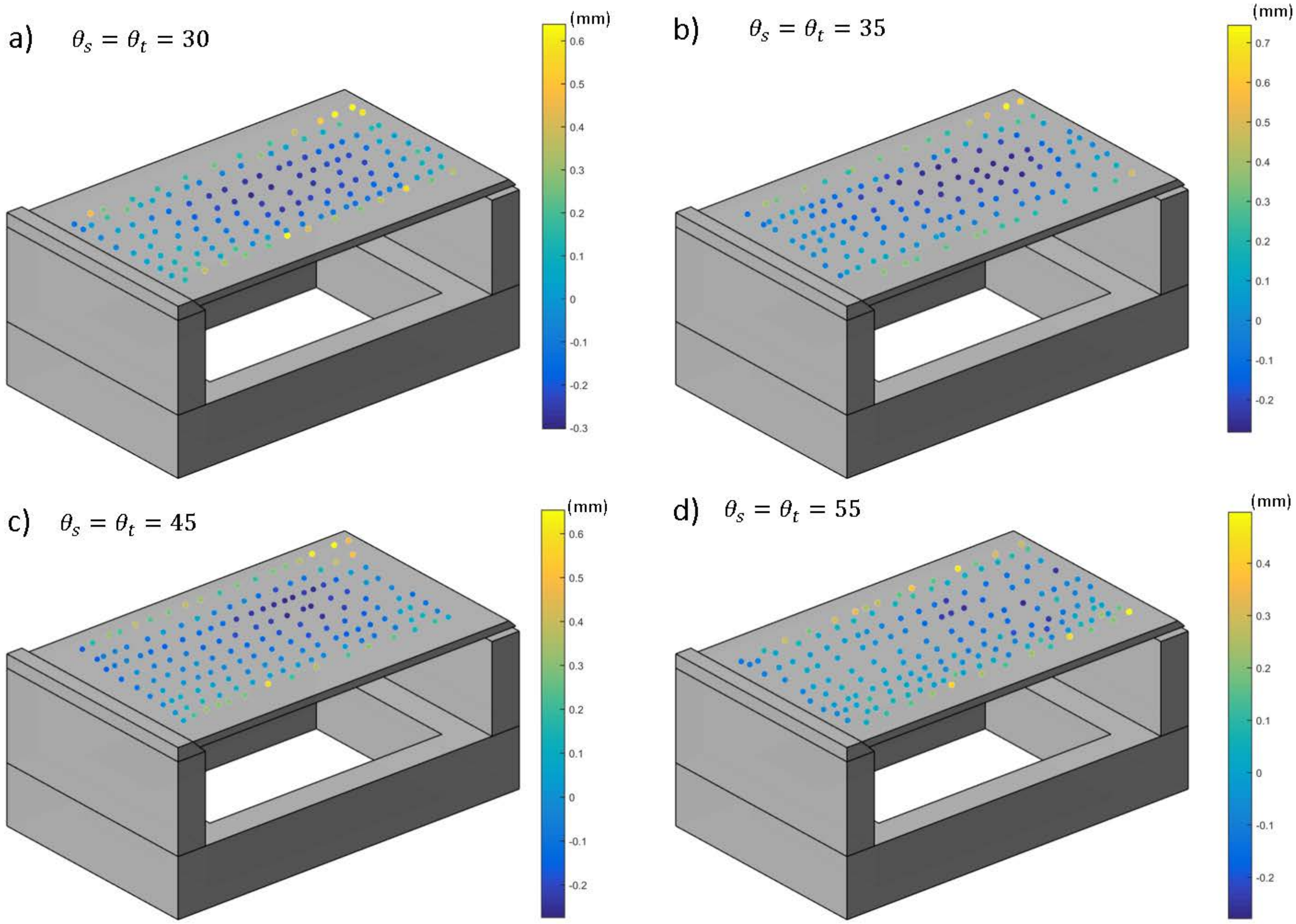

Figure 4: Error distribution at sample points on the top surface of the fabricated overhangs for various tilt angles. At the sides where the nozzle turns, there are extra accumulation resulting in elevation. The range of deviation in error shrinks when the tilt angle is increased

Some similarities are observed in Figure 4. There a is common dent at the center of the bridges and sides of the bridges are raised. Since the bridge parts are thin, the motion of the nozzle at the sides carries unsolidified material to form a fold shown in Figure 6. This is what accounts for the raised sides. Figure 6 also shows that the folding phenomenon also decreases as the tilt angle is increased. It can also be observed that this behavior does not exist on the roof sample because of the side walls that increase heat dissipation at the side corners of the roof. For the roof sample that is fabricated at slice angle of 40^0, the average deviation is 0.051mm. This is less than all the bridge samples measured.

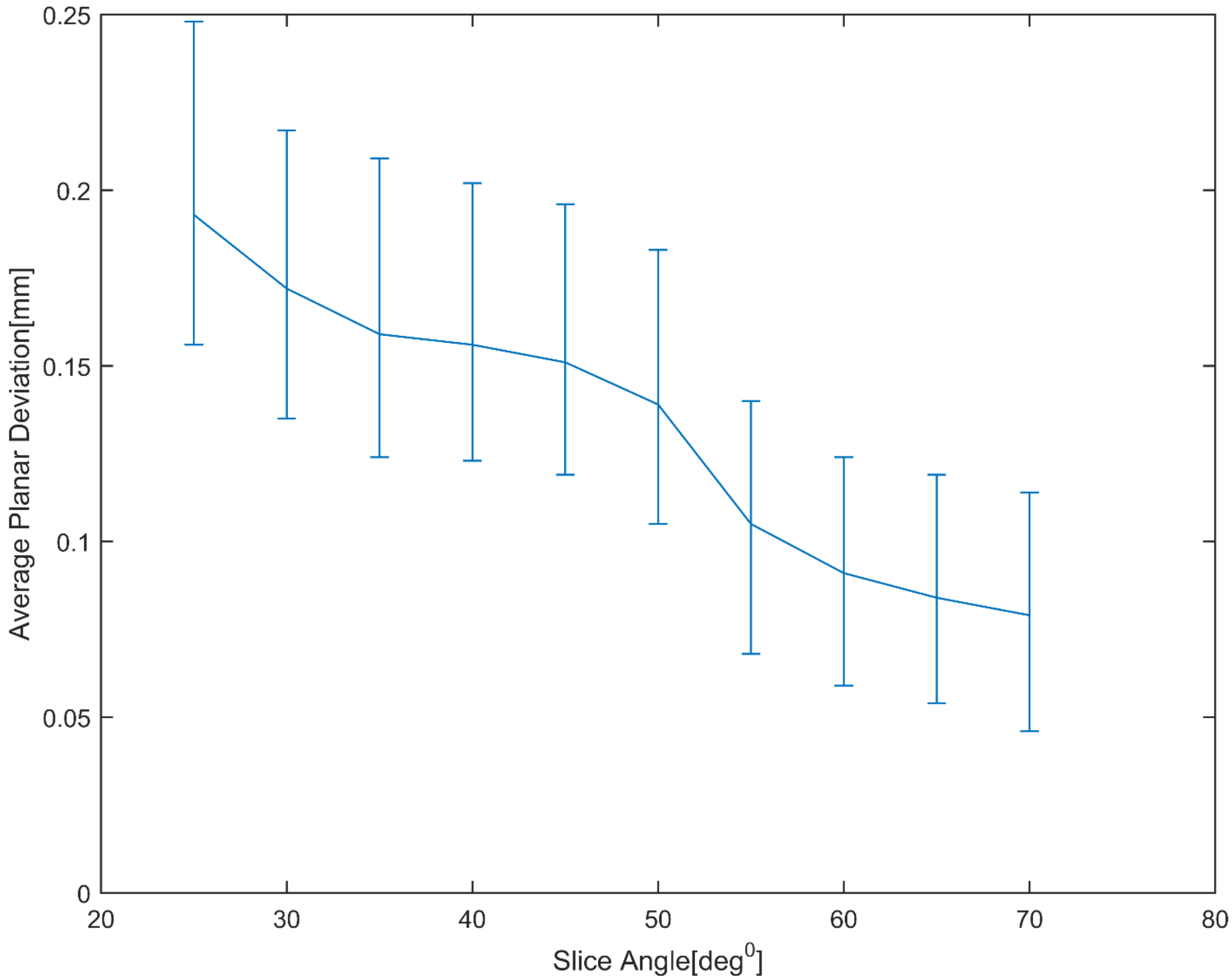

Figure 5:Plot of average planar deviation on bridge components. These are the errors of the manufactured surface measured with the desired CAD model of the bridging overhangs

The shape deviation plot in Figure 5 is obtained using repeated measurements from two samples of each part at the slice angles. The deviations of the fabricated surface from the ideal model are analyzed in MATLAB.

The higher the slice angle (which is set to match the tilt angle), the lower the effective overhang angle, which is expected to produce better surface. The tilt angle serves the purpose of changing the part's altering the build direction on the part. From the work of Zhao et.al.[9], where the slice angle and overhang angles are studied, there are combinations of the slice and overhang angles that lead to failure in part fabrication. In the paper, part failures are classified into two types. For slice angles that deviate too much from the overhang angle, the mode of failure is collapse failure. The other failure mode is the adhesion failure where slice planes deviate from the build direction. The adhesion failure is completely resolved by multi-axis AM in this paper. The collapse failure can be avoided by choosing appropriate slice angles. Introduction of tilt angle in this article expands the possible fabrication ranges of the slice and overhang angles.

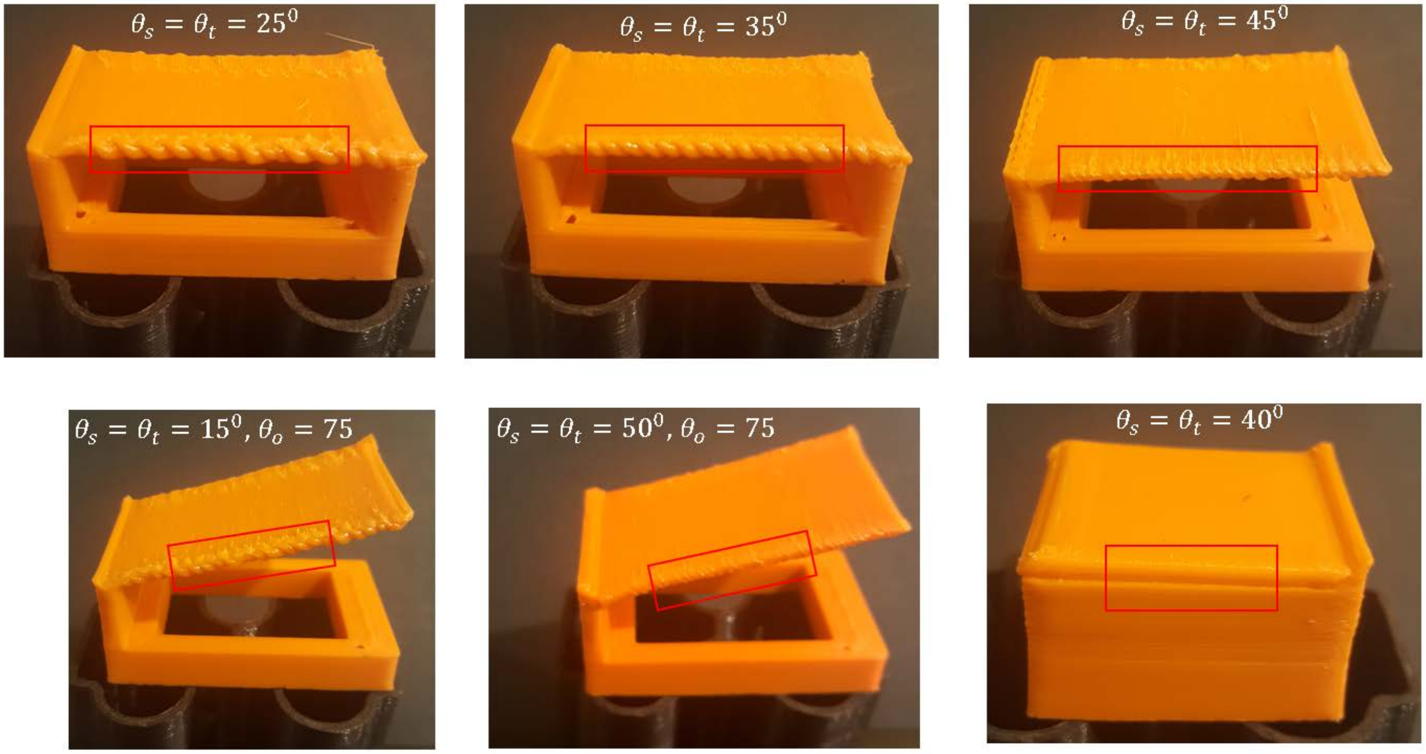

Figure 6: Image of sample overhang parts showing bridge, free hanging and roof components. Marked regions show the possible occurrence of folds. As the tilt angle is increased, the build building condition of the overhang improves, and better parts are produced

The path planning script enables manufacturing of freeform overhang structures as well. This is because the AM toolpaths are obtained from the actual overhang geometry surface. For a curved surface, a new angle θ is introduced as indicated in Figure 7a. The angle defines the tool orientation. It is chosen and fixed from the local surface normal direction while maintaining perpendicularity with the relative tool velocity vector. An identical two-pass paths are generated in each layer using 3D curves on the overhang surfaces. Figures 7b and c show error measurement and fabrication of a freeform roof component respectively. The surface normal relative tool direction is 40^0. A flat roof fabricated with the same angle in Figure 7d is shown to have less error in Figure 7e.

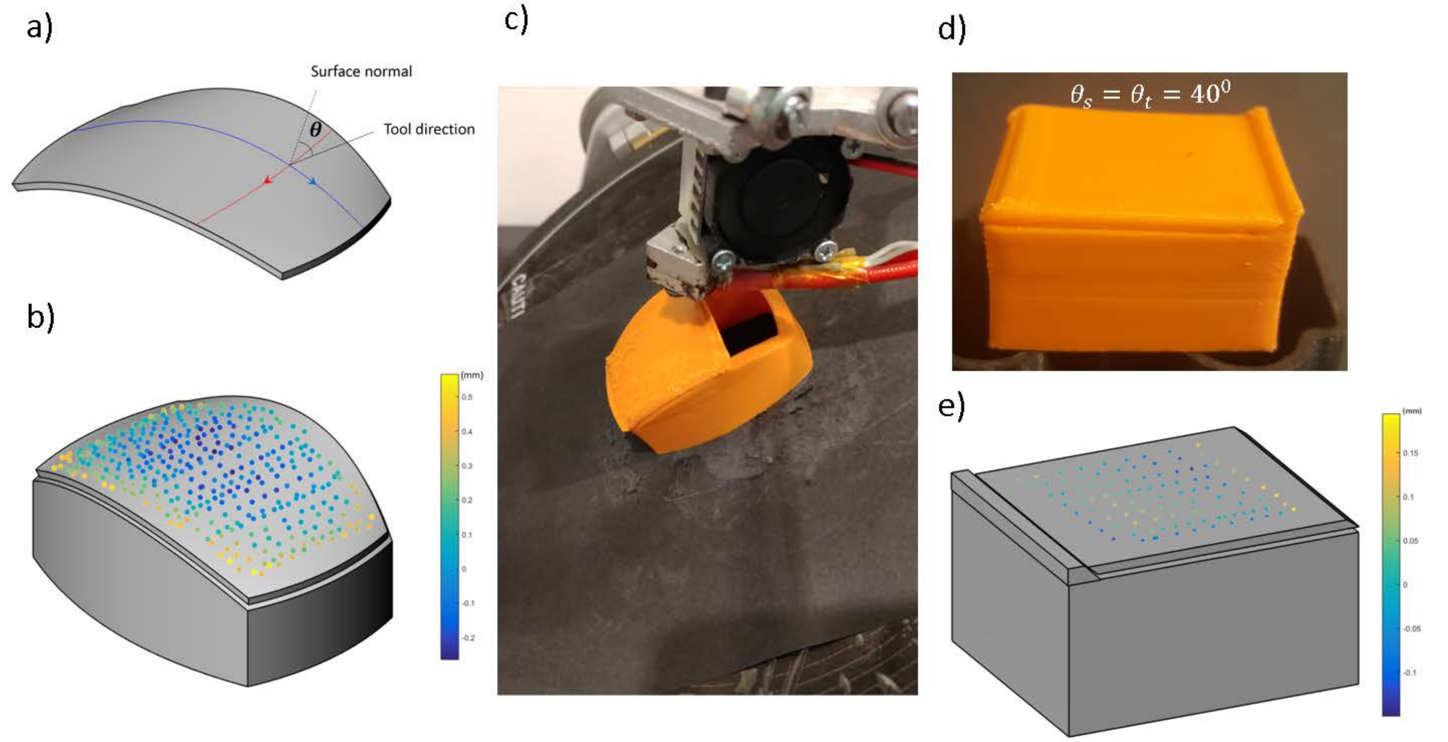

Figure 7: a) A freeform model where surface is used to generate AM toolpath with fixed tool orientation from the local normal b) Error of produced part surface from the designed model in a. c)The freeform roof in a is being fabricated on the 5-Axis AM system with 40^0 tool direction from the normal d) A flat roofing overhang components manufactured at 40^0 e) Error distribution on the flat surface of the roof in d.

Conclusion

The effects of changes in build direction on the shape of overhang features are studied in this paper. The slice angle is matched with each build direction to study the effect on the shape of overhangs. For an overhang angle of 90^0, the inclined layer slicing can only be used for slice angles between 40 to 50 degrees. However, using a changing build direction, thin overhangs are produced with slice angles from 25 degrees and above. It is shown that with the aid of tilting, slice angles from 25^0 angle and above is obtainable using a PETG filament.

Some factors that can affect the test like overhang thickness, printing temperature, filament feed rate and speed are kept constant for all the tests. Analytical and numerical thermomechanical modeling of the overhang parts can be used to study the part deformations. A good knowledge of overhang fabrication without support can improve production time, reduce postprocessing labor and decrease material usage.

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