Resource based build direction in additive manufacturing processes

Nazmul Ahsan, Ahasan Habib and Bashir Khoda*
Industrial & Manufacturing Engineering Dept.
North Dakota State University, Fargo, ND 58104, USA
Email: akm.khoda@ndsu.edu

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Abstract

Three dimensional free-form geometric shapes can be built by putting layers upon layer in a predefined direction via Additive Manufacturing (AM) processes. The fabrication processes require computational as well as physical resources and can vary not only upon the product but its process plan. Overly simplified process plan may expedite the pre-fabrication techniques, but may create difficulty during fabrication of those slices. For an example, slices with concavity or discrete contour plurality may introduce deposition discontinuity, over deposition, and higher build time during the fabrication. These issues demand more resources there by affecting the part quality and fabrication cost. In this work, we focus upon the build direction of AM process plan to address the fabrication and resource utilization. First, a set of uniform build direction is identified and the object is discretized using a set of critical points considering the object concavity along the build direction. Cutting planes are generated and the object is discretized into strips and each strip is analyzed for contour plurality and the build directions are quantified through the allocation of importance factors. The optimal build direction thus found will result in lowest possible fabrication complexity. The proposed methodology is implemented and presented with a sample example in this paper.

1. Introduction

Layer based additive manufacturing (AM) is a process of making a three dimensional solid object by depositing the material layer upon layer from a digitized model. The digital object model is usually constructed using a CAD modeler or reverse engineering techniques. The validated model needs to be sliced with a set of intersecting parallel planes perpendicular to a predetermined build direction along which the layers are placed one upon another. Thus, the 3D model is discretized into a set of closed 2D slice contours generated from the intersection between the 3D geometric model of the object and the planes. Material is added within these sliced contours and object is built by putting those consecutively.

Considering the desired attributes in the process and the product, the process planning steps can be dramatically simplified in the layer-based manufacturing approach. Such attributes includes number of layers, their shape and size, single or multiple contour in a slice, support material, functionality, build time, cost, accuracy, and surface quality [1]. Each of these attributes depends upon the execution of the process steps. The effect of these attributes is carried out between steps towards the finished object. Thus, each of the AM process steps are equally important and can have significant impact on the attributes of the manufactured part. But due to their hierarchical relationship, predecessor process steps have more influence on the finished product than their successor. Figure 1 shows the hierarchical process planning steps to fabricate an object with additive manufacturing techniques.

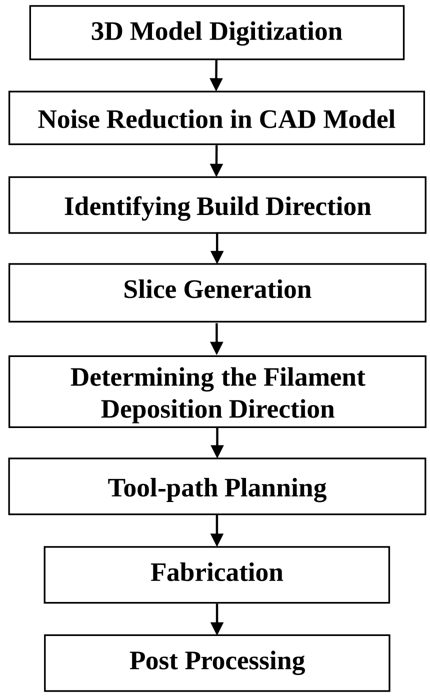


Figure 1.Hierarchical process plan for additive manufacturing.

Build direction is defined by the perpendicular vector on the imaginary plane for material deposition. It can also be considered as the part augmentation vector between bottom and top layer of fabrication. Build direction attracted least attention from the AM research community and more or less considered as a user defined parameter [2]. The most common assumption about build direction is that, it affects the build time and the volume of support structure required during fabrication [3]. However, surface quality may also depends upon the better build direction [4]. Alexander *et al*. [3] determined build direction by maximizing the external surface accuracy through minimizing the average weighted cusp height. In bottom up AM technique, which requires support structure, the build direction is often confined with the planar (flat) surfaces of the object [5-7] as base for the ease of supporting the object itself. Often time, build direction also associated with slice number [6] to control the build time attribute.

Xu *et al.* [8] proposed the selection of an optimum building direction considering the differences of building inaccuracy, surface finish, the manufacturing time and cost for multiple additive manufacturing processes. A trust region optimization method [9] is introduced to determine the optimum build direction that minimizes the surface roughness, build time and support structure. An empirical knowledge based expert system tool uses the expert questionnaire for decision matrix [10] which helps to establish the optimum or near optimal build direction. The fabrication issue such as volumetric error [11] during deposition is also been considered to find out an appropriate build direction. The work is done considering the basic primitive volume approach for constructing simple parts and then combined it to a complex shape. A multi-objective optimization method [12] is proposed to achieve good surface finish, accuracy and minimum build time.

Surface finish and build time are often time two contradictory concerns where the compromises of both are needed in AM. A research performing how minimum build time can result a good surface finish is demonstrated [13]. This work has been accomplished by a real coded genetic algorithm. Moreover dimensional accuracy and build time have been considered to determine the optimum build direction by Cheng *et al.*[14]. In this work the dimensional accuracy and the build time was the primary and the secondary objective respectively. Assuring the dimensional accuracy, the build time was minimized by increasing the layer thickness. Lan *et al.*[15] and Hur and Lee [16] considered surface quality, build time or complexity and of the support structures to determine the optimum build direction. Byan et al. [17] and Pham et al. [18] considered build time, surface quality and cost of part to determine the optimum build direction. A proposition of a mathematical model to predict the layered process error considering the fabrication orientation is demonstrated by Lin *et al.* [19] . Thus, build directions are mostly selected to improve factors such as surface finish, build time and volume of support structure required, shrinkage, curling and part cost. But often time build direction is not the sole parameter that affects those factors. In contrast, build direction can solely be represented to create multiple contours for free form shape object in the same layer.

Slicing an object along a predefined build direction creates closed contour called layer. For free form shape object with concave surface, multiple closed contours may be generated for the same layer in particular build direction. Such phenomenon is defined as contour plurality here in this paper. Continuous material deposition gets disrupted with layers with contour plurality and generates start-stop as well as non-deposition time within layers. Such deposition disruption requires machine/deposition system having quick response time, and high precision and resolution which in other word mean more resources. A curve slicing model is proposed to achieve fiber continuity which demonstrate better meso-structure and mechanical characteristics of curved parts [20]. Khoda *et al* [21] proposed computational model for continuous path planning for complex internal architecture. However, we haven't found any attempt so far reported in literature to address the contour plurality issue while determining the build direction in AM process plan. This may increase build time and the discontinuity in the filament and may lower the structural integrity [22]. In this paper, a novel approach of choosing optimal build direction for additive manufacturing is proposed that minimizes contour plurality to compensate the fabrication and resource limitations.

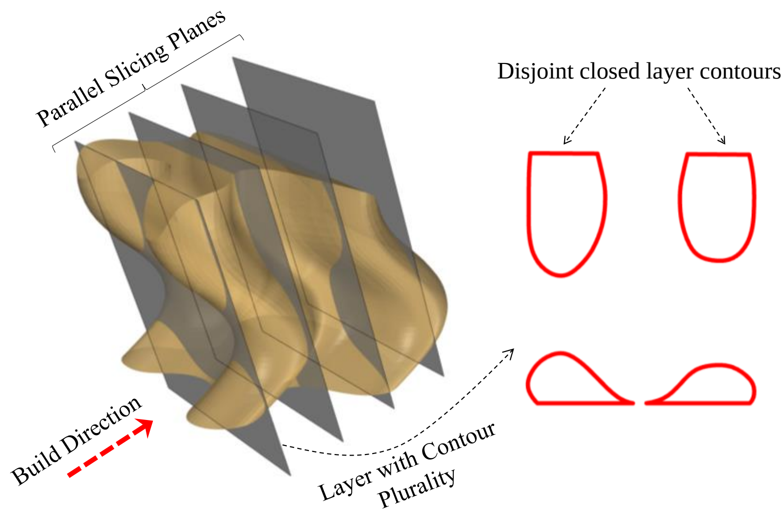


Figure 2. Slicing an object along a build direction and one of the resulting 2D layer contours with contour plurality.

2. Build Direction and Contour Plurality

For a concave object, as shown in figure 2, the slicing operation might end up with some slices which will contain more than one disjoint closed contour within each layer. This phenomenon is termed as contour plurality in this paper. Contour plurality might also happen for objects with internal hollow features. The number of layers with contour plurality is fully dependent upon the build direction. For the same object, the overall contour plurality can be varied with different build directions as shown in figure 3.

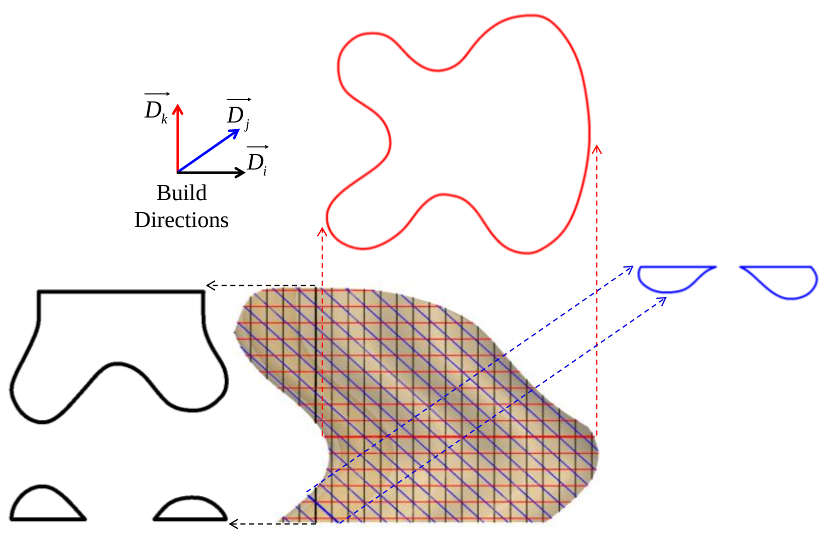


Figure 3. Build direction and contour plurality.

Therefore, choosing an arbitrary build direction could result in most of the layers as contour plurality layers. Whereas, carefully determined build direction for an object can significantly reduce the overall contour plurality throughout the layers. So, the build vector along which the total volume of the object regions having contour plurality layers is minimum can be considered as a favorable build direction. However, the build height is another criterion that is also directly related to the resource requirement and may be affected by the build direction. Increased build height will increase the number of layers, thereby increasing the build time. We have considered the contour plurality as primary criterion and build height as the secondary criterion while finding out the proper build direction. An optimization algorithm is proposed to determine a build direction favorable to resources considering contour plurality and build height.

3. Quantification of Contour Plurality

To quantify the contour plurality in layers, first we have generated a build direction through coordinate system transformation. Then the object volume is discretized considering the contour plurality along the build direction. This analysis is repeated for a number of build directions to quantify their effects on contour plurality as well as build height.

In 3D Euclidian space $\Re^3$, build direction can be represented as a 3D vector $\overrightarrow{D_i} = [x_i, y_i, z_i] \in \Re^3, \forall i = 0,\ldots,n.$ To determine a set of build vectors $\{\overrightarrow{D_i}\}_{i=1,\ldots,n}$ the global coordinate system is rotated through ψ and φ angles around Z and Y axes respectively [23] which can be represented by the following equation.

$$[x'_i, y'_i, z'_i] = [x_i \quad y_i \quad z_i].R_z(\psi).R_y(\varphi) \in \Re^3; \quad \psi = [-\pi/2, \pi/2], \varphi = [0, 2\pi]; \quad \forall i \tag{1}$$

Here, $R_z(\psi)$ and $R_y(\varphi)$ denote the rotation around Z and Y axis through ψ and φ angles, respectively. Here, $[x'_i, y'_i, z'_i]$ represents the transformed coordinate system and the Z'_i axis vector $\hat{z}_i$ is considered as the corresponding build vector $\overrightarrow{D_i}$. The 3D geometric model object is sliced by a set of intersecting parallel planes perpendicular to the corresponding build direction $\overrightarrow{D_i}$.

At any build direction $\overrightarrow{D_i}$, the object is discretized by a set of parallel planes $P_k^i = \{aX'_{i,k} + bY'_{i,k} + cZ'_{i,k} = \text{Constant}\}_{k=1,\ldots,K}$ intersecting the object surface. The parametric surface $S(u'_i, v'_i) \subset \Re^3$ of the object can be represented with parameter u'_i and v'_i where $u'_i, v'_i \in [a_i, b_i]$. A set of finite number (L) of points $\mathbf{P_i} = \{p_l^i = (x_l^i, y_l^i, z_l^i)\}_{l=1,\ldots,L}, \forall i$ associated with the corresponding parametric values $\mathbf{q_i} = \{(u'_{i,l}, v'_{i,l})\}_{l=1,\ldots,L}, \forall i$ is picked on the surface $S(u'_i, v'_i)$. For all these sampled points, the unit surface normal vectors $\vec{N}_l^i$ are determined which can be defined by equation (2).

$$\vec{N}_l^i = \frac{S_{u_i}(u'_{i,l}, v'_{i,l}) \times S_{v_i}(u'_{i,l}, v'_{i,l})}{\left| S_{u_i}(u'_{i,l}, v'_{i,l}) \times S_{v_i}(u'_{i,l}, v'_{i,l}) \right|}, \; l = 1,\ldots,L; \; \forall i \tag{2}$$

Where $S_{u_i}(u'_{i,l}, v'_{i,l}) = \dfrac{\partial S(u'_{i,l}, v'_{i,l})}{\partial u_{i,l}}$ and $S_{v_i}(u'_{i,l}, v'_{i,l}) = \dfrac{\partial S(u'_{i,l}, v'_{i,l})}{\partial v_{i,l}}$. A point is defined as critical point CP, if $S_{u_i}(u'_{i,l}, v'_{i,l}) = 0$ or $S_{v_i}(u'_{i,l}, v'_{i,l}) = 0$. Thus, a new point set $\mathbf{CP_i} = \{cp^i_m\}_{m=1,\ldots,M} \subset \mathbf{P_i}$ containing only the critical points is formed. The critical points are, therefore, the extreme points on the surface with respect to the build direction and have corresponding surface normals parallel to the build vector. A sorted critical point set $\mathbf{SCP}_i = \{scp^i_t\}_{t=1,\ldots,T} \subset \mathbf{CP_i}$ is constructed through sorting the points along the build direction $\overrightarrow{D_i}$. A rectilinear 3D bounding box [23] is constructed along the transformed coordinate system using the point set $\mathbf{V_i}$ defined by equation (3).

$$\mathbf{V_i} = \left\{ \begin{array}{l} pt^i_1 = (x'_{i,\min}, y'_{i,\min}, z'_{i,\min}), \\ pt^i_2 = (x'_{i,\max}, y'_{i,\min}, z'_{i,\min}), \\ pt^i_3 = (x'_{i,\max}, y'_{i,\max}, z'_{i,\min}), \\ pt^i_4 = (x'_{i,\min}, y'_{i,\max}, z'_{i,\min}), \\ pt^i_5 = (x'_{i,\min}, y'_{i,\min}, z'_{i,\max}), \\ pt^i_6 = (x'_{i,\max}, y'_{i,\min}, z'_{i,\max}), \\ pt^i_7 = (x'_{i,\max}, y'_{i,\max}, z'_{i,\max}), \\ pt^i_8 = (x'_{i,\min}, y'_{i,\max}, z'_{i,\max}) \end{array} \right\}, \forall i \tag{3}$$

Here, $x'_{i,\min}$ and $x'_{i,\max}$ denote the minimum and maximum extents of the part surface along the transformed X' axis and so on. The plane perpendicular to $\hat{z}_i$ is considered as the base plane as shown in figure 4.

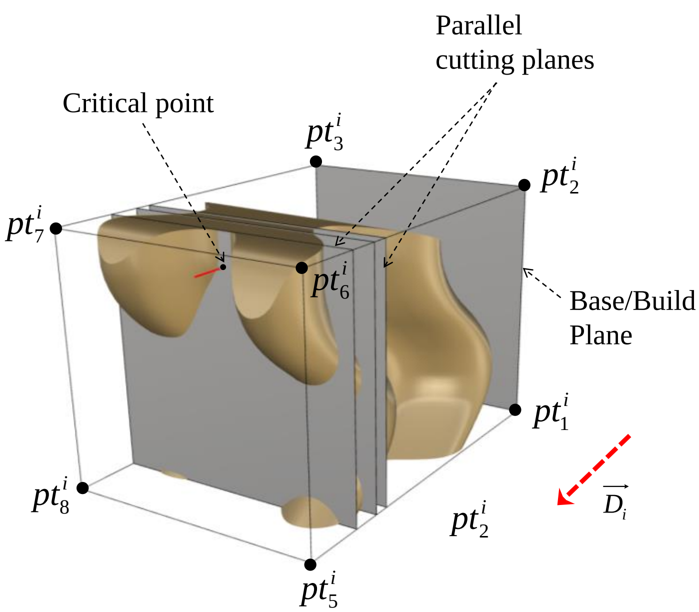


Figure 4. Bounding box and cutting plane generation through critical point.

A set of T number of cutting planes $\mathbf{CPL_i} = \{cpl_t^i\}_{t=1,\dots,T}$ are generated through the sorted critical point set $\mathbf{SCP}_i$ using equation (4), which are parallel to the base plane.

$$[\cos\psi.\cos\varphi \quad \sin\psi \quad -\cos\psi.\sin\varphi].\begin{bmatrix} X_i' - x_{i,\min}' \\ Y_i' - y_{i,\min}' \\ Z_i' - z_{i,\min\,i}' \end{bmatrix} = 0 \qquad (4)$$

After generating the cutting planes, the object volume between the consecutive planes need to be evaluated for contour plurality. The part is split into $(T-1)$ strips with the generated parallel cutting planes forming the strip set $\mathbf{ST}_i = \{st_r^i\}_{r=1,\dots,T-1}$. The total part volume generated between two consecutive parallel cutting planes cpl_t^i and cpl_{t+1}^i is termed as a part strip. If any strip contains more than one part splits as shown in figure 5, that part strip will comprise the layers with contour plurality along the corresponding build direction. So all the generated stripes are analyzed for contour plurality and a weight is determined for the corresponding build direction.

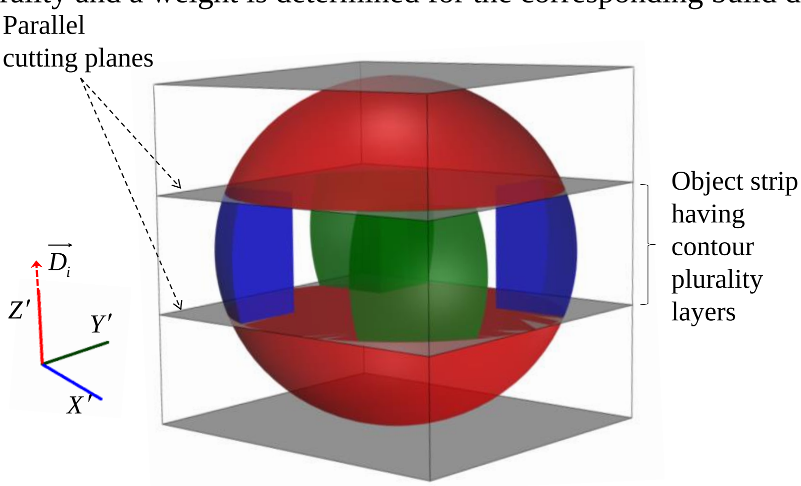


Figure 5. Cutting plane and contour plurality in strip.

The part strips generated by the parallel cutting planes can be classified as mono-split strip (red strips shown in figure 5) and multi-split strip (middle strip shown in figure 5) depending on the number of split part-volumes generated in the corresponding strip. Multi-split strip may be generated if there is any concavity on the part surface or the part has hollow feature inside it. Thus, a build direction needs to be identified along which the total volume of the multi-split strips in regard to the total part volume would be minimum. Similarly, build height which usually changes with build direction directly affects the build time. Larger build height requires longer build time. While determining a desirable build direction considering contour plurality criterion, it is also necessary to ensure that the build direction does not lead to a considerably higher build height.

The overall weight for the build direction will be the weighted sum of the volume ratio of the split part-volume and the normalized build height and can be symbolized as-

$$Weight\_BD_i = \left(\frac{\sum_{r=1}^{T-1} vol\_st_r^i}{vol\_part} \times W_{CP}\right) + \left(\frac{BH_i}{\max\{BH_i\}_{i=1,\dots,n}} \times W_{BH}\right), \quad \forall \text{i} \tag{5}$$

Here, $vol\_st_r^i$ is the volume of r^{th} strip determined for i^{th} build direction, vol_part is the total volume of the part. The build height $BH_i = z'_{i,\max} - z'_{i,\min}$, $Weight\_BD_i$ is overall weight determined for the build direction $\overrightarrow{D_i}$. W_{CP} and W_{BH} are the user defined weights assigned for contour plurality and build height, respectively. For some objects, the contour plurality is more important than the build height and for some objects the converse is true. Hence, these two weight values are selected based on the priorities of the two criteria judged by the user. Finally, the optimum build direction can be determined solving the following minimization problem-

$$\min \{Weight\_BD_i\}_{i=1,\dots,n}$$

Subject to,

$$\begin{aligned} &\overrightarrow{D_i} := \hat{z}_i \\ &\psi = [-\pi/2, \pi/2] \\ &\varphi = [0, 2\pi] \\ &W_{CP} + W_{BH} = 1 \end{aligned} \tag{6}$$

$\{Weight\_BD_i\}_{i=1,\dots,n}$ is the set of overall weights of the build directions determined for every interval of ψ and φ within their domain and the most favorable build direction would be the direction giving the minimum value of the overall weight.

4. Implementation

The proposed methodology is implemented for two objects with a 3.4 GHz core i7 PC using Visual Basic scripting language. A greedy heuristic is used to determine the optimum build direction quickly from equation (6). First a candidate set of build directions (ψ, φ) is formed for uniform α interval of both ψ and φ. Those build directions are evaluated based on the objective function presented in equation (5) and the angles ψ' and φ' that reduce the overall weight by the greatest amount is selected. The neighborhood of ψ' and φ' spread over $\psi' \pm \gamma$ and $\varphi' \pm \gamma$ range is then explored with higher resolution β, where $\beta << \alpha$. The angle pair (ψ^*, φ^*) that yields the minimum overall weight is selected as the optimal build direction.

For visual purpose we have used different colors on different segments of the first object as shown in figure 5. Because of its spherical shape, the build height of this object will not vary significantly with the change in build direction. Hence, the weights assigned for contour plurality and build height in equation (5) are considered as 70% and 30%, respectively. α, β, and γ are taken as 10°, 1°, and 5°, respectively. According to the proposed algorithm, the optimum build direction (shown in figure 6) is determined as $\psi^* = 30°, \varphi^* = 102°$ in which 16% of the layers contain contour plurality and their volume is less than 10% of the total object volume. To justify, we have used commercial software (CatalystEX by Stratasys) to determine the time required to build the object.

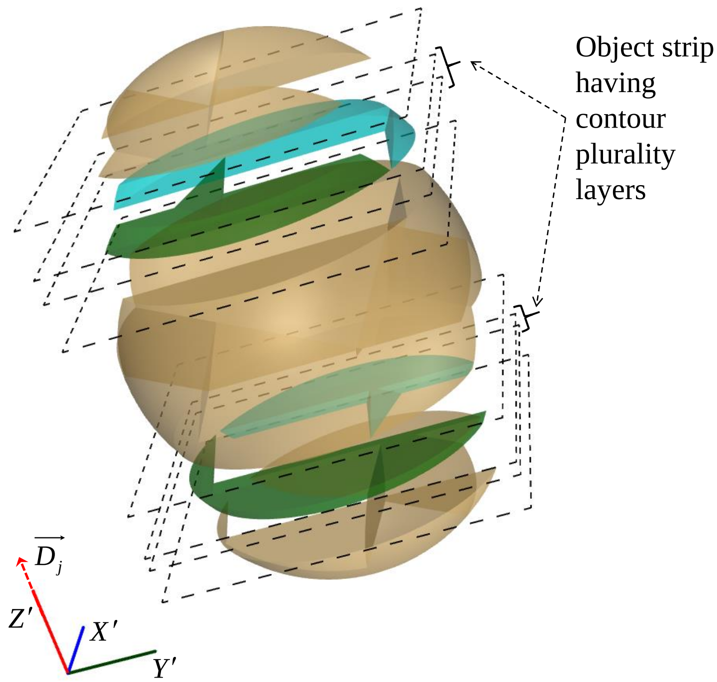
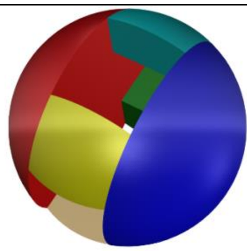
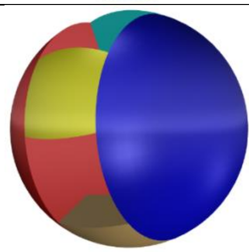
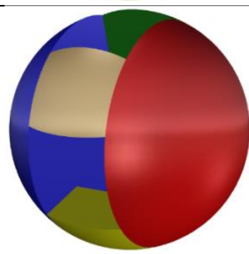


Figure 6. Strips along optimum build direction.

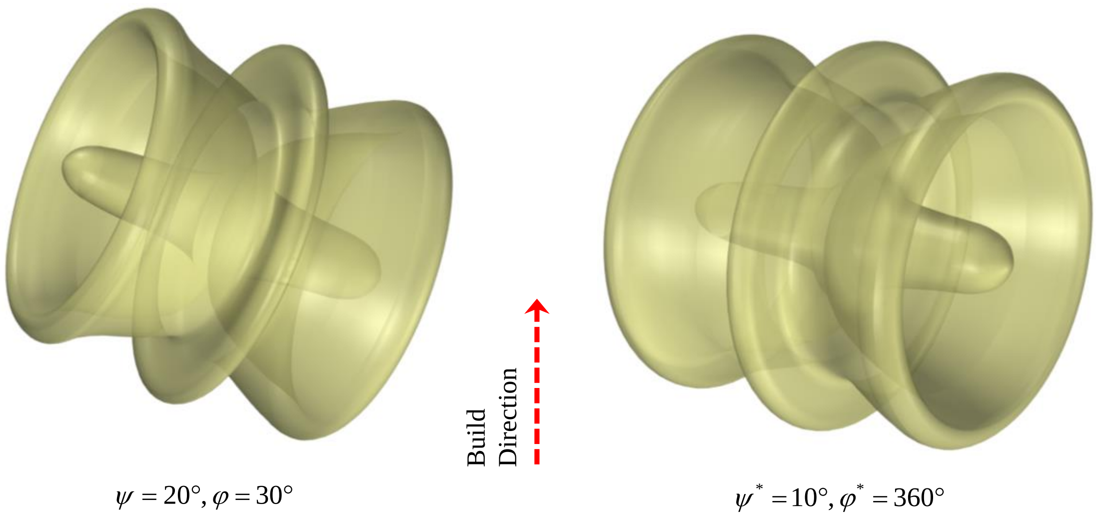
CatalystEX is designed to support Dimension 1200 FDM machine, which employs a polymeric material extrusion based additive manufacturing process. The machine consists two deposition nozzles for build and support material to fabricate the part. Thus, time generated by the CatalystEX software contains both build and support material time. To differentiate the build material time, we interpolate among the time of three different support material densities (minimal, basic and surround) for the same object along the same direction. Table 1 summarizes the result from the optimum build direction with two arbitrary build directions. As shown in the table, the optimum direction requires 13% less time compared to an arbitrary direction $\psi = 0°, \varphi = 260°$.

As shown in table 1, the optimum build direction $\psi = 30°, \varphi = 102°$ results in 48 layers with contour plurality and the build time is 405 minutes which is the lowest possible contour plurality and the build time for the given object. Though the percentage of layers containing contour plurality along $\psi = 0°, \varphi = 70°$ direction is maximum, the build time is comparatively lower than the build direction along $\psi = 0°, \varphi = 260°$. The reason may be some layers are containing more than two contour pluralities along this build direction.

Table 1. Output parameters for different build directions

Build Angle, (ψ, φ)	Oriented object	Number of contour plurality layers	% Slices	Volume of contour plurality in mm^3	% volume	Build Time in minutes
$(30°, 102°)$ *Optimum		48	15.9%	237.31	9.40%	405
$(0°, 70°)$		172	56.95%	1528.66	61%	424
$(0°, 260°)$		168	55.63%	1279.31	51.50%	465

For the second object shown in figure 7(a), both W_{CP} and W_{BH} are assumed as 50%. Like the first example, the same values of $\alpha, \beta,$ and γ are used for this object. The proposed methodology gives the optimum build direction as $\psi^* = 10°, \varphi^* = 360°$ (shown in figure 7(b)). Along this optimum build direction, 23% of the layers contain contour plurality and their volume is around 20% of the total object volume. Compared to an arbitrary direction $\psi = 20°, \varphi = 30°$, this optimum direction results in 8% lower build time.



(a) (b)

Figure 7. Object oriented along (a) an arbitrary and (b) optimum build direction.

5. Conclusion

A resource based build direction determination algorithm is proposed which considers contour plurality and build height. Various researches have proposed build direction algorithm for minimizing part quality, time, and support volume. However, multi contour layer requires more resources such as time, machine capability, and computational power which can be significant in case of free form objects. The proposed framework focuses on such areas and shows that it can reduce the number of multi-contour layers and build height that may lead to lower part building time as well as lower fabrication complexity.

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