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FEATURE-BASED SUPPORT GENERATION FOR OPTIMUM PART DEPOSITION ORIENTATION IN FDM

Khairul Fauzi Karim[1], D. Hazry[2], Abdul Halim Zulkifli[1], S. Faiz Ahmed[2], M. Kamran Joyo[2], Zuradzman M. Razlan[2], Khairunizam Wan[2] and Shahriman AB Bakar[2]
[1]Faculty of Mechanical Eng., UiTM (Pulau Pinang), Jalan Permatang Pauh, Permatang Pauh, Pulau Pinang, Malaysia
[2]Centre of Excellence for Unmanned Aerial System (COEUAS) Universiti Malaysia Perlis (UniMAP), Kangar, Perlis, Malaysia
E-Mail: khairulfauzi098@ppinang.uitm.edu.my

ABSTRACT

Support generation is the key technology for Fused Deposition Modeling (FDM) machine. It is dependent on part deposition orientation. Various part deposition orientation results in formation of different support and non-support features. Present work focuses on extracting the support features containing Externally-Supported Features (ESF) which is able to determine the volume and number of support structure. These information are utilized to obtain the optimum part deposition orientation. Artificial Neural Network (ANN) is used to determine the optimum solution. Predictions of the present methodology are in agreement with the results published earlier. The methodology proposed in this work is used to obtain the optimum part deposition orientation automatically and can be implemented in FDM technology.

Keywords: FDM, ANN, part deposition orientation, Externally-Supported Features (ESF).

INTRODUCTION

In Layered Manufacturing (LM), optimum part deposition orientation determination is a crucial task since it effects build time, support structure, dimensional accuracy, surface finish and cost of prototype [1]. In some of LM processes (e.g. FDM and SLA), the determination of part deposition orientation and generation of support structure are interrelated. The support generation depends on the part deposition orientation. The overhanging area of the part which requires support during fabrication process can be determined after the orientation is made. In current LM process planning, part deposition orientation is manually operated and possible to create errors. The best solution to this problem is to automate the selection of part deposition orientation. In concurrent engineering environment, feature based technique can provide the integration of CAD and CAM systems.

Qian and Dutta [2] proposed an algorithm for feature recognition and volume decomposition based on the ACIS geometric 3D modeling kernel. The developed system dealt with interacting feature in LM. Their work showed that the interacting feature exhibits the staircase interaction decreases the quality of surface finish. They also introduced Feature Interaction Loop (FIL) and Feature Interaction Surface (FIS) to characterize the feature interaction for LM with regardless of type of interaction.

Yang *et al*. [3] addressed LM features in the two-direction LM or orthogonal deposition manufacturing (ODM) system by using volumetric approaches. The automatic feature extraction in their work considered both layer and path adjacency from STL model. These approaches decomposed the orthogonal LM features into three different volumetric units known as Self-Supported Volume (SSV), External-Supported Volume (ESV) and Flat Volume (FV). The SSV feature is the feature which does not require the external support structure in fabrication and ESV features is vice versa. FV feature is recognized from each SSV feature in order to improve the staircase error in fabrication process.

In this paper, a feature-based support generation data extraction technique is proposed in FDM. The features are dealt as input in order to automate the selection of the part deposition orientation. Features with respect to the LM process characteristic are extracted using an area difference between top and bottom layers method. First, the externally-supported feature is identified prior to support structure generation. Next, a bottom-top approach is designed to calculate the volumes which require supporting the entire process. At the same time, the system examines the relationship between support structures for determining the number of support structures.

METHODOLOGY AND SYSTEM ORGANIZATION

The 2D slices which are planar polygon consisting of interior and exterior contour rings is produced through a slicing technique when applied to the 3D CAD part model. The interior and exterior contour rings can be differed by the nature of the surrounded areas. The contour rings are identified as exterior and interior when encircles solid and hollow regions, respectively [4]. In the present work the identification of the support feature is based on different area of two slices (i.e. top layer and bottom layer). The use of permissible overhang area to offset the interior and exterior of the bottom layer is introduced.

Permissible Overhang Area (POA) and offset generation

Permissible Overhang Area (POA) [5] is used in present work as the basis for determining whether support features between two slices which have been identified need to be supported or not. POA is based on self-support angle which is defined as an angle where support features have ability to support by them. This angle, overhang area

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of part model layer can be manufactured without support. Figure-1 shows the process of uniform slicing and the formation of support feature. This Figure shows permissible overhang area, POA, built at self-support angle, *α*, and layer thickness, *t*. The maximum self-support angle is 45°. Hence, the maximum width of the POA is equal to the layer thickness.

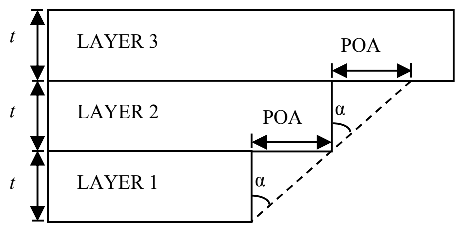

Figure-1. Permissible overhang area, POA, built at self-support angle, *α*, and uniform layer thickness, *t*.

Based on different area of two slices i.e. different area of layers 2 and 1, as well as layers 3 and 2, support features are identified on layers 2 and 3, respectively as shown in Figure-1. Support feature on layer 2 is covered in the POA; hence, it does not need the support volume. The support feature on layer 3 is partially covered in the POA, which require the support volume.

The main idea of the offset generation for the bottom layer due to the permissible overhang area is to offset the exterior and interior rings by a constant distance, *t*. In this algorithm, the exterior contour ring(s) offset outward while the interior ring(s) offset inward as shown in Figures-2(a) and 2(b), respectively. The new unit vectors for exterior rings as given by $\vec{l}_i$ and $\vec{l}_{i+1}$ are obtained from the outward offset of the original position of the vertices enclosure as indentified by V_{i-1}, V_i and V_{i+1} (Figure-2(a)), while those for interior rings are obtained from the inward offset (Figure-2(b)). The offset settings for both outward and inward offset are identified as *t*. L'_i and L'_{i+1} are the equidistant line of L_i and L_{i+1} when offset by *t*, respectively. If $\vec{l}_i$ and $\vec{l}_{i+1}$ are unit vectors of L_i and L_{i+1} respectively, hence the (1), (2) and (3) can be expressed as:

$$\begin{cases} \vec{l}_i = x_i\vec{i} + y_i\vec{j} \\ \vec{l}_{i+1} = x_{i+1}\vec{i} + y_{i+1}\vec{j} \end{cases} \qquad (1)$$

For the inward offsetting for interior rings of bottom layer:

$$\begin{cases} -y_i x + x_i y = t \\ -y_{i+1} x + x_{i+1} y = t \end{cases} \qquad (2)$$

For the outward offsetting for exterior rings of bottom layer:

$$\begin{cases} -y_i x + x_i y = -t \\ -y_{i+1} x + x_{i+1} y = -t \end{cases} \qquad (3)$$

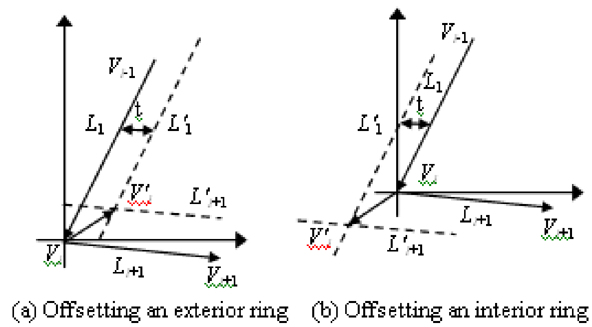

Figure-2. Offsetting a slice.

As $L'_i \nparallel L'_{i+1}$, so $x_i y_{i+1} - x_{i+1} y_i \neq 0$. Thus, by solving (2) and (3) the coordinates can be described as:
The offsetting inward coordinates:

$$(x,y)_{inward} = \left(\frac{(x_{i+1}-x_i)t}{\begin{vmatrix} x_i & y_i \\ y_i & y_{i+1} \end{vmatrix}}, \frac{(y_{i+1}-y_i)t}{\begin{vmatrix} x_i & y_i \\ y_i & y_{i+1} \end{vmatrix}} \right)$$

The offsetting outward coordinates:

$$(x,y)_{outward} = \left(-\frac{(x_{i+1}-x_i)t}{\begin{vmatrix} x_i & y_i \\ y_i & y_{i+1} \end{vmatrix}}, -\frac{(y_{i+1}-y_i)t}{\begin{vmatrix} x_i & y_i \\ y_i & y_{i+1} \end{vmatrix}} \right)$$

Area of new bottom layer due to offsetting generation

The area for new bottom layer due to offsetting generation will be repeated for each pair of layers, in sequence from the Top_most layer to the Bottom_most layer. The generation of a new area of bottom layer due to offsetting operation can be calculated as follows:

$$Area\ of\ new\ Bottom\ Area = POA_{ex} \cup A_{ex} \cup_i^n POA_{in} \qquad (4)$$

where POA_{ex} is the area of POA for exterior contour ring, A_{ex} is the area of the exterior contour ring and POA_{in} is the area of POA for interior contour ring and *n* is the number of interior contour ring.

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Methods of layer adjacency and area difference between Top and Bottom layers for features verification

In FDM LM system, the features need to be identified in order to manufacture successfully. Support structure has to be employed to improve the manufacturability of layers which do not have a layer adjacency or with only partial adjacency in the build direction. Layer adjacency and manufacturability have been discussed in detail by Yang *et al*. [3] in their previous work. In present work, an area difference between top and bottom layers method is proposed.

Figure-3 shows Cross-sectional Slice Region Area (*CSRA*) of subsequence layers for manufacturability of the sample. Layer B will be manufactured followed by layer A. Layer B' is offsetting of layer B. Layer A' is the projection of layer A to layer B in the z direction (as shown in Figures-3(a) and 3(b)).

Case Study 1: ESF support material

For this features as shown in Figure-3(a), if $((A' \cap B)' \cap A') \cap (B')' \neq \varnothing$, then layer A has partial adjacency in the vertical direction from its previous layer B and it needs an external support structure under support feature of layer A so that this layer also gains the adjacency in the building up in the z direction, and is thus manufacturable. By using the area difference between top and bottom layers method, the same result is obtained if $A' - B' > 0$.

Case Study 2: non-adjacency ESF using support material

In this case the layer A does not have the adjacency in the z direction (i.e. if $A' \cap B = \varnothing$), then support feature has been identified as shown in Figure-3(b). Layer A cannot find an adjacency in the vertical direction from its previous layer B, hence, all area contained in layer A is support features. There needs to be an external support structure under entire layer A so that this layer also gains the adjacency in the building up in the z direction, and is thus manufacturable. By using the area difference between top and bottom layers method, the same result is obtained if $A' - B' > 0$.

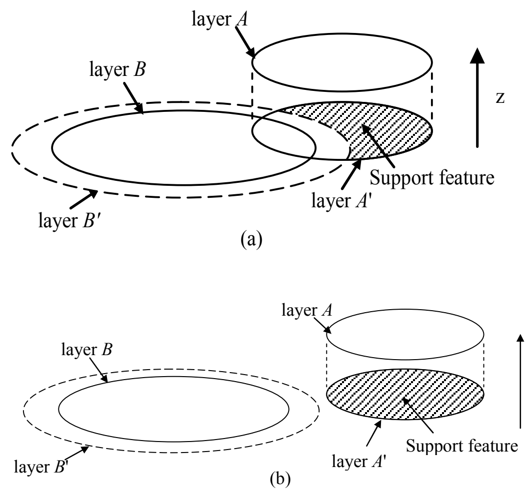

Figure-3. *CSRA* of subsequence layers for manufacturability of the sample.

SYSTEM IMPLEMENTATION

The 3D solid model of a part in FDM fabrication process is presented as a collection of 2D *CSRA*. The boundary representation of the 3D solid model is expressed in a compact way as:

$$S_{Part\ Solid\ Model} = \bigcup_{i(i=1,N)} CSRA_i \quad (5)$$

where N is the total number of part solid model layers.

Feature-based Support Generation Data Extraction and analysis system can be divided into three phases.

Phase 1: Generation of 2D polygon

The steps in Phase 1 involve the following:

(i) The part model was analyzed in six different directions corresponding to the ±x, ±y and ±z axes as shown in Figure-4. The original orientation of the part was oriented as created in CAD.

(ii) The part was sliced uniformly, layer-by-layer, from bottom to top.

(iii) Two layers were taken at one time, and the *CSRA* of the part was subtracted. This operation was repeated for each pair of layers, in sequence from the Top_most layer to the Bottom_most layer.

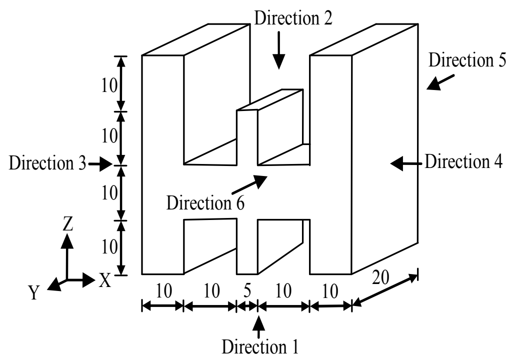

Figure-4. Example of Part Model 1.

For a 2D CSRA plane surface area formed by uniform slicing technique across the solid model at layer *k*-th, the (6) and (7) can be written as:

$$CSRA_{Top\_layer} = CSRA_{k+1} \text{ and} \quad (6)$$

$$CSRA_{Bottom\_layer} = CSRA_k \quad (7)$$

where $k \in \{1, 2, ..., (N-1)\}$

The Resultant Area (RA) between the *k*+1 and *k*-th layers is defined as a subtraction,

$$RA = CSRA_{k+1} - CSRA_k \quad (8)$$

Phase 2: Features identification

The algorithm used to search area, volume and the number of support structures is illustrated in Figure-5.

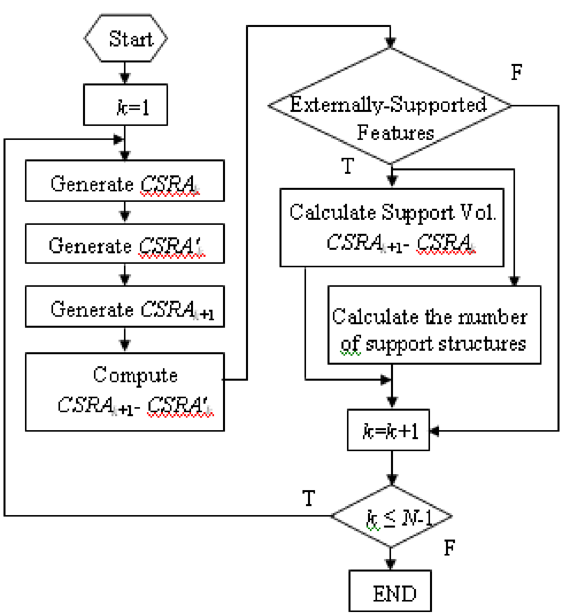

Figure-5. The flowchart of algorithm for ESF Extraction.

The system starts extracting the LM features by using the (8) by considering the offsetting generation on $CSRA_k$ in order to obtain $CSRA'_k$. The ESF is identified when the results of the (8) show $A' - B' > 0$.

Next, the system continues to compute the support area and volume using the (8). At this time, the original of $CSRA_k$ (i.e. without applying offsetting generation on $CSRA_k$) is used to determine the (9). At the same time, the system will determine the number of external support structure with certain conditions.

Condition 1

If $Support\ Area_k \cap Support\ Area_{k+1} = \varnothing$, then $Support\ Area_k$ and $Support\ Area_{k+1}$ are in the different structure.

Condition 2

If $Support\ Area_k \cap Support\ Area_{k+1} \neq \varnothing$, then $Support\ Area_k$ and $Support\ Area_{k+1}$ are in the same structure. The formation of support areas at layer *k*-th is defined as:

$$Support\ Area_k = (RA_k \cup RA_{k+1}) - Area\ of\ Part\ Solid\ Model_k \quad (9)$$

and the volume of solid support structure is defined as:

$$S_{Solid\ Support\ Volume} = \cup_{i(i=1,k)} Support\ Area_i \times t \quad (10)$$

where *t* is a layer thickness.

Base support structure is defined as a support structure which is used to sustain the FDM part model and to support external support structure for the most bottom layer (*k*=1). The total volume of solid base support structure required in entire fabrication process is defined as:

$$Base\ Support\ Vol. = mt(RA_1 \cup RA_2 \cup Area\ of\ Part\ Solid\ Model_1) \quad (11)$$

where *m* is the number of Base Support layers and *t* is a layer thickness.

The total volume of support encountered in entire fabrication process of the part model is defined as:

$$S_{Total\ Solid\ Support\ Vol.} = \sum_{i=1}^{n} S_{Solid\ Support\ Vol} + Base\ Support\ Vol. \quad (12)$$

Two examples were used to illustrate the above algorithm. The above steps were applied to the part used in this work (Figure-4). For further explanation, two of six analyzed directions corresponding to the ±x, ±y and ±z axes i.e. the direction 1 and direction 2 were taken as examples and illustrated in Figures-6 and 7, respectively. To facilitate the subtraction operation, top and front view of part model during determining for volume and numbers of support structures were graphically presented. The areas of RA obtained from this operation are compared to the

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areas of $CSRA_{Top\_layer}$ and $CSRA_{Bottom\_layer}$ which are the subjects of the subtraction operation.

The result from Figure-6 can be summarized as follows:

(i) The resultant area between layer 4 and offsetting generating of layer 3 in Figure-6(a) shows that ESF are not identified. Therefore layer 4 can be manufactured without a support volume. This condition can also be seen between layer 3 and offsetting generating of layer 2. The ESF are found for resultant area between layer 2 and offsetting generating of layer 1 as shown in Figure-6(c). By using (8), the support volume at level of layer 1 is generated immediately under ESF of layer 2 (Figure-6(c)). This process gains the adjacency of layer 2 in its building direction, and is thus manufacturable.

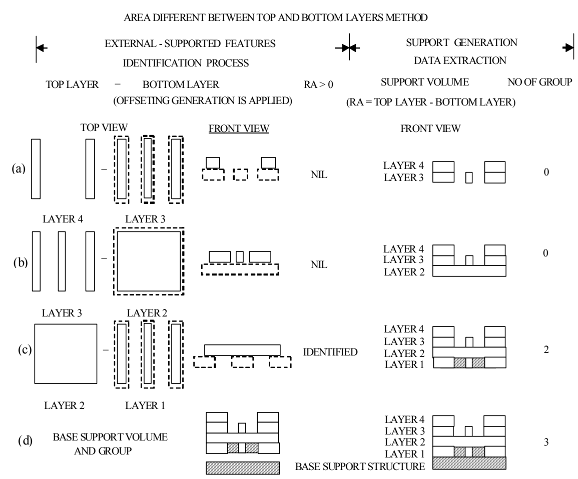

Figure-6. Example of Part model 1 in Direction 1.

(ii) Calculating the number of external support structure - level of layer 1 (Figure-6(c)) shows two groups of support volume. The intersection of these groups is not observed. As a result, these structures of support volume are identified as two different structures.

(iii) Calculating the number of base support structure - this is dependent on part solid model area or external support structure area developed at level of layer 1. By using (11), base support volume is generated (Figure-6(d)) in order to support any areas developed at this level. The intersection between generated base support volume and support volume immediately above it is not counted as a member of external support volume (since $k \in \{1, 2, ..., (N-1)\}$).

(iv) By considering (ii) and (iii), the total support structure in entire manufacturing process for this part model in direction 1 is 3 units of support structures. Next, volumes for these support structures will be calculated.

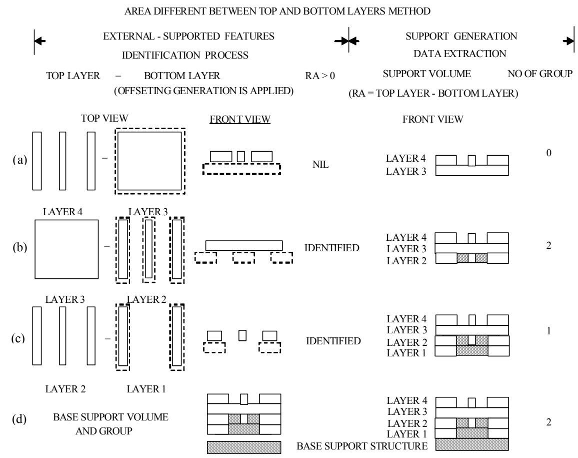

Figure-7. Example of Part model 1 in Direction 2.

The result from Figure-7 can be summarized as follows:

(i) The support volume at level of layer 1 is generated immediately under ESF of layer 2. Detail explanation is illustrated in Figure-8. The support volumes which generated at this level of layer (i.e. at the left and right hand side as shown in Figure-8(b) do not have any adjacency in their building direction. A new support volume (Figure-8(c)) is required under the support volume which has been generated at level of layer 2 by using (8). As the result, the support volumes in this level of layer, gain the adjacency in their building direction, and is thus manufacturable.

(ii) Level of layer 2 in Figure-8(c) shows two non-intersection structures of support volume. The intersection between the support volumes at levels 1 and 2 is identified as a same member. These volumes form a unit of support volume structure.

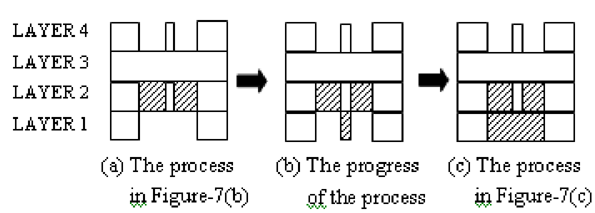

Figure-8. Detail of formation of support structure in Direction 2.

Phase 3: Optimization process

In present work, ANN was used as an optimization tool. The total volume of support and the numbers of support structure need to be translated into an input of vector or a matrix form. The neural network considered in this optimization stage is a multilayer feedforward network. The input is designed with simplicity as the primary concern.

The ANN inputs data are the results of the total volume of support from the part model in six directions corresponding to the ±x, ±y and ±z axes. The input takes

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the form of a binary 6x6 matrix. The neural network inputs data for each rotation of tessellated CAD model and analyze directions would be attributed in matrix pattern as shown in Table-1.

Table-1. Attributed matrix patterns.

D 1	D 6	D 5	D 4	D 3	D 2
D 2	D 1	D 6	D 5	D 4	D 3
D 3	D 2	D 1	D 6	D 5	D 4
D 4	D 3	D 2	D 1	D 6	D 5
D 5	D 4	D 3	D 2	D 1	D 6
D 6	D 5	D 4	D 3	D 2	D 1

Where D 1 = Direction 1

The output from the neural network is designed to have the information on the optimum part deposition orientation. The output takes the form of a binary 6x6 matrix. The six binary elements in the first column of output matrix from top to bottom represent directions 1, 2, 3, 4, 5 and 6, respectively; having a value of 1 is the optimum part deposition orientation.

In general, it possibly to have a same amount of the total volume of support in another orientation, hence, there might be more than one of value of 1 in the first column of output matrix. A secondary condition which is the numbers of support structures is considered. Therefore, a new neural network input data, R, is generated based on previous neural network output data and the number of support structures.
The function then becomes:

$$R = \frac{\sum_{i=1}^{n} \text{The Numbers of Support Structures}}{O_1} \tag{13}$$

where O_1 is the results of previous neural network output data in binary. The maximum value of R gives the optimum part deposition orientation.

RESULTS AND DISCUSSIONS

Support volume is subjected to slice height and base layer. In this work, the constant slice height, t of 0.01 mm and the base support layer, m of 5 were used for all part orientations.

The computational analysis was done by constructing a part model 1 and has been situated in six different part deposition orientations (Figure-4). The results of the computational analysis using ANN is presented in Table-2.

From Table-2, the data shows that the directions 5 and 6 have same value of support volumes. The same number of support structure enable part model to be fabricated in direction 5 or 6. For directions 3 and 4, part model is able to fabricate in direction 3 or 4 since their situation is similar with directions 5 and 6. In case of directions 1 and 2, the input data (support volume) in the direction 1 is smaller than in the direction 2. Hence, the direction 1 is better than the direction 2. The optimum part deposition orientation is the direction with minimum value of ANN input; hence, in this case out of six directions, the selection should be either direction 5 or 6.

From Table-2, there are two maximum of R value. The solution obtained from ANN output, O_2 shows that the part model 1 with direction 5 is selected as the optimum part deposition orientation.

Table-2. Input and output of ANN for part model 1 in six orientations.

Orientation	Support Volume (mm^3)	Number of Support Structure	ANN output, O_1	R	ANN output, O_2
1	4045	3	0	0	0
2	9045	2	0	0	0
3	13040	4	0	0	0
4	13040	4	0	0	0
5	57.5	1	1	1	1
6	57.5	1	1	1	0

The validation of this method is carried out by constructing part model 2 as shown in Figure-9. Cheng *et al*. [6] used part model 2 in attempted to verify their methodology in stereo-lithography process. In other work done by Thrimurthulu *et al*. [1], the same model was tested using a FDM.

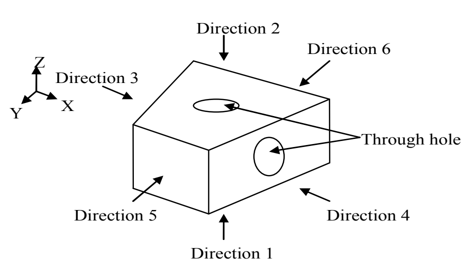

Figure-9. Part model 2.

The results of part model 2 for current work are presented in Table-3. From this Table, there are two maximum of *R* value (orientations 1 and 2). The solution obtained from ANN output, O_2 shows that the part model 2 with direction 1 is selected as the optimum part deposition orientation. This result is in agreement with solutions obtained by Cheng *et al*. [6] and Thrimurthulu *et al*. [1].

Table-3. Input and output of ANN for part model 2 in six orientations.

Orientation	Support Volume (mm^3)	Number of Support Structure	ANN output, O_1	R	ANN output, O_2
1	44018.47	3	1	1	1
2	44018.47	3	1	1	0
3	58191.38	4	0	0	0
4	137691.38	4	0	0	0
5	152373.41	2	0	0	0
6	106998.41	2	0	0	0

CONCLUSIONS

The present work can be concluded as following:

- Features based are successfully applied in this work for support generation in FDM.
- The volume and number of support structure for ESF and base support effect in determining the optimum part deposition orientation. In this optimization, the number of support structure is considered when obtaining the same minimum amount of the total volume of support.
- The selection of part deposition orientation has been automated using ANN.

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