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Optimum part deposition orientation in fused deposition modeling

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Abstract

Surface finish and part deposition time are two important concerns in rapid prototyping (RP). These two concerns contradict with each other. Generally, a compromise is made between the two aspects pertaining to model building in RP. A compromise between these two contradicting issues can be achieved by using an adaptive slicing scheme; however, selection of a proper part deposition orientation will further provide an improved solution. Present work is an attempt towards obtaining an optimum part deposition orientation for fused deposition modeling process for enhancing part surface finish and reducing build time. Models for evaluation of average part surface roughness and build time are developed. A real coded genetic algorithm is used to obtain the optimum solution. Predictions of the present metzhodology are in good agreement with the result published earlier. Proposed methodology can be used to obtain the optimum deposition orientation for any type of component without selecting the preferred orientations.

Keywords: Fused deposition modeling (FDM); Surface roughness (*Ra*); Adaptive slicing; Building time; Average part surface roughness; Optimum part deposition orientation

1. Introduction

Rapid prototyping (RP) is a process in which a part is produced using layer-by-layer deposition of material. It is an important technology as it has potential to reduce the manufacturing lead time of the product up to 30–50% even the relative part complexity is very high [1,2]. The RP cycle consists of creation of geometric model using a solid modeler, determination of suitable deposition orientation, slicing, generation of material deposition paths, part deposition and then post processing operations. Most of the steps in RP are automatic; however, part deposition orientation is selected manually among few options shown by the RP software. Orientation for part deposition on a RP machine platform has significant effect on many key characteristics that determines the final quality and cost of the prototype [3]. The automation of orientation selection process eliminates operator's involvement and hence reduces possible errors.

Selection of optimum part deposition (build) orientation is very important factor as it effects build time, support structure, dimensional accuracy, surface finish and cost of the prototype. A number of process specific parameters and constraints have to be considered while making this decision. Determining the optimal part deposition orientation is a difficult and time consuming task as one has to trade-off among various contradicting objectives [1] like part surface finish and build time.

There have been several attempts [3–5,7–13,15,16] to determine suitable part deposition orientation for different objectives like accuracy, build time, support structure etc. Alexander et al. [3] determined part deposition orientation for accuracy and cost. Surface accuracy was maximized by minimizing average weighted cusp height. Cost models were presented for stereolithography (SL) and fused deposition modeling (FDM) in such a way that the cost of the component can be estimated for different orientations. A suitable orientation for one of the objectives is determined from the list of pre-selected candidate base planes. Frank and Fadel [4] developed an interactive system to decide suitable part

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Nomenclature

a_n	cross-sectional area of the nozzle
A_i	area of i^{th} trapezium
d_s	density of support structure
F	ratio of supported area to total area of the part
(n_x, n_y, n_z)	position vector of axis of rotation
N_l	number of layers or slices
O	objective function to be minimized
Ra	surface roughness (centerline average)
Ra_{av}	average surface roughness of the part
Ra_i	surface roughness of i^{th} trapezium
$Ra_{70^\circ}, Ra_{90^\circ}$	surface roughness for 70° and 90° build orientation, respectively
t	slice or layer thickness
T_e	an estimation of build time of FDM part (dimensionless)
T_p	build time of the part if no idle times are considered
T_r	transformation matrix for rotation about an arbitrary axis
V_p	volume of the FDM part
w_1, w_2	weight for surface roughness and build time, respectively
ϕ	angle of rotation
θ	build orientation

deposition orientation. Surface finish, build time or support structure is considered as an objective and guidelines were framed to decide suitable orientation. Cheng et al. [5] presented an approach for determining suitable part deposition orientation for stereo-lithography parts considering dimensional accuracy and build time as objectives. Part accuracy was treated as primary objective and was calculated based on experience for different types of surfaces. The secondary objective was to minimize build time and it was achieved by reducing the number of slices. Adaptive slicing with pre-specified cusp height [6] was also introduced in their work. Possible base planes were first identified by finding the planar (flat) surfaces of the object. First, few orientations were short-listed based on accuracy considerations and later one or two suitable orientations were selected by minimizing the build time. Lan et al. [7] determined deposition orientation for stereo-lithography parts based on the considerations of surface quality, build time or complexity of the support structures. Surface quality was evaluated either by maximizing the area of non-stepped surfaces or by minimizing the area of worst quality surfaces. Build time was indirectly assessed by using the height of the part in the deposition direction. Support structure was minimized by minimizing number of supported points. Suitable orientation for one of the objectives at a time is determined from the list of pre-selected base planes. An approach based on volumetric error is attempted by Rattanawong et al. [8,9]. In their work, the difference in the volume of deposited part and the CAD model is minimized for finding a suitable orientation. The volume of deposited part is calculated by assuming slice edges as rectangular. Goyal et al. [10] obtained the best orientation that gives minimum number of adaptive slices among few pre-selected orientations. Pham et al. [11] developed a system to orient CAD models for part deposition in stereo-lithography to obtain the best trade-off among build time, cost and accuracy. Their tool is a feature-based system that considers cost, build time, problematic features, optimally oriented features, over hanging areas and support volume for recommending a build direction. Their system has six modules, namely the orientation module, the support module, the timing module, the cost module, the problematic feature module and the display module. Candidate orientations are first chosen in orientation module based on considerations of critical surfaces, holes, cuts, shafts, protrusions, shells and axes. Recommendations for the pre-selected candidate orientations are obtained for depositing the part; however, there may be a better part deposition orientation other than the pre-selected candidate orientations. West et al. [12] developed a process planning method for improving build performance, i.e. shorter build time, better accuracy and high surface finish in stereo-lithography. Process planning has been carried out by them in three steps, namely orientation, slicing and parameter modules. Part deposition orientation, layer thickness, sweep period, *Z*-height, fill over-cure and hatch over-cure are the six process variables were decided using the support structure and horizontal planes as the constraints. The part deposition orientation module developed by them works on evaluation of a set of the most feasible orientations based on the planar, conical and cylindrical surfaces present on the part. The part is oriented in these pre-selected orientations and is sliced uniformly to trade-off among three above-stated objectives satisfying the constraints. Four most feasible alternative orientations were selected for further investigations in slicing and parameter modules to end up with the most suitable process plan. Xu et al. [13] presented an adaptive slicing method similar to Kulkarni and Dutta [14] that slices CAD models represented by analytical surfaces. The basic difference in between the two schemes is that Xu et al. [13] used genetic algorithms (GA); however, Kulkarni and Dutta [14] used sequential quadratic programming (SQP) to find out layer thickness at $z(u,v) =$ constant contours. Xu et al. [13] also investigated the best part deposition orientation for SL parts among few pre-selected orientations for build time, accuracy and stability of the part as criteria. By trading-off among these objective function values, the best orientation is selected. McClurkin et al. [15] developed statistical models to predict build time, accuracy and surface finish of SL parts using response surface methodology. Goal programming technique was used by them to determine the part deposition orientation. More recently, Masood et al. [16] presented a generic algorithm for determining best part deposition orientation using the volumetric error [8,9] for tessellated CAD models in FDM. They have used uniform slicing of tessellated CAD model and determined volumetric error considering the build edges as rectangular; however, Pandey et al. [17,18] reported that the build edges are parabolic for FDM processed parts. An axisymmetric part has been chosen for demonstrating their algorithm [16]. The axisymmetric part is rotated in the interval of 5° about an axis perpendicular to the axis of axisymmetric part. The angle that gave minimum volumetric error is recommended as the best orientation.

Literature review presented above reveals that most of the attempts [3,5,11–13,15] to determine part deposition orientation are related to SL process. Very few attempts [3,9,16] have been made to determine part deposition orientation for FDM process in which the surface finish problem is more dominant due to staircase effect as compared to SL process. In most of these attempts [3–5,7–13,16] suitable or the best part deposition orientation is selected among the few pre-selected orientations although part can be deposited in infinite possible orientations. Pre-selection of the candidate base planes for depositing part is impossible for a completely freeform part like bones, horse saddle, etc. Average weighted cusp height [3] or volumetric error approach [8,9,16] implicitly assume build edge profiles as rectangular; however, slice edge profiles are found to be parabolic for FDM [17,18]. Estimation of part surface quality in terms of standard *Ra* value instead of weighted cusp height is more appropriate. Although approximate build time for FDM can be evaluated by the procedure given by Alexander et al. [3], however it may be computationally cumbersome as it involves computation of slice areas, material deposition paths, etc. Approximate estimation of build time based on number of adaptive slices and consideration of support structure may prove computationally efficient. Therefore, in the present work, the problem of determination of optimum part deposition orientation is formulated as a single objective optimization problem by adding two objectives, i.e. average part surface roughness and build time after multiplying by appropriate weights. The weights assigned to the two objectives represent the preference for them in determining the optimum part deposition orientation. Average part surface roughness is evaluated by slicing the tessellated CAD model of the part adaptively [18]. Build time is estimated indirectly by considering number of adaptive slices and weighing them with the ratio of supported area to the total surface area of the part. The optimization problem is solved using a real coded genetic algorithm [19].

2. Problem formulation

The build time of a prototype can be reduced by depositing it with thicker layers; however, this will lead to rougher surface. Deposition using thin layers increases built time drastically. In the present work, average part surface roughness and the build time of the part are considered as two objectives and they are minimized by minimizing their weighted sum. The problem formulation is presented in the following section.

2.1. Average part surface roughness of the prototype

2.1.1. Surface roughness model

On the basis of published literature [20,21], Pandey et al. [17,18] has considered layer thickness and build orientation, as the two most significant process variables that effect surface finish. To study the surface roughness of FDM processed part surface, a part with different build orientations (angle between surface tangent and vertical direction as shown in Fig. 1) was fabricated on FDM-1650 machine with 0.254 mm slice thickness, 270° C polymer melt temperature of part material, i.e. ABS, 265° C polymer melt temperature of support material, 70° C envelope temperature and zero air gap. Surface roughness (*Ra*) values of the different faces have been measured by them using *Surf-Analyzer5000*. It has been observed that there is a gap between deposited roads if the build orientation is in between 70° and 90°; however, no gap is observed

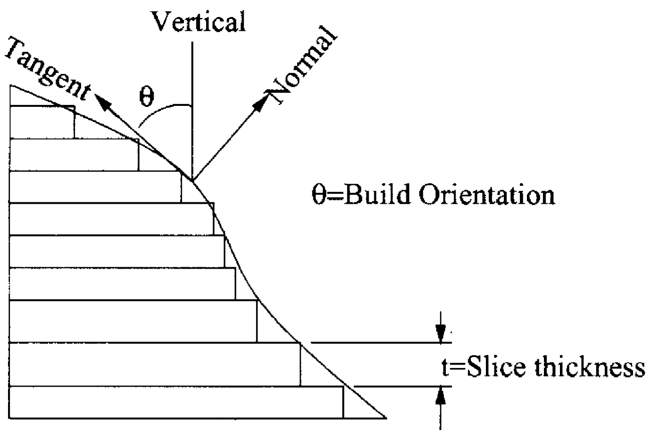

Fig. 1. Staircase effect in RP parts.

between roads in the range of 0–70° build orientation. Typical surface profiles obtained over a 2 mm sample length for 45° and 70° build orientations are shown in Fig. 2. It can be seen from Fig. 2(a) ($\theta = 45°$) that there is no gap between deposited roads while there is gap between deposited roads ($\theta = 70°$) in Fig. 2(b), where θ is the build orientation. The surface profiles presented in Fig. 2(a) clearly indicate that the geometry of build edge profiles can be approximated as a parabola. A stochastic model was developed for the range $0° \leq \theta \leq 70°$ by approximating the layer edge profile as parabolic. The expression for surface roughness is given [17]

$$Ra\,(\mu m) = (69.28\text{–}72.36)\frac{t\,(mm)}{\cos\theta} \quad \text{for } 0° \leq \theta \leq 70° \qquad (1)$$

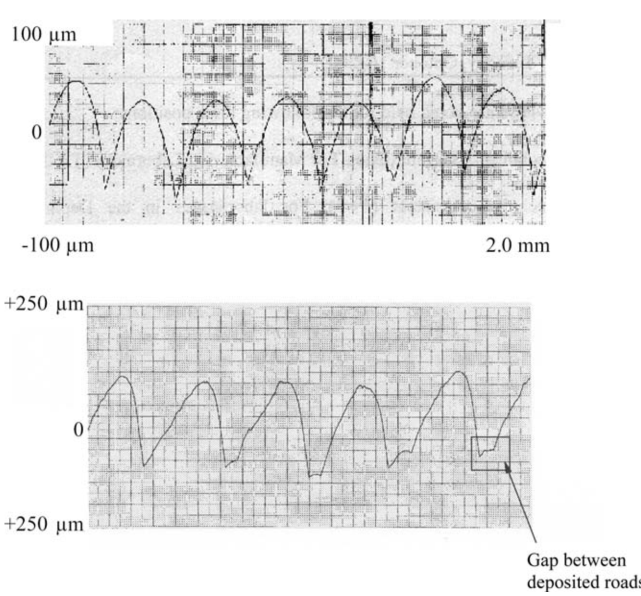

Fig. 2. Surface profiles of FDM processed part, slice thickness = 0.254 mm.

Surface profile for $\theta = 90°$ (horizontal surface or surface parallel to FDM platform) is idealized as semicircle (instead of parabola) having base length t and height $0.5 \times t$. Surface roughness value for $\theta = 90°$ is given by [17]

$$Ra\,(\mu m) = 112.6 \times t\,(mm) \quad \text{for } \theta = 90° \qquad (2)$$

Surface roughness in the range of $70° \leq \theta < 90°$ is calculated by assuming linear variation between $Ra_{70°}$ and $Ra_{90°}$, i.e.

$$Ra\,(\mu m) = \frac{1}{20}[90Ra_{70°} - 70Ra_{90°} + \theta(Ra_{90°} - Ra_{70°})] \quad \text{for } 70° \leq \theta < 90° \qquad (3)$$

Pandey [22] measured the values of surface roughness of the supported faces also and observed that surface roughness of supported face is approximately 1.2 times the surface roughness of an upward facing surface for the same build orientation. Therefore, in the present work, the effect of support structure on the surface quality is incorporated by considering the surface roughness of supported trapezium to be $1.2 \times Ra_i$, where Ra_i is the surface roughness corresponding to i^{th} trapezium [18] if there is no support below the triangular facet.

2.1.2. *Adaptive slicing*

In most of the earlier works [6,14,23–34], limited cusp height [6,14,23–32] and limited area deviation [33,34] are the two criteria used by researchers to slice a CAD model. These two criterions have limitations, as they are not standard measure of surface quality. Pandey et al. [18] used the surface roughness model presented in the previous section to slice a tessellated CAD model. In the present work, the same slicing scheme is used to slice a tessellated CAD model adaptively. The slice thickness is calculated by the following expression in the present work.

$$t\,(mm) = \frac{Ra\,(\mu m) \times \cos\theta}{70.82} \qquad (4)$$

where Ra is the maximum value of surface roughness (bound kept on Ra) permitted on the part. The average part surface roughness (surface quality) has been calculated using the following expression

$$Ra_{av} = \frac{\sum Ra_i A_i}{\sum A_i} \qquad (5)$$

where Ra_{av} is average surface roughness of the part, Ra_i is the roughness and A_i is the area of the i^{th} triangular facet of STL file.

2.2. Build time of the prototype

Accurate estimation of build time for FDM processed parts need slicing of the part, calculation of area of slices and generation of roads for laying material. The build time is influenced by the acceleration and deceleration of nozzle tip during material deposition. Non-productive times like time taken in lowering the platform after depositing a layer, time between ending and starting of a new raster path for laying road, time taken during wiping of nozzle, etc. also contribute in increasing build time of FDM prototype. Non-productive time is elapsed in between shifting of part material nozzle to support material nozzle; however, support material is deposited with less density. True estimation of build time of a FDM prototype is therefore computationally cumbersome. In the present work, a simple and effective methodology to assess the build time is used.

If V_p is the volume of the part, a_n is the cross-sectional area of the nozzle that lays material and T_p is the ideal build time of the prototype assuming that there is no interruption during the deposition process, (i.e. non-production times are ignored) then the build time is independent of the part deposition orientation as

$$V_p = a_n \times v_e \times T_p \tag{6}$$

where v_e is the extrusion velocity of molten ABS thread and is equal to the speed of laying the road of the material. Therefore, it is obvious that the difference in the build time of the prototype for different deposition orientations is due to non-production times. Here, one should note that volume of support structure is also different for different orientations and its presence increases build time; however, its effect is ignored in the above expression. As our ultimate goal is to minimize the build time, minimizing support structure along with minimizing non-productive time will minimize the build time of the prototype. Different non-productive times like time taken in lowering the platform after deposition of layer, time between ending and starting of a new raster path for laying road of material, time taken for wiping of nozzle, etc. can be reduced by reducing the number of slices.

In the present work, the assessment of the build time of the FDM prototype is done using the following expression

$$T_e \equiv N_l(1 + F \times d_s) \tag{7}$$

where T_e is a measure of build time, N_l is number of adaptive slices, d_s is the density of support material and F is the ratio of supported facets of tessellated CAD model to the total surface area of the part.

Therefore, the complete problem of part deposition orientation determination can be written in the form of a single objective optimization problem by assigning weights w_1 and w_2 for the two objectives, i.e.

$$\text{Minimize } O = w_1 \times Ra_{av} + w_2 \times T_e \tag{8}$$

where w_1 and w_2 can be thought as the preferences for the two objective functions such that

$$w_1 + w_2 = 1 \tag{9}$$

A part for which optimum deposition orientation is to be determined is modeled in I-Deas in a known orientation and STL file is exported. In this work, it is needed to calculate the objective function (expression (8)) for various orientations of the part. An STL file (i.e. the co-ordinates of vertices and normal vectors) corresponding to an orientation (i.e. rotation about an axis described by unit vector (n_x,n_y,n_z) by angle ϕ as shown in Fig. 3) of the part is calculated using the following transformation matrix [35].

$$T_r = \begin{bmatrix} n_x^2 v\phi + c\phi & n_x n_y v\phi - n_z s\phi & n_x n_z v\phi + n_y s\phi \\ n_x n_y v\phi & n_y^2 v\phi + c\phi & n_y n_z v\phi - s\phi \\ n_x n_z v\phi & n_y n_z v\phi + n_z s\phi & n_z^2 v\phi + c\phi \end{bmatrix} \tag{10}$$

where $v\phi = 1 - \cos\phi$, $c\phi = \cos\phi$ and $s\phi = \sin\phi$. Therefore, the decision variables for the present optimization problem are unit vector (n_x,n_y,n_z) and angle ϕ.

3. Solution procedure

Two objective functions discussed above (Section 2) are computed and converted into a single objective (using expression (8)) for different orientations of a given tessellated CAD model. A real coded genetic algorithm [19] has been used to solve the above-mentioned optimization problem. In real coded genetic algorithm, the decision variables are coded in real numbers unlike the binary numbers as in the case of

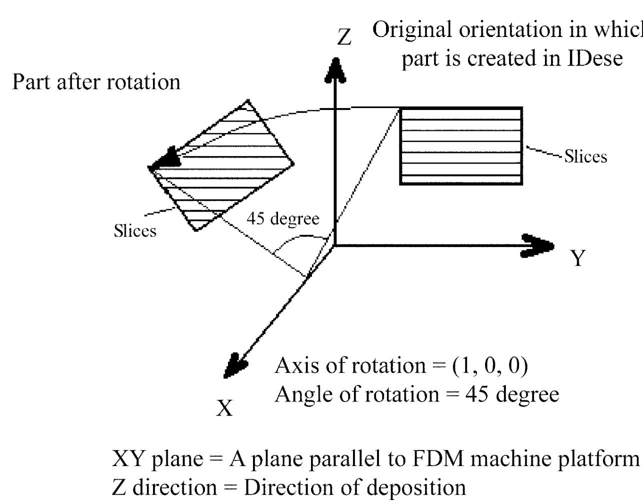

Fig. 3. Rotation of tessellated CAD model.

binary coded genetic algorithms; however, the other steps of real coded GA are similar to binary GA. Generation of decision variables in real numbers eliminates various problems (like continuous search space descretization, inability to achieve arbitrary precision in the solution, fixed mapping of problem variables, etc.) faced while using binary coded genetic algorithms [19]. Use of real coded GA is justified here as it is a search problem among all infinite possible orientations. At the same time, the complexity of the part's surface affects the solution very much. In the present problem, it can be thought that the mathematical functions describing the objective (expression (8)) keep changing with the change in the part geometry. This problem is also multi-modal in nature, therefore, it can be handled better by using GA rather than conventional gradient based optimization techniques.

In real coded GA, the axis vector (n_x,n_y,n_z) and angle of rotation ϕ are first generated randomly between the two limits as given below to form the initial population.

$$\left.\begin{array}{l} 0 \le n_x \le 1 \\ 0 \le n_y \le 1 \\ 0 \le n_z \le 1 \\ \text{and } 0 \le \phi \le 360^\circ \end{array}\right\} \tag{11}$$

The axis vector (n_x,n_y,n_z) is normalized to unit vector by dividing it with its magnitude. Value of the objective function O is computed for user specified values of weight factors w_1 and w_2 using the expression (8). Before this the values of two objective functions are computed using the expressions (5) and (7). Tournament selection operator with selection pressure as two is used in the present work, where selection pressure in case of tournament selection is same as the number of solutions compared randomly to reproduce multiple copies of better solutions in a generation. Simulated binary crossover and mutation operators [19] are used with more than 75% and less than 20% probabilities, respectively. The program is executed for user specified number of generations and runs and optimum solution is obtained. The implementation procedure is given in Fig. 4. This approach can be used for a simple as well as complex part which may be completely freeform. However, this method may prove computationally inefficient for simple parts. The inputs to the developed system are STL file of the part, minimum and maximum slice thickness, bound to be kept on Ra at any point on the part and various parameters for GA. The procedure explained above is validated by comparing its predictions with the results available in the literature [5]. Examples are presented to demonstrate the capabilities of the developed system.

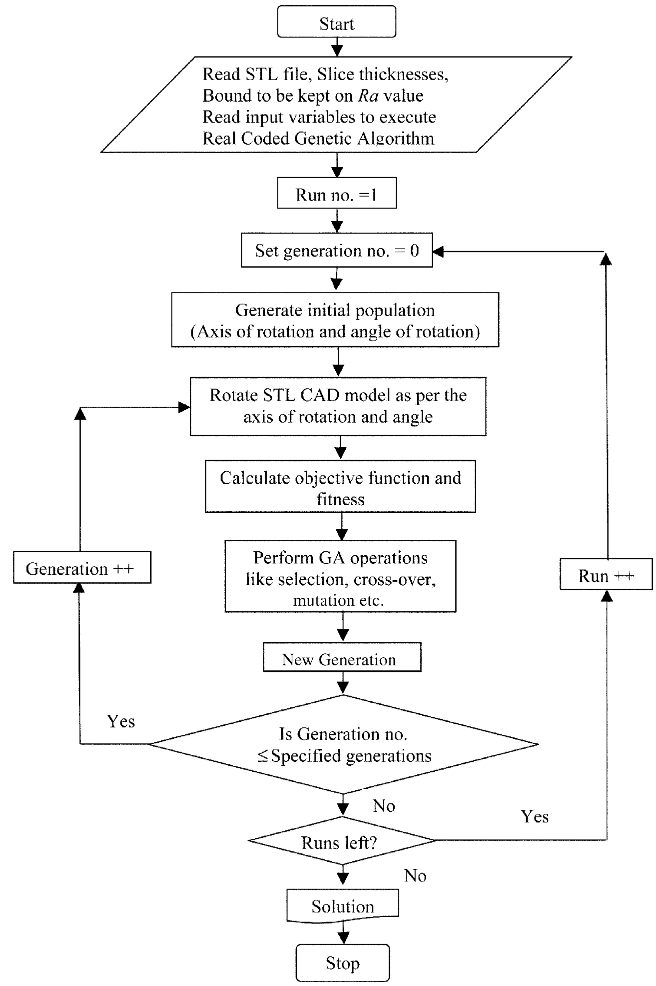

Fig. 4. Implementation procedure.

4. Results and discussion

A part (shown in Fig. 5) considered by Cheng et al. [5] for stereo-lithography process is taken for the purpose of validation. A dimensionally proportionate solid model of the part is created in I-Deas in the same

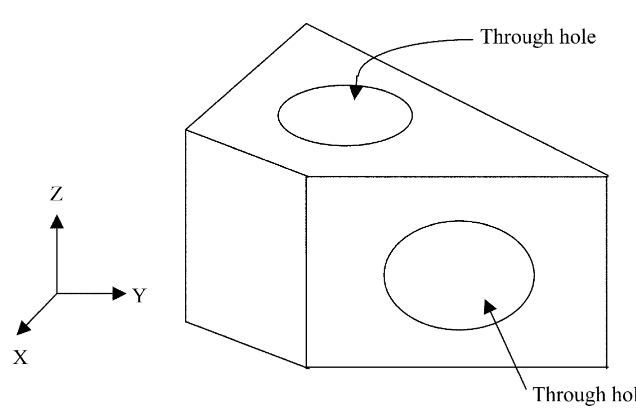

Fig. 5. Part used for validation of the developed system.

Table 1
Different input parameters used to execute the developed system for optimum part deposition orientation determination

FDM machine parameters/ others	GA parameters
Minimum slice thickness = 0.254 mm	No. of population = 50–100
Maximum slice thickness = 1.27 mm	No. of generations = 60–100
STL file	Distribution index for real coded crossover = 20
Bound on Ra = 40 μm	Distribution index for real coded mutation = 200
	Crossover probability = 0.8–0.9
	Mutation probability = 0.05–0.2
	Random seed value = 0.123
	Number of runs = 5–10

orientation as shown in Fig. 5. The STL file is exported. This STL file is used as an input to the developed system. Different other input parameters used to execute the program are given in Table 1. The weights w_1 and w_2 (of expression (8)) are chosen to be 0 and 1, respectively as the validation is carried out for build time only.

The optimum solution obtained corresponding to the input data presented in Table 1 and STL file of the part shown in Fig. 5 is presented in Table 2.

It can be seen from Table 2 that the preference is given to build time only (w_1= 0 and w_2= 1) and there is no preference for surface quality of the part. The obtained solution shows that the part is to be rotated by $0.132^\circ \approx 0^\circ$ about an axis represented by position vector as (0.023, 0.316, 0.293). This result implies that the orientation shown in Fig. 5 corresponds to minimum build time. This result is in conformity with that of solution obtained by Cheng et al. [5].

5. Examples

Optimum part deposition of an axisymmetric part and a 3D part is determined in order to demonstrate the capabilities of the developed system.

An axisymmetric part is modeled in an orientation shown in Fig. 6 using I-Deas and STL file is exported. This STL file is used as an input to determine optimum

Table 2
Solution obtained by the developed system for the part used to validate it

Weights	n_x	n_y	n_z	ϕ (°)	Ra_{av} (μm)	T_e	O
$w_1 = 0$, $w_2 = 1$	0.023	0.316	0.293	0.132	30.89	12.87	12.87

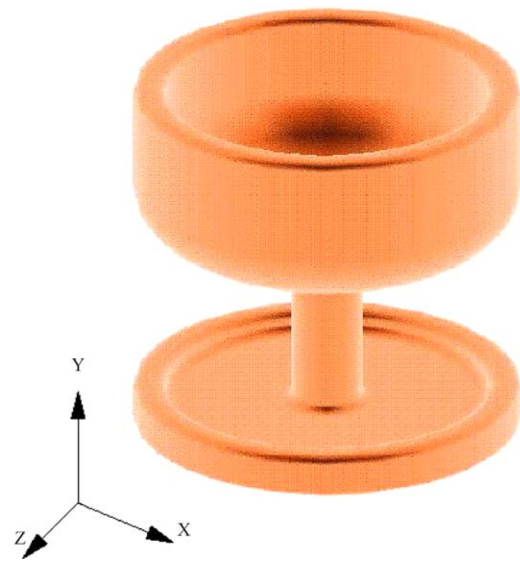

Fig. 6. Solid model of axisymmetric part.

part deposition orientation. Other input parameters used to determine the optimum part deposition orientation are given in Table 1. Here, 100 generation with 100 population size is used. The solutions obtained from this system for different values of weights (w_1 and w_2 in expression (8)) are presented in Table 3. The obtained optimum part deposition orientations for minimum average part surface roughness and minimum build time are presented in Fig. 7. In Fig. 7, xy represents the plane parallel to FDM machine platform and z-axis represents the direction of deposition.

Optimum part deposition orientation is estimated for a 3D part shown in Fig. 8. The part is modeled in I-Deas in the same orientation as shown in Fig. 8 and STL file is exported. This STL file is used as an input to the orientation system to determine optimum part deposition orientation. The program is executed for 60 generations with 100 population size. The solutions obtained from the present system for 3D part for

Table 3
Results obtained for axisymmetric part by the optimum part deposition determination system

Weights	n_x	n_y	n_z	ϕ (°)	Ra_{av} (μm)	T_e	O
$w_1 = 1$, $w_2 = 0$	0.79	0.20	0.78	221.70	25.29	323.13	25.29
$w_1 = 0.75$, $w_2 = 0.25$	0.06	0.42	0.29	332.00	34.21	177.13	177.78
$w_1 = 0.5$, $w_2 = 0.5$	0.09	0.83	0.46	333.66	35.83	177.71	106.77
$w_1 = 0.25$, $w_2 = 0.75$	0.15	0.70	0.72	326.96	35.64	177.71	142.19
$w_1 = 0$, $w_2 = 1$	0.15	0.72	0.75	326.86	35.41	176.66	176.66

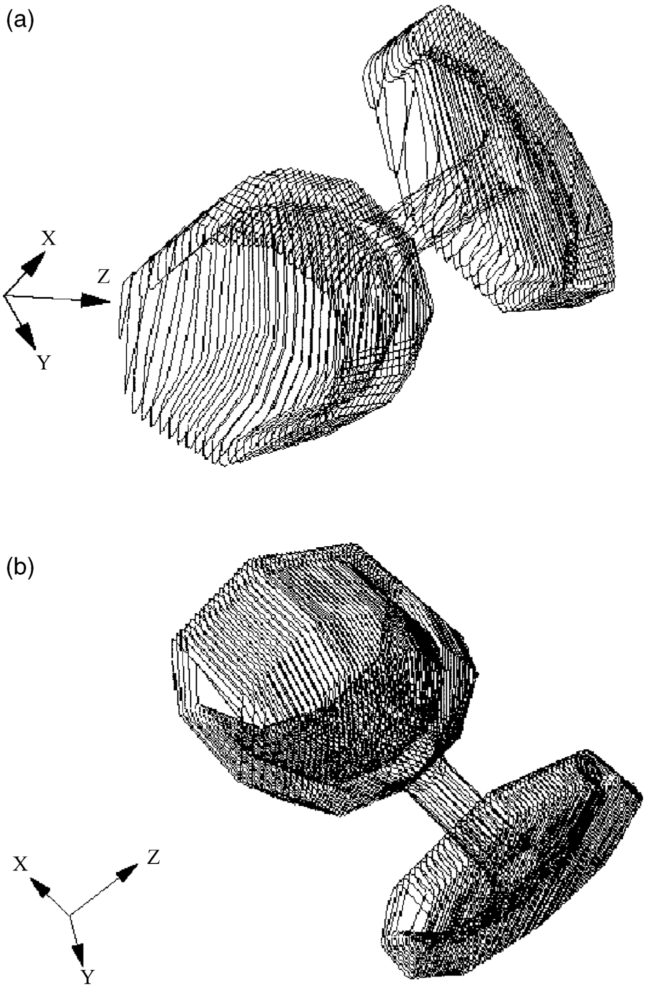

Fig. 7. Graphical output obtained from the developed system of optimum part deposition orientation determination for axisymmetric part. (a) Part deposition orientation for best part surface quality; (b) Part deposition orientation for minimum building time.

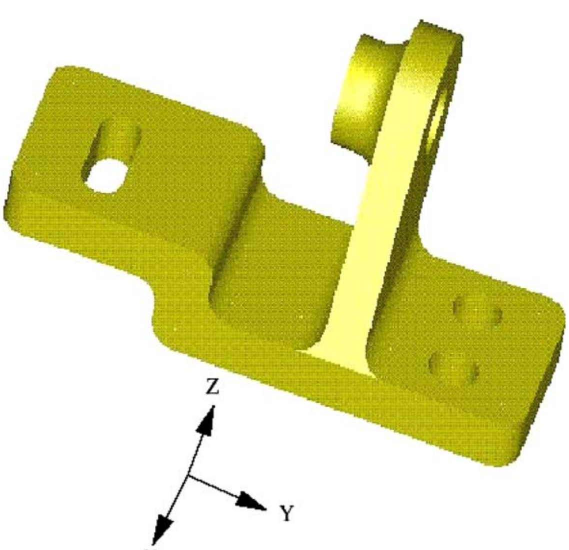

Fig. 8. Solid model of 3D part.

Table 4
Results obtained for 3D part by the optimum part deposition determination system

Weights	n_x	n_y	n_z	ϕ (°)	Ra_{av} (µm)	T_e	O
$w_1 = 1$, $w_2 = 0$	0.76	0.87	0.5	130.27	21.72	371.70	21.27
$w_1 = 0.75$, $w_2 = 0.25$	0.58	0.83	0.24	92.86	30.1	181.24	67.89
$w_1 = 0.5$, $w_2 = 0.5$	0.59	0.85	0.19	91.74	31.02	178.55	104.79
$w_1 = 0.25$, $w_2 = 0.75$	0.54	0.74	0.19	92.33	30.29	181.1	143.34
$w_1 = 0$, $w_2 = 1$	0.67	0.77	0.07	90.57	31.01	195.25	195.25

different values of weights (w_1 and w_2 in expression (8)) are presented in Table 4. The obtained optimum part deposition orientations for minimum average part surface roughness and minimum build time are presented in Fig. 9. In Fig. 9, xy represents the plane parallel to FDM machine platform and z-axis represents the direction of deposition.

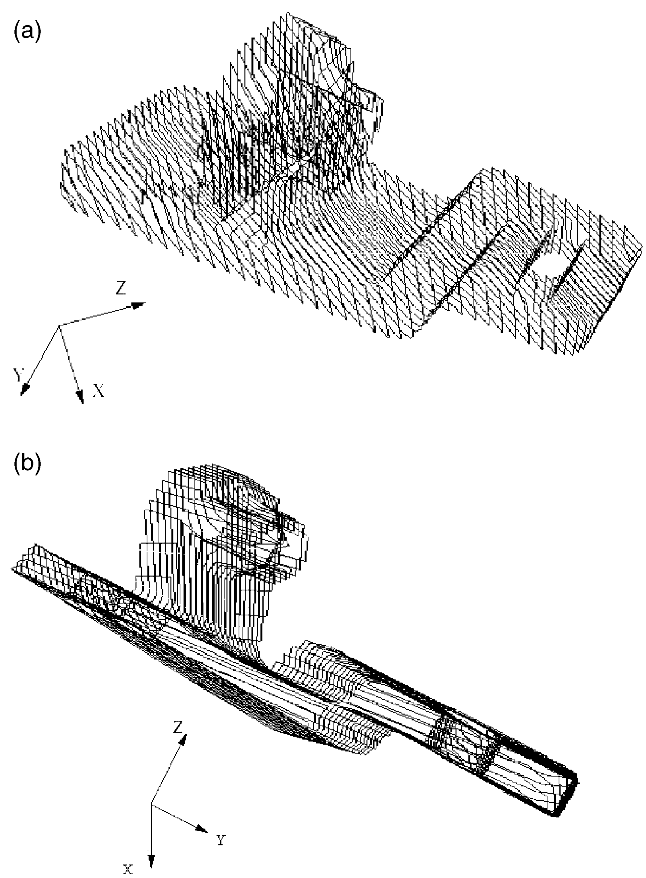

Fig. 9. Graphical output obtained from the developed system of optimum part deposition orientation determination for 3D part. (a) Part deposition orientation for minimum average part surface roughness; (b) Part deposition orientation for minimum building time.

It can be seen from Tables 3 and 4 and Figs. 7(a) and 9(a) that for $w_1 = 1$ and $w_2 = 0$ the solution corresponds to 100% preference for part's surface quality only. There is no preference for build time. In this case, the system finds out the orientation in such a way that the slice thicknesses (satisfying Ra restriction) tend towards minimum possible slice thickness available in RP machine. At the same time, if full preference is given to build time minimization, i.e. $w_1 = 0$ and $w_2 = 1$, then system orients parts (refer Tables 3 and 4 and Figs. 7(b) and 9(b)) in such a way that thicknesses of all slices (satisfying Ra condition) tend towards the maximum slice thickness available in RP machine. It appears in the present work that the developed system considers minimization of build time and average part surface roughness and it does not consider support structure. But due to consideration of effect of support structure in estimation of surface roughness and build time, the minimization of support structures is done implicitly.

It is observed that the computational time can be reduced if a coarse STL file in place of a fine STL file is used as an input to the present system. This does not effect the solution significantly (the difference in the two solutions is due to use of real coded GA); however, change in the values of objective functions is observed.

6. Conclusions

This paper presents an approach that determines the optimal part deposition orientation for FDM process. Two contradicting objectives, namely build time and average part surface roughness, are minimized by minimizing their weighted sum. The effect of support structure is considered in the evaluation of two objectives. Thus, the support structure minimization is also implicitly included in this work. The adaptive slicing is simultaneously used in the determination of optimum part deposition orientation. The predictions of the developed system are validated using the results published earlier. Two case studies are presented to demonstrate the capabilities of the system. Proposed methodology can be used to determine optimum part deposition orientation for any complex part that may be completely freeform.

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References

[1] D.T. Pham, S.S. Demov, Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling, Springer-Verlag London Limited, 2001.

[2] C.C. Kai, L.K. Fai, Rapid Prototyping: Principles and Applications in Manufacturing, World Scientific, 2000.

[3] P. Alexander, S. Allen, D. Dutta, Part orientation and build cost determination in layered manufacturing, Computer Aided Design 30 (5) (1998) 343–356.

[4] D. Frank, G. Fadel, Expert system based selection of the preferred direction of build for rapid prototyping, Journal of Intelligent Manufacturing 6 (1994) 334–339.

[5] W. Cheng, J.Y.H. Fuh, A.Y.C. Nee, Y.S. Wong, H.T. Loh, T. Miyajawa, Multi-objective optimization of part-building orientation in stereolithography, Rapid Prototyping Journal 1(4) (1995) 12–23.

[6] A. Dolenc, I. Makela, Slicing procedure for layered manufacturing techniques, Computer Aided Design 1 (2) (1994) 4–12.

[7] Po-Ting Lan, S.Y. Chou, L.L. Chen, D. Gemmill, Determining fabrication orientation for rapid prototyping with stereolithography apparatus, Computer Aided Design 29 (1) (1997) 53–62.

[8] W. Rattanawong, S.H. Masood, P. Iovenitti, A volumetric approach to part-build orientation in rapid prototyping, Journal of Material Processing Technology 119 (2001) 348–353.

[9] S.H. Massod, W. Rattanawong, P. Iovenitti, Part build orientations based on volumetric error in fused deposition modelling, International Journal of Advanced Manufacturing Technology 16 (2000) 162–168.

[10] A. Goyal, A. Sudha, A. Kumar, P.V.M. Rao, Optimum part orientation for rapid prototyping based on estimated number of adaptive slices, Proceedings of International Conference on E-manufacturing, 2002, pp. 247–253.

[11] D.T. Pham, S.S. Demov, R.S. Gault, Part orientation in stereolithography, International Journal of Advanced Manufacturing Technology 15 (1999) 674–682.

[12] A.P. West, S.P. Sambu, D.W. Rosen, A process planning method to improve build performance in stereolithography, Computer Aided Design 33 (2001) 65–79.

[13] F. Xu, Y.S. Wong, H.T. Loh, J.Y.H. Fuh, T. Miyazawa, Optimal orientation with variable slicing in stereolithography, Rapid Prototyping Journal 3 (3) (1997) 76–88.

[14] P. Kulkarni, D. Dutta, An accurate slicing procedure for layered manufacturing, Computer Aided Design 28 (9) (1996) 683–697.

[15] J.E. McClurkin, D.W. Rosen, Computer-aided build style decision support for stereolithography, Rapid Prototyping Journal 4 (1) (1998) 4–13.

[16] S.H. Massod, W. Rattanawong, P. Iovenitti, A generic algorithm for part orientation system for complex parts in rapid prototyping, Journal of Material Processing Technology 139 (1–3) (2003) 110–116.

[17] P.M. Pandey, N.V. Reddy, S.G. Dhande, Surface roughness simulation for FDM processed parts, Proceedings of 18th International Conference on Computer Aided Production Engineering, 2003, pp. 413–421.

[18] P.M. Pandey, N.V. Reddy, S.G. Dhande, A real time adaptive slicing for fused deposition modelling, International Journal of Machine tools and Manufacture 43 (1) (2003) 61–71.

[19] K. Deb, R.B. Agrawal, Simulated binary cross-over for continuous search space, Complex Systems 9 (1995) 115–148.

[20] V. Bharath, P.N. Dharam, M. Henderson, Sensitivity of RP surface finish to process parameters variation, Solid Free-form Fabrication Proceedings (2000) 251–258.

[21] K. Gautham, M.I. Novi, M. Henderson, A design tool to control surface roughness in rapid fabrication, http://prism.asu.edu/publication/Manufacturing/abs_design.html.

[22] P.M. Pandey, Enhancement of surface finish in fused deposition modeling, Ph.D. Thesis, I.I.T., Kanpur, India, 2003.

[23] E. Sabourin, S.A. Houser, J.H. Bohn, Adaptive slicing using stepwise uniform refinement, Rapid Prototyping Journal 2 (4) (1996) 20–26.

[24] J. Tyberg, J.H. Bohn, Local adaptive slicing, Rapid Prototyping Journal 4 (3) (1998) 118–127.

[25] E. Sabourin, S.A. Houser, J.H. Bohn, Accurate exterior fast interior layered manufacturing, Rapid Prototyping Journal 3 (2) (1997) 44–52.

[26] K. Tata, G. Fadel, A. Bagchi, N. Aziz, Efficient slicing for layered manufacturing, Rapid Prototyping Journal 4 (4) (1998) 151–167.

[27] D. Cormier, K. Unnanon, E. Sanni, Specifying non-uniform cusp heights as a potential for adaptive slicing, Rapid Prototyping Journal 6 (3) (2000) 204–211.

[28] R.L. Hope, P.A. Jacobs, R.N. Roth, Rapid prototyping with sloping surfaces, Rapid Prototyping Journal 3 (1) (1997) 12–19.

[29] R.L. Hope, R.N. Roth, P.A. Jacobs, Adaptive slicing with sloping layer surfaces, Rapid Prototyping Journal 3 (3) (1997) 89–98.

[30] K. Mani, P. Kulkarni, D. Dutta, Region-based adaptive slicing, Computer Aided Design 31 (5) (1999) 317–333.

[31] M. Weiyin, H. Peiren, An adaptive slicing and selective hatching strategy for layered manufacturing, Journal of Material Processing Technology 89–90 (1999) 191–197.

[32] K.H. Lee, K. Choi, Generating optimal sliced data for layered manufacturing, International Journal of Advanced Manufacturing Technology 16 (2000) 277–284.

[33] R. Jamieson, H. Hacker, Direct slicing of CAD models for rapid prototyping, Rapid Prototyping Journal 3 (1) (1995) 12–19.

[34] Z. Zhao, L. Laperriere, Adaptive direct slicing of the solid model for rapid prototyping, International Journal of Production Research 38(3) (2000) 89–98.

[35] I. Zeid, CAD/CAM Theory and Practice, Mc Graw-Hill, 1991.