Optimum Part Deposition Orientation in Stereolithography

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ABSTRACT

In the present work an attempt has been made to achieve minimum average part surface roughness (best overall surface quality) for Stereolithography processed parts by determining optimum part deposition orientation. A conventional optimization algorithm based on Trust Region Method (available with MATLAB 6.5 optimization tool box) has been used to solve the optimization problem. It is observed that the problem is highly multi-modal in nature and a suitable initial guess, which is used, as an input to execute optimization module is important to achieve a global optimum. A simple methodology has been proposed to find out initial guess so that global minimum is obtained. Finally the surface roughness simulation is carried out with optimum part deposition orientation to have an idea of surface roughness variation over the entire part's surface before depositing the part. Case studies are presented to demonstrate the capabilities of the developed system

Keywords: Stereolithography (SL), Part deposition orientation, Average part surface roughness.

1. INTRODUCTION

Stereolithography (SL) process is the most popular [6] Rapid Prototyping (RP) process, which creates three-dimensional plastic objects directly from CAD data. The process begins with the vat filled with the photo-curable liquid resin and the elevator table set just below the surface of the liquid resin. The operator loads a three dimensional CAD (solid) model into the system. The translator tessellates three-dimensional CAD data into STL file by first order piece-wise approximation of surfaces and an error namely facet deviation is introduced [12]. Support structure is designed to stabilize the part during building. The control unit slices the model and support structure into a series of cross sections from 0.025 to 0.5 mm (0.001 to 0.020 in) thick. The computer-controlled optical scanning system then directs and focuses the laser beam, so that it solidifies a two dimensional cross-section corresponding to the slice on the surface of the photo curable liquid resin to a depth greater than one layer thickness. The elevator table then drops enough to cover the solid polymer with another layer of liquid resin. A leveling wiper or vacuum blade moves across the surfaces to recoat the next layer of resin on the surface. The laser then scans the next layer. This process continues building the part the bottom up, until the system completes the part. The part is then raised out of the vat for post processing and excess polymer is cleared. The main components of the SL system are a control computer, a laser, an optical system and process chamber. The workstation software used by the SL system is known as Maestro™ [3,15].

The quality of a rapid prototype is governed by its surface finish, accuracy and strength however the cost is directly related with the build time. The accuracy and surface finish enhancement requires deposition of finer slices which leads to drastic increase in build time. Thus these issues contradict with each other. By choosing a proper part deposition orientation and then slicing the CAD model adaptively, may be a solution to handle this contradicting issue. A suitable part deposition orientation can improve part accuracy and surface finish and reduce the production time and support structures needed for building the part [13,17].

There have been several attempts [1,2,5,8-11,13-14,16-18,20] to determine suitable part deposition orientation for different objectives like accuracy, build time, support structure, etc. Frank and Fadel [5] developed an interactive system to decide on a suitable part deposition orientation. Surface finish, build time or support structure were considered as an objective and guidelines were framed to decide a preferred orientation. They emphasized that surface roughness should be considered as a primary objective being the geometrical limitation of layer-by-layer deposition. Build time should be given second preference as the rapid prototyping machine fabricates a prototype quite faster as compared to traditional prototyping techniques. Support structures were given least preference in their work being the intrinsic process characteristics. Cheng et al. [2] presented a multi-objective approach for determining a suitable part building orientation for SL parts considering dimensional accuracy and build time as objectives. Part accuracy was treated as the 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 a pre-specified cusp height [4] was also introduced in their work. Possible base planes were identified by finding the planar (flat) surfaces of the object. First, a few orientations were short-listed based on part accuracy from the possible orientations. Finally, the best orientation was found among the short-listed orientations considering build time as a criterion.

Lan et al. [8] determined the deposition orientation for SL parts based on the considerations of surface quality, build time or the 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 assessed indirectly by the height of the part in the deposition direction. Support structure was minimized by minimizing the number of supported points. Suitable orientation for one of the objectives at a time was determined from the list of pre-selected base planes. Alexander et al. [1] determined suitable part deposition orientation for better part accuracy and lower cost. Major source of part inaccuracy considered in their work was due to the stair stepping effect and is measured in terms of cusp height [4]. The cusp height for a triangular facet is calculated as the maximum normal distance between facet and the deposited part considering the edges of the slices to be rectangular. Slicing with constant layer thickness is considered. The weighted cusp height was defined as the multiplication of the area of the facet with the cusp height. Cusp height was weighed for the supported facets as it increases the inaccuracy. The average weighted cusp height was calculated by dividing the sum of weighted cusp height by the total area of facets. Surface accuracy was maximized by selecting an orientation that gives minimum average weighted cusp height among few pre-selected part deposition orientations. Alexander et al. [1] proposed a generic cost model for RP part in which total cost of a model is sum of pre-build, build and post-processing costs. Build cost is due to manufacturing time and idle time. Difference in costs of model and support materials was taken into consideration. The post-processing cost is dependent on support removal cost and finishing cost. Specific cost models for Fused Deposition Modelling (FDM) and SL were developed. In their work, orientation module generates a set of orientations from the faceted 3D convex hull of the part. From these, a list of candidate orientations to be used for testing is distilled by selecting a user defined number of orientations with the largest footprint i.e. the shadow of the convex hull projected on to a plane perpendicular to build direction.

Xu et al. [19] presented an adaptive slicing method similar to that due to Kulkarni and Dutta [7], which slices CAD models represented by analytical surfaces. Xu et al. [19] used Genetic Algorithms (GA) however Kulkarni and Dutta [7] used sequential quadratic programming (SQP) to find out layer thickness at z=constant contours, where z is the direction of deposition. Xu et al. [19] also investigated the best part deposition orientation for SL parts among few pre-selected orientations considering weighted sum of build time, accuracy and stability of the part as a criterion. In their work, build time was estimated by the ratio of number of adaptive slices to largest possible number of slices, accuracy was estimated by ratio of overhang area to the total surface area and stability was estimated by the penalty approach. The value of penalty was set equal to zero if the projection of centre of mass of the part lies within the convex hull (at the candidate base plane) otherwise value of penalty was calculated by the ratio of multiplication of closest distance between the center of gravity (CG) projection in the base plane to the convex hull of the base and height of the CG of the part to the base plane area. A trading-off among these objectives was performed by choosing suitable values of weights for stability, accuracy and build time to achieve the best orientation.

McClurkin and Rosen [11] developed statistical models to predict build time, accuracy and surface finish of SL parts using response surface methodology. A face centered central composite experiment design was used to plan experiments. Layer thickness, hatch spacing, z-height and part volume were selected as variables. In order to formulate a quadratic response surface for each goal, each variable was considered at three equally spaced levels. They fabricated block-shaped and cylindrical parts in various sizes and orientations to be consistent with the experimental factors and their levels. Minitab^{TM} software was used to define and fit the response surfaces. They formulated a compromise Decision Support Problem (DSP) to minimize the difference between the targets and design point. Layer thickness, hatch spacing and part deposition orientation were selected as design variables to be determined and build time, accuracy and surface finish as goals. Pham et al. [14] implemented a decision support system to provide part deposition orientation advice to the designer for SL. In their system, a user can select one or more than one options among the features namely user specified critical surfaces, co-ordinate systems, holes, cuts, shafts, protrusions, shells and axes as per the need to select candidate part deposition orientations. The unit vector in the build direction for each candidate part deposition orientation was stored. Each candidate orientation was then compared based on criteria namely overhanging area, volume of support structure, build time, cost of the part and problematic features. Their system sorts the candidate orientations for each criterion and a position score is assigned. User needs to specify a weight factor for each criterion as per the preference. The final score of each candidate orientation is then calculated by summing the multiplication of criterion weight and position score for individual criterion. The orientation that obtains maximum score is the most suitable part deposition orientation among the list of pre-selected orientations.

Masood and his co-workers [9,16] used a volumetric error based approach to determine suitable part deposition orientation. In this methodology, difference in the volume of the part deposited using uniform slices and the CAD model of the part is minimized for selecting a suitable orientation. Here, the build edges of slices are assumed to be rectangular. This methodology involves a primitive volume approach, which assumes a complex part to be constructed from a combination of basic primitive volumes. Recently Masood et al. [10] presented a generic approach in which tessellated CAD models are used in place of basic primitives which forms a part. Best part deposition orientation for tessellated CAD model is obtained by minimizing the volumetric error [9,16]. West et al. [18] developed a process planning method for improving build performance, i.e., shorter build time, better accuracy and high surface finish in SL. Process planning has been carried out by them in three steps namely orientation, slicing and parameter selection. Part deposition orientation, layer thickness, sweep period, z-height, fill over-cure and hatch over-cure are the six process variables considered in their work. 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 (presence of support structure trapped volume, large horizontal planes and small or thin features). Four most feasible alternative orientations were selected for further investigations to develop the most suitable process plan.

Very recently two attempts [13,17] have been made to find out optimum part deposition orientation rather than finding out suitable part deposition orientation among few pre-selected orientations. Thrimurtullu et al. [17] determined optimal part deposition orientation for Fused Deposition Modelling (FDM) by considering weighted sum of average part surface roughness and build time as an objective function to minimize. They used real coded Genetic Algorithm for optimization. Pandey et al. [13] used trading off between average part surface roughness and build time of a prototype and used Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to find out pareto optimal part deposition orientations for FDM process for a given part's tessellated CAD data.

Literature review presented above reveals that most of the attempts [2,5,8-11,14,16,18,20] (except two [13,17] for FDM process) have been made for determination of suitable part deposition orientation among few pre-selected orientation although part can be deposited in infinite possible orientations theoretically but no attempt appears to be made for determining optimum part deposition orientation related to SL process. Pre-selection of the candidate base planes for depositing part is impossible for a completely freeform part like bones, horse saddletree etc. Estimation of part surface quality in terms of standard *Ra* value [13,17] instead of weighted cusp height [1] is more appropriate. Use of conventional optimization technique is expected to be computationally more efficient and may use lesser function evaluation as compared to Genetic Algorithm [13,17] based approaches. Therefore, in the present work an attempt has been made to determine optimum part deposition orientation for SL process by minimizing average part surface roughness. In order to make the procedure computationally efficient, a conventional optimization technique based on trust region methods (available with MATLAB 6.5 optimization tool box) has been used and multi-modality present in the problem has been handled by finding out an initial guess closer to global optima by the discrete search in regular intervals of decision variables.

2. PROBLEM FORMULATION

RP processes have the common problem of stair stepping, which means that layer thickness will have a significant effect on surface roughness. It is often desirable for an RP model to have minimized surface roughness, particularly in areas of aesthetic or functional importance. Reducing layer thickness will generally improve surface finish but will add to the build time for the model. It is also possible to improve the surface roughness of RP model through post process surface treatments; however, once again this is time consuming and adds to the cost. In the present work, an attempt has been made to minimize the overall average part surface roughness of SL part by selecting an optimal part deposition orientation.

McClurkin and Rosen [11] developed surface roughness model based on statistical design of experiments technique, which can be used (based on experimental results for layer thickness =0.006 inch) to estimate the surface roughness of a triangular facet of STL file. The equations used to predict surface roughness of a triangular facet of a tessellated CAD model (after modification for our purpose) in the present work are given by

$$Ra_i\,(\mu m) = \left\{2\cos\theta\sin\theta \times 937 + 3.5\theta + 48\right\} \times 0.0254 \qquad for \quad 0 \le \theta \le {}^{\pi}\!/_{2} \tag{1}$$

$$Ra_i\,(\mu m) = \left\{2\cos\left(\pi - \theta\right)\sin\left(\pi - \theta\right) \times 937 + 3.5\theta + 48\right\} \times 0.0254 \qquad for \quad {}^{\pi}\!/_{2} < \theta \le \pi \tag{2}$$

where θ is known as build orientation and is the angle of the facet normal with the vertical axis (z axis) as shown in Fig. 1. The variation of surface roughness (equation 1 and 2) with respect to build orientation θ is given in Fig. 2. It can be observed from Fig. 2 and equations 1 and 2 that the surface roughness values in the range of $\pi/2 \le \theta \le \pi$ are little higher than in the range of $0 \le$ □ $\le \pi/2$. This is due to the presence of support structure (removal of support structure detracts surface quality) below the surfaces having build orientations in the range of $\pi/2 \le \theta \le \pi$.

The average surface roughness of the part can be calculated by

$$Ra_{av} = \frac{\sum Ra_i A_i}{\sum A_i} \tag{3}$$

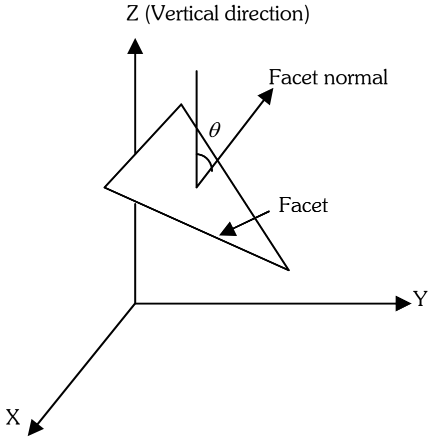

Fig. 1. Build orientation of a triangular facet

where Ra_i and A_i are surface roughness and area of i^{th} triangular facet of STL file respectively.

A part for which optimum part deposition orientation for minimum surface roughness is to be determined is modeled in AutoCAD, in a known orientation and STL file is exported. In this work, it is needed to calculate objective function for various orientations of the part. STL file corresponding to an orientation (i.e., rotation about an axis described by unit vector (e_x, e_y, e_z) by angle ϕ as shown in Fig. 3) of the part is calculated using the following transformation matrix [20]

$$[R] = \begin{bmatrix} e_x^2 v\phi + c\phi & e_x e_y v\phi - e_z s\phi & e_x e_z v\phi + e_y s\phi \\ e_x e_y v\phi + e_z s\phi & e_y^2 v\phi + c\phi & e_y e_z v\phi - e_x s\phi \\ e_x e_z v\phi - e_y s\phi & e_y e_z v\phi + e_x s\phi & e_z^2 v\phi + c\phi \end{bmatrix} \tag{4}$$

where $v_\phi = 1 - \cos\phi$, $c\phi = \cos\phi$ and $s\phi = \sin\phi$.

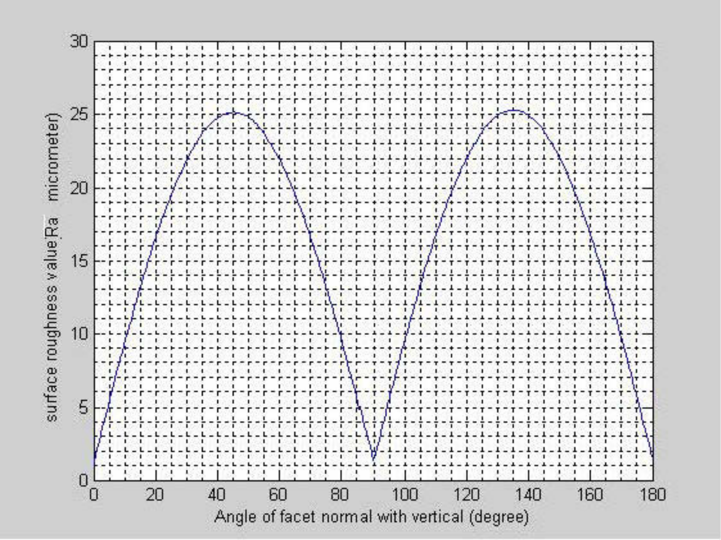

Fig. 2. Variation of surface roughness with build orientation (generated by equations 1 and 2)

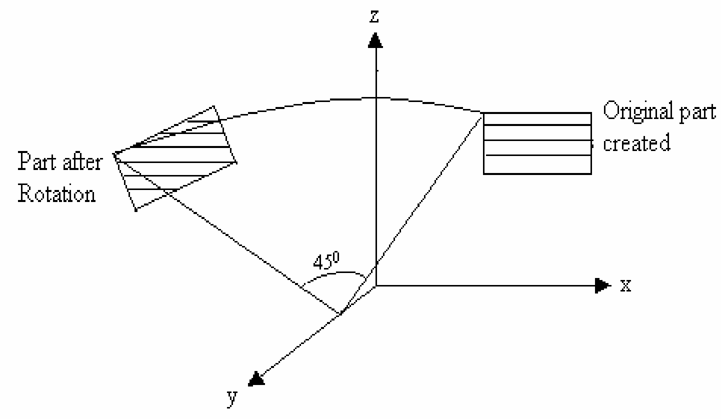

Fig. 3. Rotation of tessellated CAD Model about Y-axis by 45° angle [17]

Therefore decision variables for the present optimization problem are unit vector (e_x, e_y, e_z) and angle ϕ. In the optimization process the three components of axis vector, i.e., e_x, e_y, and e_z and kept in between 0 and 1, and angle of rotation ϕ is kept in between 0° to 360°. Thus the complete problem of optimum part deposition orientation is as given below.

$$\left.\begin{array}{ll} & \text{Minimize } (Ra_{av}) \\ \text{Subjected to} & 0 \le e_x \le 1 \\ & 0 \le e_y \le 1 \\ & 0 \le e_z \le 1 \\ & 0^o \le \phi \le 360^o \\ & e_x^2 + e_y^2 + e_z^2 > 0 \end{array}\right\} \qquad (5)$$

3. OPTIMIZATION TECHNIQUE

Optimization process used in the present work is based on trust region method, which is a simple and powerful concept. In the developed optimum part deposition orientation system minimization of average part surface roughness is performed by the standard optimization toolbox of MATLAB 6.5.

3.1 Trust-Region Methods for Nonlinear Minimization

In the trust-region method objective function $f(x)$ is approximated by a simpler function $q(x)$, which reasonably reflects the behavior of function f in a neighborhood N around the point x. The function $f(x)$ takes vector argument and returns scalar. This neighborhood is known as the *trust region*. A trial step s is computed by minimizing $q(s)$ (or approximately minimizing) over N. This is the trust-region subproblem and is mathematically given by

$$\min_{s}\left\{q(s); \quad s \in N\right\} \tag{6}$$

The current point is updated to be $x+s$ if $f(x+s)<f(x)$; otherwise, the current point remains unchanged and N, the region of trust, is reduced and the trial step computation is repeated. In the standard trust-region method, the quadratic approximation q is defined by the first two terms of the Taylor approximation to f at x. The neighborhood N is usually spherical or ellipsoidal in shape where the quadratic approximation is reasonably accurate. Mathematically the trust-region subproblem is to find vector s that minimizes

$$\min\left\{\frac{1}{2}s^{T}Hs + s^{T}g \quad \text{such that} \quad ||D_{s}|| \leq \Delta\right\} \tag{7}$$

subjected to constrained $||D_s|| \leq \Delta$. The length of the step is accepted if $||D_s|| \leq \Delta$. Here g is gradient of f (a vector of first derivatives) at the current point x, H is the Hessian matrix (the symmetric matrix of second derivatives), D is a diagonal scaling matrix, Δ is a positive scalar and $||\ \ ||$ is a 2 norm.

There is no need to provide an accurate solution to equation 7 because it requires large computation time, which is proportional to several factorizations of H. Therefore for large-scale problems an approximation approach is recommended and the same is used in the present work. The approximation approach followed in the optimization is to restrict the trust-region subproblem in to a two-dimensional subspace S. Once the subspace S has been computed, the solution of equation 7 is trivial. The dominant work has now shifted to the determination of the subspace. The two-dimensional subspace S is determined with the preconditioned conjugate gradient process described below.

3.2 Preconditioned Conjugate Gradient Method

In the conjugate gradient algorithm, the step size is adjusted at each iteration. A search is made along the conjugate gradient direction $\boldsymbol{S}$ to determine the step size s, which minimizes the performance function along that line. The two-dimensional subspace $\boldsymbol{S}$ is given as $\boldsymbol{S} = (s_1, s_2)$, where s_1 is in the direction of the gradient g, and s_2 is either an approximate Newton direction, i.e., a solution to

$$H \cdot s_2 = -g \tag{8}$$

or a direction of negative curvature,

$$s_z^{T} \cdot H \cdot s_2 < 0 \tag{9}$$

The philosophy behind this choice of $\boldsymbol{S}$ is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence.

A framework for the optimization approach to constrained minimization-using trust-region ideas can be summarized as

- Formulate two-dimensional trust-region subproblem.
- Solve equation 7 to determine the trial step s.
- If $f(x+s) < f(x)$ then $x=x+s$.
- Adjust Δ.

These four steps are repeated until the convergence (Hessian matrix H should be positive semi definite) is achieved.

4. IMPLEMENTATION PROCEDURE

The optimum part deposition orientation system is implemented using MATLAB 6.5. AutoCAD platform is used for solid modeling. First the part is solid modeled in AutoCAD 2000 and STL file (ascii) is imported. This STL file is used as an input to the developed system of optimum part deposition orientation. In the beginning, system rotates the part about various possible axes in certain discrete intervals and calculates the average part surface roughness in each orientation as given below in the form of pseudo-code. In this step, the system finds out the axis and angle of rotation that gives minimum average part surface roughness and this information is used as an initial guess for optimization algorithm explained in section 3. This step is essential as the problem of part deposition orientation is highly multi-modal in nature and a conventional optimization technique is most likely going to stick at local minimum. By this step, an attempt has been made to assure that the optimization algorithm (explained in the section 3) will be started with initial guess that is very close to the global minimum and there is fairly good chance that it converges to global minimum.

```
Do ex = 0: 0.25: 1
    Do ey= 0: 0.25: 1
        Do ez = 0: 0.25: 1
            Do angle = 0: 1: 359
                Average surface roughness computation
                Store (ex,ey,ez) and angle that give minimum average part surface roughness
            End {do}
        End {do}
    End {do}
End {do}
```

Algorithm 1. Pseudo code to find out initial guess for optimization module for convergence to global minimum

Once the initial guess for optimization module is obtained the developed system uses the standard optimization toolbox of MATLAB 6.5 to find out the optimum part deposition orientation. A standard function of MATLAB 6.5 namely '*fmincon*' that can handle a large-scale optimization problem with nonlinear equality as well as inequality constraint is used for the purpose. The principle of optimization is based on trust region method and is explained in section 3.1. Since the axis vector ($e_{x,}$ $e_{y,}$ e_z) cannot have all elements as zero, a constraint as given in equation 10 (below) is imposed.

$$e_x^2 + e_y^2 + e_z^2 > 0 \tag{10}$$

Once the optimum value of decision variables (e_x $e_{y,}$ e_z and ϕ) is obtained the system generates a graphical simulation of surface roughness over the entire part with minimum average part surface roughness. Here the color of each triangular facet corresponds to its surface roughness value.

5. RESULTS AND DISCUSSION

Two case studies are presented and the obtained results are discussed in detail in order to demonstrate the capabilities of the developed system of optimum part deposition orientation.

A three dimensional part shown in Fig. 4 is considered for determination of optimum part deposition orientation if it is to be produced using Stereolithography. A solid model of the part is created in AutoCAD 2000 in the same orientation as shown in the Fig. 4 and STL file is imported. This STL file is used as an input to the developed system of optimum part deposition orientation determination. Various other parameters related to optimization module are decided like maximum iteration, maximum function evaluations, tolerance for function for convergence, tolerance for decision variable and tolerance for equality constraint.

If the part is deposited in the same orientation as shown in Fig. 4 (without going for optimum part deposition orientation) the average part surface roughness is obtained as 4.1547 µm (Fig. 5). The developed system of optimum part deposition orientation computes the initial guess for the part as (0.2425, 0, 0.9701, 6.000) and surface roughness value as 4.1346 µm. After the convergence, the optimization module gives minimum average part average surface roughness as 4.1345 μm. The obtained results after convergence are given in Tab.1 and the obtained surface roughness simulation is presented in Fig. 6.

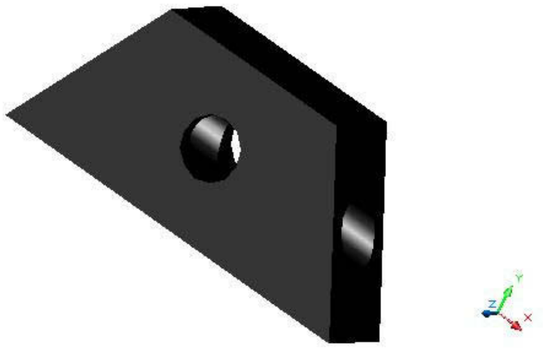

Fig. 4. Solid model of a wedge shaped part with perpendicular through holes

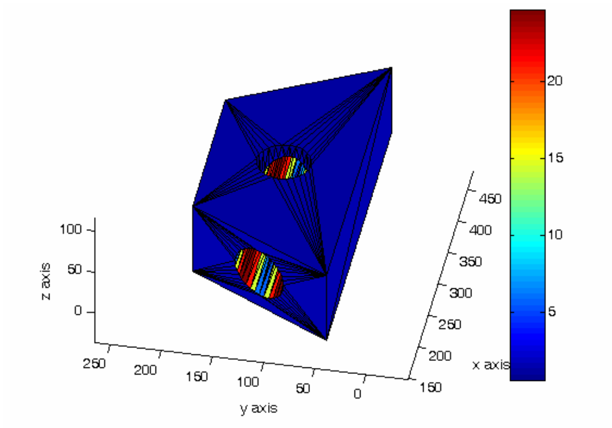

Fig. 5. Surface roughness simulation if the part is deposited in the same orientation as shown in Fig. 4 Average part surface roughness = 4.1547 μm

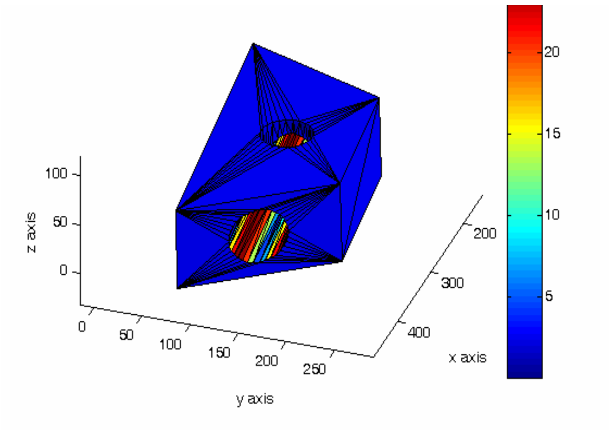

Fig. 6. Graphical output obtained from the developed system of optimum part deposition orientation determination, Average part surface roughness = 4.1345 μm

e_x	e_y	e_z	**ϕ (Degree)**	**Ra_{av} (μm)**
0.2444	0.0002	0.9697	6.0001	4.1345

Tab. 1. Results obtained from the developed system of optimum part deposition orientation determination for the part shown in Fig. 4

Solid model of a bracket type of part is shown in Fig. 7 and is considered for optimum part deposition orientation determination. STL file corresponding to this solid model is obtained from AutoCAD 2000 and used as an input to the developed system. If this part is deposited in the same orientation as shown in Fig. 7 the average part surface roughness is obtained as 2.7427 (Fig. 8) however the optimum solution and corresponding graphical output has been reported in Tab. 2 and Fig. 9 respectively. In this case the initial guess computed by the system for optimization toolbox was (0.2425, 0, 0,9701, 6.000) and the average part surface roughness was 2.7213 μm.

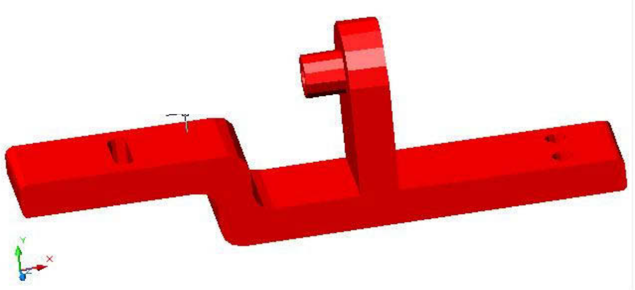

Fig. 7: Solid model of a bracket type part

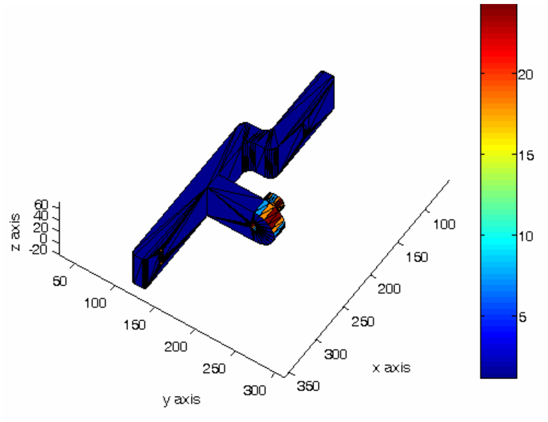

Fig. 8. Surface roughness simulation if the part is deposited in the same orientation as shown in Fig. 7 Average part surface roughness = 2.7427 μm

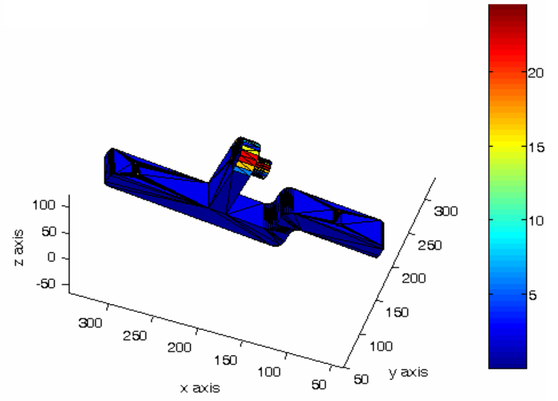

Fig. 9. Graphical output obtained from the developed system of optimum part deposition orientation determination, Average part surface roughness = 2.7213 μm

e_x	e_y	e_z	ϕ **(Degree)**	Ra_{av} **(μm)**
0.2452	0.0001	0.9695	6.0001	2.7213

Tab. 2. Results obtained from the developed system of optimum part deposition orientation determination for the part shown in Fig. 7

The obtained solution shows that the part is to be rotated by approximately 6° about an axis represented by position vector as (0.2452,0.0001,0.9695) for obtaining minimum average part surface roughness.

6. CONCLUSIONS

From the case studies presented above it is concluded that developed system has capability of minimizing overall average part surface roughness. The multi-modality present in the problem has been tackled by finding out an initial part deposition orientation (guess) that gives quite small value of average part surface roughness and may be very close to global minimum. This initial guess, used to execute optimization module, is obtained by rotating the part in discrete intervals about various combinations of axes. The developed system is able to handle any geometry of the parts as well as it converges to global minimum. The generated surface roughness simulation gives the idea of surface roughness variation over the part's surface well in advance before going for actual part fabrication. Therefore the modification in the part design can be carried out at very early stages to improve its functionality. The computational time required in the present method is expected to be lesser than the computational time required if Genetic Algorithm based optimization method is used. The work is in progress to enhance capabilities of developed system by including different modules for simultaneously minimizing the amount of support material, build time and maximizing the accuracy and strength of the SL part.

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