International Journal of CAD/CAM Vol. 6, No. 1, pp. 51~58 (2006)

INTERNATIONAL JOURNAL OF CAD/CAM
www.ijcc.org

Determination of Optimal Build Orientation Based on Satisfactory Degree Theory for RPT

Jibin Zhao[1]*, Weijun Liu and Jianhuang Wu

Key Lab of Advanced Manufacturing Technolog Shenyang Institute of Automation China Academy of Sciences, Shenyang, 110016, PR China.

Abstract – In rapid prototyping, the optimal part orientation during fabrication is critical as it can improve part accuracy, minimize the requirement for supports and reduce the production time. Through investigating the geometric issues of STL model and process planning of RPM, This paper establishes optimizing model based on the considerations of staircase effect, support area and production time. The general satisfactory degree function is constructed employing the multi-objective optimization theory based on the general satisfactory degree principle. The best part-building orientation is obtained by solving the function employing generic algorithm. Experiment shows that the methods can effective resolve the part-building orientation in RP.

Key Words **: Rapid Prototyping, STL file, satisfactory degree, multi-objective optimization, generic algorithm**

1. Introduction

In rapid prototyping, the various stages in the process are automatic, except for the selection of the part orientation. Currently, in lots of commercial rapid prototyping system, part-building orientation is decided by an experienced user. In this way, part-building orientation depends heavily on the knowledge, which is a combination of skill and experience [13]. It is a strongly subjective skill, and has yet to be organized into a precise and objective methodology. Without a suitable computational approach, it will be difficult to determine the optimal orientation as evident in the different solutions produced by current manual methods.

In rapid prototyping technology, the orientation of part during fabrication is critical as a suitable orientation can improve part accuracy, reduce the production time and minimize the support needed for building the model. Thus, it will help minimize the cost of making the prototype [10]. It is easier to understand the importance of build orientation by studying the semi-column in Fig. 1 where vector d indicates the build orientation. If the part is built as Fig. 1(a), the best surface finish can be obtained because no staircase effect is incurred. However, a longer time is needed to build the part because more layers are required. If it is built as Fig. 1(b), a staircase effect will occur on surface, but a shorter build time is required, because the number of layers is minimized. If the part is oriented as Fig. 1(c), a support structure will be required for surface and the part is unstable, so we have to make some trade-off in the determination of build orientation. Part accuracy, build time, support structure, and part stability are the main factors for consideration [6]. Tool accessibility is not considered in LM because the part is built incrementally by thin layers. Parts with any geometric complexity, including internal features, can be made by LM. Taking into account the aforementioned sources of affecting part-building orientation, a part should be:

(1) Minimize the staircase appear along inclined surface.
(2) Minimize the total area of overhang surface.
(3) Minimize the total number of slice.

There have been several works done the orientation problem for rapid prototyping. Cheng et al [2]. developed a procedure for optimization of part-building orientation in SLA by assigning weights to various surface types affecting part accuracy. Majhi et al. [7] present a number of optimization algorithms to minimize staircase error, support volume and support contact area. Hur and Lee [5] developed an algorithm to calculate the staircase area, quantifying the process errors by the volume supposed to be removed or added to the part. Rattanawong et al. [12] discuss the fabrication orientation problem from geometric and algorithmic points of view, and establish decision criteria for the determi-nation of good fabrication orientations in SLA. Masood [9] compute the volumetric error (VE) in a part at different orientations and applied generic algorithm (GA) for the optimal solution based on the minimum VE in the part. These methods optimize the part building orientation by only one objective, but the optimization of part building orientation is multi-objective problem involved part accuracy, production time and support. There are also several works [3, 8, 11] do the problem accounting

*Corresponding author:
Tel: +86-24-23970030
Fax: +86-24-23970534
E-mail: jbzhao@sia.cn

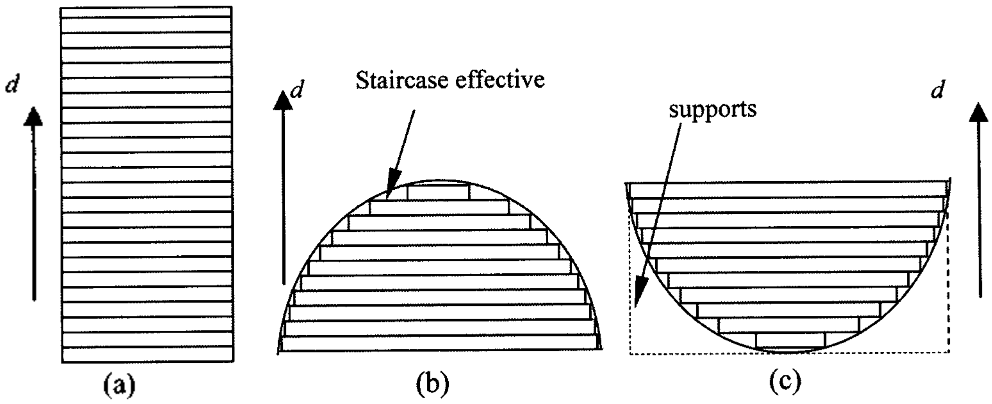


Fig. 1. Effects of build orientation.

for the three objectives, but the result is not satisfying. The cause is the three objectives are often incompatible each other. In this way, the optimal result sometimes does not exist.

Contrasting with problem of single-objective optimization, the problem of multi-objective optimization can be not solved perfectly and systemic in theory and calculating method. Thereby, it is necessary to create theory and method system of multi-objective optimization. Satisfactory theory [1, 4, 14, 15] is regarded as more ordinary mode of optimization theory. A new means must be provided to solve the practical problems along with perfect and progress of satisfactory theory.

2. Multi-objective optimization model

2.1 Mathematics model of optimization objective for staircase effect

Fig. 2 shows the staircase effect during part building of layered manufacturing in rapid prototyping. The volumetric error in each layer stem from staircase effect is written as:

$$V_i = \sum_j \frac{h^2 \cos\theta_j}{2 \sin\theta_j} l_{ij} \tag{1}$$

Where h is layer thickness. Suppose the model is STL file, θ_j is the angle between triangle facet j of model surface and build orientation, l_{ij} is the length of intersect line segment between No. i layer and facet j

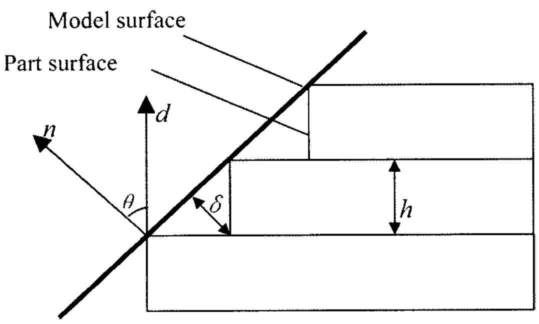


Fig. 2. Staircase effective.

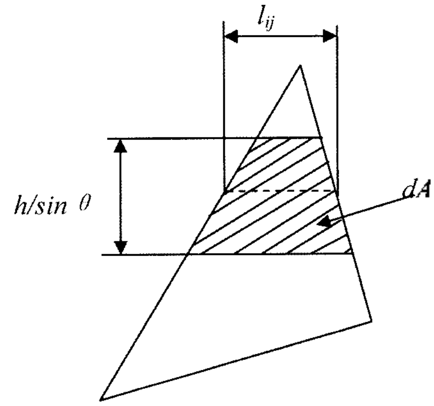


Fig. 3. Staircase effective in one facet.

as illustrated in Fig. 3.

The followed equation is obtained from Fig.3.

$$\begin{cases} \cos\theta_j = \dfrac{|d \cdot n|}{|d| \cdot |n|} \\ \sin\theta_j = \dfrac{|d \times n|}{|d| \cdot |n|} \end{cases} \tag{2}$$

Where, d is the unit vector of the build direction, n is the unit normal vector of triangle facet.

Substitution of Eq. (2) into Eq. (1) yields a new equation given by

$$V_i = \sum_j \frac{h^2 \cdot |d \cdot n|}{2|d \times n|} l_{ij} \tag{3}$$

The VE of the whole part stem from staircase is express as:

$$V_i = \sum_i \sum_j \frac{h^2 \cdot |d \cdot n|}{2|d \times n|} l_{ij} = \sum_j \sum_i \frac{h^2 \cdot |d \cdot n|}{2|d \times n|} l_{ij} = \sum_j V_j \tag{4}$$

$$V_j = \sum_i \frac{h^2 \cdot |d \cdot n|}{2|d \times n|} l_{ij} \tag{5}$$

Fig.3 shows the case that a triangle facet is sliced, then area that a triangle facet lays in No. i layer is given by

$$dA = l_{ij}\cdot h/\sin\theta = l_{ij}/|d\times n| \tag{6}$$

Substitution of Eq. (6) into Eq. (5) yields a new equation given by

$$V_j=\sum_i \frac{h^2\cdot|d\cdot n_j|}{2}=\frac{h^2\cdot|d\cdot n_j|\cdot A_j}{2} \tag{7}$$

Where, A_j is area of facet j. Suppose the coordinate of three vertex of triangle A_j is (x_j,y_j,z_j), j = 1, 2, 3, the area of triangle is given by

$$A_j=\frac{1}{2}\sqrt{\begin{vmatrix} x_2-x_1 & y_2-y_1 \\ x_3-x_1 & y_3-y_1 \end{vmatrix}+\begin{vmatrix} y_2-y_1 & z_2-z_1 \\ y_3-y_1 & z_3-z_1 \end{vmatrix}+\begin{vmatrix} z_2-z_1 & x_2-x_1 \\ z_3-z_1 & x_3-x_1 \end{vmatrix}} \tag{8}$$

So the VE is

$$V=\sum_j \frac{h^2\cdot|d\cdot n_j|\cdot A_j}{2} \tag{9}$$

The VE stem from staircase should be minimized to improve part accuracy. Thus the optimization problem can be stated as follows:

Problem 1. Find a part building orientation such that the VE is minimized. It is expressed as follow:

$$f_1(d)=\min\sum_i \frac{h^2\cdot|d\cdot n_j|\cdot A_j}{2} \tag{10}$$

2.2 Mathematics model of optimization objective for supports area

The quantity of supports used affects not only the building time and the cost but also surface finish and postprocessing. The quantity of supports used has two meanings. One is the quantity of supports area; another is the quantity of supports volume. Supports volume particularly affects the building, But computing the supports volume is very complex. If the shape of part is convex, the supports volume is the volume of the region lying between the solid of part and platform, the vertical polyhedral cylinder which is bounded below by the platform and above by the facets of the part whose outward normal point downward. But if the shape of the part is non-convex, the problem is more complex, since the supports for some faces may actually be attached to other facets instead of to the platform. (Fig. 4 illustrates this-in 2D, for convenience).

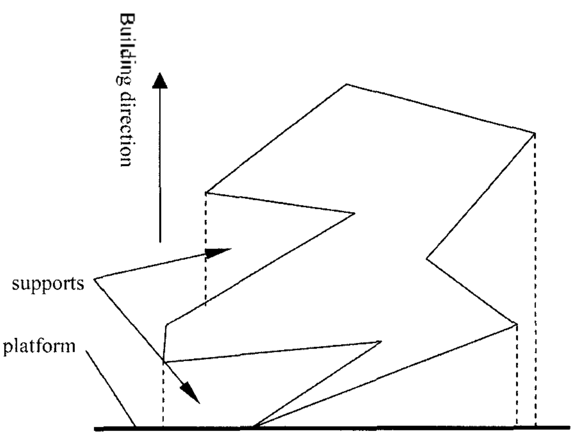


Fig. 4. Supports of non-convex.

The quantity of supports area particularly affects postprocessing and surface finish. Support area is the total area of the downward-facing facets. So computing the supports area is relatively simple. At the same wile, supports area has more significant impact on the part accuracy than support volume. So the part building direction optimization account for the supports area.

Thus the optimization problem can be stated as follows:

Problem 2. find a part building direction such that the supports area is minimized. It is expressed as follow:

$$f_2(d)=\min\sum_j A_j\cdot|d\cdot n_j|\cdot\delta \tag{11}$$

Where, δ is a threshold function

$$\delta=\begin{cases}1, & d\cdot n_j<0\\ 0, & d\cdot n_j>0\end{cases} \tag{12}$$

2.3 Mathematics model of optimization objective for production time

Part building time include scanning time and preparing time. Where, scanning time include solid scanning time T_f, contour scanning time T_c, support scanning time T_s.

$$T_f=\frac{V}{h\bullet h_s\bullet v_f} \tag{13}$$

$$T_c=\frac{S}{\Delta h v_c} \tag{14}$$

$$T_s(i)=\sum_{i=1}^{n}\frac{A_s(i)d}{l_w v_c} \tag{15}$$

Where h is the layer thickness, S is the total surface area of STL model, V is the volume of STL model, h_s is the line space of solid scanning, L_w is the line space of supports scanning, v_f, v_c and v_s is differently the scan speed of solid scanning, contour scanning, support scanning, $A_s(i)$ is the supports area of the No. i layer.

Some inclusions are obtained from Eq. (13), (14), (15). Solid canning time and contour scanning time are independent of part building direction, while supports scanning time is dependent of supports volume.

Prepare time include the time needed to move down the platform during recoating $t_z(i)$, the scraping time $t_r(i)$ and other prepares time $t_p(i)$.

$$T_a(i) = t_z(i) + t_r(i) + t_p(i) \quad (16)$$

Prepare time is dependent of the number of total layers, while the number of layers is dependent of the height of part building direction. Therefore minimizing the height of part building direction can cut down the part building time. Thus the optimization problem can be stated as follows:

Problem 3. Find a part building direction such that the number of total layer is minimized. It is expressed as follow:

$$f_3(d) = \min(\max(d \cdot v_1, d \cdot v_2, \Lambda\ d \cdot v_n) \\ -(\max(d \cdot v_1, d \cdot v_2, \Lambda\ d \cdot v_n) \quad (17)$$

Where v_i is the vertex of facets.

2.4 Substitution of optimal parameter

Let the unit vector of part building direction be $d = x_i + y_j + z_k$, then

$$x^2 + y^2 + z^2 = 1 \quad (18)$$

As Fig. 5 shown, the angle between building direction and Z axis of reference frame is β. α is the angle between the projection of d in XOY and X axis, thus x, y, z is expressed as followed:

$$\begin{cases} x = \sin(\beta \cdot \cos\ \alpha) \\ y = \sin(\beta \cdot \cos\ \alpha) \\ z = \cos \end{cases} \quad (19)$$

The three problems above mentioned is changed to solve two parameters α and β from to solve three parameters x, y and z. Thus the three problems is translated as:

Problem 4. Find a part building orientation such that the VE is minimized. It is expressed as follow:

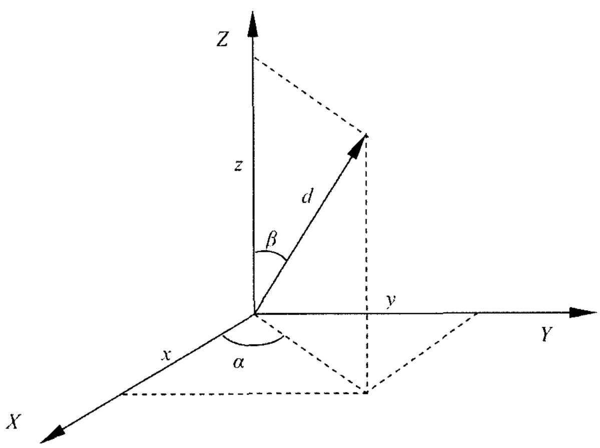


Fig. 5. Unit vector of build orientation

$$f_1(\alpha,\beta) = \min \sum_j \frac{h^2 \cdot |d \cdot n_j| \cdot A_j}{2} \quad (20)$$

$$\text{s.t. } 0 \le \alpha \le 2\pi \\ 0 \le \beta \le \pi/2$$

Problem 5. find a part building direction such that the supports area is minimized. It is expressed as follow:
Where, δ is a threshold function

$$f_2(\alpha,\beta) = \min \sum_j A_j \cdot |d \cdot n_j| \cdot \delta \quad (21)$$

$$\text{s.t. } 0 \le \alpha \le 2\pi \\ -\pi/2 \le \beta \le \pi/2$$

Problem 6. Find a part building direction such that the number of total layer is minimized. It is expressed as follow:

$$f_3(\alpha,\beta) = \min(\max(d \cdot v_1, d \cdot v_2, \Lambda\ d \cdot v_n) \\ -(\max(d \cdot v_1, d \cdot v_2, \Lambda\ d \cdot v_n) \quad (22)$$

$$\text{s.t. } 0 \le \alpha \le 2\pi \\ -\pi/2 \le \beta \le \pi/2$$

3. Brief introduction of multi-objective optimization method based on general satisfactory degree

The concept of satisfactory includes two-phase meaning: one is satisfactory theory aiming at optimization theory. Satisfactory theory is regard as the even more common form of optimization theory. Its perfect and development could certainly offer a new means to solve practical problems. Another is to transform looking after the optimal solution for the optimizing course into looking after satisfactory solution, namely satisfactory optimization. This phase of work is mainly the improvement of some part of theory and method of optimization. So it is regard as the middle phase from optimization theory to satisfactory theory.

Define 1 Satisfactory criterion: a criterion system to evaluate the satisfactory degree of user for the solution of problems is called satisfactory criterion. The satisfactory criterion could be fuzzy, and also precise.

Define 2 Satisfactory order: In one satisfactory criterion, each feasible solution holds only a evaluation result. If there exists a partially order among the evaluation results of any two feasible solutions, the partially order is called satisfactory order.

Define 3 Satisfactory degree: For the problem P that user set, its feasible domain is D, d is the elements of D, namely feasible solutions. In certain satisfactory criterion C, there exits a mapping from a set D of feasible solutions to evaluation set S of solution, that is $f: D\text{->}S$

If there is satisfactory order in S, $s \in S$ is called user satisfactory degree for solution d in criterion C, the set S is call satisfactory degree set.

For example, for the students' grade, according to the satisfactory criterion, the satisfactory degree function is expressed as followed

$$S=\begin{cases} c/100 & c\geq 60 \\ 0 & c<60 \end{cases} \tag{23}$$

Here, the completeness of satisfactory degree set is not demand.

Define 4 Level of satisfactory degree: Satisfactory level for short. In certain satisfactory criterion, each feasible solution has a satisfactory degree. Let s1 be a satisfactory degree. If user (decision-maker) is satisfied with the solution for s1, he would be satisfied with the feasible solutions above all the satisfactory degree by terms of define of satisfactory degree and satisfactory order. In this way, s1 is called one level of satisfactory degree.

Define 5 Satisfactory solution: In certain satisfactory criterion, for a satisfactory level , if the satisfactory degree of the solution d meets or exceed the satisfactory level, namely $s(d) \geq \lambda$

The solution d is called the satisfactory solution in the satisfactory level λ.

Define 6 Satisfactory solution set: solution set with satisfactory level λ, $U(F,\ \lambda) = \{s \mid s(u) > \lambda\}$ is called satisfactory solution set in satisfactory level λ.

Define 7 Independent satisfactory degree: the satisfactory degree of a independent problem is called independent satisfactory degree.

Define 8 Synthetical satisfactory degree: the satisfactory degree of a compound problem composed of some sub-problems is called synthetical satisfactory degree. Synthetical satisfactory degree is composed of satisfactory degree of all sub-problems.

The concept of general satisfactory degree is put forward for the optimization, maximization and the most efficiency. The satisfactory degree is the concept with more commonly meaning than the optimization, maximization and the most efficiency and the concept can more exhibit the essence of human capacity. Therefore, it can be applied in the domain of optimizing, decision-making and controlling et al.

The problems of multi-objective optimization has the common form as followed:

$$V-\min_{x\in R^n} F(x) = \min_{x\in R^n}[f_1(x), f_2(x), \Lambda, f_l(x)]^T \tag{24}$$

$$\text{s.t } g_j(x) \leq 0 \quad j=1,2,\cdots p$$
$$h_k(x) = 0 \quad k=1,2,\cdots q$$

where $F(x) = [f_1(x), f_2(x), \cdots, f_l(x)]^T$ is called vector objective function.

$V-\min_{x\in R^n} F(x)$ is the shortening of minimized model of multi-objective (vector form).

V-min is vector minimizing.

Objective function can be minimized coordinately or incoordinately. $g_j(x) \leq 0, (j=1,2,\cdots,p)$ and $h_k(x)=0, (k=1, 2,\cdots,q)$ is constraint conditions.

The problems of multi-objective optimization are commonly very difficult to demand all objective obtaining optimization solution. Especially when there exist conflict among each objective, namely there exist conflict among the solution of each objective, sometimes there is not the optimal solution. For instance, the least weight and the most intension are often the object of one another conflict in mechanical designing. Near several years, a lot of scholar in home and abroad have done a great deal of researching and proposed much method, mainly the method of engineering application. Compared with single-objective optimization, multi-objective objective is not quite perfect and systemic in theory and computing method. Hence, it is quite necessary to create a set of knowledge system evaluating the quality of solution of multi-objective optimization and to create perfect theory and method system of multi-objective optimization.

Define 9 Objective satisfactory degree: There exist one or multiple objective function for a optimizing problem. The satisfied degree of one of feasible solution for certain objective function is called objective satisfactory degree for the objective.

Define 10 Constraint contented degree: For a constraint optimizing problem, the constraint condition must be meet. The degree of one feasible solution according with one constraint condition is called constraint contented degree.

Define 11 Satisfactory degree of multi-objective optimization problems: The degree of the solution of problems meeting multi-objective and multi-constraint is called Satisfactory degree of multi-objective optimization problems and it is marked $S(F, f)$

Problem 7 Existence of satisfactory solution of multi-objective optimization problems If there exist feasible solution of multi-objective optimization problems, there must exist satisfactory solution meeting one satisfactory level in certain satisfactory criterion. Namely, for problem F of multi-objective, x is variable,

if $X^p \neq \Phi$

$\exists\ x^s$ and s, let

$$\{x^s \mid s(x^s) > s, x^s \in X^p\} \neq \Phi \tag{25}$$

where, X^p is feasible solution set, x^s is satisfactory solution.

The problems of multi-objective optimization could be regarded as a sort of non-simple combination of multiple problems of single-objective optimization (namely, it could be not simple arithmetical combination). In this paper, we use classical reductive method, which analyzed reasonably the problems of multi-objective optimization and then synthesized it to obtain the solution of primary problems. The common solving steps multi-objective optimizing problems based on satisfactory degree.

Step1: analyzing the problems. The satisfactory degree of a complicated problem is comprised of the satisfactory degree of its sub-problems.

Step2: solving the solution of each sub-problem respectively and establishing the corresponding independent satisfactory degree.

Step3: obtaining the function of synthetical satisfactory degree by terms of the concrete problem. The general satisfactory degree is regarded as the new objective function of entitle optimizing problem.

Step4: continually adjusting the level of synthetical satisfactory degree employing the strategy of conflict-concession. Transferring the Step5 and Step6 to solving and evaluating by phases, until obtaining the solution set of maximal satisfactory level.

Step5: solving the sub-problem using concrete method (generic algorithm, artificial neural network and so on).

Step6: evaluating the satisfactory solution of multi-objective optimization.

Consequently, we can find out that analyse of problems and combination of satisfactory degree are the emphases of entire algorithm. General satisfactory degree demands a few basic combination principles to meet. These principles confirm the combination relation of primary problems and sub-problems after the primary problems are decomposed. We can apply some principals so-called "maximal/minimal", "weight combination", "conflict intercession" and other appropriate combination principal.

4. Multi-objective optimization method of part-building orientation based on satisfactory degree principle

The problems of multi-objective optimization are regard as the problems of multiple single-objectives optimization no-simple combination (It is not simple arithmetic combination). To obtain the solution for original problems, the reducing method is employed, which multi-objective optimization is decomposed, then synthesized. In this paper, generic algorithm (GA) is used to solve the every problem of single-objective optimization.

4.1 Single-objective optimization based on GA

The three independent optimizations are solved by GA, and the optimal and worst solution is obtained. The parameter selecting and basic operation in GA is discussed as followed.

1) Coding method

Two parameters α and β are taken binary system coding. The chromosome length is 24 bit, and each

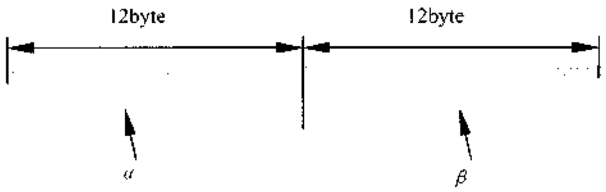


Fig. 6. Coding of chromosome

variable takes 12 bit. The range of α and β is respective $[0, 2\pi]$ and $[-\pi/2, \pi/2]$.

2) Computing of fitness function

Optimal objective is the optimal and worst solution of every objective in the subject. Therefore, the fitness function stem from the three optimal objective of problem 4, 5 and 6.

The optimal solution is given by

$$F(X) = 1/f(X) \tag{26}$$

The worst solution is given by

$$F(X) = f(X) \tag{27}$$

3) Crossover operator

Because each chromosome is composed of two variables, to prevent loss the diversity, two-point crossover is occupied. The position of crossover point lies in range of the first and second variable. Namely crossover point k_1 lies in the range [0, 11], and crossover point k_2 lies in the range [12, 23].

4) Parameters setting in GA

Parameters setting in GA is given by table 1.

4.2 Multi-objective optimization of part-building orientation

Single satisfactory degree (SSD) constructed by linear interpolative. The single satisfactory is computed by

$$S_i = \frac{R_i - R_{iworst}}{R_{ibest} - R_{iworst}} \; 1,2,3 \tag{28}$$

Where s_1, s_2 and s_3 are single objective satisfactory degree of staircase effective, supports area and building time and its range is [0,1]. Objective satisfactory degree equation to 1 means the most satisfactory. Objective satisfactory degree equation to 0 means the least satisfactory.

The selection of part-building orientation regards synthetical satisfactory degree (GSD) as Optimization objective. Computing of synthetical satisfactory degree is the result of synthesizing all single objective satisfac-

Table 1. GA parameters.

Length of chromosome	Crossover probability	Mutation probability	Population size	Maximal generation
24	0.75	0.05	120	200

tory degree. The synthetical satisfactory degree is computed by means of minimization operator and weighted exponent [1, 15]. Thus the GSD is

$$S=s_1^{w1}\wedge s_2^{w2}\wedge s_3^{w3} \tag{29}$$

In this paper the method of linear weighed is employed

$$S=\sum_{i=1}^{3} w_i s_i,\quad \sum_{i=1}^{3} w_i=1,\quad w_i>0 \tag{30}$$

The weight is given by decision-maker by means of interaction, and then the GA still employed. Eq. (29) or (30) is regard as fitness function, and then the maximal GSD is obtained

5. Illustrative examples

A software implementation of the methodology was undertaken in C++ programming language using OpenGL environment.

Fig. 7 shows a tractor model part of STL file. This program computes the part-building optimal orientation.

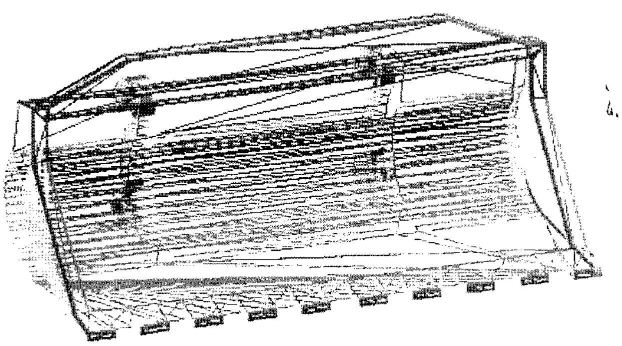


Fig. 7. Optimization of Part-building orientation.

Table 2. The optimal and worst solution of three objectives.

Objective	Staircase effective	Supports area	Part-building time
The optimal solution	42.2	64.1	4
The worst solution	145.4	254.6	15

Firstly, the optimal and worst solution of three optimize objectives are obtained, as shown in table 2. Secondly, eq. (29) is regard as fitness function, and then the general satisfactory degree is computed using GA again. Table 3 shows the result of operation, and the No.8 item is the optimal synthetical satisfactory degree. In the subject the weight of staircase effective, supports area, building time is respective $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$. The slice thickness is $h = 0.12$.

6. Conclusions

Through process planning of rapid prototyping and geometric feature of STL model is investigated, three objective of part-building orientation optimization is created, that is minimized VE due to staircase effective, minimized supports area and minimized part-building time. The paper discussed multi-objective optimization of part-building orientation based on satisfactory degree principle. The general satisfactory degree function is created, and the optimal part-building orientation is obtained through solving the GA.

Experiment and analyses show that it is reasonable and feasible method to employ multi-objective optimization in part-building orientation base on satisfactory degree theory. The shortcoming of the method is consuming too much computing time due to using GA time after time for huge STL file.

7. Acknowledgement

This project is supported by the National High Technology Research and Development Program of China (863 Program No:2001AA421160). The authors would like to thank the International Conference of CAD and Computer Graphics 2005 and thanks for the support of advanced manufacturing lab, Shenyang Institute of Automation, The Chinese Academy of Science.

Reference

[1] Bai Guangchen and Wang Rongqiao (2001), The Satisfactory Solution of Multi-objective Optimization Design for Reliability of Mechanical parts, *Chinese Mechanical Engineering*,

Table 3. The result of experiment (note: SS is The Solution of Satisfactory and SD is The Degree of Satisfactory).

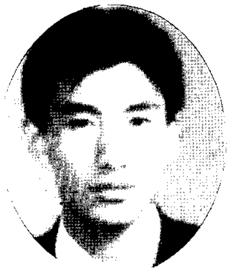
No.	α / (⁰)	β / (⁰)	SE		SA		PT		GSD
			SS(mm³)	SD	SS (mm²)	SD	SS (mm)	SD	
1	12.3	73.5	48.5	0.94	109.3	0.76	313.8	0.89	0.896
2	118.5	54.5	89.4	0.54	68.3	0.98	400.4	0.76	0.716
3	75.3	82.6	106.8	0.37	89.7	0.87	291.5	0.92	0.630
4	38.2	77.5	48.6	0.94	189.4	0.34	528.3	0.56	0.704
5	294.6	24.7	71.9	0.71	133.9	0.63	438.2	0.70	0.684
6	300.4	16.9	51.6	0.91	204.8	0.26	714.5	0.28	0.589
7	125.6	69.4	63.5	0.79	111.5	0.75	428.6	0.71	0.762
8	31.2	28.6	42.2	1.0	82.7	0.88	360.15	0.82	0.928
Remark	The data in the table is taken out by random, á is the originally position and â is optimal position of model.								

12(8), 851-853.
[2] Cheng W., Fuh J.Y.H. and Nee A.Y.C. (1995), Multi-objective optimization of part-building orientation in stereolithography, *Rapid Prototyping Journal*, **1**(4), 2-23.
[3] Hong Jun, Wu Dianliang, Li Dichen et al (2001), Multi-Objective Optimization of the Part Building Orientation in Stereolithography, *Journal of Xi'an Jiaotong University*, **35**(5), 506-509.
[4] Huang Hongzhong, Yao Xinsheng, Zhou Zhongrong (2003), Multi-objective Optimizztion Design of the Working Unit of Loader Based on the Satisfactory Degree Theory. *Chinese Journal of Mechanical Engineering*, **39**(5), 97-103.
[5] Hur J., and Lee K. (1998), The development of a CAD environment to determine the preferred build-up derection for layered manufacturing, *International Journal of Advanced Manufacturing Technology*, **14**, 247-254.
[6] Jacobs P.F. (1992), *Rapid Prototyping and Manufaxturing: Fundmental of Stereolithgraphy, Society of Manufacturing Engineers*, Dearborn, MI, 1-11.
[7] Jayanth Majhi, Ravi Janardan, Michiel Smid et al (1999), On some geometric optimization problems in layered manufacturing, *Computational Geometry*, **12**, 219-239.
[8] Lan Po-ting, Chou Shuo-Yan, ChenLin-Lin t et al (1997), Determining fabrication orientations for rapid prototyping with stereolithography apparatus, *Computer-Aided Design*, **29**(1), 53-62.
[9] Masood S.H., Rattanawong W. and Iovenitti P. (2003), A generic algorithm for a best part orientatin system for complex parts in rapid prototyping, *Journal of Materials Processing Technology*, 6730, 1-7.
[10] Paul Alexander, Seth Allen and Debasish Dutta (1998), Part orientation and build cost determination in layered manufacturing, *Computer-Aided Design*, **30**(5), 343-358.
[11] Pham D.T., Dimov S.S. and Gault R.S. (1999), Part Orientation in Stereolithgraphy, *The International Journal of Advanced Manufacturing Technology*, **15**, 674-682.
[12] Rattanawong W., Masood S.H. and Ivoenitti P. (2001), A volumetric approach to part-build orientations in rapid prototyping, *Journal of Materials Processing Technology*, 119, 348-353.
[13] Yang Z.Y., Chen Y.H. and Sze W.S. (2001), Determining Build Orientation for Layer-Based Machining, *International Journal of Advanced Manufacturing Technology*, **18**, 313~322.
[14] Yao Xinsheng, Huang Hongzhong, Zhou Zhongrong et al (2002), A Study of the Multi-objective Optimization Theory Based on the Generalized Satisfactory Degree Principle, *Journal of Applied Sciences*, **20**(3), 275-281.
[15] Yao Xinsheng, Huang Hongzhong, Zhou Zhongrong (2003), Generalized Satisfactory Theory and Its Charac-terization, *Journal of Southwest Jiaotong University*, **38**(6), 712-716.

Jibin Zhao is an Associate Professor in Key Lab of Advanced Manufacture Technology, Shenyang Institute of Automation, Chinese Academy of Sciences. He received his PhD degree from Shenyang Institute of Automation, Chinese Academy of Sciences, in 2004. His research interests include rapid prototyping, CAD/CAM, reverse engineering. Tel: 86-024-23970030, E-mail: jbzhao@sia.cn.

Weijun Liu is a Professor in Key Lab of Advanced Manufacture Technology, Shenyang Institute of Automation, Chinese Academy of Sciences. He received his PhD degree from Dalian university of technology, in 1998. His research interests include rapid prototyping, robotics, reverse engineering.

Jianhuang Wu is a PhD student in Key Lab of Advanced Manufacture Technology, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China. His research interests are computer-aided design and computer graphics.



Jibin Zhao

Jianhuang Wu

Weijun Liu