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ORIGINAL ARTICLE

Sloping wall structure support generation for fused deposition modeling

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Abstract Support generation is a key technology for some rapid prototype manufacturing processes. A novel support structure with sloping walls, as well as its generation algorithm, based on the STL model, was designed and tested for fused deposition modeling process in this paper. Three different types of support structure are generated according to different overhang geometrical features. Compared to the generally adopted straight wall structure, this support structure significantly reduces the volume of support structure, hence optimizes the fabrication process. Experiments show that it assists the fabrication of parts well and reduces the support material consumption and processing (or fabrication) time by about 30%.

Keywords Rapid prototype manufacturing · Support · Sloping wall structure · Fused deposition modeling · STL model

1 Introduction

Support is required for fabrication parts of overhang geometry structures [1, 2] in some rapid prototype manufacturing (RPM) processes such as stereolithography apparatus (SLA) and fused deposition modeling (FDM). The feasibility of building a support directly determines whether a part can be fabricated successfully or not. A high quality support also saves a lot of material, fabrication time, and can be removed easily.

Current supports adopted generally are designed with straight wall structures such as web or column for SLA and Zigzag for FDM [3] (as shown in Fig. 1a). However, support can be fabricated successfully when it is of a slant wall structure (as shown in Fig. 1b), the slope of which is within an appropriate range (i.e., no smaller than self-supporting angle). This change in structure may bring positive effects such as decreasing volume and facilitating the removability. In order to reduce the maintenance cost and enhance the building efficiency of rapid prototyping equipment, a novel support structure with slant walls, together with its generation algorithm, is designed and tested in this paper.

The remainder of this paper is organized as follows. The problem of support generation based on STL model is analyzed and the configuration of sloping wall structure support is defined in details in Section 2. In Section 3, the entire generation scheme and algorithm is presented in detail. Some case studies are done to validate the robustness of the algorithm in Section 4. Finally, conclusion and future work is contained in Section 5.

2 Problem analysis and formulation

In practice, supports are generated usually by algorithmic methods, which can be classified into three types according the input and output data. The first one inputs the part scan lines and outputs the support scan lines, in which Boolean operation on scan lines in adjacent layers is employed [4]. Part slices are inputted and the support slices are outputted in the second one, which adopts Boolean operation on part slices in adjacent layers [5]. The third algorithmic method utilizes part STL model as input data and generates support entities STL model [6–9].

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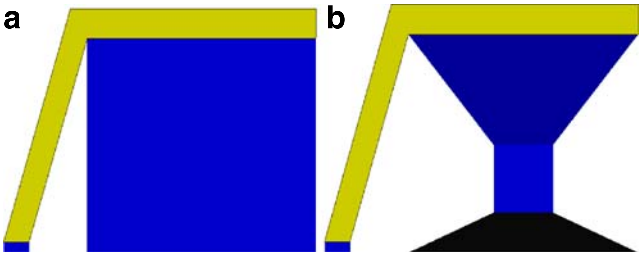


Fig. 1 **a** Straight wall support generated by traditional method; **b** slant wall support generated by the proposed algorithm

The algorithm method based on STL model is adopted in this paper considering on-line slicing as the calculation in the scan lines or slices-based methods must be implemented again once the process parameters like layer thickness and hatch space are changed.

2.1 STL model and problem analysis

STL file format, now a de facto standard interface between CAD and RPM systems, utilizes triangles to approximately represent the surfaces of a part CAD model. A triangle facet consists of four data items including three vertex coordinates and a normal vector which is the criterion to calculate the inclination of the facet.

The problem of support generation based on STL model can be described as follows: given a STL file with specified orientation, find and determine the minimum support structure required to manufacture the part.

For a part entity shown in Fig. 2, its surfaces consists two types of features. Features requiring supports, called to-be-supported features, are bottom surfaces, surfaces with small inclination, hanging edges, and hanging points while features requiring no support consist of top surfaces, vertical surfaces, and small inclination surfaces.

The inclination of a triangle facet on a surface of a STL model is measured up from the horizontal plane, as shown in Fig. 3. While recognizing to-be-support features, α, the inclination of a triangular facet can be calculated as follows:

$$\cos\alpha = \mathbf{n}\cdot\mathbf{k} = |\mathbf{n}||\mathbf{k}|\cos\alpha \qquad (1)$$

where $\mathbf{n}$ is the normal unit vector of the facet to be judged, and $\mathbf{k}=[0, 0, -1]$ is the unit vector of negative direction of Z axis. Self-supporting angle is used to control when beginning to create supports on angled walls and surfaces. It represents the minimum angle of the part wall that will be built without supports. Facets with an inclination larger than the self-supporting angle will be built without supports. Facets that are closer to flat and having an inclination less than the self-supporting angle will be built on tops of supports. A specified value can be obtained by experiments for different materials and processes.

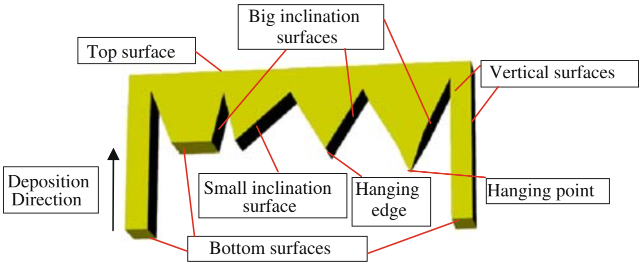
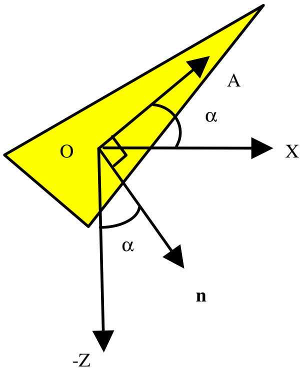


Fig. 2 Geometry feature classification of part entity

Fig. 3 Surface inclination



2.2 Sloping wall support configuration

There are three types of supports defined in this paper. A support entity with an integrated sloping wall structure (as shown in Fig. 4a and b), called type III support in later sections, which is transformed from overstable straight wall support entities, consists of three parts: upper part, middle part, and bottom part. Surfaces of it are divided into top surfaces, bottom surfaces, and side surfaces. Side surface consists of upper flank, bottom flank, and middle flank. The periphery of top surface is the boundary of corresponding to-be-supported surface which is projected into projected boundary to make up of bottom surface's boundary. Upper cervix ring and bottom cervix ring connect the mid flank with upper flank and bottom flank. These rings with the same X and Y coordinates but different Z coordinates are generated by offset projected boundary.

For hanging edges, hanging points, and some unstable straight wall support entities, the structure will change into another type of support entity called type II support which cuts off the upper part and leaves the middle and bottom parts (as shown in Fig. 4c). Some other straight wall support entities which may be exactly stable are called type I support with only middle part (as shown in Fig. 4d) of type III support.

In the procedure of calculating sloping wall support automatically, some other relevant parameters are defined as follows. θ, called upper flank inclination, is measured as surface inclination mentioned above. The minimum value of θ is the self-supporting angle. H_1, called support surface boundary height, is the Z coordinate of the lowest point of

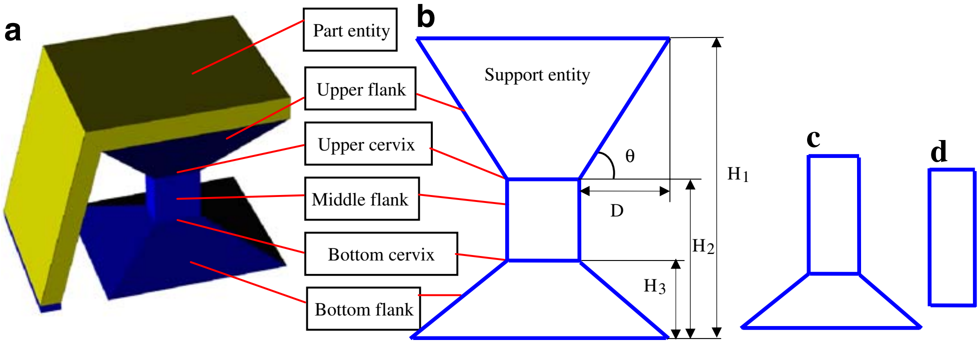


Fig. 4 Geometry feature of type support entity: **a** 3D view of III support entity with part entity; **b** sectional view of III support entity; **c** sectional view of II support entity; **d** sectional view of I support entity

surface boundary. H_2 is height of upper cervix ring. H_3 is the height of bottom cervix ring. D is the maximum offset value when generating cervix ring from projected boundary. Positive value of D means the type I support is overstable and can be transformed to type III support. Negative value of D means type I support will be unstable and should be reinforced and modified into type II support. Stability coefficient C_S, used to determine which type of support is selected, is defined in the following formula

$$C_S = H_1 / OBBW \tag{2}$$

where variable OBBW is the minimum length of oriental bounding box (OBB, which is a versatile tool adopted in collision detection [10]) which can be figured out by the rotation of projected boundary in latter section (3.4). The stable coefficient interval [C_{Slow}, C_{Shigh}] can be set up via experiments for different materials and process parameters. Some other relationships between these parameters can be deduced:

$$0 \leq \theta_{self-supporting} \leq \theta \leq 90^\circ \tag{3}$$

$$0 \leq H_3 \leq H_2 \leq H_1 \tag{4}$$

$$\tan\theta = (H_1 - H_2)/|D| \tag{5}$$

How to calculate the value of each parameter will be presented in the next section in detail.

3 Generation scheme

It is complicated to address this problem. The whole algorithm flow is shown in Fig. 5. First, original data of STL is read in and restructured to build geometrical topological information for later data process. Second, local geometrical features (including hanging edges, hanging points, and triangle facets) requiring supports are recognized. Third, triangle facets adjacent with each other are combined into independent surfaces, and then the surface boundaries are extracted and projected to X–Y plane to establish 2D projected boundaries. For hanging edges and points, top rings are given and then projected into projected boundaries. Then select different support structures for different features by classifying 2D projected boundary in the fourth step. Fifthly, cervix rings are generated by offsetting the projected boundaries. In the sixth step, support triangle facets are generated for each feature according to different support types. Lastly, some Boolean operations will be made on slices to address intervene between support entities and part entities.

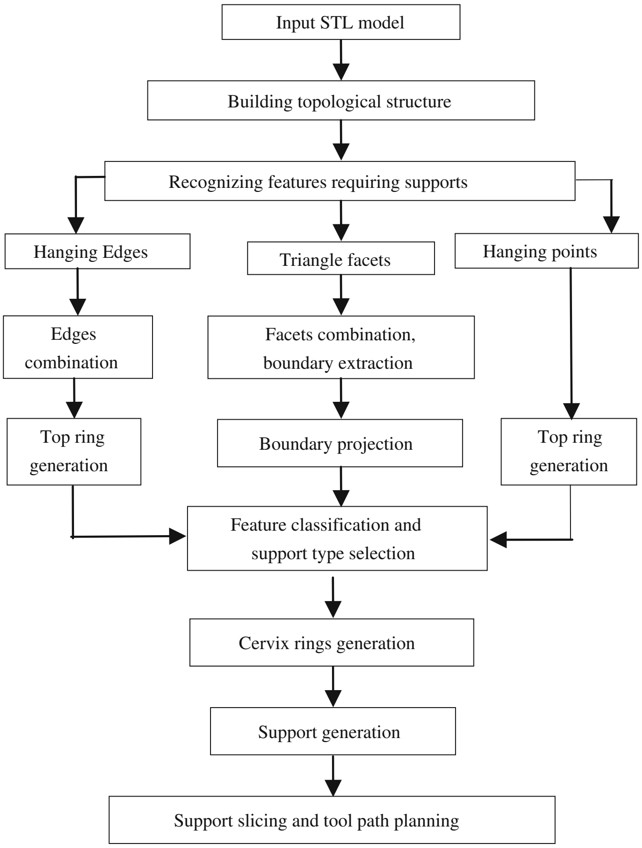


Fig. 5 Algorithm flow chart

Compared to the straight wall structure support generation process based on STL mode [6–9], the generation algorithm of slant wall structure support has its own specialties: support type selection, cervix ring generation, support slicing, and tool path planning, which make the uniqueness of the slant wall support and enable its potential in reducing support volume.

3.1 Building a topological structure for the STL model

The triangular facets written in the STL file are unordered and each vertex of the mesh is written by its coordinates in the file as many times as it is shared by the facets. They do not catch any topological information like links, pointers to another element, or proximity. Therefore, we must reconstruct the topological structure to obtain the topological relationship between the facets according to the vertex-to-vertex rule. A good data structure with topological information is very helpful to latter calculation for saving time and space consumption of computer. The more concrete method can be followed in reference [11].

3.2 To-be-supported features recognition

The features requiring supports can be detected as follows.

Step 1. Facets classification and finding to-be-supported facets. A triangle facet needs support only if its inclination is less than the self-supporting angle. According to formula (1), the inclination α can be figured out easily. Then by calculating the dot product of **n** and **k**, two separated facets index arrays for facets requiring support and facets dis-requiring support are set up. For the former one, facets of it are combined to different surfaces. And for the latter one, it will be used for generating hanging edges and points.

Step 2. Finding to-be-supported edges. An edge which satisfies the following limits will be judged as a hanging edge: the angle between it and the horizontal plane must be less than self-support angle; the facets the edge attaches to must be facets needing no support, i.e., the ID of them are contained in the facets index array for dis-requiring support, and at least one inclination of them is less than 90°; addition of normal vectors of the two adjacent facets points down; if normal vectors point to two different directions in Z, i.e., one points down and the other up, then the angle between positive Z axis and the facet with normal vector pointing down must be larger than that between positive Z axis and the facet with normal vector pointing up.

Step 3. Finding to be-supported points. A point which satisfies the following limits will be seen as a hanging point: it must be in a lower position than any of the other point of the same edge, i.e., the Z coordinate is the smallest; any edge it attaches to is not a hanging edge and any facet it attaches to is not a to-be-supported facet; no normal vectors of the facets it attaches to points up, i.e., the Z coordinates of normal vectors are not positive.

3.3 Facets combination and surface boundary extraction

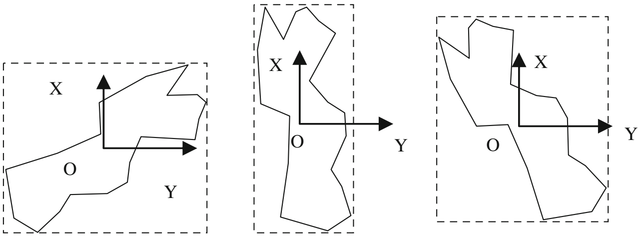
All elements detected and identified as to-be-supported facets or edges above are unordered, unsystematic, and possibly with large scale amount. So it is necessary to combine those that are next to each other into a surface or chain. Seed combination algorithm [9] is used to address this issue.

Periphery of the facet surface is extracted by boundary identification. Edge which is not shared by two facets in the surface is a part of the boundary. Edges detected as parts of boundary are combined into boundary rings.

Hash Table is adopted for searching for consideration of efficiency. And more concrete methods about recognition of hanging edges and points and combination of facets and edges are followed in reference [9].

3.4 Feature classification and support type selection

Top rings added for hanging points and edges or surface boundaries extracted from to-be-supported surface are projected to the XOY plane. Then the oriental bounding box (OBB) of projected rings or boundaries is calculated by rotation method [9]. The rings or boundaries are rotated by a small step angle per time in a 90° range (as shown in Fig. 6) and axis-aligned bounding box (AABB) is figured out for boundary in every different states. The AABB with the minimum area is used to substitute OBB approximately. The smaller the step angle value is, the more exactly the OBB can be figured out.



a Original state **b** Rotated by 45° **c** Rotated by 90°

Fig. 6 Calculating OBB of the projected boundary

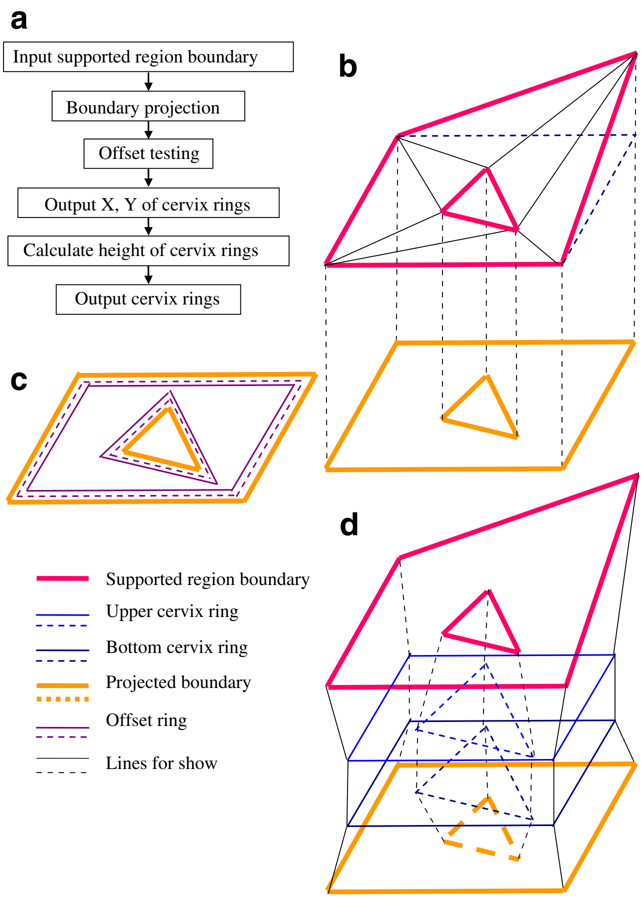


Fig. 7 Cervix boundary generation. **a** Flow; **b** projection; **c** offset testing; **d** given a height

Thus the stable coefficient can be obtained via the formula (2), and the to-be-supported features can be classified into different types with different types of support. A closed interval [C_{Slow}, C_{Shigh}] can be set up for stable coefficient by experiments. Whether an original straight wall support is unstable, stable or overstable is determined according to the position that the correspondent C_{S} locates at in the value interval. Type III support entity is implemented to overstable one (i.e., $C_{\mathrm{S}}<C_{\mathrm{Slow}}$), type II support entity is selected for unstable one (i.e., $C_{\mathrm{S}}>C_{\mathrm{Shigh}}$) and type I support entity is selected for neither more nor less than stable one (i.e., $C_{\mathrm{Slow}}\leq C_{\mathrm{S}}\leq C_{\mathrm{Shigh}}$).

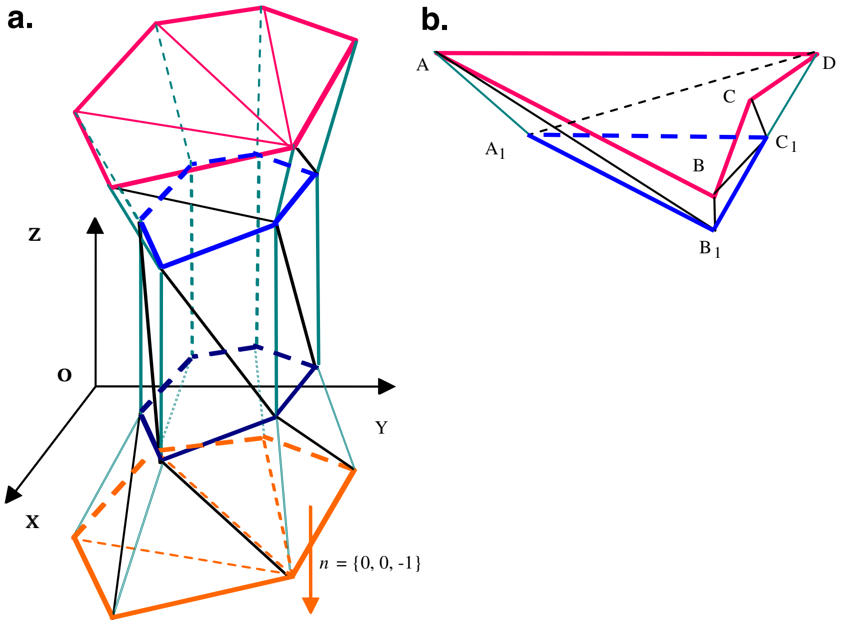
3.5 Cervix ring generation

What distinguishes sloping wall support most from straight wall support is the cervix ring. Its height and reduced amount of area through offsetting determines the decreased amount of volume of slant wall support III compared to straight wall support.

Cervix rings are generated through different methods for different types of support. For type I support, upper cervix ring is overlapped by support top boundary and the bottom cervix ring is overlapped by support bottom boundary. Upper cervix ring of type II support is overlapped by top boundary of support too. The bottom cervix ring is generated by projecting top cervix ring to XOY plane as a height of H_3.

Cervix ring generation process for type III support is shown in Fig. 7a. First, top boundary of support is

Fig. 8 Support generation. **a** An integrated support entity with no vertexes disappearing in cervix ring; **b** an upper flank with vertexes disappearing in cervix ring



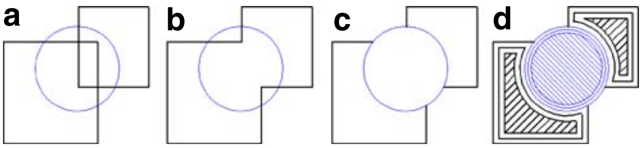


Fig. 9 Slices Boolean operation. **a** Original slices; **b** middle support slice after internal Boolean operation; **c** final support slice after external Boolean operation with part slice; **d** tool paths planning

projected to the bottom plane (Fig. 7b). Offset testing is made on the projected boundary in the second step (Fig. 7c). Offset the boundary from outer side to inner side by a small step distance each time until the summary distance reaches $D_{\max}$ (set $H_2=0$, $\theta=\theta_{\text{self-supporting}}$, calculate it via formula (5)) or some rings on the boundary intersect. In the third step, with the summary offset distance D, the final value of H_2 can be figured out by the same formula when setting $\theta=\theta_{\text{self-supporting}}$. H_3 can be obtained by linear interpolation with the corresponding C_S in the stability coefficient interval [C_{Slow}, C_{Shigh}], i.e., $H_3 = H_2 * (C_S - C_{\text{Slow}}) / (C_{\text{Shigh}} - C_{\text{Slow}})$.

For type II support, H_3 is defined as: $H_3=\text{OBBW}_{\text{Bottom boundary}} * C_{\text{Slow}}$. So the bottom boundary, which is obtained by inflating the projected boundary, must be calculated first. This time, offsetting testing adopts a reverse direction from inner side to outer side and stops when $H_1/\text{OBBW}_{\text{Bottom boundary}} \geq C_{\text{Shigh}}$.

Since all cervix rings, together the height and every points of them are obtained, the final rings including their top boundaries, cervix rings, and bottom boundary can be determined (as shown in Fig. 7d) for support STL generation in the next section.

3.6 Support STL generation

In this section, an independent STL model is set up for each to-be-supported feature. And then each independent STL model is written into one support STL file for convenient storage and exchange.

Surfaces of a support entity are classified into three kinds according to different triangular facet calculation methods. One is the top surface. For some supports, it is overlapped by the corresponding to-be-supported surface, so triangular facets of this surface are equal to those of to-be-supported surface on three vertexes coordinates and reverse equal to on normal vector. For other supports, i.e., supports of hanging edges and points, the top surface is a quadrangle and the facets can be obtained by segmenting it with its shorter diagonal.

Bottom surface is another kind of support surface. All normal vectors of its facets are pointing to negative Z axis (as shown in Fig. 8a). There are two methods to generate these facets. One is the projection method, in which every facet is obtained by projecting facet in the to-be-supported surface to the bottom plane. Another method is generating facets by triangulation [12] to bottom boundary. In general, the former one is faster in time, larger in STL volume, and adopted for types I and III support for consideration of efficiency; the latter one is more time consuming, generates less data, and is employed for type II support.

The third kind of surface, also the most complicated one, is the flank surface of support entity. Type III support owns an integrated feature and contains three flanks while type II support has middle and bottom flanks and type I support has only middle flank. For the upper flank, if the upper cervix ring has the same count of vertexes as the top surface boundary (as shown in Fig. 8a), every face of the flank is a quadrilateral, and the problem would become easy. Cut this quadrilateral into two triangles with its shorter diagonal aiming for resulted triangles with out-pointed normal vectors. If different number of vertexes occurs, for every two adjacent vertexes (like B and C or C and D in Fig. 8b) on the surface boundary, find the nearest vertexes in the cervix ring. If the two nearest vertexes are in fact the same

Table 1 Experiment data

Case	Part entity			Support entity						
	Triangle facets NO	Box ($X\times Y\times Z$) mm^3	Volume (mm^3)	Straight wall			Sloping wall			Reduced volume (%)
				Triangle facets NO	Time (ms)	Volume (mm^3)	Triangle facets NO	Time (ms)	Volume (mm^3)	
1	66	120.3×14.4×56.4	42,462.4	72	46	34,389.3	152	93	16,918.1	50.80
2	26,456	100.4×72.4×68.2	40,045.7	11,210	2,931	98,353	13,198	16,609	80,658.6	17.99
3	58,204	91.7×75.0×82.0	108,862.0	21,942	9,344	199,171.0	22,040	150,953	134,976.0	32.23
4	104,776	101.7×101.7×34.7	53,506.2	83,294	29,0344	71,122.7	86,512	47,1203	60,862.0	14.43

one (like C_1 in Fig. 8b), the upper two adjacent vertexes and this one make up a triangle which is the one to be aimed. If they are different vertexes (like B_1 and C_1 in Fig. 8b), the four vertexes make up a quadrilateral again and the same method can be then applied. Bottom flank can be dealt with by the foregoing method. For middle flank, every flank is a standard rectangle which can be processed as a quadrangle.

3.7 Support slicing and tool path planning

Support STL model obtained according to the procedure mentioned above may be an invalid STL model. Some interventions may take place among support entities or between support entities and part entities since each support entity crossing a span from to-be-supported feature to the substrate plane. This may cause overlapping on corresponding slices and tool paths. One basic principle of tool paths planning is that for any point in one layer there must be no more than one path line passing across, or the material will overflow around this point. Thus measurements should be taken to deal with those interventions.

One method is to deal with the intervention with a 3D Boolean operation directly on the solid entities after support generation. However, Boolean operation between two STL models [11] is a complex process which may consume a lot of CPU time and RAM. An alternative, indirect method proposed here is decreasing the problem's dimensions and address it on slices before path planning. Thus a very important process after slicing is a 2D Boolean operation between those intervened slices.

The 2D slices Boolean operation is shown in Fig. 9. Using general slicing algorithm [13] from support STL entities obtained through the above method, we can get support slice which may intervene with each other or part slice as shown in Fig. 9a. Firstly, internal intervention in original support slice is dealt with. Each ring in a slice has information of internal or external attributes. Addition operation is made among external rings and subtraction operation is made between external rings and internal rings. The resulted middle support slice is shown in Fig. 9b. The final support slice used for support tool paths planning is obtained by subtracting the middle support slice with part slice as shown in Fig. 9c. Then tool paths can be calculated out as shown in Fig. 9d for final filling process.

When path planning is made for the support slice, it is important that contour offset paths must appear at least for one time if the interior filling paths are made by sparse style. Otherwise, the material on the path of the upper part of type III support will drop down and the support entity cannot be fabricated successfully.

4 Experiments and results

The overall generation process is implemented with Microsoft Visual C++. On a low-end PC platform (CPU= Intel Celeron 1.72 GHz; RAM 504 MB; OS=Microsoft Windows XP with Service Pack 2), four parts are taken to be calculated to validate the efficiency with C_{Slow}= 4.0, C_{Shigh}=10.0. The experiment results are shown in Table 1 and Fig. 10a–d. The speed of the process is acceptable when the number of triangle facets of STL

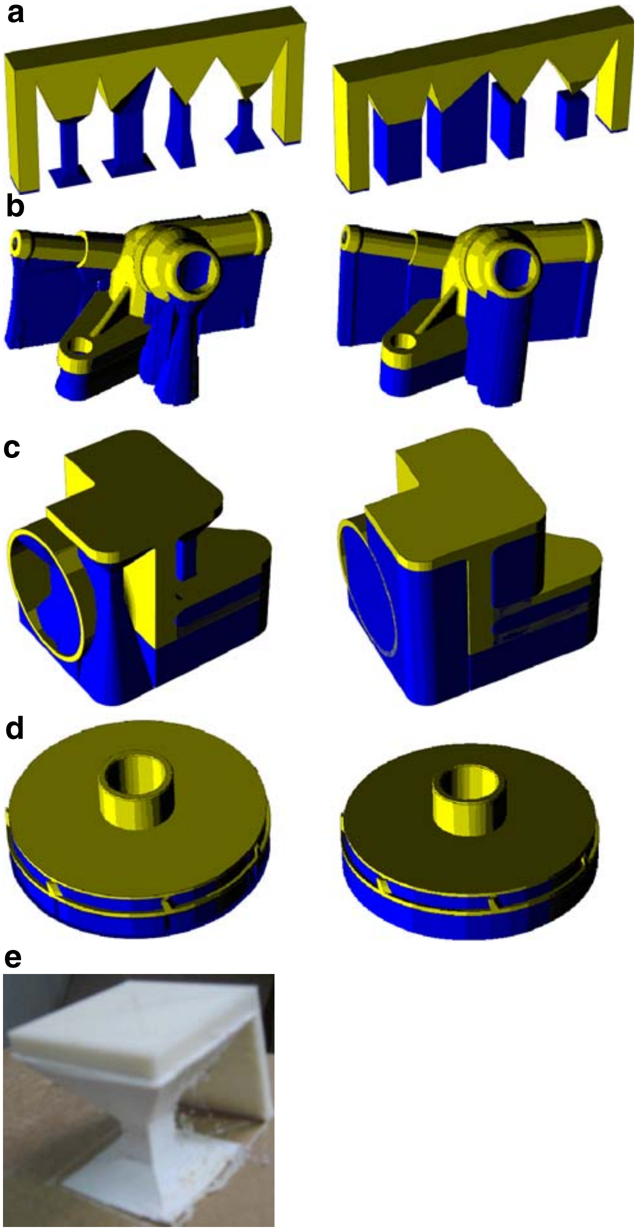


Fig. 10 Some cases. **a** Case 1 with support of sloping and straight walls; **b** case 2 with support of sloping and straight walls; **c** case 3 with support of sloping and straight walls; **d** case 4 with support of sloping and straight walls; **e** photo of a fabrication case

model is less than 60,000, but the CPU time ascends sharply when the number increases to 100,000. Compared to the straight wall structure, with this sloping wall support structure, the average reduced volume rate is about 28.86%, which means the corresponding time and material consumed can be saved by about the same proportion.

A fabrication case as shown in Fig. 10e was made with ABS part material and BASS support material in a FDM process-based HRPR-I system of Huazhong University of Science & Technology. The support assists the fabrication successfully and can be removed easily.

5 Conclusions and future work

A novel support structure with sloping walls, as well as its generation algorithm, based on the STL model was designed and tested for fused deposition modeling (FDM) process. Compared to straight wall structure, this support structure can significantly reduce the volume of support and hence optimize the fabrication process. It helps to reduce the maintenance cost and enhance the building efficiency of rapid prototyping equipment.

A fast and efficient algorithm for the 3D Boolean operation on STL model is to be developed to further reduce the volume of support. The CPU time is acceptable when the triangle facets number is less than 60,000. More efforts should still be spent to further improve the efficiency and reduce the CPU time.

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References

1. Kulkarni P, Marsan A, Dutta D (2000) A review of process planning techniques in layered manufacturing. Rapid Prototyping J 6(1):18–35 doi:10.1108/13552540010309859
2. Dutta D, Prinz FB, Rosen D, Weiss L (2001) Layered manufacturing: current status and future trends. Trans ASME J Comput Info Sci Eng 1:60–71
3. Marsan AL, Kumar V, Dutta D, Pratt MJ (1998) An assessment of data requirements and data transfer formats for layered manufacturing. Technical Report NISTIR 6216. NIST, Gaithersburg, MD
4. Chen Z-J, Wang C-J, Zhang L-C (2004) An algorithm of automatic support generation of FDM based on linescan. J Huazhong Univ Sci Technol 32(6):60–62 J. Nature science edition
5. Kumar C, Larry J, Larry R (1995) Support generation for fused deposition modeling, Solid Freeform Fabrication Symposium, University of Texas, Austin, pp: 229–241
6. Swaelens B, Pauwels J, Vancraen W (1995) Support generation for rapid prototyping, Proceedings of the 6th International Conference on Rapid Prototyping, University of Dayton, pp: 115–21
7. Webb D, Verdes V, Cassapis C (1994) Computer aided support-structure design for stereolithography models, Proceedings of the 5th International Conference on Rapid Prototyping, University of Dayton, pp: 221–228
8. Kirschman CF, Jara-Almonte CC, Bagchi A, Dooley RL, Ogale AA (1991) Computer aided design of support structures for stereolithographic components, Proceedings of the 1991 ASME Computers in Engineering Conference, Santa Clara, CA, pp: 443–448
9. Hong J, Wang W, Zhang Y-H, Lu B-H (2004) Research on auto-support in stereolithography. Chin J Mech Eng 40(11):134–138 in Chinese
10. Ding S, Mannan MA, Poo AN (2004) Oriented bounding box and octree based global interference detection in 5-axis machining of free-form surfaces. Computer-Aided Des 36(13):1281–1294 doi:10.1016/S0010-4485(03)00109-X
11. Guo K-B, Zhang L-C, Wang C-J, Huang S-H (2007) Boolean operations of STL models based on loop detection. Int J Adv Manuf Technol 33:627–633 doi:10.1007/s00170-006-0487-5
12. Surazhsky V, Gotsman C (2004) High quality compatible triangulations. Eng Comput 20(2):147–156
13. Zhang L-C, Han M, Huang S-H (2002) An effective error-tolerance slicing algorithm for STL files. Int J Adv Manuf Technol 20:363–373 doi:10.1007/s001700200164