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Determination of optimal build orientation for hybrid rapid-prototyping

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Abstract

To overcome the limitations of the layered manufacturing process, hybrid rapid-prototyping systems that allow material removal and deposition are being introduced. This approach should benefit from the advantages of conventional layered manufacturing and traditional CNC machining processes. To realize these advantages, however, an intelligent process plan must be generated. In the hybrid rapid-prototyping process, a part is decomposed into thick-layered 3D shapes, such that each layer can be machined and stacked easily. When each layer is generated from the part's shape, the build orientation is an important factor to be considered, because it greatly influences the lead-time, the machining accuracy, and the number of tool-accessible features in each setup. In this paper, an algorithm to determine the build orientation is described. It considers the deposition process attributes and the machining process attributes simultaneously.

Keywords: Build orientation; Build time; Hybrid rapid-prototyping; Tool approach direction

1. Introduction

The existing layered manufacturing process has the advantages of rapidly manufacturing 3D RP-models directly from 3D CAD models, but on the other hand has limitations, such as limited choice of material, small part size, and low part accuracy. One solution to these problems that is being introduced is a new rapid-prototyping system called the hybrid rapid-prototyping system that combines conventional layered manufacturing and traditional CNC machining processes. Even though hybrid rapid-prototyping systems can be developed to overcome these limitations, they will function as desired only when the process plans are generated wisely. When generating the process plans, the build orientation is an important factor to be considered, because the build direction has a major effect on tool-accessible features in a single setup, and also on the determination of the layers of the part.

In this paper, to maximize the build efficiency, an algorithm to determine the build direction that is suitable for both layered manufacturing and CNC machining processes is proposed by considering the layered manufacturing process attributes and the CNC machining process attributes at the same time.

1.1. Related work

Because of the importance of the build direction in rapid-prototyping process planning, methods of determining the build direction in layered manufacturing systems and the orientation of workpiece in CNC machining systems have been widely discussed [1–6], but none of them can be applied to the hybrid rapid-prototyping systems. There have been many published papers on hybrid rapid-prototyping [7–11]. They have presented systems, algorithms, and techniques for hybrid rapid-prototyping, but the build orientation has not been touched on. Gupta et al. [12] provided a method to find the near-optimal build orientation for shape deposition manufacturing system by considering the build time only. Yang et al. [13] presented a method to determine the optimal build orientation for robot-based layered manufacturing by considering part accuracy, tool accessibility, and number of supports as optimization factors, but the build time was ignored. So far, the problems of determining the build direction in hybrid rapid-prototyping have not been fully solved, especially those embracing both the layered

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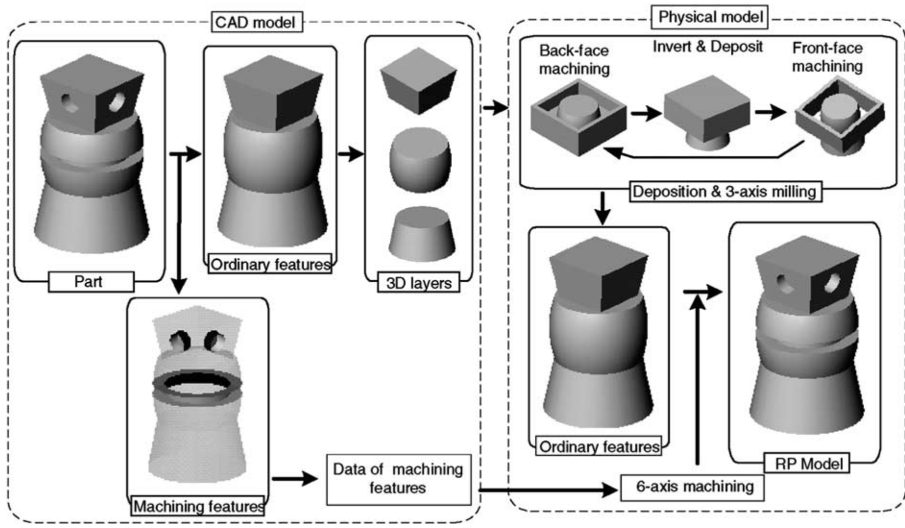

Fig. 1. Process planning of hybrid rapid-prototyping.

manufacturing process attributes and the CNC machining process attributes.

1.2. Hybrid rapid-prototyping system

A new hybrid rapid-prototyping system, named Eclipse_RP, was proposed by Hur et al. [7]. Fig. 1 shows the process planning of Eclipse_RP. For a given part, all the shapes of the part are divided into two types, i.e. the shapes of the machining features, and the shapes of ordinary features. The shapes of the machining features are extracted before the given part is decomposed, and manufactured by 6-axis machining after the shapes of the ordinary features have been generated. The shapes of the ordinary features are decomposed into 3D layers, and are generated by performing both deposition and 3-axis milling while ignoring all the machining features. Every shape of the decomposed 3D layer is generated from a hexahedron workpiece by performing two-directional machining in two setups, i.e. back-face machining and front-face machining.

2. Decision criteria for build orientation

2.1. Tool accessibility of machining features

Machining features defined in the current system are features such as holes, slots, and pockets, which could only be generated effectively by special machining methods. There may be many possible tool approach directions to machine machining features in a 6-axis machine, but only the directions for efficient machining operations should be used. However in a number of cases, some of the possible tool approach directions are invalid, because of interference between the tool and other portions of the part. It is therefore necessary to check the tool approach directions of the machining features to ascertain whether a tool interferes with sections of a part as the tool approaches the part along given directions. To perform such checks, the system generates the tool sweep volume by sweeping the section shape of the machining feature along the tool approach direction, or along the tool path.

In the Eclipse_RP process, a specially designed 6-axis machining center was developed based on the parallel mechanism, which can perform machining operations on all five faces of the prismatic workpiece in a single setup, with its spindle tilting from 0° to 90°. The tool approach directions that can be realized by the 6-axis machining center, called tool-accessibility map, can be represented by a hemisphere, as shown in Fig. 2.

For a machining feature, if an extented line of the vector that defines the tool approach direction of a machining feature intersects with the hemisphere, and the tool sweep volume of the machining feature has no interference with another section of the part, then the machining feature can be machined in the setup. In the 6-axis machining center, the tool accessibility of the machining features can be represented as follows:

$$F_a(\mathbf{n}) = \frac{N_a}{N_t}$$

N_a is the number of the machining features that can be approached by the tool in the setup, N_t the total number of the machining features in the part, $\mathbf{n}$ indicates the build direction, and $F_a(\mathbf{n})$ is the tool accessibility of the machining features.

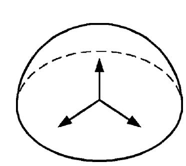

Fig. 2. Hemisphere representing the tool accessibility of the 6-axis machine.

2.2. Build time for generating a part without machining features

Unlike a layered manufacturing process where build time mainly depends on the deposition time, the hybrid rapid-prototyping process, in which a part is decomposed into several thick-layered 3D shapes, consumes much time in the machining process, and this takes up a large portion of the lead-time. Therefore, the build time of the hybrid rapid-prototyping process should be evaluated by considering both the time spent in the deposition process, and the time in the machining process.

Deposition time includes the time spent for the workpiece transfer and deposition actions, and is proportional to the number of the layers. In this system, to minimize the number of the layers, the part is decomposed into several 3D layers with variable thickness, according to the existence of undercut regions. Therefore, the number of undercut regions, the build height of a part, and the available thickness of the workpiece determine the number of the layers. Machining time is spent in machining the 3D layer from the workpiece, and is proportional to the machining volume. The machining volume, as shown in Fig. 3, can be divided into two volumes: machining volume_A and machining volume_B. Machining volume_A is required because of the thickness difference between the 3D layer and the workpiece. Machining volume_B is the volume that should be removed for the boundary machining of the part.

In summary, when determining the build direction of the hybrid rapid-prototyping process, we should consider both the machining time and the deposition time as follows:

$$T_{\mathrm{d}}(\mathbf{n}) \propto N_{\mathrm{l}}, \qquad T_{\mathrm{m}}(\mathbf{n}) \propto V_{\mathrm{m}}$$

where $T_{\mathrm{d}}(\mathbf{n})$ is the deposition time, $T_{\mathrm{m}}(\mathbf{n})$ the machining time, N_{l} the number of layers, V_{m} the machining volume, N_{l} can be calculated using the slicing algorithms presented by Hur et al. [7], and V_{m} can be calculated using the following steps:

(1) For a given part, we use the slicing algorithm of Ref. [7] to determine the slicing positions.
(2) Group the faces of the part for each layer, and project the grouped faces to the bottom plane of the workpiece.
(3) Search for the boundary curves of the projected shape and offset the boundary curves outward by the tool diameter.
(4) Generate the *raw-volume* by extruding the offset curves along the build direction up to the top plane of the workpiece.

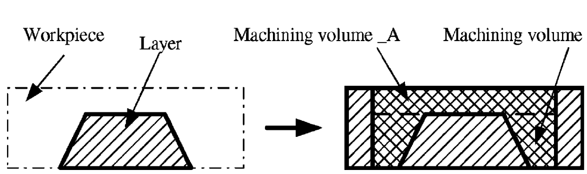

Fig. 3. Machining volume.

(5) As above, we can obtain the *raw-volume* of each layer, and the total *raw-volume* by summing all the *raw-volumes* from each layer.
(6) V_{m} is calculated by subtracting the part volume from the total *raw-volume*.

2.3. Number of bridges

As mentioned above, layers can be machined from two directions, i.e. back-face machining and front-face machining. When performing front-face machining as shown in Fig. 4(b), the workpiece is glued to the lower layer, and it is not necessary to use a fixture to fix the workpiece. However, for back-face machining, the workpiece must be firmly fixed using universal fixtures as shown in Fig. 4(a).

However, if the part to be machined has the shape shown in Fig. 5(a), then all the boundaries of the part must be machined from the back face. After back-face machining, the back-face machined part will be completely separated from the outer wall of the workpiece (Fig. 5(b)), and the outer wall of the workpiece will not have the function of fixing the back-face machined part. These problems can be solved by adding bridges to the CAD model of the layer as shown in Fig. 5(c). That is, physical bridges connecting the part with the outer wall of the workpiece will be generated after any back-face machining as shown in Fig. 5(d). These bridges are removed by front-face machining, and the remains of the undercut are post-processed manually. More bridges result in a higher cost for finishing the RP-model. It is therefore important to minimize the number of bridges by adjusting the build direction.

To judge whether bridges should be added to a back-face machined part, we use the effective area that connects the back-face machined part and the outer wall of the

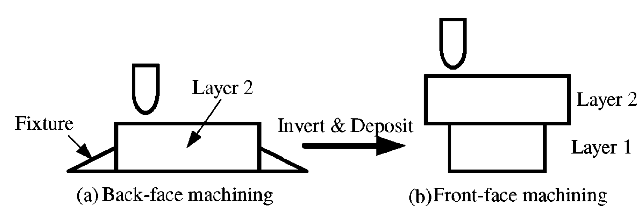

Fig. 4. Methods of fixing parts.

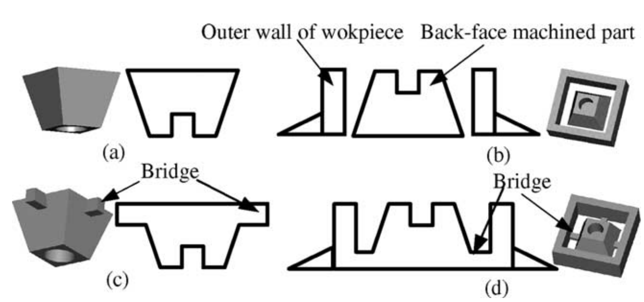

Fig. 5. Essentiality of bridges.

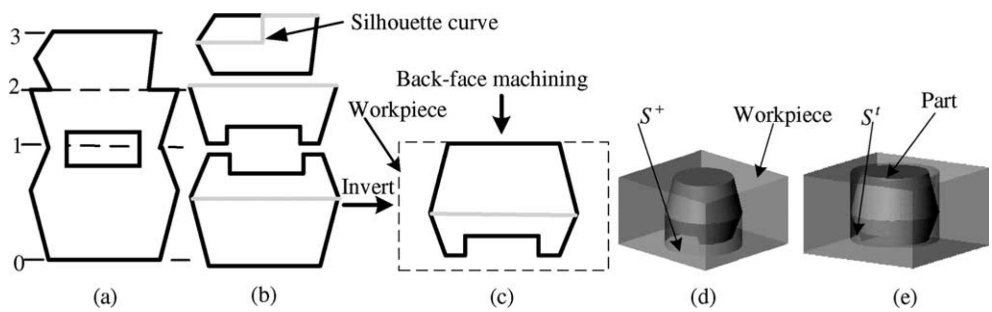

Fig. 6. Concept of S^+ and S^t.

workpiece. The back-face machined part requires bridges only if:

$$\frac{S^+}{S^t} \leq T$$

where T is a coefficient related to the rigidity of the material and the cutting force, and is specified by the user. S^+ is the effective area that connects the back-face machined part and the outer wall of the workpiece, and can be calculated using the following steps:

(1) For a given part, we use the slicing algorithm of Hur et al. [7] to determine the slicing positions (Fig. 6(a)).
(2) Group the faces of the part for each layer.
(3) Find the silhouette curves for the grouped faces, which are used as the borderlines between back-face machining and front-face machining (Fig. 6(b) and (c)).
(4) Generate a cylindrical surface by extruding the silhouette curves along the build direction up to the bottom plane of the workpiece (Fig. 6(d)).
(5) S^+ is the area of the cylindrical surface generated by the above.

S^t is the effective surface area of a layer, which can be calculated using the following steps:

(1) Project all the faces belonging to a layer onto the bottom plane of the layer.
(2) Find the boundary curves of the projected shape.
(3) Generate a cylindrical surface by extruding the boundary curves along the build direction up to the top plane of the layer (Fig. 6(e)).
(4) S^t is the area of the cylindrical surface generated by the above.

For a given build direction, the number of the necessary bridges can be evaluated by the following equation:

$$N_b(\mathbf{n}) = C_b \sum_{i}^{k} ((S^t)_i - (S^+)_i)$$

where k is the number of the layers in the given build direction, $N_b(\mathbf{n})$ the number of bridges, and C_b the equivalent coefficient assigned by the user.

2.4. Number of supports

In the SLA process, overhangs and most of the downward-facing facets require support. However, in hybrid rapid-prototyping, not all of the overhangs require support, because the part has been decomposed into thick-layered 3D shapes, and also because of the stiffness of the material. After the given part has been decomposed, as shown in Fig. 7(a), there will generally be some independent, separated shapes that require supports. Fig. 7(b) shows that Layer 2 is composed of two independent and separated shapes, and shape A will not be connected to the lower layer even when it is deposited. Such shapes are called island shapes and are difficult to generate without supports. It is therefore very important that the system should find any island shapes that arise from slicing, and then automatically generate some support structures as illustrated in Fig. 7(c). When determining the build direction, we must select the direction such that there are minimum island shapes.

The island shapes that require support can be found as follows (Fig. 8):

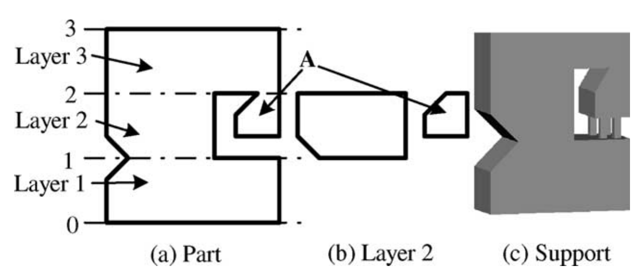

Fig. 7. Island shape.

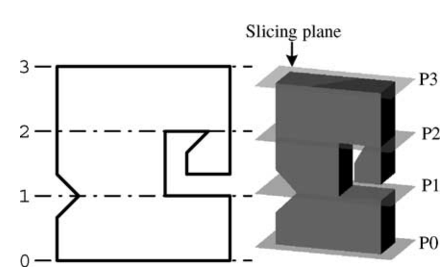

Fig. 8. Determination of an island requiring support.

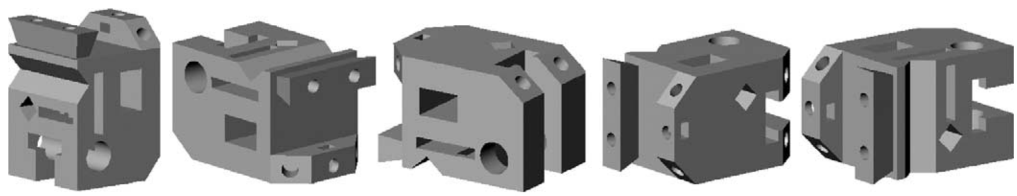

Fig. 9. Example model and candidate build orientations.

(1) For a given part, we use the slicing algorithm of Hur et al. [7] to determine the slicing positions.
(2) When a slicing plane (e.g. P2) intersects with a given part at a slicing position (e.g. position 2), and if there are more than two independent loops, then it is possible that island shapes are generated by the slicing plane.
(3) After finding the edges of these loops, then we find the faces connected to these edges, and then judge whether these faces intersect with the slicing plane (e.g. P1) at the lower slicing position (e.g. position 1).
(4) As long as a face, which is connected to edges on a loop, intersects with the slicing plane at the lower position, then the shape including the loop is not an island shape.
(5) On the contrary, if none of the faces connected to the edges on a loop intersect with the slicing plane at the lower position, then search for all the faces in order that are adjacent to these faces, and judge whether they intersect with the slicing plane one by one. If no adjacent faces intersect with the slicing plane, then the shape, including the loop, is an island shape and requires supports.

For a given build direction, the number of supports required by the island shapes can be estimated using the following equation:

$$N_s(\mathbf{n}) = C_s \sum_j^l (A_p)_j$$

where l is the number of the island shapes in a given build direction, A_p the area of the island shape projected onto the horizontal plane, $N_s(\mathbf{n})$ the number of the supports, C_s the equivalent coefficient specified by the user.

3. Optimization of the build orientation

The optimization system can be implemented with a user interface allowing the user to try various weighted values so that the optimized build direction is verified to reflect the user's intention. To reduce the calculation cost, the system lets the user select some build directions as candidates based on their experience, and calculates the *cost* of these candidates. Among these candidates, the one with the minimal cost is the best build orientation.

$$\text{cost} = w_d T_d(\mathbf{n}) + w_m T_m(\mathbf{n}) + w_b N_b(\mathbf{n}) + w_s N_s(\mathbf{n}) - w_a F_a(\mathbf{n})$$

where w_d is the weighted value of deposition time, w_m the weighted value of machining time, w_a the weighted value of the tool accessibility of the machining feature, w_b the weighted value of bridge, w_s the weighted value of support structure.

Table 1
Calculation results

Criterion	(a)	(b)	(c)	(d)	(e)
Accessibility	0.8	0.7	0.9	0.8	0.9
Deposition time	3.5	2.1	2.1	2.1	2.1
Machining time	1.251	1.107	1.107	1.233	1.233
Bridge	0.9	0	0	0	0
Support	0	0	0	0.2808	0
Cost	4.951	2.507	2.307	2.845	2.433

4. Case study

The proposed algorithm has been implemented using the C language and the Parasolid modeling kernel. Fig. 9 shows the candidate build orientations chosen for the example model that is used to demonstrate the proposed method. Among these candidate build orientations, Fig. 9(c) is the best one according to Table 1.

5. Conclusion

In this paper, an algorithm to determine the optimal direction of a hybrid rapid-prototyping process has been developed by considering both the CNC machining process attributes and the deposition process attributes. The main criteria for determining the build direction are the tool accessibility of the machining features, the build time, the number of bridges, and the number of supports. In addition, a method is presented to secure a part with bridges instead of using specially designed fixtures.

Currently, the bridges and the supports are generated interactively. Automatic generation of the bridges and the supports, and research on finding the optimal locations of the bridges and the supports based on mechanical analysis are left for future study.

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