ON THE COMPUTATION OF PART ORIENTATION USING SUPPORT STRUCTURES IN LAYERED MANUFACTURING

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ABSTRACT

During the construction of an object by layered manufacturing, it might be necessary to build external supports either to prevent the object from toppling, or to support floating components and overhanging material. The support structures, if necessary, must be built simultaneously with the object, and hence must be accounted for in the path planning of the laser beam or the deposition nozzle. In this paper, we find the best direction of formation of an object by layered manufacturing process that allows the use of support structures. In the orientation determined by the best direction of formation, the object is constructible with a minimal support structure, is stable, and rests on a planar base. Implementation results are also included.

1. INTRODUCTION

Layered manufacturing is a method of rapid prototyping where objects are constructed layer by layer; see [1] for an overview of various methods and application areas. Many different processes are available for layered manufacturing, but we are concerned only with those processes that might require the use of external support structures during the formation of the object. Two common examples of machines that use this type of process are stereolithography as found in 3D Systems machines and material deposition methods as found in machines built by Stratasys. (To the best of our knowledge, in the layered manufacturing machines of Cubital, Helisys, DTM, and MD* the object is enclosed in material that acts as support, so no external support structure is needed.)

By external support structures, we refer to the scaffolds that have to be built simultaneously with an object in order to prevent it from toppling and to support material that would otherwise droop or fall. Therefore, for some layered manufacturing methods the inclusion of support structures increases the domain of parts that are constructible.

In this paper, we describe a method for determining the best orientation for constructing an object by layered manufacturing. The criteria for choosing the orientation include stability of the object and minimum area of contact with support structures.

2. NEED FOR SUPPORT STRUCTURES

To motivate the need for support structures, we briefly describe the stereolithography process, a popular layered manufacturing technique. The object is constructed in a vat of photocurable liquid on a platform whose height can be controlled. At first the platform is just below the surface of the liquid at a distance of one layer thickness. A laser 'draws' the first layer of the object on the liquid, causing the liquid to harden. The platform is lowered to expose another layer of liquid on the surface and the laser draws the next layer of the object. This process continues until the object is formed. In material deposition methods, the concept is similar, except here a material laying nozzle plays the role of the laser and liquid. Note, in the current methods, layers of constant thickness are used [2]; a method for determining best orientation for minimizing the number of slices of variable thickness and the total stair-case area see [4].

Consider an object to be built in a given orientation. Support structure will be needed in three different situations. The most common need for support structure occurs when material on one layer overhangs the previous layer by more than a specified amount. In Figure 1 based on the allowable overhang, face B might require a support but not face A. Note, in this case, supports are not required to prevent the object from toppling.

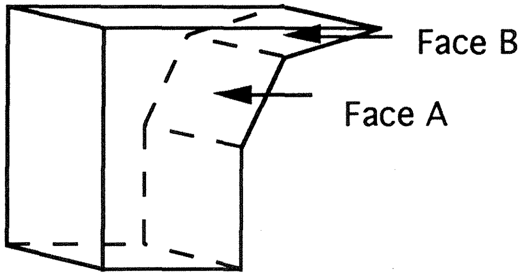

Figure 1. Support required for face B but not for face A.

Including support structure to take care of this case is often sufficient to handle the remaining two cases (and currently in practice the automatic computation of support structure stops here). The second situation where support structures are needed is when a 'floating' component is introduced during the construction. These are parts of the object introduced at a height greater than zero but not joined to the rest of the object until later in the construction; see, for example, Figure 2.

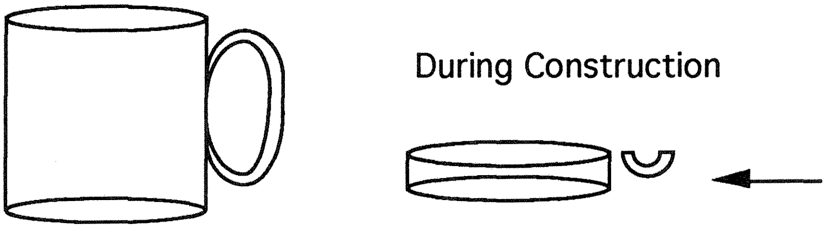

Figure 2. During the construction of the object, support structure is required to carry the floating component.

The third case where external supports might be required is when the object becomes unstable during the construction. In Figure 3, the object will topple if the face indicated by the arrow is not supported. Note, this situation is different from the one illustrated in Figure 1 where the object is in a stable orientation.

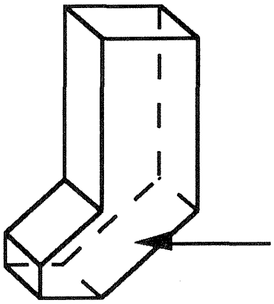

Figure 3. To prevent the object from falling, support structure is needed on the indicated face.

We note, the need for support structures in the third case is somewhat weak if considered in light of the physical process. Factors include the fact that the object's base usually weakly adheres to the platform on which the object is grown, and in the case of stereolithography the liquid in which the object sits adds further stability. However, situations where stability is an issue are conceivable.

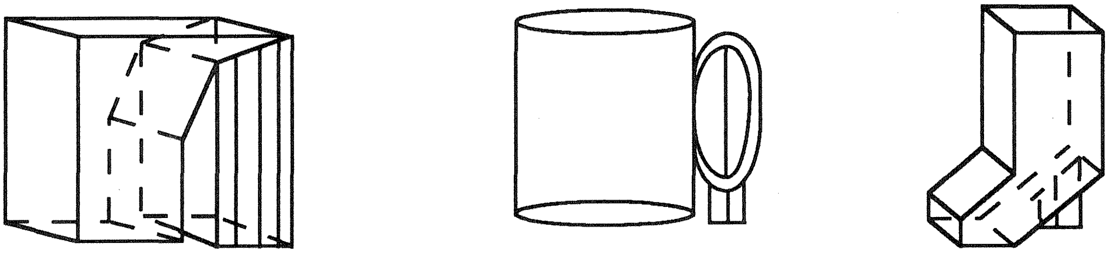

Figure 4. Examples of support structure for the objects shown in the Figures 1, 2, and 3. Notice that the second object needed support structure at the top of the handle because of overhang between layers, and support at the bottom of the handle because of a floating component.

Our approach imposes no restrictions on the geometric domain of objects. In addition to solid objects with or without voids, we also consider the layer manufacture of (thin) surfaces, e.g., a hollow cylinder, sheet metal parts, etc. However, we make the assumption that a curved surface cannot act as a base for the construction. This assumption stems from the observation that whenever a physical object, at rest on some plane P, is in a stable orientation, it has at least a 3-point contact with P. This contact requirement can be met whenever the object has either of the following in contact with P: (i) three distinct non-collinear points, (ii) a line and a point, (iii) a plane, (iv) a non-degenerate planar curve. For example, a sphere resting on a plane will not meet any of the aforementioned requirements, and hence is unstable.

For any object G, every planar face on the convex hull of G will either be an (original) face of G, or will be a (new) face that satisfies the contact criteria. Therefore, our approach to determine stable orientation involves reasoning based on the convex hull of the object. To compute the convex hull of an object we require *sample points* on its surface. We adopt this point based approach due to the difficulties in computing the convex hull of free form objects. In this paper, we first facet (triangulate) the object and then use the vertex set of the faceted object as sample points.

We assume every object to be constructible and every orientation (for construction) to be valid with the addition of sufficient support structures; see Figure 4. The interested reader can compare this use of support structures to the approach taken in [5]. In that paper, polyhedral objects are tested for orientations in which the object has no overhanging material between layers. Any object without such an orientation, according to [5], is not constructible.

The support structures are built, layer by layer, simultaneously with the object. After the object is constructed, the support structure must be removed, often manually. For a complicated object this removal may be difficult, requiring the supports to be dug out of tight spaces, while also reducing the quality of the surface finish. To reduce the time required to manufacture the object and to improve the quality of the surface finish, we wish to minimize the surface area of the support structure that is in contact with the object. Finally, given two orientations of an object with the same amount of support structure, our algorithm will pick the orientation in which the object is more stable, i.e., has lower center of mass.

In addition to [5], the problem of determining optimal orientation in layered manufacturing has been considered in [3] where simulated annealing (SA) is used for selecting the orientation. Orientations are evaluated with respect to the object's height, the total area of the surfaces of the object subject to staircase effect, and the volume of the trapped liquid (specific to SLA process without regard to support structure).

3. DEFINITIONS

We define the following with respect to an object G that is being considered for layered manufacture with a direction of formation along the z-axis.

Up_vector: The up_vector is a unit vector that specifies an orientation of G.

Base: The base of G is the convex hull of the set of points on G whose dot product with the up_vector is minimal.

The orientation of G during formation is obtained by rotating G so that the up_vector is parallel to the positive z-axis and then translating G so that its base rests on the x-y plane. See Figure 5.

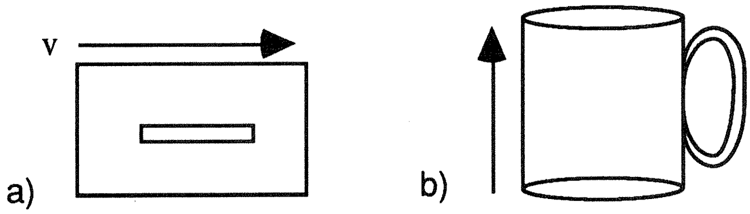

Figure 5. a) An object given in it's initial orientation with an up_vector v, and b) the orientation determined by v.

Supported_Point: A point p on the surface of G is a supported_point if the following hold:

i. the outward pointing normal at p has a negative z coordinate
ii. p lies on the surface of a support structure for G

All other points on G are unsupported_points. Each sample point chosen on G is classified as supported or unsupported. This information is used later to construct an approximation to the necessary support structure.

Extended Base:

An extended base of G is the convex hull of point sets P_1 and P_2 where P_1 contains all sample points of G that lie in the x-y plane and P_2 contains the projection into the x-y plane of all supported_points of G; see also Figure 6.

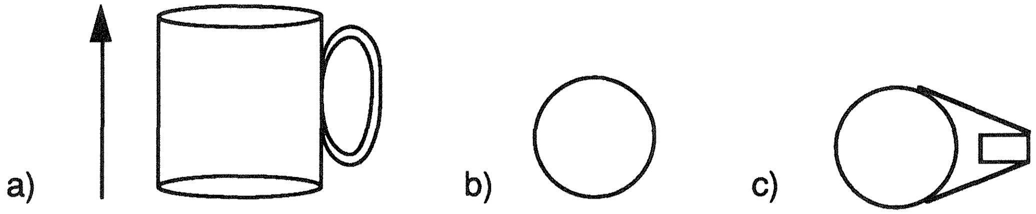

Figure 6. a) An object and its direction of formation. Note that some of the sample points on the handle must be supported, since during the construction a floating component is introduced. b) The base of the object. c) The extended base of the object.

4. THE ALGORITHM

Our method for the determination of the best orientation for the layered manufacture of an object consists of three steps. First, a candidate list of orientations for the object is made. Second, for each orientation in this list, an approximation to a sufficient support structure for the construction of the object is computed. Also, the center of mass of the object in this orientation is found. Finally, the best orientation is selected from the candidate list. The selection criteria includes (i) the surface area of contact between the support structure and the object, which we seek to minimize, and (ii) the stability of the object.

4.1 Determination of Candidate List of Orientations

Consider an object G. The sample points of G are elements of the vertex set of the faceted representation (triangulation) of G. Let CH(G) denote the convex hull of the set of sample points. Note, if G did not contain any planar faces, then CH(G) could possibly contain a large number of faces depending on the coarseness of the triangulation.

The inward pointing normal to each face f of CH(G) corresponds to the up_vector for the orientation of G with f as the base. In order to limit the number of candidate orientations, we use only those up_vectors that correspond to faces of CH(G) with a relatively large area. First, we set a threshold value λ for the surface area of a face. In general, λ is chosen higher than the value for the area of a facet that corresponds to a curved surface region of the original object G. Next, all faces that have surface area less than λ are eliminated. The up_vectors corresponding to the remaining faces of CH(G), with surface area greater than λ, form the list of candidate orientations. In these orientations, G sits on a large base which acts to increase stability and decrease the size of the support structure needed.

4.2 Computation of the Support Structure

Consider an object G and an up_vector v. The computation of the approximate support structure for G in the orientation corresponding to v can be broken down into the following steps. First, G is moved into the orientation corresponding to v. Second, the sample points on G are classified as either supported or unsupported. Third, using the classification of the sample points and normals on G's surface, an approximate support structure is made. We elaborate on the second and the third steps next.

4.2.1 Classification of Sample Points

Initially all sample points in G are classified as unsupported. A sample point *p* will be classified as supported if, after adding support at *p*, either of the following hold:

(i) a floating component introduced during the construction of G is supported
(ii) a component, that would otherwise topple as the object is grown, is stabilized; see Figure 7.

To determine which sample points need to be supported, the growth of G is simulated. This simulation is necessary due to the difficulties in tracking the center of mass of a curved object as the object is formed. We note that if the object domain were restricted to polyhedral objects, such an approach would not be necessary.

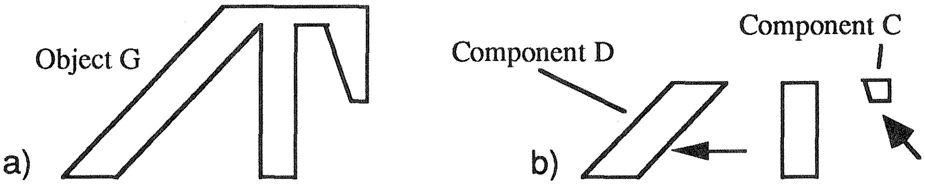

Figure 7. a) The profile of an object G, and b) the connected components of G during formation. The component D is unstable. C is floating. Adding support at the indicated sample points would stabilize these components.

If a new component C is introduced during G's growth, then C is floating since its extended base does not lie on the x-y plane. See Figure 7. To indicate the need for support on C, all sample points in the new component are classified as supported. When the next layer is added, the component is no longer new. Global methods exist for the detection of floating components that do not involve the growth of G. However, since G must be grown to test for unstable components, we make use of this simulation here.

As layers are added, the center of mass of each connected component of the partially formed object is computed. If the center of mass of some connected component D is not directly above its extended base then component D is unstable. D can be stabilized by adding support to G at sample points that lie in D, so that D's center of mass lies above the new extended base. (See Figure 7.)

4.2.2 Computing Approximate Support Structure (Rays Structure)

Assume the object G is in some (candidate) orientation. The approximate support structure for the object in a particular orientation is stored in a (n¥n) array which we refer to as the *rays_structure*. The cells of rays_structure correspond to a grid of rectangles in the x-y plane. The projection of G onto the x-y plane is contained in the union of these rectangles. Let p_{ij} denote the center of rectangle (i,j) in the x-y plane and let L_{ij} be the half-line originating at p_{ij} and parallel to the z-axis. The points of intersection between the object G and L_{ij} is stored in the cell (i,j) of rays_structure. Note, there can be several points of intersections between L_{ij} and G. These points are stored in the same order as L_{ij} intersects G, i.e., the points have increasing z values.

Next, these points of intersection are classified. The primary classification is based on the direction of the face normal. If the face normal points upwards the corresponding point on G does not require support; all other points may require support. Next, for points that may require support, a classification of *supported* or *unsupported* is done. Initially, support will be added to those points where the angle α, between the face normal and the negative z axis, is smaller than a user specified angle β. Decreasing values of α (down to 0 degrees) correspond to increasing material overhang from the previous layer during the construction; see Figure 8. So, if α is less than the user specified β, the point of intersection is classified as supported; all others are classified as unsupported.

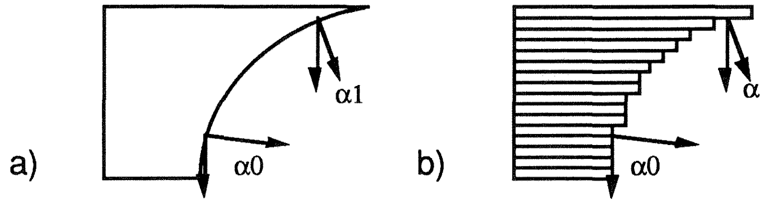

Figure 8. a) An object G and the angles α_0 and α_1 between the normals to G's surface and the negative z-axis. b) The layers added in the formation of G. Note the overhang between layers is greater for the smaller angle α_1.

After the initial rays_structure classification, the support information that was attached to the sample points is used to complete the approximate support structure. A sample point p of an object G is classified as supported only when the support structure added at p helps stabilize G or carries a floating component of G. So to ensure that adding support at p doesn't create a new unstable component, the support structure here is grown from the x-y plane; see Figure 9. With this in mind, let p be any supported sample point. Suppose p lies above the rectangle in the x-y plane that has center p_{ij}. Then each point of intersection of G and L_{ij} with support type *not_supported* that has z value near or below the z value of p is changed to type *supported.* Once each sample point's contribution is included, the approximate support structure stored in rays_structure is a sufficient support for the object during its manufacture.

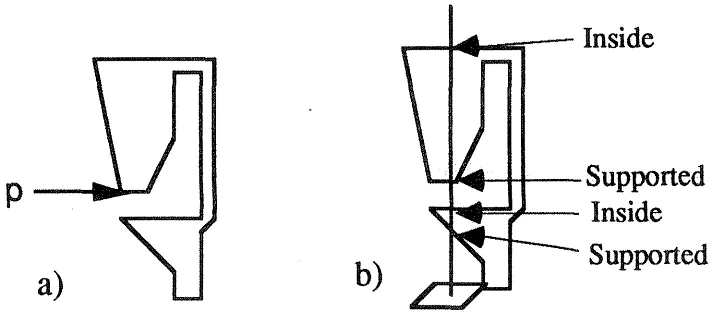

Figure 9. a) Supported sample point *p* on G, and b) the classification of the points of intersection of L_{ij} and G.

By the above process, all points of intersection corresponding to each half-line are classified (as inside, supported, or unsupported). These points break the half-line into several line segments; those segments between consecutive points of intersection along the ray. Since, the points are stored in rays_structure in order of increasing z-values, the points alternate between inside and supported/unsupported; see Figure 9.

Finally, we add the approximate support structures by considering the directed line segments corresponding to each half-line. First, a support structure is added to each line segment l = (u,v) where the endpoints u = point on the x-y base, and v = supported point on G. This corresponds to adding support structures A in figure 10 (b). Next, support structures are added to line segments l = (u,v) where the end points u = inside and v = supported. This step corresponds to adding the support structure B in figure 10 (b). This is required to add support at intermediate levels. Finally, the total surface area of contact between a support structure and the object G is computed as the product of the area of the base of the cell times the number of places where the support touches the object.

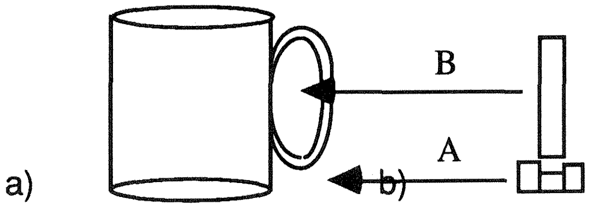

Figure 10. a) An object G, and b) a graphical representation of the support structure approximated by the rays structure for G. Note that support A is added to carry a floating component and support B is added to support overhangs.

Therefore, by using each half line L_{ij} to approximate the support structure needed over the corresponding box in the x-y plane, the information stored in the rays_structure is used to quickly calculate the surface area of the support structure in contact with the object.

The best orientation is chosen from the list of candidate orientations. In this orientation the support structure for G has minimal surface area of contact with G. If two orientations require support structures with equal surface areas of contact, the orientation in which G has a lower center of mass is chosen as best.

5. IMPLEMENTATION AND RESULTS

This algorithm was implemented in C++ with the geometric modeler ACIS. The support types of the sample points on a face of the object are controlled by a height attribute attached to the face. The height signals that all vertices in the faceting of the face with z values less than or equal to the height are supported. Individual control of the support attributes of the sample points is lost, but in most cases the resulting support structure has little excess.

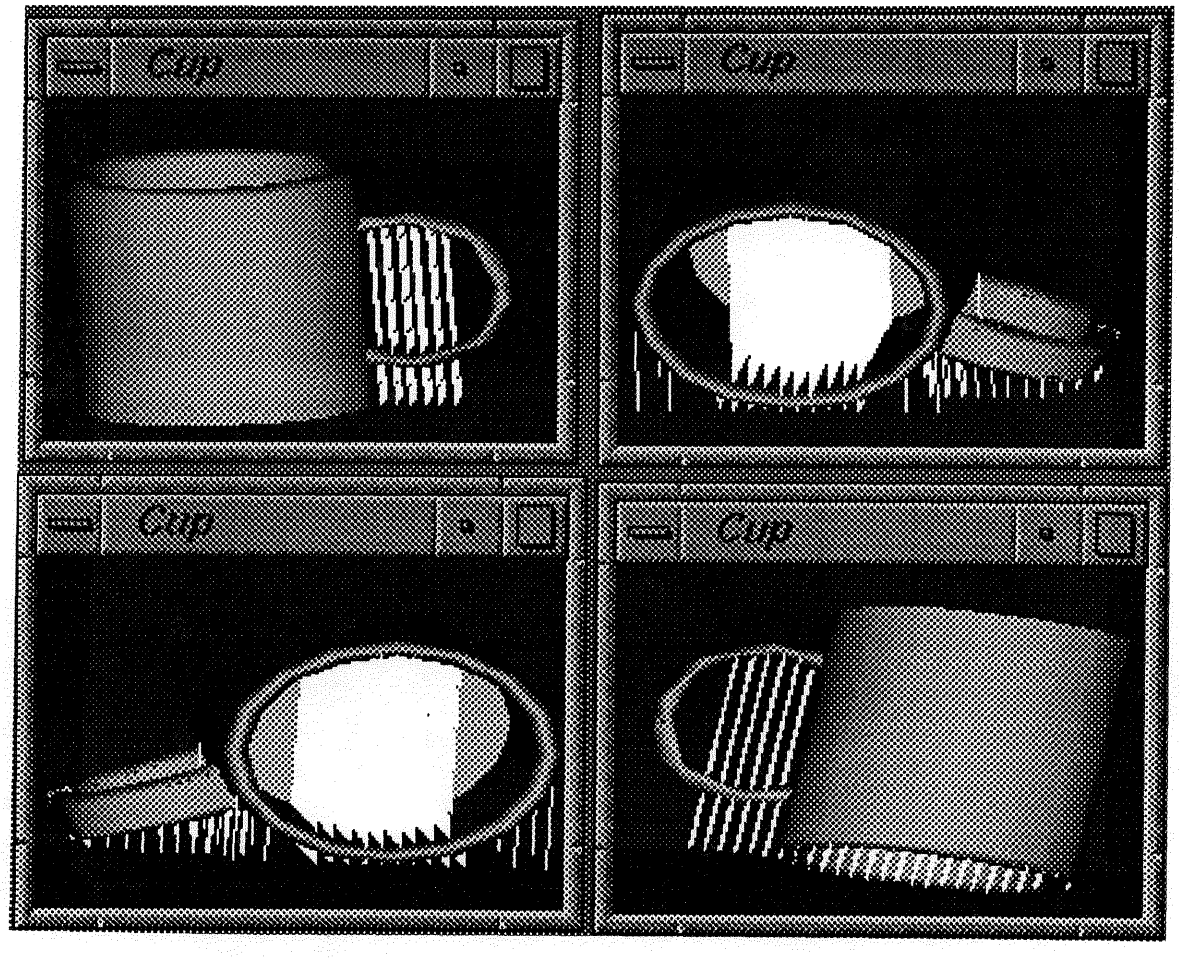

Figure 11. The four candidate orientations for a coffee cup and the support structure necessary for each.

The output as shown in Figure 11 shows the four stable orientations that our program found for a coffee cup and indicates the required support structure for each orientation. The coffee cup is an ACIS model with faces from planes, cylinders, and tori. The first orientation (with the cup opening upward) is the best orientation. The worst is with the cup opening downward, since in this case the flat surface near the top must be supported. The program was run with an overhang threshold of 30 degrees (see Figure 8), a 30x30 rays_structure, and 15 layers in the cups simulated growth. This example took about 45 minutes to run on a Silicon Graphics Indigo workstation, where most of this time was spent doing the initial rays_structure computation for each orientation.

6. CONCLUDING REMARKS

Layered manufacturing is often described as an attractive rapid prototyping method where CAD models can be simply down loaded and physical prototypes realized, without having to incur "set up" costs. However, the computation of part orientation, support structures, and layer thickness in layered manufacturing are quite complicated and time consuming if done manually. In fact, such tasks are the analogue of set-up functions (i.e., tooling, fixtures, operations sequencing, etc.) in conventional NC machining. We conjecture, the overall efficiency of layered manufacturing as a production tool will depend among other things upon the availability of efficient procedures for tasks such as the one addressed in this paper.

7. REFERENCES

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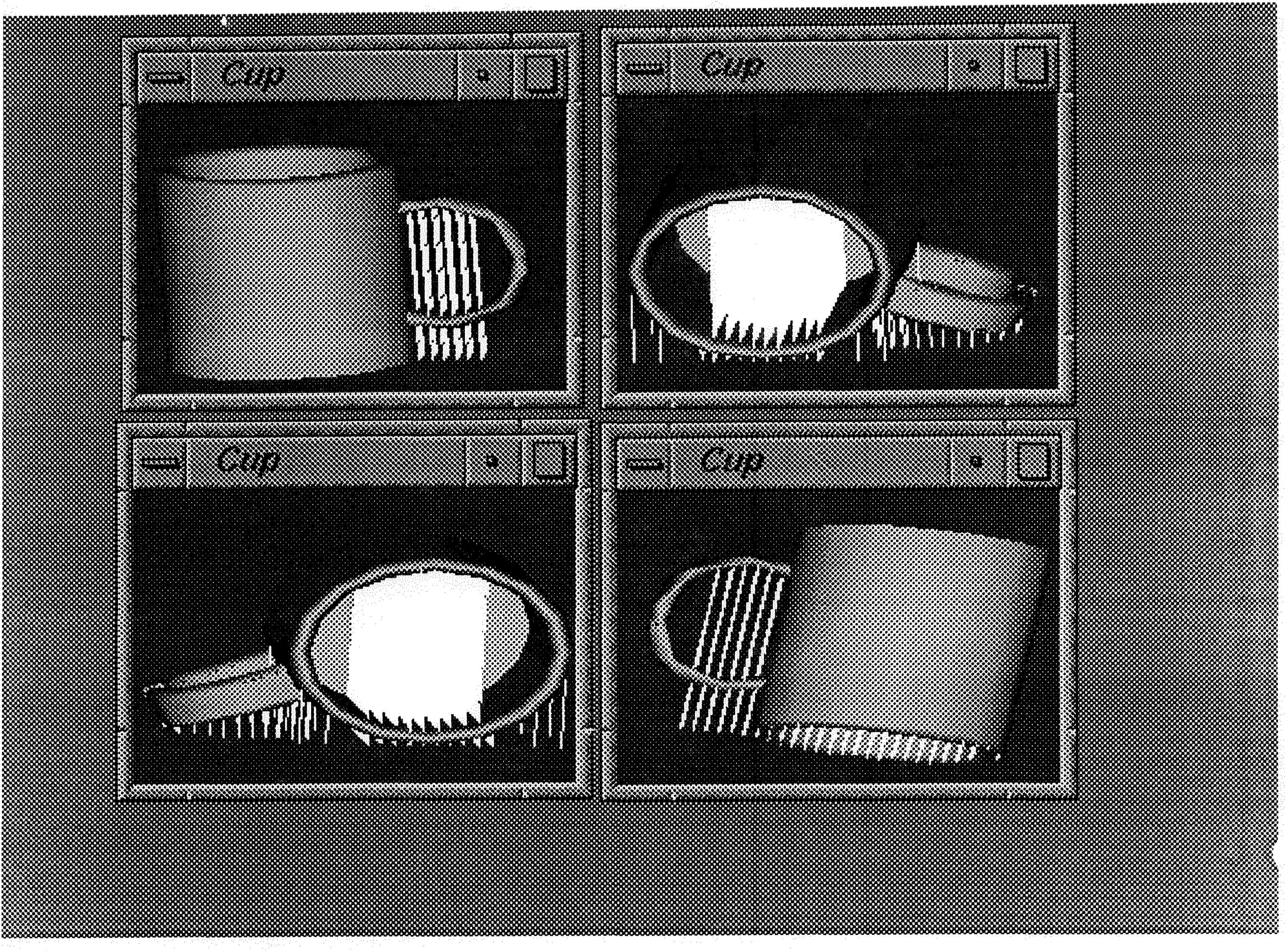
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