Determining fabrication orientations for rapid prototyping with stereolithography

by

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CHAPTER 1. INTRODUCTION

Overview

Prototypes are essential in the life cycle of product development as they provide effective means for design verification, manufacturability, determination, and marketing evaluation. The main benefits for producing a prototype are that people can immediately grasp the engineer's intention from a three-dimensional model and although a designer may usually catch problems in the CAD drawing, they may not see a problem until they look at the model to see if it will fit the mating part. The construction of prototypes usually depends on highly skilled model builders, who in turn rely on conventional machining and hand-crafting. Prototype builders must work closely with designers to assure proper interpretation of design drawings, sketches, or computer rendering. This manual prototyping process is time-consuming and costly.

The traditional methods for manufacturing are being challenged by the imposing needs to improve competitiveness and reduce the time to market for a new product. A new class of prototyping technology has been developed recently called rapid prototyping or desktop manufacturing. This method provides a means to rapidly and effectively create prototypes. With rapid prototyping methods, both designers and manufacturing engineers can see and hold physical models of designed parts in a matter of hours instead of weeks. They can examine prototypes and fix flaws in a much

shorter cycle. In other words, rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. The technology for rapid prototyping can be roughly divided into two major categories. The most widespread are the photopolymer-solidification systems. A second front consists of systems that use various material deposition techniques. In this paper, we will investigate some of the issues involved while using a particular photopolymer-solidification system, called *stereolithography apparatus*(SLA). Stereolithography creates plastic prototypes of arbitrary geometric complexity directly from computer models of designed parts. The planning for such processes is vastly simplified and so is the requirement for fixturing. The parts are synthesized via photopolymerization. Cured by a laser beam directed across an x-z surface, a liquid monomer mix is converted to solid plastic objects, point by point, layer by layer, true as allowed by the photopolymer in all three dimensions.

Research Objective

The objective of this thesis is to discuss the orientation problem from geometric and algorithmic points of view, and establish decision criteria for the determination of good fabrication orientations in SLA. In this research, three factors, surface quality, build time and support structure, are discussed as they relate to the problem of searching for the best orientations to fit the special requirements.

Organization of the Thesis

The content of this thesis is organized in five chapters. Chapter 1 introduces the motivation and objective of this research. Chapter 2 gives the basic components of

the SLA and a review of the related research in this area. Chapter 3 categorizes the factors that influence the orientation of a part in three classes and presents decision criteria to search best orientations based on these factors. Implementation of the proposed decision criteria is discussed in chapter 4. Finally, chapter 5 summarizes this research work and future research.

CHAPTER 2. BACKGROUND

Stereolithography Apparatus

There are two different types of stereolithography processes: point-by-point and layer-by-layer solidification. The former, which is most commonly used, employs a laser beam to scan the liquid surface and solidify a series of points. The latter which has been developed recently, solidifies a whole layer at the same time.

Point-by-Point Solidification

Equipment SLA, as depicted in Figure 2.1, is composed of a vat of photo-sensitive liquid polymer, an x-z scanning ultraviolet laser beam typically with a 0.01 inch beam diameter, a y-axis elevator in the vat, and a process control computer. The laser beam is focused on the surface of the liquid, and cures or solidifies a thin layer of the polymer along the trace of the focused light. The depth of cure is dosage dependent and is a function of the laser power and scanning speed. The process control computer is coupled with a user supplied CAD solid modeling system. The physical object to be created, as described by a boundary representation model, is first sliced into thin horizontal cross-sectional layers. For each slice, the trajectory of the laser beam on the surface of the liquid polymer is dictated by the cross-sections boundary and by the bounded region.
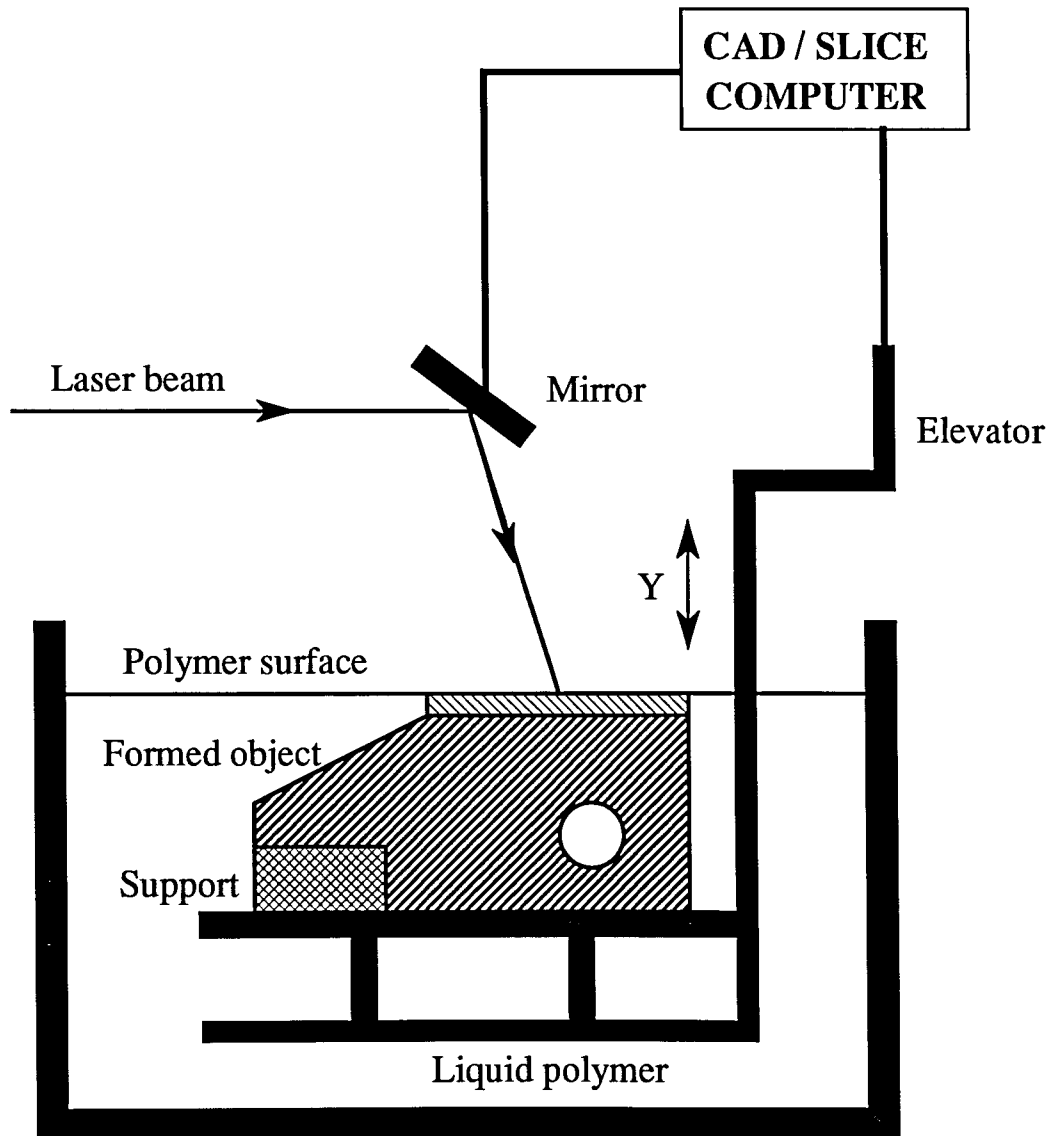
Figure 2.1: Stereolithograph apparatus (point by point)

Fabrication Process The first step is to create a 3-D solid model of a part in a CAD system. We then design a structure that will link the part to the elevator platform and provide supports during part fabrication, especially for designs with overhanging features. The CAD model and support structure are converted to a .STL file format, which consists of triangulated faces of the designed part. The .STL format of the part is then converted into .SLI format which consists of cross-sections that can range from 0.005 to 0.030 inches (0.13-0.76mm) thick. Further processing allows the data to be read by the computer controlling the movement of the laser and elevator mechanism. The galvanometer mirror x-z scanner, driven by vectors of the cross sections, controls the movement of the laser as it prints and solidifies the first cross section on the surface of the liquid polymer. The elevator containing the solid layer then lowers to enable the liquid polymer to flow over the top of the solid layer. A wiper blade passes across the liquid surface to speed leveling. Successive curings of cross sections, each adhering to the preceding layer, create the prototype part. Fabrication time depends on the thickness of the specified layer and the size of the part. Thin slices create a smooth, accurate surface but require more build time. To save time, the SLA laser does not fully cure each cross section. Rather the laser cures the boundary of a section, and then cures an internal structure or honeycomb that traps the uncured fluid. Top and bottom layers, on the other hand, are fully cured. This process is called *skin-fill*. After the part is processed in the SLA, ultrasonic cleaning removes excess material from crevices and openings. An alcohol bath then removes unused polymer. Operators also can use a method called wicking, where blotting material soaks up any excess polymer.

Post Process The part, after the process of building has been completed, requires final ultraviolet curing. First, the part is raised out of the vat and excess liquid is drained from the part. Next, the remaining excess liquid is removed with solvent, ultrasonic or wicking. Intense long-wave UV light is then applied to the part to solidify the uncured liquid trapped in the honey-comb-like part cavities (natural light curing is also possible). After about 30 minutes, the user can cut away the support structure from the part and sand-blast, hand-finish, and coat the prototype to provide an appropriate surface finish.

Layer-by-Layer Solidification

Compared to the fabrication process using point by point solidification described above, more recent SLA equipment solidifies a whole layer at once (Kruth, 1991). As depicted in Figure 2.2, a whole layer of the desired part is generated when the light passes through the mask representing a cross section of the workpiece. A new mask made from translucent photo-sensitive plastic foils is deposited for each different layer to be solidified (Fudim, 1991). Cubital and MAHO commercialize machines in which the masks are generated by charging electrostatically a glass plate with a toner, as done in photocopy machines (Pomerantz, 1990). This allows the glass plate to be reused for successive masks. Cubital's system is special in such that the whole part is embodied in wax: after lighting a layer, the unsolidified polymer is first wiped off and replaced by wax that is cooled in order to solidify in turn. The wax serves as a support structure for hangovers and isolated potions of the product. It is also claimed that it reduces product distortion. Each layer of solidified polymer and wax is first milled to the right thickness before a new layer is applied. Fudim (1991) describes two

systems that eliminate the need for creating the successive masks in a separate line (Shown in Fig. 2.3). The first one applies flat-panel liquid crystal displays similar to those used for overhead projection of a computer screen. The CAD computer directly controls the translucence of the LCD (Liquid Crystal Displays), put between the lamps and the liquid monomer. The second system applies a rectangular array of light emitting diodes put directly above the polymer vat. Those programmable masks or lighting arrays can be put in direct touch with the liquid monomer, provided they have a special anti-adhesion coating. This enables the speeding up of the formation of a new layer by squeezing the liquid between the programmable mask and the part, rather than relying on free surface flooding. Moreover, the fact that the whole cross section of a layer is illuminated and solidified on the machine eliminates the need for post-solidification of encapsulated liquid in a light oven. Other types of post-processing may however still be required: removing the support or wax, thermal annealing, or post-machining.

In this thesis, the issues of orientating the designed part to be fabricated by a point-by-point solidification process are investigated.

Literature Review

The SLA does not require experienced model makers to operate, and the machine runs unattended once the building process starts. It is relatively straight forward for the designer to program and run the SLA. Thus, the overall cycle time is considerably reduced, especially when objects are complicated or delicate. Due to these advantages, SLA has been applied in some practical fields. In the manufacturing area, Weiss et al. (1989) in Carnegie Mellon University reported a system for rapid
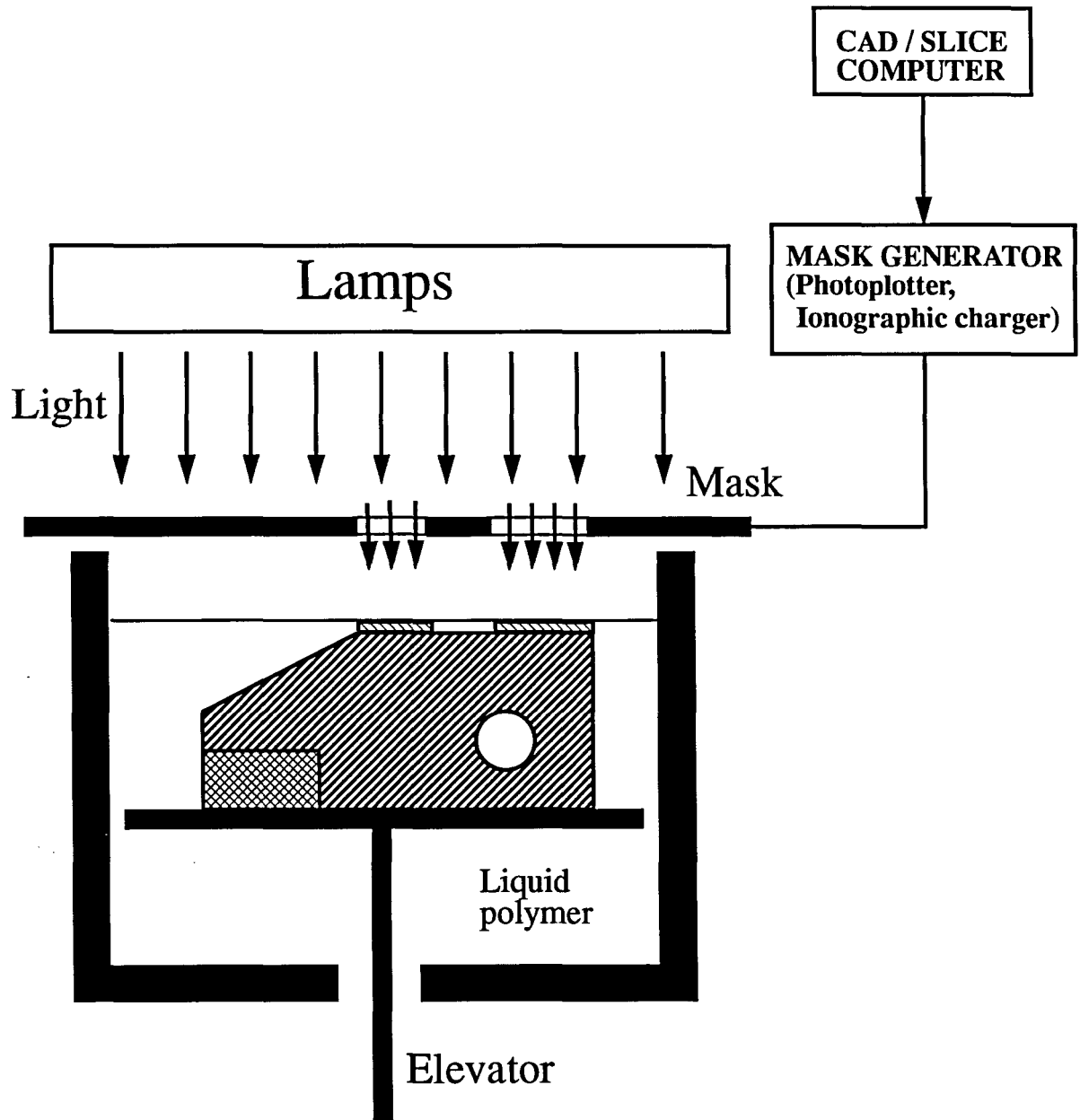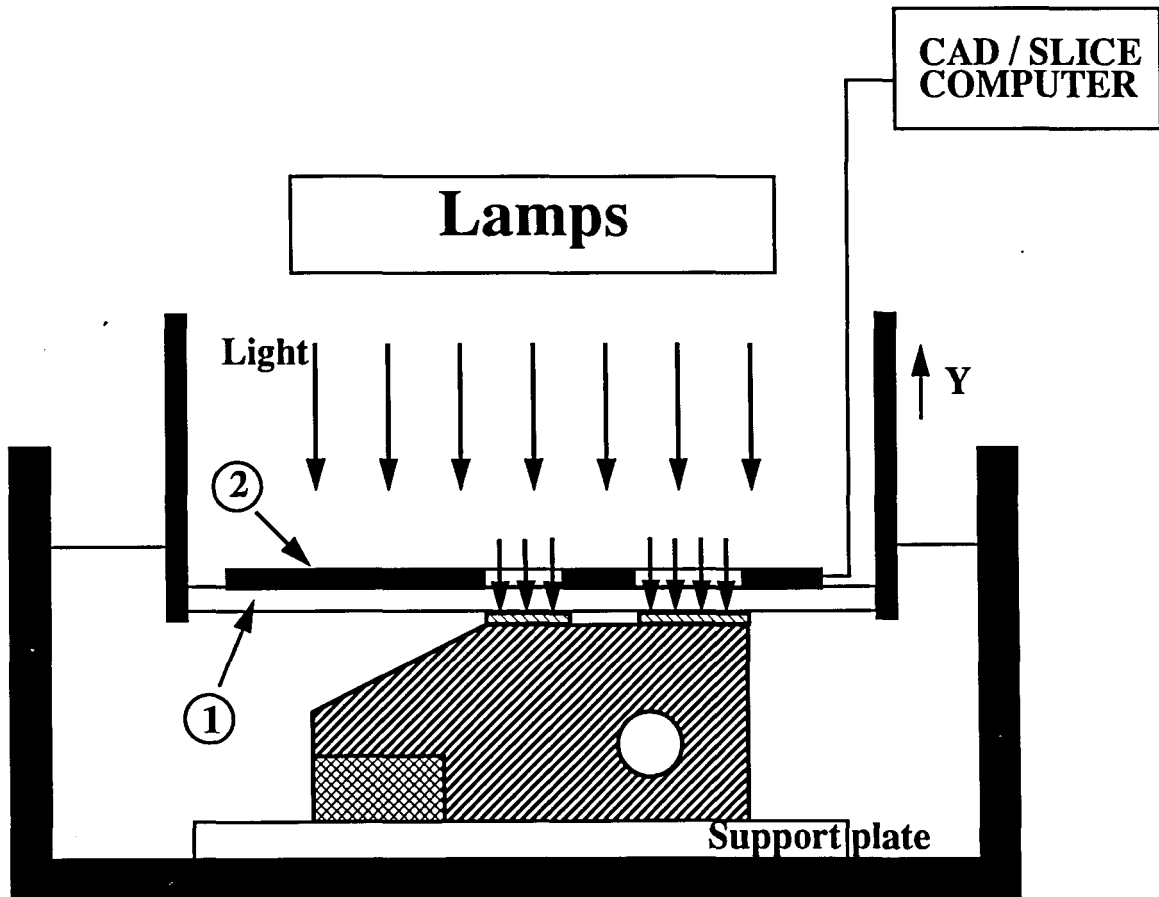
Figure 2.2: Stereolithograph apparatus (layer by layer)

① **Glass plate .**

② **LCD mask (with lamps) or LED array (without lamps) .**

Figure 2.3: Stereolithograph apparatus (layer by layer)

tool manufacturing based on the integration of stereolithography and thermal spraying. Thermal spraying is used to incrementally deposit metal onto the SLA model. A broad range of tooling can be fabricated including injection molds, forming dies and EDM electrodes. Odette (1992) described the use of castable silicone or RTV (Room Temperature Vulcanization) rubber to create molds directly from stereolithographic masters and compares the result to the prototyping methods used historically. Thomas (1992) reported that the progression of SLA technology development, from tooling aids to master tooling for flexible reinforced rubber (FRR) parts, provides a unique rapid tooling technique. In the medical field, Evenhouse and Chen (1991) suggested that the introduction of SLA technology can have a beneficial effect upon the aesthetic outcome of an ear restoration. This fact may make successful rehabilitation available to greater number of persons. Waymire (1991) reported that from combining CAT or NMRI generated data with stereolithography, it is possible to design models to fit each individual patient whose body parts need to be replaced. The combination of these processes could have a profound effect and even revolutionize the internal and external prosthetic industry. In aerospace, SLA is changing the way aerospace contractors design, test and build parts. Aerospace companies have widely accepted the technique and are using the prototypes to review designs, to check form and fit, and as templates to make flyable epoxy or aluminum components. Brown (1991) reported that the Air Force tried to model a safety modification of the B-52 pedal by SLA, and Boeing Commercial Aircraft built wind tunnel models by SLA. An interesting application area, characterizing the unlimited complexity of the parts, is given in the jewelry industry. The first applications were demonstrated by Chua (1991)

However, there is still plenty of room for improvement on SLA as well as other rapid prototyping systems. For example, Neckers (1990) traced the chemical progress of the polymer in SLA in order to improve the photopolymer properties in modeling applications, increase the overall photospeed, and reduce the shrinkage of the solidification prototype. Renault and Ogale (1991) were concerned with the issues related to the manufacturing of glass fiber reinforced composites by stereolithography using a photosensitive epoxy acrylate resin as the matrix material. The tensile strength of those samples in their research indicate a definite improvement over the resin properties with the addition of the reinforcing fibers. Karrer (1992) reported on an original approach of the formulation of photo-sensitive resins leading to solid polymers in which the shrinkage is practically completely suppressed. The basic idea used in these formulations is the incorporation of particular fillers with porous structures. Kotchetov and Neckers (1993) attempted to analyze the post-polymerization process. Results indicate that the dark polymerization is less important in highly cross-linked polymers formed from TMPTA than in less cross-linked systems.

In addition to the normal development of the problem, it seems most important to contribute to a good utilization of the available systems. The orientation in which a part is fabricated in the vat affects many aspects of the performance of SLA processes. The CAD modeler needs a great deal of practice and experience on the stereolithograph process. This results from the specifics of the features of the working steps, especially the building procedures. These problems have been studied from an algorithmic point of view. Asberg et al. (1993) demonstrated an algorithm which determines in O(n) time whether or not the object can be constructed using stereolithography. Furthermore, if the answer is in the affirmative, the algorithm

reported a description of all the positions in space in which the object can be made. However, the scope of the feasibility in that paper is too narrow. Many objects which can actually be produced in SLA are shown as infeasible in the proposed algorithm. In this research, the range of the feasibility is extended and the optimal orientation of model designs for SLA is determined based on three factors by formula or algorithm.

CHAPTER 3. DECISION CRITERIA

In this chapter, the decision criteria for determining an orientation of an object in SLA according to three factors, surface quality, building time and support structure are described. Before introducing the decision criteria, it is useful to provide the definitions of baseplane and candidate baseplane.

Baseplane A surface of the desired object which contacts the table of the elevator in SLA.

Candidate baseplane For the purpose of computer modeling, the surfaces which are common between the desired object and its convex hull are candidate baseplanes.

Surface Quality

No matter what kind of products are manufactured, it is impossible to ignore the requirement of surface quality, even for prototypes. We can imagine how an exquisite part enhances the chance of being accepted by a customer. Furthermore, a better surface quality also implies the ability to achieve better accuracy of dimensions, which in turn facilitates assembly of parts and improves functionality of the real products. We will discuss some criteria for evaluating the surface quality.

Maximizing the Total Area of Non-Stepped Surfaces

Due to the 2-1/2 dimensional layered build-up of SLA, the sloping surfaces of designed parts will inevitably be represented as a stepped surface texture. This stepped texture is one of the primary factors that detract the surface quality, and should be eliminated as much as possible.

Surfaces Parallel or Perpendicular to XZ-plane One of the possible criteria for seeking an orientation with better surface quality is to reduce the total area of sloping surfaces. In other words, we need to search for an orientation which maximizes the total area of perpendicular or horizontal surfaces. As shown in Figure 3.1, the total area of slant surfaces is changed when we use different surfaces as the baseplane. Suppose that for the ith candidate baseplane, the total area of the planes which are parallel or perpendicular to this plane is S_i. Thus, this maximization problem can be formulated as follows:

$$\max_{i \in B} S_i$$

where

$$S_i = \sum_j Q_j$$

$$Q_j = \begin{cases} A_j & \text{if } N_j \cdot N_i = 0 \text{ or } \pm 1, \\ 0 & \text{otherwise.} \end{cases}$$

In the above formulation, B is the set of indices of the surfaces which can be the candidate baseplane; S_i is the total area of the surfaces which are parallel or perpendicular to the ith candidate baseplane; A_j is the area of surface j; N_j is the
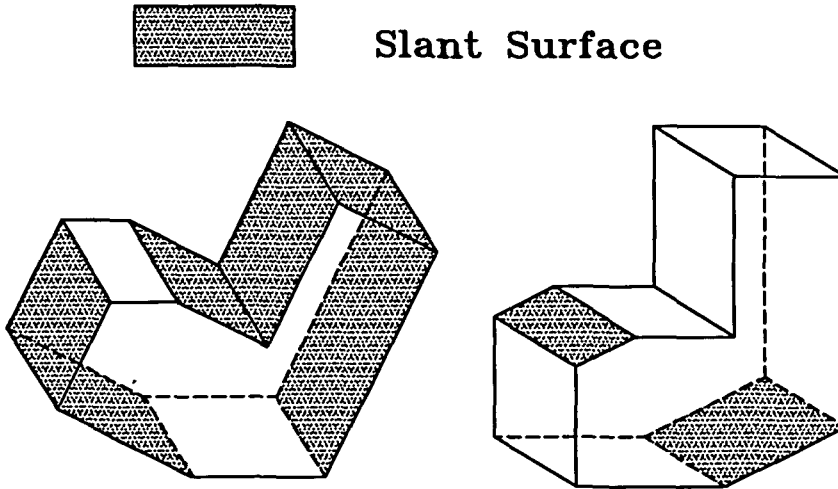
Figure 3.1: Example of the effect of orientation on the number of slant surfaces

outward-pointing normal of an arbitrary surface j; N_i is the outward-pointing normal of candidate baseplane i; and $\mid N_i \mid = \mid N_j \mid = 1$. We select the candidate baseplane i with the maximal S_i value to be the baseplane.

The following procedure describes the maximization of the total area of parallel or perpendicular surfaces of the given object. First, find all the surfaces which can be used as the baseplane. Recall that only the common surfaces between a desired object and its convex hull can be candidate baseplanes. The convex hull of a polygonal object can be computed efficiently with the algorithm developed by Day (1990). Second, choose the baseplane which yields the largest total area of surfaces with outward-pointing normals perpendicular or parallel to the outward-pointing normal of this baseplane.

Functionally or Aesthetically Important Surfaces For functional reasons, we may have to require certain surfaces to be very smooth. And for aesthetic reasons, surfaces which are responsible for the sense of the whole part should also be as smooth as possible. When considering the orientation of the part, we should avoid making these surfaces slope. Furthermore, because vertical and upward-facing horizontal surfaces are smoother than downward-facing surfaces, it is better for us to maximize the total area of functionally or aesthetically important surfaces oriented vertically or horizontally and upward-facing. Suppose that for the ith candidate baseplane, the total area of smooth or aesthetically important surfaces which are oriented vertically or horizontally and upward-facing with respect to the ith candidate baseplane is S_i. This maximization problem can be formulated as follows:

$$\max_{i \in B} S_i$$

where

$$S_i = \sum_k Q_k$$

$$Q_k = \begin{cases} A_k & \text{if } N_k \cdot N_i = 0 \text{ or } -1, \\ 0 & \text{otherwise.} \end{cases}$$

In the above formulation, B is the set of the indices of the surfaces which can be the candidate baseplane; A_k is the area of the surface k; S_i is the total area of functionally or aesthetically important surfaces oriented vertically or horizontally and upward-facing with respect to the ith candidate baseplane; N_i is the outward-pointing normal of a surface which can be the baseplane; N_k is the outward-pointing

normal of every surface which is required to be smooth; and $\mid N_i \mid = \mid N_k \mid = 1$. We select the candidate baseplane i with the maximal S_i value as the baseplane.

Minimizing the Worst Quality

The other criteria for searching a better orientation for better surface quality in SLA is to focus on the degree of the steepness of a surface. In the previous section, we specialized our desired plane to be parallel or perpendicular to the candidate baseplane. By that criteria, a baseplane can be easily decided. However, in some real cases, there may not be any planes which are parallel or perpendicular to each other, or some different candidate baseplanes may have the same amount of total area of surfaces parallel or perpendicular to them. It is necessary to establish a rule to help us to select a baseplane by cataloging those "non-parallel" or "non-perpendicular" planes which are ignored by the previous section.

The degree of the surface steepness characterized by the smaller angle between a surface and a baseplane can be referred to as an index of slope. We prefer slopes with larger absolute values. The reason for such a preference can be illustrated with the examples shown in Figure 3.2. In Figure 3.2(a), the sloping surfaces are steeper. Since the thickness between two layers is a constant, it is easy to see that the difference between the actual surface and the required surface of the two adjacent layers is smaller than the example in Figure 3.2(b). This means the actual surface in Figure 3.2(a) is a better approximation of the desired surface.

Here, we would like to introduce a new concept, "quality-decided value" of an angle. First, let's define the angle between two arbitrary vectors a and b, denoted by α, as the angle between two vectors when taken from a common initial point. The
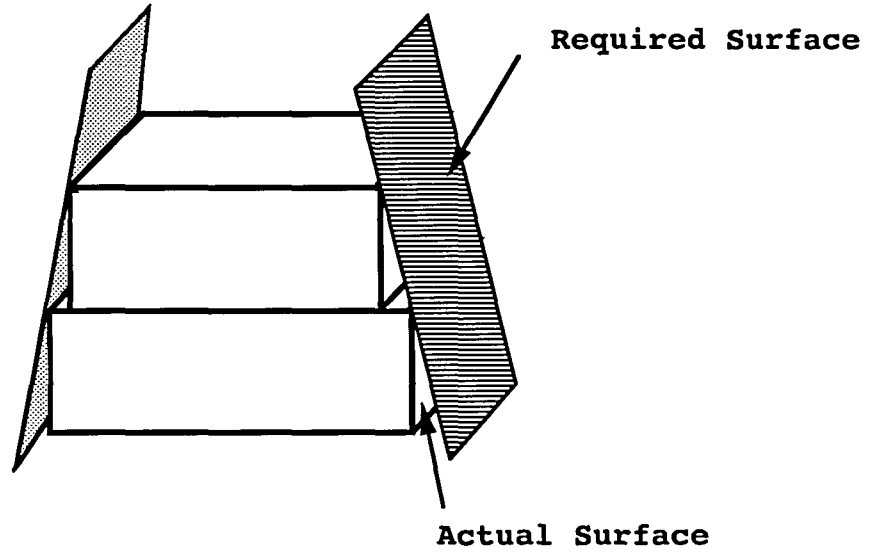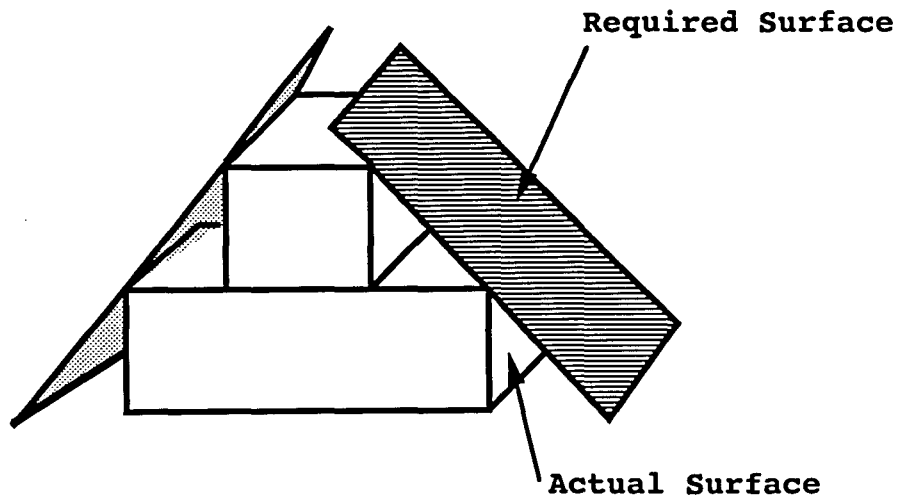
Figure 3.2(a)

Figure 3.2(b)

Figure 3.2: Steeper desired surfaces possess a better approximation to the actual surfaces

angle α is restricted to the interval $0 \leq \alpha \leq \pi$. This definition is depicted in Figure 3.3. In Figure 3.4, B, S_1 and S_2 are three surfaces in an object. B is parallel to the bisection plane of S_1 and S_2. If we select B to be the baseplane, the quality, after SLA procedure, of surface S_1 and S_2 will be identical, although the angle between the outward-pointing normals of S_1 and B is not equal to the angle between the outward-pointing normals of S_2 and B. Provided that we subtract these two angles from $\pi/2$ respectively and take the absolute values of the results, we will find the two absolute values are equal to each other. These absolute values are referred to as the quality-decided values of angles. This concept can help us to sense how poor the surface quality is. Since a large quality-decided value corresponds to a lightly slanted surface, the larger the quality-decided value, the worse the surface quality. However, when the angles between the out-pointing normals of any surfaces and the baseplane are equal to 0 or 180, it means the surfaces are parallel to the baseplane. In these situations, although the quality-decided values, which are 90, are the largest ones of quality-decided values, the surface quality is still as good as that of vertical surfaces whose quality-decided values are 0. For calculation purposes, we define the quality-decided values under these conditions to be 0.

We assume that there exists a critical value, an index of the critical surface, of the quality-decided value of an angle. When the quality-decided value of the angle between the outward-pointing normals of a surface and its associated baseplane is larger than this critical value, then the quality of this surface is below acceptable quality. Then, this surface is an unacceptable surface. Otherwise, it is an acceptable surface. These three types of surfaces, acceptable surface, critical surface and unacceptable surface are shown in Figure 3.5. We can minimize the worst quality by
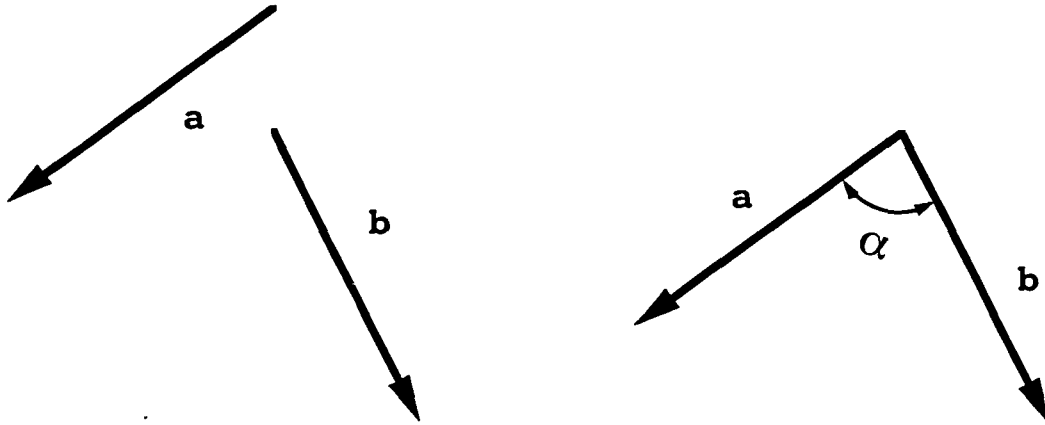
Figure 3.3:   The definition of the angle between two arbitrary vectors
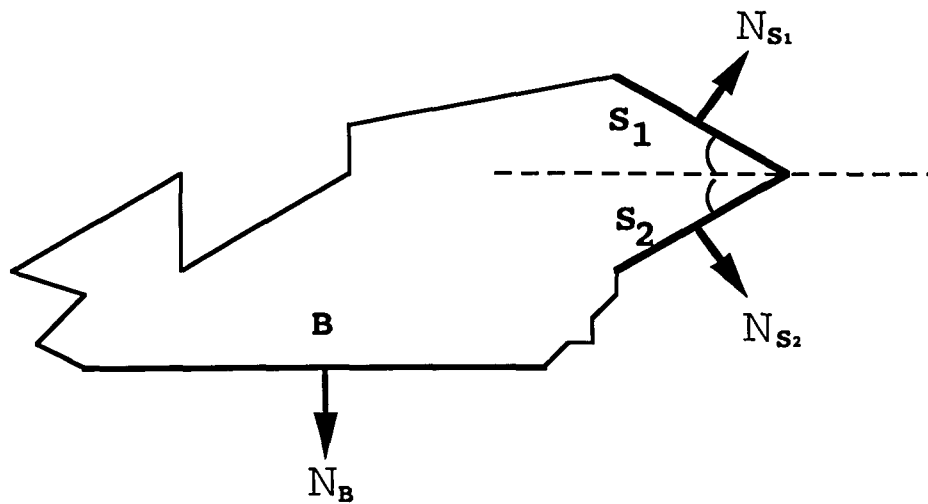
Figure 3.4:   Surfaces with different outward-pointing normals have the same quality
with respect to a special baseplane
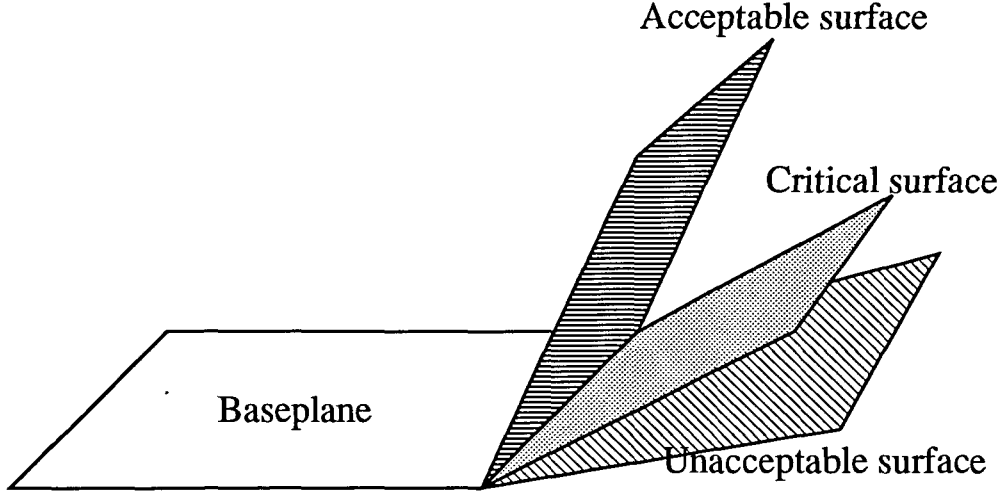
Figure 3.5: The acceptable surface, critical surface and unacceptable surface

minimizing the total area of the unacceptable surfaces. This minimization problem can be formulated as follows:

$$\min_{i \in B} \mathcal{S}_i$$

where

$$\mathcal{S}_i = \sum_j \mathcal{Q}_{ij},$$

$$\mathcal{Q}_{ij} = \begin{cases} A_j & \text{if } \Gamma_{ij} > R, \\ 0 & \text{otherwise.} \end{cases}$$

$$\Gamma_{ij} = \begin{cases} 0 & \text{if } \Delta_{ij} = 0 \text{ or } \Delta_{ij} = 180, \\ \mid \Delta_{ij} - \left(\frac{\pi}{2}\right) \mid & \text{otherwise.} \end{cases}$$

$$\Delta_{ij} = cos^{-1}(N_j \cdot N_i)$$

In the above formulation, B is the set of the indices of the surfaces which can be the candidate baseplane; S_i is the total area of surfaces whose quality-decided values of the angles between the outward-pointing normals of surfaces and candidate baseplane i are larger than the critical value; Q_{ij} is the area of surface j whose quality-decided value of the angle between the outward-pointing normals of surface j and candidate baseplane i is larger than the critical value; A_j is the area of surface j; Γ_{ij} is the quality-decided value of the angle between the outward-pointing normals of surface j and candidate baseplane i; Δ_{ij} is the angle between the outward-pointing normals of surfaces j and candidate baseplane i; N_j is the outward-pointing normal of an arbitrary surface j; N_i is the outward-pointing normal of the surface which can be a candidate baseplane; R is the critical value decided by the designer or customer; and $\mid N_i \mid = \mid N_j \mid = 1$. We select the candidate baseplane i with the minimal S_i value to be the baseplane.

An additional decision criteria is now proposed to solve the problem, when the same minimal value S_i is derived for different candidate baseplanes. It combines two influential factors, the area of unacceptable surfaces and the quality-decided values of angles between the outward-pointing normals of unacceptable surfaces and their associated candidate baseplanes. The following procedures are the detailed description of this decision criteria. First, identify all of the candidate baseplanes which have the same minimal S_i derived by the formula in the previous section. Second, compute the quality-decided value of the angle between the outward-pointing

normals of each unacceptable surface and it's associated candidate baseplanes. Third, select the candidate baseplane which has a minimal sum value of the products of the area of unacceptable surfaces and the quality-decided values of the angle between the outward-pointing normals of the unacceptable surfaces and this candidate baseplane, to be the actual baseplane in SLA. This minimization problem can be formulated as follows:

$$\min_{i \in B_s} T_i$$

where

$$T_i = \sum_j A_j \cdot \Gamma_{ij}$$

$$\Gamma_{ij} = \begin{cases} 0 & \text{if } \Delta_{ij} = 0 \text{ or } \Delta_{ij} = 180, \\ \mid \Delta_{ij} - \left(\frac{\pi}{2}\right) \mid & \text{otherwise.} \end{cases}$$

$$\Delta_{ij} = cos^{-1}(N_j \cdot N_i)$$

In the above formulation, B_s is the set of the indices of the candidate baseplanes which have the same minimal S_i value; T_i is the sum of the products of area of unacceptable surfaces j and the quality-decided value of the angles between the outward-pointing normals of unacceptable surfaces j and the candidate baseplane i; A_j is the area of surface j; Γ_{ij} is the quality-decided value of the angle between the outward-pointing normals of surface j and candidate baseplane i; Δ_{ij} is the angle between the outward-pointing normals of surfaces j and candidate baseplane i; N_j is the outward-pointing

normal of an unacceptable surface j; N_i is the outward-pointing normal of the surface which can be a candidate baseplane in set B_s; and $\mid N_i \mid = \mid N_j \mid = 1$. We select the candidate baseplane i with the minimal T_i value to be the baseplane.

Build Time

The build time of an SLA includes the active creation of a designed part, post-processing, and the removal of supports. In this section, we will consider only the time for creating a designed part.

The process of *'dip-delay'* is an important factor for determining the time to generate a design. To wet the newly solidified layer with fresh liquid in preparation for making the next layer, the elevator is lowered sufficiently below the liquid surface, allowing the liquid to flow over formed layers. Since the polymers are fairly viscous, some slack time is required to permit the liquid surface of the vat to become flat.

Since dip-delay time between layers can be quite long, we hope to reduce the number of layers in order to shorten the build time. In this section, an algorithm developed by Houle and Toussaint (1988) is applied to achieve this objective. Before introducing the decision criteria, it is useful to provide the definitions of some terminology in this section.

Supporting plane A supporting plane of a convex polyhedron P is a plane S passing through the exterior of P such that the interior of P lies entirely on one side of S.

Width Given a set of points $P = \{p_1, p_2, \cdots, p_n\}$ in three dimensions, the width of P, $w(p)$, is defined as the minimum distance between parallel supporting planes of P.

Diameter of a convex polyhedron Given a set of points $P = \{p_1, p_2, \cdots, p_n\}$ in

three dimensions, the diameter of P, $d(p)$, is defined as the greatest distance between parallel supporting planes of P.

Minimizing the Height of the Part

The height of the part is the index of the number of layers required in the SLA process. Since the thickness of each layer in SLA is usually a constant, a higher part implies more layers in this part. For example, a long, narrow cylinder possesses fewer layers if it is built on its side. Re-orienting the cylinder with its major axis in the y direction will greatly increase the number of layers (Shown in Figure 3.6). We expect to find an orientation with the minimal height. This means that we have to derive the width of the part. The three-dimensional width problem has received some attention from the computational point of view. In the actual computational process, the vertices of the part are represented by a set of points P. The notion of width is closely related to that of diameter. Before we examine the three-dimensional problem, let's review the two-dimensional problem. Algorithms for solving the two-dimensional width-problem have been proposed by Kurozumi and Davis (1982). They provide two algorithms to compute the width of a convex polygon with n vertices. One algorithm runs in $O(n^2)$ time in the worst case and the other incorporates binary search to reduce the complexity to $O(n \log n)$. Houle and Toussaint also suggested two algorithms to find the width of a convex polygon. One is based on Shamo's "rotating calipers" method for computing the diameter (1978), and the other on Brown's method using geometric transforms (1979). Both of these algorithms run in $O(n)$ time and $O(n)$ space.

Furthermore, a modification of Brown's algorithm for finding the diameter of a
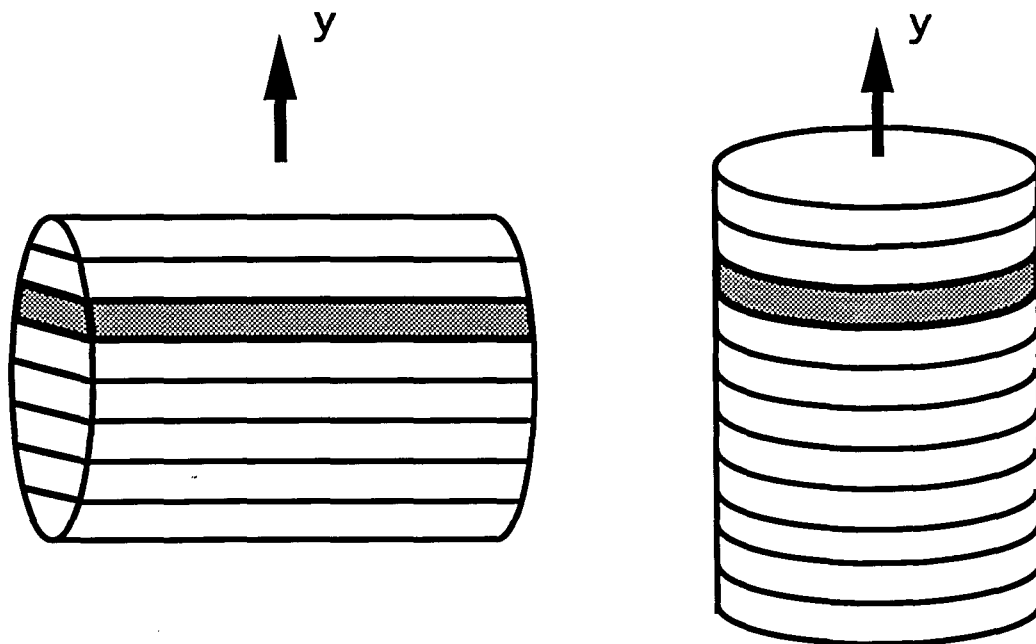
Figure 3.6: A long and narrow cylinder in two different orientations

convex polyhedron in three dimensions was proposed by Houle and Toussaint. It can compute the three-dimensional width in $O(n + I)$ time, where I is the number of pairs of edges of the polyhedron that admit parallel planes of support. In the worst case, I can be $\Omega(n^2)$, but typically, it is only $O(n)$. In that report, they define that two edges of the convex hull of a set of points P in three dimensions as being an *antipodal edge-edge* (E-E) *pair* if parallel planes of support of P contain these edges. Similarly, they define vertex-vertex (V-V), vertex-edge(V-E), vertex-face(V-F), edge-face(E-F), and face-face(F-F) pairs. The following theorem is developed by Houle and Toussaint:

Theorem 3.1: The width of a set of points of P in three dimensions is the minimum distance between parallel planes of support passing through either an antipodal vertex-face pair or an antipodal edge-edge pair of the convex hull of P.
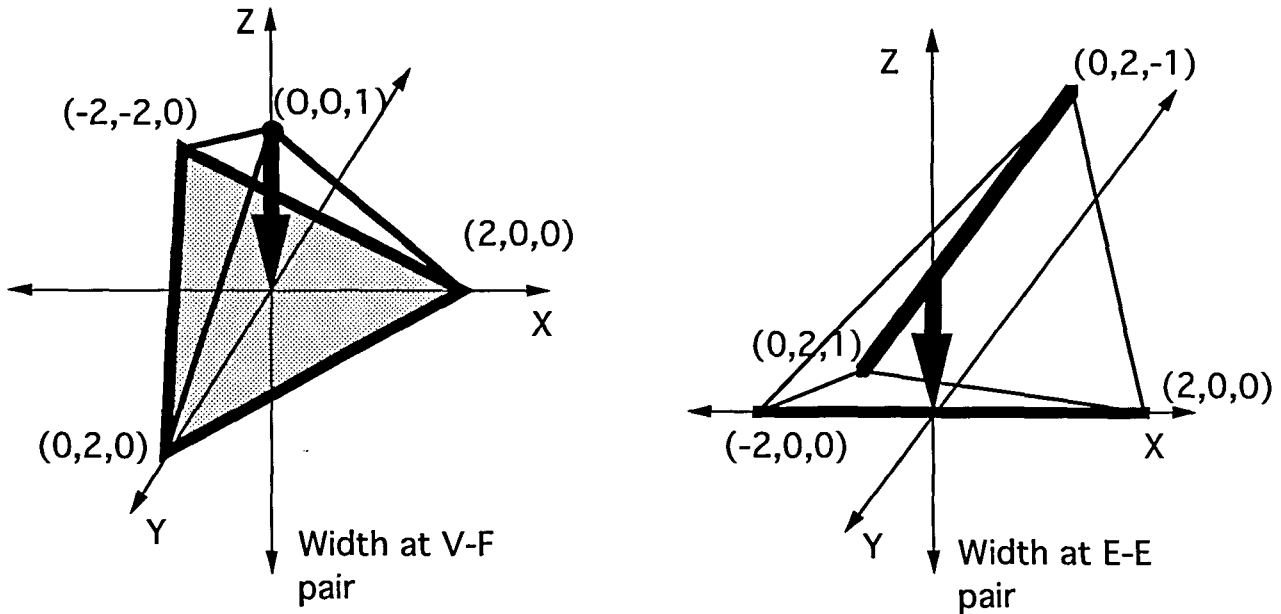
Figure 3.7: Example of polyhedra where the minimum distance between parallel planes of support occurs at a vertex-face pair and an edge-edge pair.

The tetrahedra in Figure 3.7 are examples of polyhedra where the minimum distance between parallel planes of support occurs at a vertex-face and an edge-edge pair, thus establishing both possibilities. In our case, the former one, minimum distance between parallel planes of support passing through an antipodal vertex-face pair, is applicable. The reason is that we need a surface item to be the baseplane in order to create the prototype. The following procedures are the algorithm, a modification of the algorithm proposed by Houle and Toussaint, to search for surfaces to be the baseplane in SLA.

1. Construct the convex hull in $O(n \log n)$ time by using Preparata and Hong's algorithm (1977).

2. Transform the polyhedron into two planar subdivisions in $O(n)$ time as de-

scribed in Brown's paper (1979).

3. Compute the overlay of the two planar subdivisions using Guibas and Seidel's algorithm (1986) in $O(n + I)$ time.

4. Examine all vertices of the overlay to generate vertex-face pairs in $O(I)$ time, and report the faces in the vertex-face pairs whose antipodal pair distances are the smallest.

After setting the surfaces derived by this algorithm, the orientations with a minimal height of the model object fabricated in SLA are determined.

Support Structure

An inherent limitation of the stereolithography process is that part overhangs and undercuts must be accommodated by building a support structure. Supports should be located as needed to provide a rigid foundation on which the object can be built. Supports should also be added to anchor or strengthen other surfaces. Part design must incorporate support structures, such as tresses, buttresses, and piers, to support cross-sections during construction and to support the entire structure until it is fully cured. For example, in Figure 3.8, when the first layer of the ledge is drawn, it is thin and fragile and may break off or warp without additional support. Also, in the figure, when the first layer of the overhang is drawn, it is not connected to the rest of the part body and would float away without the additional pier support. We should consider the supports as parts of the whole desired object when we are going to generate the layered process in SLA. The CAD files for object and supports are merged and drawn as a single file in the stereolithographic process.
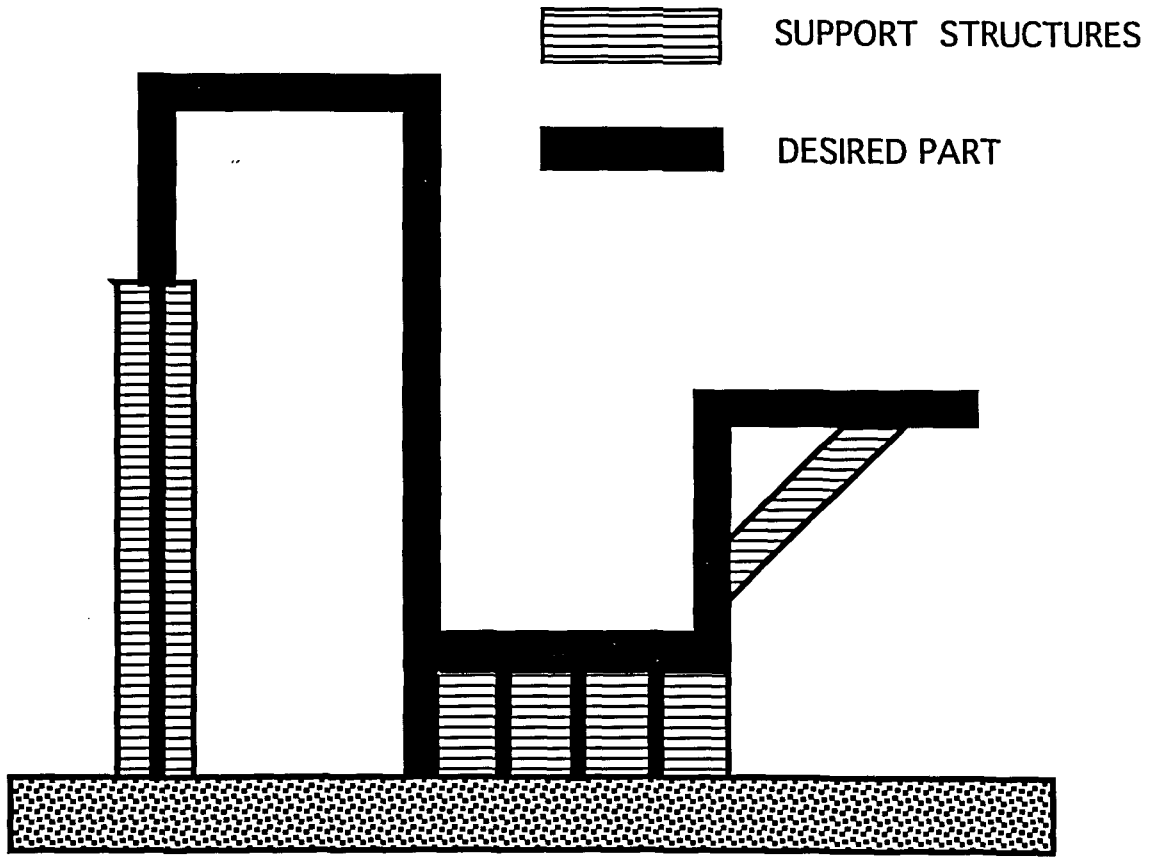
Figure 3.8: Support structure

Notation and Preliminaries

The support structures are broken off and sanded down after the model is fully cured. It is desirable to use minimal support structure to minimize the amount of manual postprocessing required, as well as minimize the time required to draw the structure. The most appropriate consideration to determine whether an orientation has a good support structure is the number of supports. We hope to reduce the number of supports as much as possible. In other words, the criteria developed in this section is to search for an orientation which yields a minimal number of supports. Let us first introduce some assumptions and the terminology we will be using in this section.

- Let A be a polyhedron with n vertices.

- Let f be a face with m extreme points of A.

- Let $f(1)$, $f(2)$, $\cdots$,$f(k_f)$ be the faces of A that share at least one edge with f.

- Let N_f be the outward-pointing normal of f.

- Let $k_1(f)$, $k_2(f)$, $\cdots$,$k_m(f)$ be the extreme points of f and $k_{1(y)}$, $k_{2(y)}$, $\cdots$,$k_{m(y)}$ be the y-coordinate of these extreme points.

- Let $e_1(f)$, $e_2(f)$, $\cdots$,$e_m(f)$ be the edges of surface f.

- Let $\theta_i(f)$ be the angle interior to A between the plane P containing f and the plane $P(i)$ containing $f(i)$ about the line of intersection of P and $P(i)$.

Direction of formation In SLA, the direction given by a normal to the table pointing to the laser is called the direction of formation for the object.

List of support points A list of points to which supports should be added.

Lowest point of f $k_i(f)$ is an extreme point of f and $k_{i(y)}(f)$ is the y-coordinate of $k_i(f)$. If $k_{l(y)}(f) = \min_{1 \leq i \leq m} \{k_{i(y)}(f)\}$, then $k_l(f)$ is a lowest point as f. (Shown in Figure 3.9).

Lowest edge of f $e_i(f)$ is an edge of f. If any end point of $e_i(f)$ is a lowest point of f, then $e_i(f)$ is called the lowest edge and denoted as $e_l(f)$. (Shown in Figure 3.9).

Supportless edge If f and $f(i)$ are both in the upper half space with respect to the horizontal plane h in contact with the lowest end point of $e_l(f)$, $\theta_i(f)$ is less than π, and no other edges of f or $f(i)$ are on the horizontal plane h, then $e_l(f)$ is a supportless edge which is denoted as $e_s(f)$. A support under this edge is required (Shown in Figure 3.10).

Local lowest point If a point k_{ll} is the lowest point of each edge connected at k_{ll}, then k_{ll} is called a local lowest point. (Shown in Figure 3.10).

Supported plane and supportlike plane If $k_{l(y)}(f)$ is larger than $k_{l(y)}(f(i))$, or $k_{l(y)}(f)$ is equal to $k_{l(y)}(f(i))$ and $f(i)$ is a horizontal plane, then f is called a supported plane and $f(i)$ is called a supportlike plane. (Shown in Figure 3.11).

Supportlike edge The edge shared by supported and supportlike planes is called the supportlike edge and denoted as $e_j(f)$. (Shown in Figure 3.11).

Supportless plane If $k_{l(y)}(f)$ is less than $k_{l(y)}(f(i))$, or $k_{l(y)}(f)$ is equal to $k_{l(y)}(f(i))$ and $f(i)$ is not a horizontal plane, then f is called a supportless plane. (Shown in Figure 3.12).

Critical angle An angle, denoted as C, providing an index of the surface for which supports may be needed. If the angle between the outward-pointing normals of a surface and the baseplane is less than or equal to the critical angle, then supports
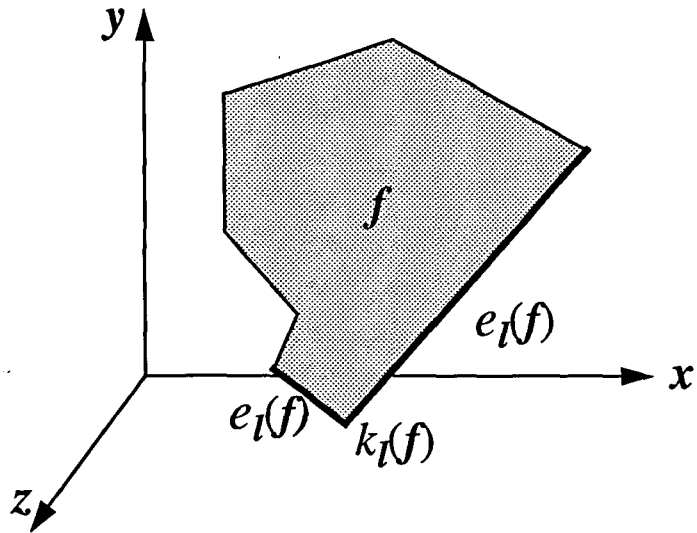
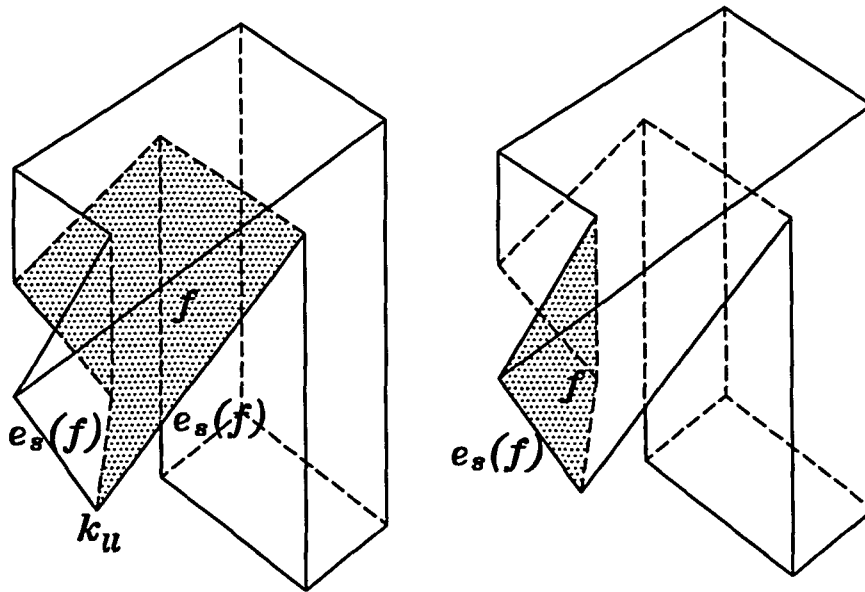Figure 3.9: The lowest point and lowest edges of f

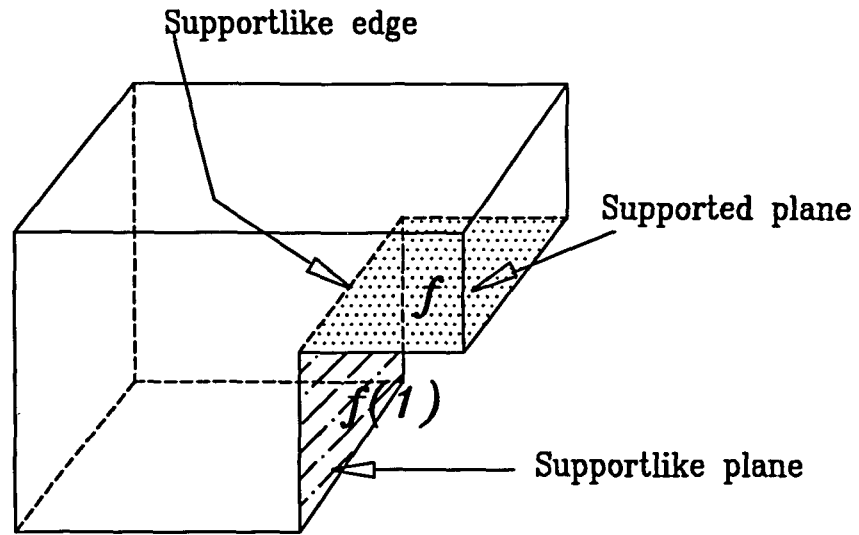Figure 3.10: The supportless edges and local lowest point

Figure 3.11:   The supported plane, supportlike plane and supportlike edge
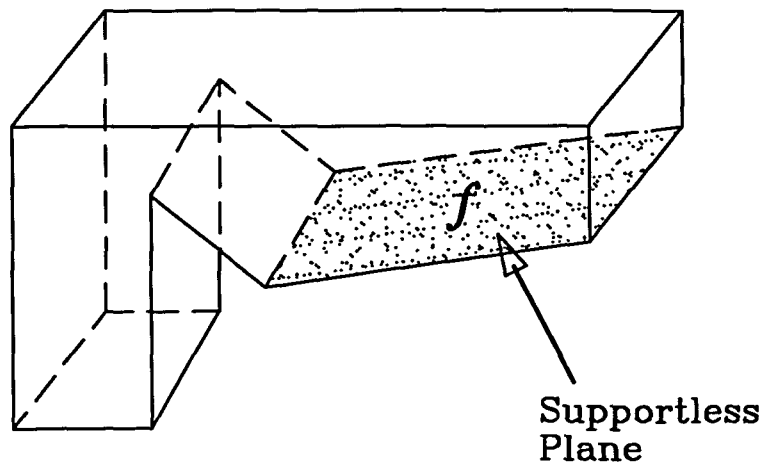
Figure 3.12:   The supportless plane

may be needed for the surface. Otherwise, do not bother to consider this surface for adding supports. The critical angle is decided by the designer and the character of the liquid polymer in SLA.

Supportneed plane Let N_b be the outward-pointing normal of the baseplane and C be a critical angle. If $0 \leq \mid \Delta_{fb} \mid \leq C$, where $\Delta_{fb} = cos^{-1}(N_f \cdot N_b)$, then f is called an supportneed face and denoted as R.

Algorithm for Minimizing the Number of Supports

The parameters used in this section are defined as follow:

$k_l(R)$: The lowest point on supportneed plane R.

$k_i(R)$: An extreme point on supportneed plane R.

$k_s(R)$: An extreme point on supportneed plane R where support has been added.

$e_j(R)$: A supportlike edge on supportneed plane R.

$e_s(R)$: A supportless edge on supportneed plane R.

h : A horizontal plane which contacts $k_l(R)$.

$k_i(h)$: A point resulting from projecting $k_i(R)$ on h.

$k_s(h)$: A point resulting from projecting $k_s(R)$ on h.

$e_j(h)$: An edge resulting from projecting $e_j(R)$ on h.

D : A critical distance determined by the designer.

D_{is} : The distance between $k_i(h)$ and $k_s(h)$.

D_{ij} : The distance between $k_i(h)$ and $e_j(h)$, if the projection of $k_i(h)$ on $e_j(h)$ actually lies on $e_j(h)$.

If a specified extreme point possesses the characteristics described as follows, it may be necessary to add a support to this point :

1. A point which is an end point of supportless edges $e_s(f)$.

2. A point isolated by other extreme points and supportlike edges on the same plane. This means the projecting distances between this specified point and the other extreme points and supportlike edges are larger than D.

3. A point which is the geometric center point of a suspension plane. This always occurs when a plane is a supportless plane and parallel to the baseplane.

Our objective is to search for an orientation with a minimal number of such points. For each candidate baseplane, the number of support points can be determined using the following steps. First, orient the object so that the candidate baseplane is in contact with the $y = 0$ plane. Second, find the supportless edges $e_s(f)$ and add supports to appropriate points. Then, record these points as support points. Third, find the supportneed planes R and classify these planes to be supported planes or supportless planes. If R is a supported plane and some isolated points are on this plane, record these isolated points as support points. If R is a supportless plane and parallel to the candidate baseplane, let the geometric center of this plane to be the support points. Then, follow the procedures dealing with the supported plane. If R is a supportless plane and not parallel to the candidate baseplane, some support points should have been derived from the first step, follow the procedures dealing

with the supported plane. After every candidate baseplane has been tested, select the candidate baseplane with minimal support points as the baseplane. According to these basic concepts, the following procedures are the algorithm for minimizing the number of supports. The flow chart for this algorithm is shown in Figure 3.13.

1. Find all the surfaces B, a subset of f of polyhedron P, which could be candidate baseplanes.

2. Orient the object so that a candidate baseplane contacts the $y=0$ plane and the direction of formation being discussed is the positive y-direction.

3. Let $t=0$. Test all planes f to search for supportless edges $e_s(f)$.

   (a) If the length of $e_s(f)$ is larger than D, put the end points of $e_s(f)$, which also are local lowest points and have not been recorded in the list of support points, into the list of support points. Increase t by the number of points recorded. If there were no such end points, then do not increase t. Furthermore, if $e_s(f)$ is parallel to the candidate baseplane, other $e_s(f)$ which connect to the two ends of this parallel $e_s(f)$ can be deleted to increase the efficiency.

   (b) If the length of $e_s(f)$ is smaller than D, put one of the end points of $e_s(f)$, which also are local lowest point and has not been recorded in the list of support points, into the list of support points. Increase t by 1. If there were no such end points, then do not increase t. If $e_s(f)$ is parallel to the candidate baseplane, other $e_s(f)$ which connect to the two ends of this parallel $e_s(f)$ should be deleted.

4. Find all supportneed planes R, a subset of f, and test them. If R is a supported plane, go to 5. If R is a supportless plane, go to 6.

5. If R is a supported plane, then

   (a) Project R to the horizontal plane h which is in contact with the lowest point $k_l(R)$ of plane R. The projections of $k_i(R)$, $e_j(R)$, and $k_s(R)$ are $k_i(h)$, $e_j(h)$, and $k_s(h)$ respectively.

   (b) Record all $k_i(h)$, $e_j(h)$, and $k_s(h)$.

   (c) Calculate D_{ij} and D_{is}. For a specified point $k_i(h)$, if D_{ij} and D_{is} are larger than D and $k_i(R)$ has not been recored in the list of support points, then put the $k_i(R)$ into the list. Let $k_i(h)$ become $k_s(h)$. Increase t by 1 and go to 5(b).

6. If R is a supportless plane, then

   (a) If R is parallel to the baseplane, then put point $k_c(R)$ which is the center of geometry of R into the list of support points. Let $k_c(R)$ become $k_s(R)$. Increase t by 1, then go to 5.

   (b) If R is not parallel to the baseplane, one or more supportless edges $e_s(R)$ exist. According to 3, some end points have been put into the list of support points. Let these points become $k_s(R)$, then go to 5.

7. If any candidate baseplane B hasn't been arranged to contact the $y = 0$ plane, go to 2.

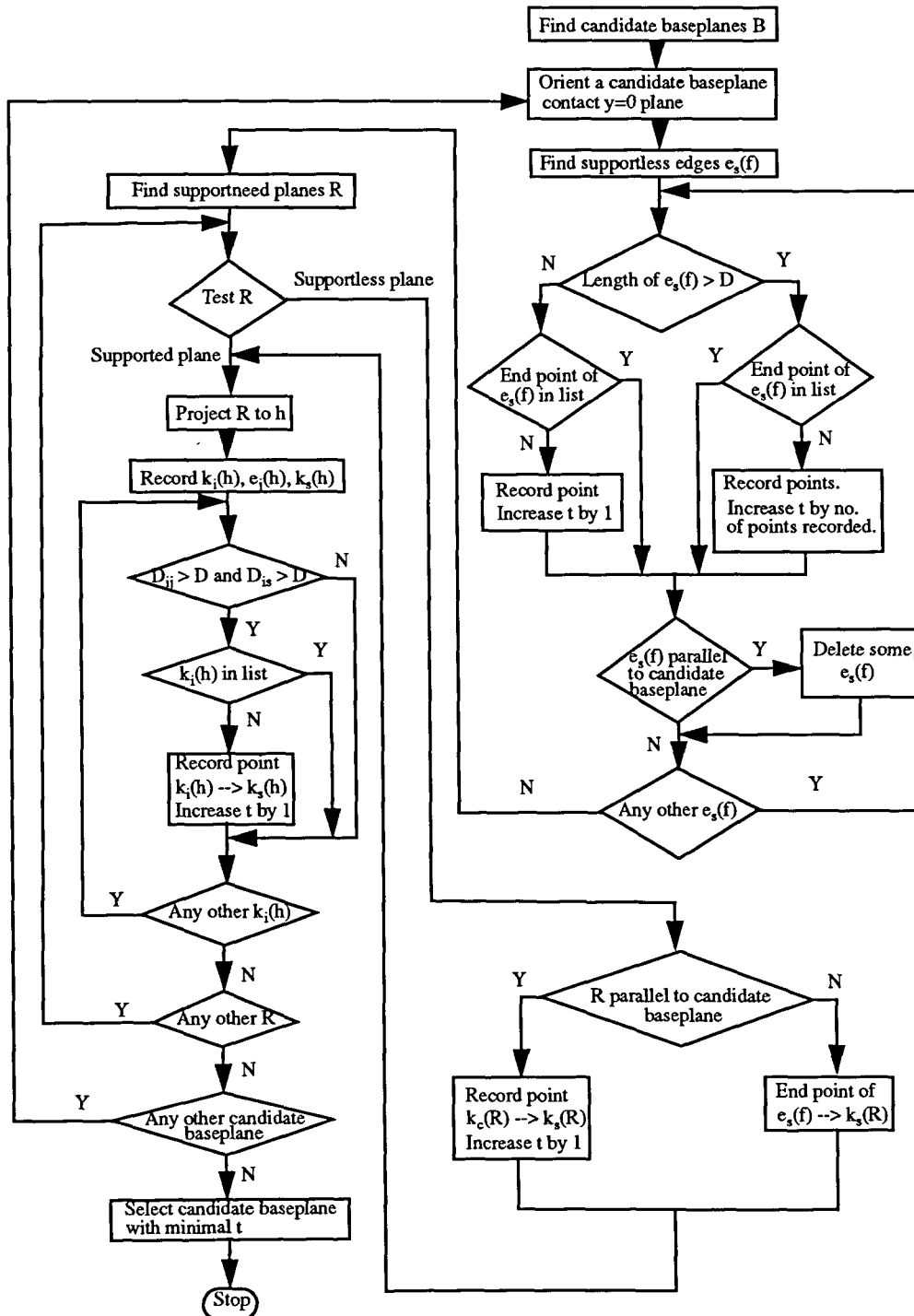8. Select the candidate baseplane B with the minimal t value as the baseplane.

Figure 3.13: The flow chart of the algorithm for minimizing the number of supports

Part without supports   Part with supports
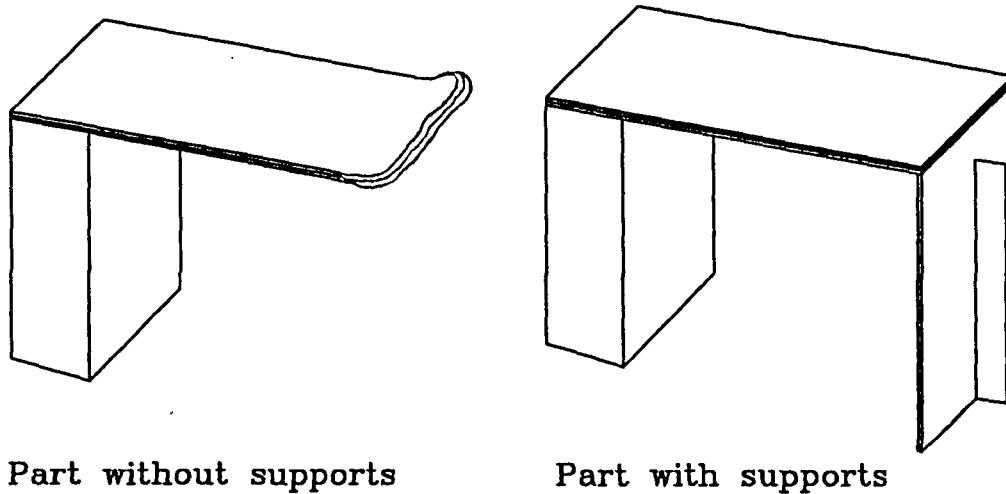
Figure 3.14:   The influence of supports

In real SLA procedures, the supports always serve the purpose of preventing the first layer of an overhang from floating away or the first layer of a ledge from warping. For example, in Figure 3.14, the first layer of the cantilevered beam may be permanently deformed by static resistance of the liquid when the part is dipped. In addition, the layer could curl upward when the next layer is formed. Both of these problems are solved by adding supports. The interesting point is that the support is added under the end edge of the cantilevered beam, rather than the whole downward-facing surface of the beam. Moreover, in Figure 3.15, different ways for supporting a cantilevered beam are depicted. The designer may use a support at right angles for more stability or a diagonal support for saving material. These are the reasons for not using the area or volume of supports to be the decisive factor for determining an orientation
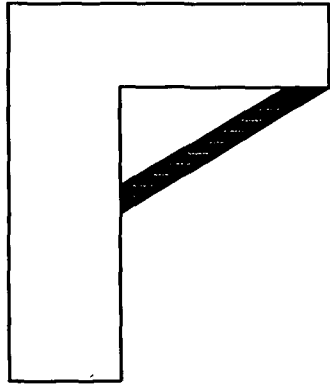
A cantilevered beam
with diagonal support
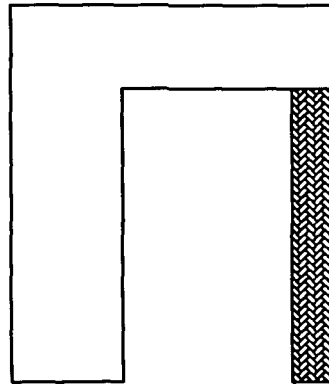
A cantilevered beam
with right angle support

Figure 3.15:   Different types of supports

with minimal supports. Instead, we use the number of supports to be the decisive factor because it can reflect the relative quantity of supports needed by an object in different orientations more accurately.

CHAPTER 4. IMPLEMENTATION

In this chapter, the implementation of the decision criteria developed in first section of chapter 3 (surface quality) is discussed. The proposed methodology has been coded in the C programming language under the UNIX environment and the geometric rapid prototyping model was created by using I-DEAS (SDRC, 1990) on a DEC 5000/200 workstation.

The Implementation of I-DEAS

Before the implementation is discussed, a further introduction to I-DEAS is needed. I-DEAS (Integrated Design Engineering Analysis Software) is an Integrated package of mechanical engineering software tools. The purpose of this software is to facilitate a concurrent engineering approach to mechanical engineering product design and analysis. I-DEAS is composed of a number of "Families" of software modules, each subdivided further into "Tasks," all executed from a common menu and sharing a common database. The main families are: Solid Modeling, Drafting, Numerical Control, Finite Element Modeling & Analysis, Frame Analysis System Dynamics Analysis, Plastics Analysis and Test. Since the solid model is the starting point of a part in a design project, the solid modeling family is the foundation of I-DEAS. It is a flexible modeling system that has been used to model geometry for many

applications. In this research, two tasks, Object Modeling and Rapid Prototyping of solid modeling are used. A brief description of applying I-DEAS for obtaining the program inputs is as follows:

1. Create a desired model in the Object Modeling task and output the universal file.

2. Label the surfaces on the object and find labels of the surfaces which are candidate baseplanes and the surfaces which need to be identified as aesthetic planes.

3. Switch to Rapid Prototyping task and output the stereolithography file.

The Inputs to the Program

The inputs to the program are:

1. The universal file of the solid model that contains the geometric information describing the product design.

2. The stereolithography file of rapid prototyping model in the STL format specified by 3D Systems, Inc.

3. The baseplane file and aesthetic plane file constructed by users.

These three inputs will be described in the following sections.
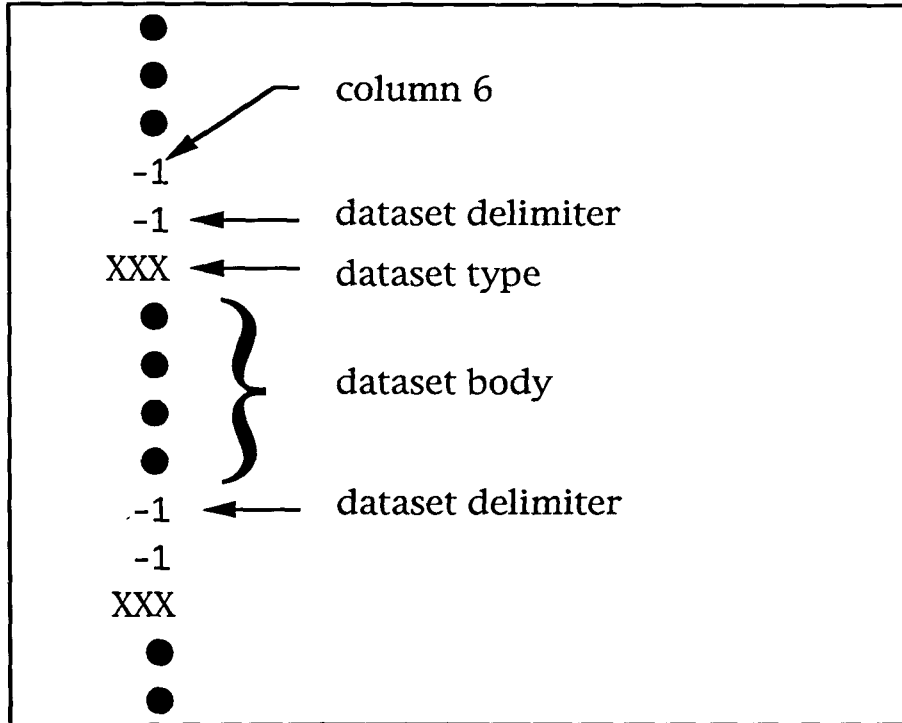
Figure 4.1: Basic structure of a universal file

Universal File

Universal files are designed so that they may be easily read and written using user-written programs. Each universal file is a sequential formatted file with records which have a maximum of 80 characters. The file is compatible with the text editor on the system. The basic structure of a universal file is shown in Figure 4.1. The universal file is divided into sections called datasets. The first record of each dataset is a dataset delimiter. This is a line containing a minus sign in column 5 and a 1 in column 6. The remainder of the line is blank. The second record of the dataset contains the data type. This is a number in the range 1 through 32767 right justified in columns 1 through 6. Following the data type record, the body of the dataset contains data which is dependent on the dataset type. The final record of the dataset

contains a delimiter line containing a minus sign in column 5 and a 1 in column 6 with the remainder of the line blank. Processing of the universal file begins by searching for the first delimiter line. Next, the dataset type line is processed to determine whether or not the program reading the file should process this dataset. The most useful dataset type in our implementation program is 544. The name of this dataset type is Node/Leaf-Faceted B-REP. It means the object is stored by Boundary Representation(BREP) in this dataset. Figure 4.2 shows a portion of a type 544 dataset. Each record extracts the first set from the real universal file of the object we use as an example model which is discussed in appendix A. When the program identifies this desired dataset type, it begins to retrieve the required material from the remainder of the dataset. For example, the information necessary from the dataset and their exact meaning in Figure 4.2 are :

- Record 1: FORMAT(6I10)

  - Field 1 -Number of Bodies

  - Field 2 -Number of Surfaces

  - Field 3 -Number of Facets

- Record 4: FORMAT(2I10)

  - Field 1 -Facet Label Number

- Record 6: FORMAT(7I10)

  - Field 1 -Surface Label Number

  - Field 2 -Number of Facets

```
record
number

                 -1
                544
    1            1          22         60        32        481          1
    2           32          60         22     2.9999999E-02    2.5000000E-02    6.3989230E-02
    3            1   0.0000000E+00    0.0000000E+00    1.1398923E-01    0.0000000E+00
    4            1           3
    5           29           9         3
    6            1           4         1        0         1          1          1
    7            1           3         9
    8    1.5000001E-01    3.0000000E+01    2.0000000E-01    0.0000000E+00    1.0000000E-01
    9    8.5000002E-01    0.0000000E+00    1.0000000E+02
   10            1          1
   11    0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00
         0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00
         0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00
         0.0000000E+00    0.0000000E+00    0.0000000E+00    0.0000000E+00
                 -1
```

Figure 4.2:   Brief structure of the 544 dataset

− Field 3 -First Facet Label

Stereolithography File

The model we create in I-DEAS must be translated to a planar faceted representation file, called a stereolithography file, for use by the SLA software. This triangle file is also called "STL" for stereolithography file and it is typically given a file extension of .STL. In an .STL file, facet normal information and triangle vertex order is used to properly distinguish the interior from the exterior of an object. Specifically, each facet must have a corresponding unit normal vector pointing away from the solid object. The .STL file provides important information for the program, the outward-pointing normals of the facets. The .STL file can be considered the soul

```
line
number

1       SOLID  <<MODEL>>
2         FACET NORMAL   0.00000000E+00   0.00000000E+00   1.00000000E+00
3           OUTER LOOP
4             VERTEX  9.99999978E-01   3.99999991E+00   1.13989237E+01
5             VERTEX  1.99999996E+00   3.99999991E+00   1.13989237E+01
6             VERTEX  0.00000000E+00   5.00000007E+00   1.13989237E+00
7           ENDLOOP
8         ENDFACET

              •

              •

              •
```

Figure 4.3:   Basic structure of a stereolithography file

of the program. All the criteria developed in the surface quality section are based on dealing with the normals of the facets. Figure 4.3 illustrates the basic structure of an .STL file. The order must be maintained at all times. The line numbers are added to this example .STL file to simplify the explanation of the file. Data in Line 1 is the name of the part. Data in Line 2 is the facet unit normal. From Line 4 to Line 6 are the coordinates of the three points constructing the facet. The generation processes of the .STL file are described in the rest of this section. The operations must combine the two tasks, Solid Modeling and Rapid Prototyping, of the Object Modeling family in the I-DEAS environment.

1. Creat a model using I-DEAS Solid Modeling and triangulate its facets. Store the object or leave it on the workbench.

2. In the Rapid Prototyping task, pick "Create_Prototype."

3. Select a prototyping device from the list.

4. Select the object to prototype. You may screen-pick the object on the work-bench, or use the secondary menu to select it by label. You may also use the secondary menu to select a stored object. The software will check the object's facets, size, and position. Use Modify_Facets to make necessary modifications to the object's facets.

5. Enter the prototype file name. This is the output file in the STL format. The software will report its progress when it has completed the output file.

Baseplane File and Aesthetic Plane File

Every surface of the object created by I-DEAS is assigned a label. These labels can be shown on the exact surfaces they represent by the process described as follows:

1. In the Object_Modeling task, pick "Display_Options."

2. In the Display_Options manual, pick "Object_Entities...". A selection block will appear on the screen.

3. Pick the item "Surface" in the selection block, then pick "Done."

The content of the baseplane file is a list of labels representing the surfaces which could be candidate baseplanes. The candidate baseplanes are distinguished from other surfaces by applying the criterion that only the common surfaces between a desired object and its convex hull can be candidate baseplanes. After showing all the labels of the surfaces on the screen, select those labels which are candidate baseplanes and type all of them into a baseplane file created by the user. The

```
line
number

1          model
2            5
3            6
4            7
5            8
6            9
7           13
8           18
9           -1
```

Figure 4.4:   Basic structure of a baseplane file

structure of the baseplane file is shown in Fig 4.4. The line numbers are added to simplify the explanation of this file. Data in the first line is the name of the part, then each following line contains a label of candidate baseplanes. The file is ended with a negative number. Basically, creating an aesthetic plane file, its content and structure are similar to the baseplane file. However, beginning in the second line, each line contains a label for a surface of the model object required to be very smooth for functional reasons or aesthetic reasons.

User's Guide

This program, stored under the file name **quality.c**, determines the orientations of an object produced in SLA based on the surface quality factor. The results, stored under the file name **result.dat**, of this program are one or several labels of surfaces. It implies that if we use these surfaces to be the baseplane in SLA, the surface quality

of the object will be the best for the special purposes we desire to achieve. Before executing the program, the users should create the input files, a universal file, a stereolithography file and a baseplane file. In addition, an aesthetic plane file is needed when a special task, maximizing the area of aesthetically important surfaces, is chosen. These input files have been introduced in the previous sections. Basically, this program is composed of three modules. The first module searches for candidate baseplane surfaces based on maximizing the total area of perpendicular or parallel surfaces. The second module searches for candidate baseplane surfaces based on maximizing the area of aesthetically important surfaces. The objective of the final module is to search for candidate baseplane surfaces based on minimizing the worst quality of a model object. The instructions for running this program are described in the following steps.

1. Type **cc quality.c** in the DECterm window, and press 'RETURN' key.

2. Type **a.out** in the DECterm window, and press 'RETURN' key. Then the program will show following information on the screen.

******** ORIENTATION IN SLA *************

The quality.c can perform three tasks:

(1) maximizing the area of parallel or perpendicular surfaces

(2) maximizing the area of functionally or aesthetically important surfaces

(3) minimizing the worst quality

Which task are you going to perform ?

—>(1/2/3)

****

3. If enter 1, steps 4 to 7 should be followed. If enter 2, steps 3 to 7 should be followed. If enter 3, a value of critical angle decided by the user is required. Input the value of the critical angle and press 'RETURN', then steps 4 to 7 should be followed.

4. Input the name of the aesthetic plane file and then press 'RETURN'.

5. Input the name of the universal file and then press 'RETURN'.

6. Input the name of the stereolithography file and then press 'RETURN'.

7. Input the name of the baseplane file and then press 'RETURN'.

8. Type **more result.dat** in the DECterm window, and hit the 'RETURN' key. The labels of candidate baseplane surfaces which satisfy the special objectives of the tasks chosen by the user will be shown on the screen.

CHAPTER 5. CONCLUSION

Summary

Products often make several complete cycles through design, prototyping, and fabrication before reaching mass production for market. Studies have shown that a major contributor to the time to market for a new product is the time required to fabricate prototypes. An initial idea, created by a designer, often needs a physical model in order for the designer to identify and correct flaws. This step actually is a loop because many design modifications are usually needed before a suitable model is achieved. Typically, it is possible to use SLA to achieve a 70% improvement over traditional methods in the time required to create a model. It will undoubtedly revolutionize the present design and manufacturing practice in a wide range of applications. However, many research developments are still needed to bring SLA to maturity. Presently, designers use their experience to fabricate polymer models in SLA. There are no rules that they may follow in SLA in order achieve the best results.

In this study, three influential factors, surface quality, build time, and support structure for determining the orientations of a desired part fabricated in SLA, are illustrated. Also, the decision criteria for dealing with these factors are proposed. This research facilitates the designer or model builder's ability to search for the best orientations of an object fabricated in SLA for special objectives such as best surface

quality of the object, minimizing the build time or minimizing the number of supports. Before executing SLA, designers may evaluate the expected result by applying the methodology proposed in this study and reorient the object. Thus, the cycle time between design and prototype is greatly reduced. In addition, the decision criteria for surface quality have been coded in the C programming language. An example of searching for the best orientations of a model part according to the surface quality factor is demonstrated in Appendix A.

Future Work

Activities for future research are stated in the following:

1. Implementation of the criteria of build time and support structure.

   Two criteria proposed in this thesis based on build time and support structure are still in algorithm status. Coding these two algorithms for implementation should be executed.

2. Trade-off of the proposed factors and determination of an optimal orientation.

   The three proposed factors, surface quality, build time, and support structure, sometimes conflict. When one character is demanded, it may detract from other performance aspects. Weighing these decision factors against one another in order to meet an overall goal should be evaluated.

3. Incorporate a decomposition factor into the criteria.

   The vat capacity of SLA is limited. If the size of the object exceeds the vat capacity, a decomposition process is necessary. A decomposition factor needs

to be considered, which will maintain good product character.

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APPENDIX A. AN EXAMPLE PROTOTYPE MODEL

In this appendix, an example prototype model expected to be fabricated in SLA is created for demonstrating the program quality.c. The example model is the base of a slider-crank mechanism. The groove constructed by surface 10, surface 11, and surface 12 should be very smooth for the required function of the base. Figure A.1 is the solid graphic for this workpiece. In Figure A.2, each number indicates the surface label. Figure A.3 illustrates the two-dimensional drawings of the example object and all of the necessary dimensions. In Figure A.4, the results of the program, the best surfaces for the selected tasks, are indicated by shadow surfaces. The universal file, stereolithography file, baseplane file and aesthetic plane file are stored under the file names of model.unv, model.stl, model.bas, and model.aes respectively. The following describes the processes to execute the program quality.c

vincent% cc quality.c

vincent% a.out

******** ORIENTATION IN SLA *************

The quality.c can perform three tasks:

(1) maximizing the area of parallel or perpendicular surfaces

(2) maximizing the area of functionally or aesthetically important surfaces
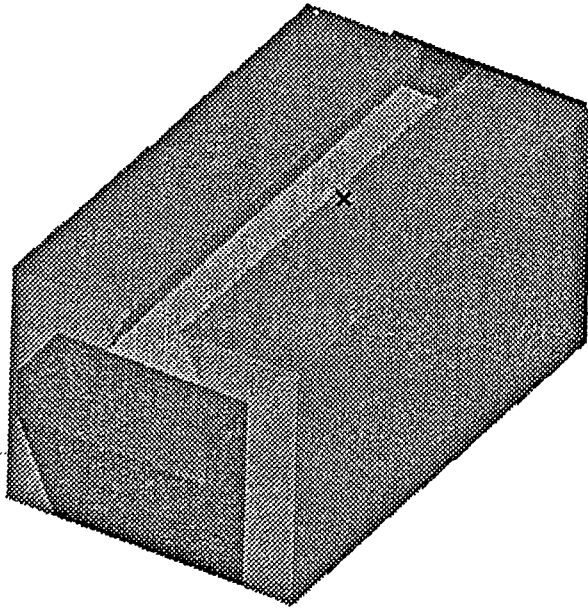
(3) minimizing the worst quality
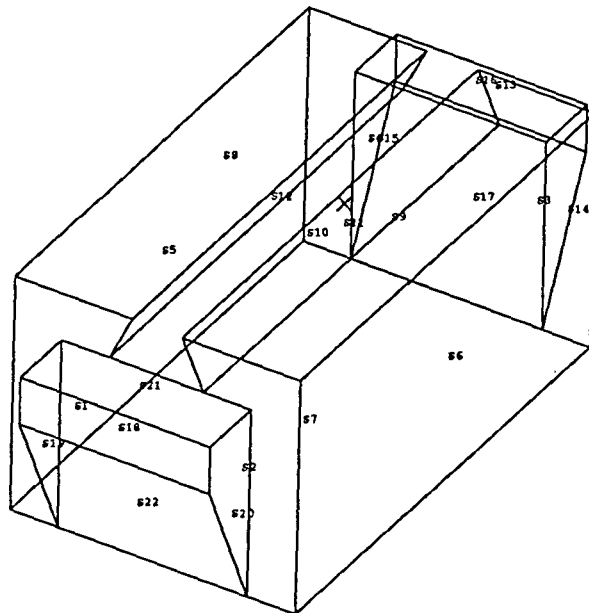
Figure A.1: The solid graphic for example prototype model

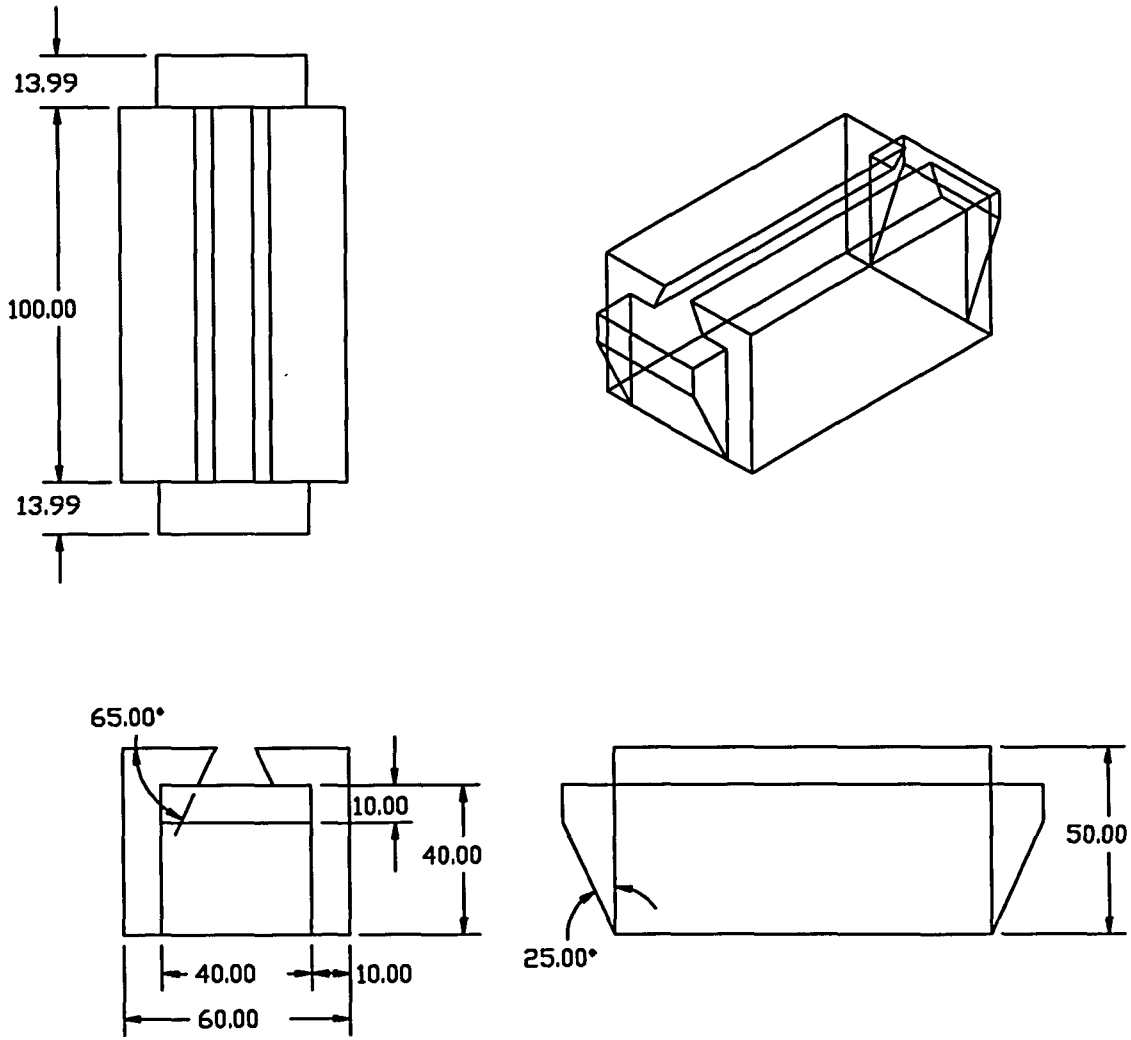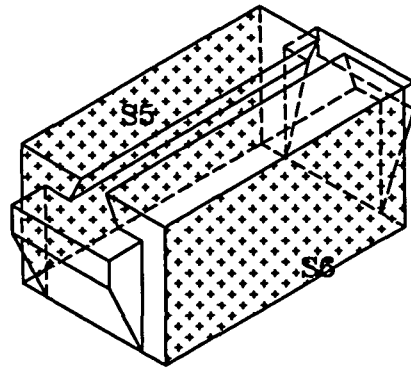Figure A.2: The graphic for example prototype model with surface labels
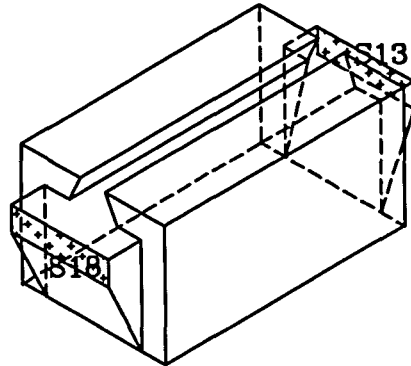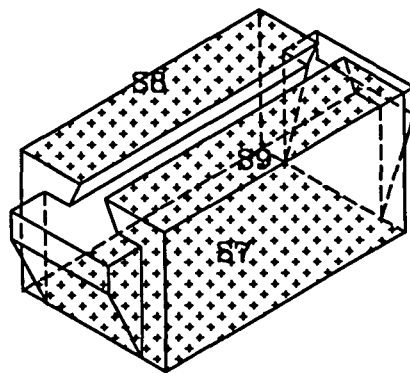
Figure A.3:   Two-dimensional drawings of the example prototype model

Best surfaces to be the
baseplane for the task 1

Best surfaces to be the
baseplane for the task 2

Best surfaces to be the
baseplane for the task 3

Figure A.4:   The best candidate baseplane surfaces for the selected tasks

Which task are you going to perform ?

—>(1/2/3)

****

1

Please enter the name of universal file :

model.unv

Please enter the name of stereolithography file :

model.stl   .

Please enter the name of baseplane file :

model.bas

vincent% more result.dat

The best surfaces to be the baseplane for task 1 are :

surface 5

surface 6

vincent% a.out

******** ORIENTATION IN SLA ************

The quality.c can perform three tasks:

(1) maximizing the area of parallel or perpendicular surfaces

(2) maximizing the area of functionally or aesthetically important surfaces

(3) minimizing the worst quality

Which task are you going to perform ?

—>(1/2/3)

****

2

Please enter the name of aesthetic plane file:

model.aes

Please enter the name of universal file :

model.unv

Please enter the name of stereolithography file :

model.stl

Please enter the name of baseplane file :

model.bas   .

vincent% more result.dat

The best surfaces to be the baseplane for task 2 are :

surface 13

surface 18

vincent% a.out

******** ORIENTATION IN SLA ************

The quality.c can perform three tasks:

(1) maximizing the area of parallel or perpendicular surfaces

(2) maximizing the area of functionally or aesthetically important surfaces

(3) minimizing the worst quality

Which task are you going to perform ?

—>(1/2/3)

****

3

Please enter the critical value of angle.

30

Please enter the name of universal file :

model.unv

Please enter the name of stereolithography file :

model.stl

Please enter the name of baseplane file :

model.bas

vincent% more result.dat

The best surfaces to be the baseplane for task 3 are :

surface 7

surface 8

surface 9