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**AUTOMATED EJECTABILITY ANALYSIS AND
PARTING SURFACE GENERATION FOR
MOLD TOOL DESIGN**

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Abstract

This report describes a CAD approach for automated ejectability analysis and parting surface generation for mold tool design. This design automation is incorporated into a Rapid Tool Manufacturing system which integrates stereolithography (SLA) and thermal spraying into a CAD/CAM environment for manufacturing tooling like injection molds. Design models are first evaluated for part ejectability given the desired draw direction and constrained to be manufactured in a two part mold. This information helps the designer to create manufacturable designs. The parting line and parting surface models are then created subject to geometric and process constraints. The union of part design and parting surface models forms impressions of the mold cavities. Cavity patterns are then quickly built with SLA and the molds are fabricated by spraying metal onto SLA patterns.

1 Introduction

The design of injection mold tooling has traditionally been a forte of skilled, experienced tool designers. Relatively little of this design process has been automated in the majority of industrial settings, rendering it a long and tedious task. Moreover, several *time consuming* iterations through product design, tool design and fabrication are often required to manufacture a successful tool. This is due in part to product designers creating product designs which are not "manufacturable", because they do not fully understand the constraints of downstream manufacturing processes. There are other difficulties as well, associated with predicting a tool design's actual performance, particularly for those with complex geometries or for those with new shapes for which the designer does not has any previous experience.

Two major efforts that can help reduce the tool development time include automation and integration of various aspects of design and analysis cycle and development of new manufacturing processes themselves. In recent years there have been several research initiatives and commercial developments to address the first one of these issues i.e. CAD packages to help reduce the tool design time and at the same time to analyze the tool from various perspectives. A large number of these analysis tools operate on a finite element mesh representation of the part. Generally, these packages which assist in analysis of designs fall in following three categories:

- **Stress Analysis:** examples include commercial systems like PATRAN, ABAQUS, ANSYS etc.
- **Mold Solidification:** Packages like C-Cool can analyze the solidification characteristics of the plastics and temperatures developed across the part during mold cooling and thus evaluate the tool from a process perspective.
- **Mold Filling Analysis:** Simulation of mold filling process is possible by specifying fixed gate positions and initial pressure or temperature. The designer can also view predicted temperature, stress, or pressure

distributions. C-Flow and MoldFlow are examples of two such analysis packages.

Finally all the above simulations can factor into a number of cost equations and thus lend themselves to an economic analysis as well.

Knowledge engineering based approaches have also been introduced in design automation. These approaches make use of heuristics and design standards used by experts in the design and manufacturing domain. PIMES, an expert system developed at Carnegie Mellon, performs a manufacturability assessment of plastic injection molded parts based on their CAD designs[1]. The heuristics employed are formally represented as rules and rely on key aspects of a part's shape features. These shape features are *extracted* from the actual part i.e. they are recognized and created from the low level CAD structures[2]. Several mold-design knowledge bases have also been developed containing rules describing complex interrelationships between temperatures and viscosities of the plastic materials, the plasticizing rate and shot capacity of injection molding equipment, pressure distribution in mold cavities and runners etc.[3]

While such automation can effectively reduce the time for tooling design and minimize the number of redesign/retooling iterations, there will always be modeling limitations and ultimately the real tool must be built and tested. For product manufacturers to be competitive they must be able to build these tools more quickly to respond to today's rapidly changing market demands.

As per the current manufacturing trends are concerned, today almost 90% of all the molds are made by machining operations, primarily turning, milling and grinding. There are several other mold making techniques particularly suited for complex part geometries e. g. investment casting, electro-deposition, cold hobbing, pressure casting, spark machining, and sprayed tooling[4]. The sprayed tool approach is one method which has long held the promise to speed up tool fabrication. This method, however, has several process limitations¹,

¹ Commercialized spray tooling is limited primarily to soft zinc alloys, Concave shapes with small aspect ratios are hard to spray, Process may be too tedious for a technician to execute, Substrate pattern fabrication is a prerequisite

and like many other manufacturing processes, has not been systematically integrated with earlier product design stages.

To address these problems, Carnegie Mellon University [CMU] is developing a Rapid Tool Manufacturing [RTM] system. The aim of the project is to reduce the time required to develop mold tooling by an *order of magnitude* by incorporating automation of design processes and their integration with the Stereolithography² technique [SLA] and thermal spraying into a CAD/CAM environment [5].

In this process, mold halves are fabricated by robotic arc spray deposition³ on plastic patterns of the desired part. The sprayed metal shells are then backed with appropriate materials to form the tool. Relative to conventional machining methods, this approach has the potential to more quickly and less expensively produce tools, particularly for parts with complex geometries⁴ or large dimensions.

As mentioned earlier, RTM system incorporates design automation and computer aided process planning capabilities. Some of the key features being developed in this CAD/CAM approach include:

- DFM critique of product design.
- Ejectability analysis of product designs.
- Generation of geometric models of the mold half patterns, which are to be sprayed, directly from product design models.
- Off-line robotic trajectory planning based upon design models and process information.

Each of these functions, as well as the initial product design, are implemented in a single *unifying* CAD environment based upon a non-manifold, linear, ge-

²Stereolithography is a relatively new free form fabrication technique which generates 3D objects by curing a polymer using laser beam. It has been commercialized by 3D Systems, Inc. (Valencia, CA)

³Current process research at CMU involves steel based sprayed tooling, methods for of metal onto plastic SLA, "hard-to-spray" shapes and robotic spray automation.

⁴Solid Freeform Fabrication [SFF] technologies such as SLA are easier to plan and to execute than CNC operations, but there are currently limitations with SFF precision.

ometric modeling system *nODdles* [6],[7], Currently the modeling system is linear which means that curves are represented by a combination of linear line segments and a model is composed of planar facets (called faces) with consistent topology and geometry. The models can be created using boolean operations on some primitives like cylinder, cone, sphere, toros etc. which are provided in the system or one may use a triangulation scheme[8] to create a model from a set of nonlinear surfaces provided in an IGES format. This modeling system provides a very powerful geometric engine for object representation and manipulation and ensures a smooth, efficient flow of information from design to manufacturing.

In this automation process, the geometrical aspects of mold design are among the first to be considered. Before analyzing the mold for a part one needs to know if such a mold is at all geometrically possible. The mold halves whose analysis is desired must be generated automatically from the part description itself. This report focuses on automated ejectability analysis and pattern generation for a part whose injection mold is desired. This sets up the input for other analysis and manufacturing processes downstream.

Automated ejectability evaluation is needed when one wants to ascertain if the part being considered can be taken out of the mold. This is very important for parts that have been designed on the computer because one may, unintentionally, design a surface which leads to an unejectable situation. Such situations can be very non-intuitive and hard to detect by visual inspection. This may lead to cracks in the final molds and molded parts during production and even failure.

Automated pattern generation involves finding the parting lines and creation of surfaces as well as the runner and gating systems⁵ for ejectable parts. Some definitions are presented below which are commonly used in this paper and other literature in the field.

The parting surfaces of a mold are those surface areas of both mold halves, adjacent to the impressions, which are pressed against each other when

⁵Currently design of runner and gates is being developed in form of an interactive process where the designer is provided with a standard library of runners and gates. The designer selected runner and gates may then be added to the mold halves.

the mold is closed. The direction along which the mold is opened to remove the molding is known as the **draw direction**. Further, the line which forms the boundary of the cavity in the mold is termed the **parting line**. The part geometry determines the regions in which the parting line can lie and then a combination of several mechanical, metallurgical and process parameters[9] can be used to arrive at an *optimal* parting line. One important geometric consideration is that the molding should, as far as possible, be ejectable from the mold without using any sliding parts since their use is detrimental to dimensional accuracy and increases the cost of making and maintaining molds. The presented approach considers only two halves in a mold and hence parts which need slide actions are termed non ejectable.

Thus, given a part one should quickly be able to tell whether it can be ejected from a mold in a particular draw direction without any slide action. A *particular* draw direction is specified, since it is usually determined as a function of various metallurgical and geometric parameters. For example, one may wish to choose a draw direction along the width for molding a cuboidal part, whose depth is greater than its width, to minimize the pullout distance. A particular draw direction may be most suited to ensure uniform filling of the mold. Another draw direction may minimize the projection area which may be critical with respect to the capacity of molding machine at hand. Thus the decision to analyze ejectability in a particular direction seems reasonable.

Once the part is found to be ejectable, automatic generation of the parting line is the next logical step. Again, for complex parts, this step is very non-intuitive. In general, the parting line is a three dimensional, closed curve which is difficult to specify precisely by visual inspection. This is more so in case of computer designed parts where one should be able to represent the parting line accurately and in a suitable format so that it can be used in further design processes like parting surface design. However, if the part is not ejectable, the designer should be informed of the non ejectable areas. On the whole, this approach helps the designer to create manufacturable designs and reduces the expensive, time consuming iterations from design to manufacturing.

The rest of the report describes a system for such an ejectability analysis.

The following flowchart (fig. 1) highlights the major components of the system which are explained in greater detail in the following sections.

In the course of this report some simple test parts are used to describe the approach and finally some more complicated real life examples are presented to illustrate the utility of the system.

2 Ejectability Analysis

The aim of ejectability analysis is to determine whether a part is ejectable or not from a two part mold along a specified draw direction. The algorithm is primarily based on an analysis of the relationships of surface normals of the design model to the draw direction. Various regions of a given part have varying slopes with respect to the draw direction and this forces certain parts to lie in the top half or the bottom half of the mold to avoid unejectable situations. This idea is captured in mathematical terms along the following lines:

Given draw direction (\vec{dd})

Let f_{ri} = face normal of face i ;

and θ = angle between f_{ri} and dd ;

Then if

$$abs(\theta) < 90^\circ$$

\Rightarrow Face f_i will lie in the top mold half.

$$90^\circ < abs(\theta) \leq 180^\circ$$

$=^{\wedge}$ Face f_i will lie in the bottom mold half.

$$\theta = \pm 90^\circ$$

\Rightarrow Face i , may lie in either mold half.

2-1 Theory of Patches

The above classification conforms to the intuitive idea that all the visible areas of the part, when viewed from the draw direction, should belong to the top

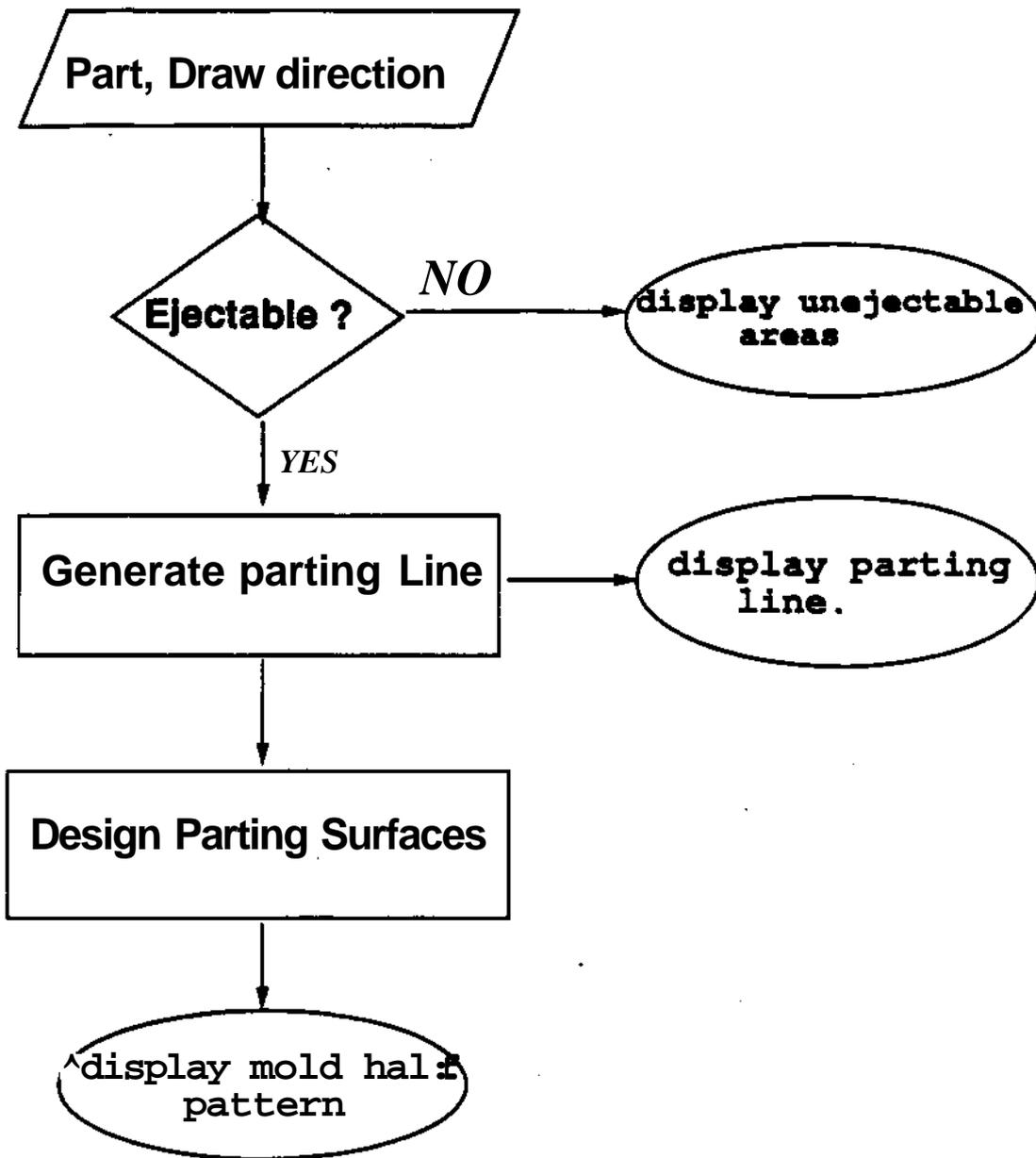


Figure 1: System Flowchart

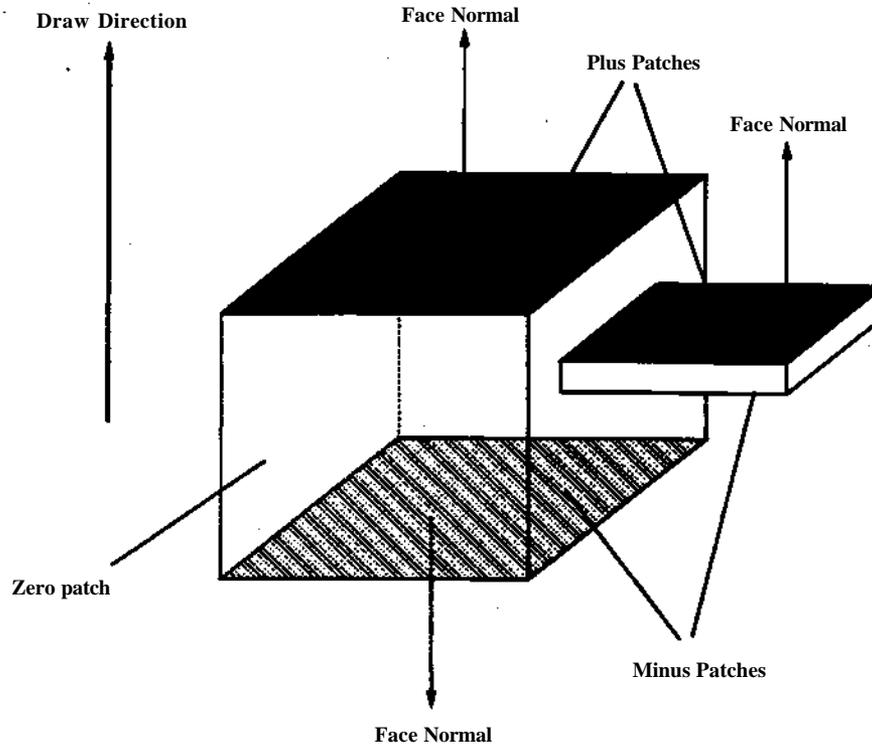


Figure 2: Classification into patches

mold half and the invisible areas to the bottom one. Thus as a first step, the part is classified into groups of faces called patches (fig 2). As is clear from the preceding material, there are three distinct types of patches which will be needed to exhaustively classify a part. These three types of patches are defined as—

Plus: Collection of adjacent faces which are to lie in the top mold half, i.e. the face normals make an acute angle with the draw direction.

Minus: faces that should go to the bottom mold half.

Zero: faces whose normals are at right angles to the draw direction and thus they may lie in either mold half. In practice, these patches are rare, since all surfaces have some draft on them.

Plus and minus patches are collectively termed as signed patches. A patch may only have unlike signed neighbor patches and a part may have multiple patches of the same type i.e. plus, minus or zero. During the development of patches, we keep track of the following three attributes which are very useful later on—

Faces A list of constituent faces which make up the patch is maintained.

Boundary The boundary, in terms of linear line segments, of the *collection* of faces in the patch. This is readily applicable to cases where the patch may include a hole. In those situations the boundary edges form multiple loops.

Neighbors This is a list of all the neighbor patches for a patch. As noted earlier, the neighbor patches are of different type as compared to the patch.

An important concept in regard to patches is the possibility of further reductions in total number of patches themselves. In case a zero patch is completely surrounded by a plus (or minus) patch or by a pair of plus (or minus) patches then it can be treated as plus (or minus) patch instead of a zero patch as depicted in fig 3.

Since all the plus (or minus) patches *have* to lie in one mold half, the zero patch which is completely enclosed by them will also lie in the same mold half. This is permissible by the definition of a zero patch according to which it can go to either top or bottom mold half. So in such cases this enclosed zero patch serves as a *link* to connect together its plus neighbor patches to form the top mold half and minus neighbor patches to form the bottom mold half. Hence, such a zero patch can be considered *reduced* to a signed patch with a simultaneous update of the attributes (outlined above) of the involved patches.

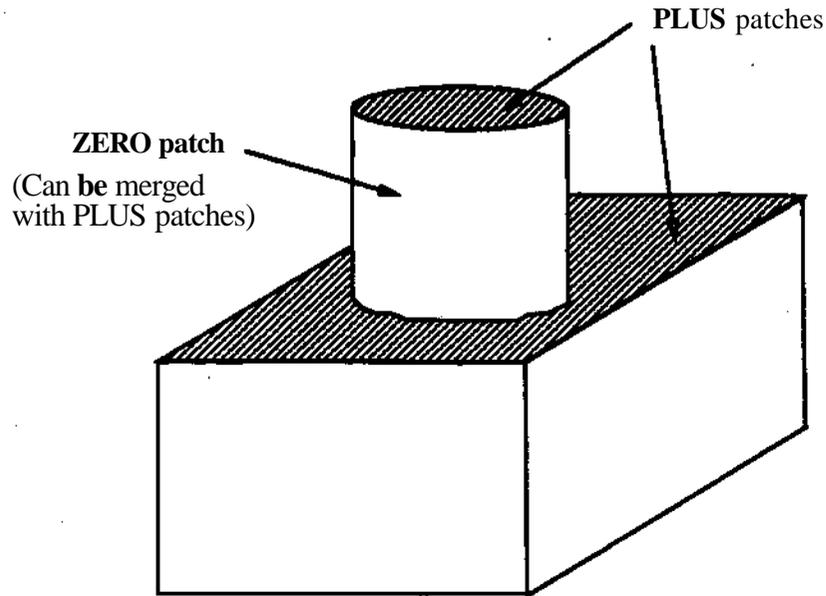


Figure 3: Reduction of patches

2.2 Ejectability Tests

The classification of a part into patches, captures the essence of faces of the part from an ejectability point of view and makes it feasible to reason with only a handful of patches instead of thousands of faces. It also helps define the ejectability conditions i.e. A part is ejectable if—

- No two *same* signed patches intersect when projected on to a common plane perpendicular to the draw direction.
- No patch boundary intersects *itself* when projected onto a plane perpendicular to draw direction.

To implement the first check, concept of projected patch areas is employed in this approach. If the sum of individual projected patch areas turns out to be greater than the merged patch area of the two patches it signifies an overlap (fig. 4) of portions of the part along the draw direction, hence forming an undercut. For projections of patches, we make use of the patch boundaries stored earlier during the patch growing stage. The second check is implemented by

looking for **edge** intersections among constituent edges of the patch boundary (refer to fig. 4).

However, some preliminary analysis regarding part's ejectability can also be done with the help of these patches e.g. If a part has more than one plus/minus patch and no zero patch, it is *not* ejectable. This is so because two patches of the same sign can never be adjacent and without a zero patch there is nothing which can link these same signed patches together in one of the mold halves. In fact this indicates the presence of undercuts in the part.

In the RTM system, such unejectable geometries are brought to the attention of designer by highlighting the relevant patches on the CAD screen. The designer may now choose to redesign/reorient the part or use a sliding component to deal with the problem.

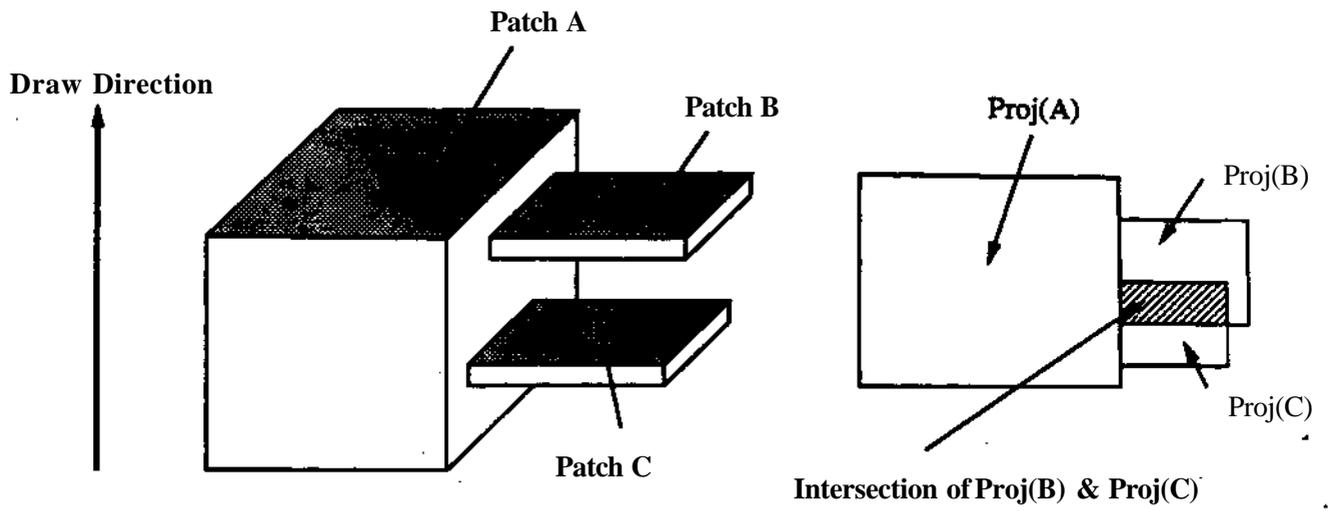
3 Parting Line Design

If the part is ejectable then the next step is to obtain a parting line and thus clearly identify the two mold halves. For ejectable parts the general idea of a parting line as put forth by Pye[10] is:

The parting line must occur along the line round the position of maximum dimension when viewed in the draw direction.

This idea can be easily related to the boundary of the patches. In fact, the boundaries of plus and minus patches, in a plane perpendicular to the draw direction, **are** the same and this is also the *projection* of parting line (fig 5). However, as shown in the figure, this is not the *true* projection of parting line. The shaded area on the part represents a region, which belongs to a zero patch, where parting line cannot pass through. This area maps into a line in the projection since zero patches are always projected as lines.

Such regions are identified by looking for coincident boundaries of projected patches of any one sign (plus *or* minus). By eliminating these coincident boundaries and ordering them to form closed loops, a true projection (fig 5) of the parting line is obtained. This projection of parting line is represented as a



IF $area(B \cup C) < area(B) + area(C)$
 \Rightarrow Intersection of B and C. "area" refers to projected area.

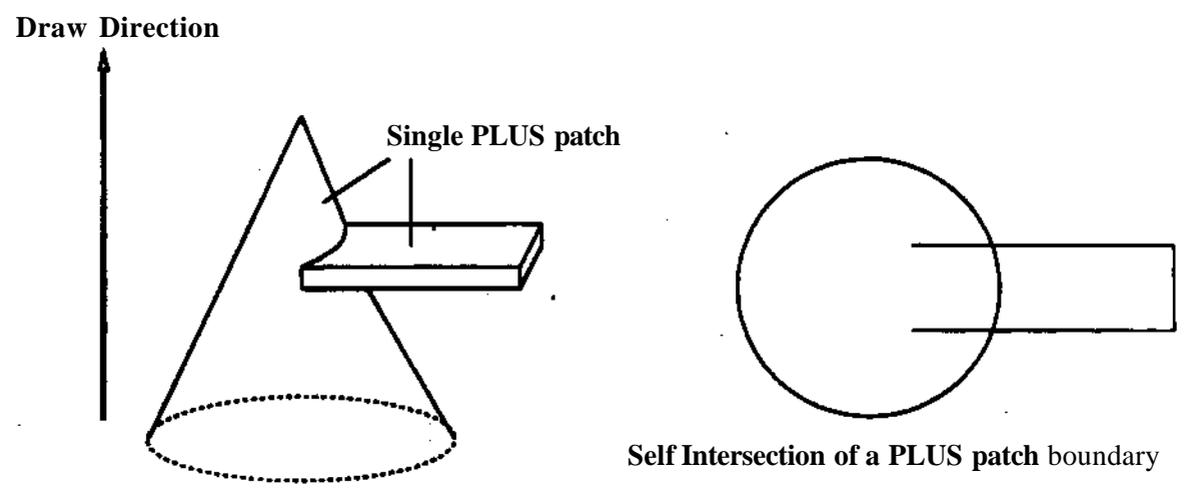


Figure 4: Checking patch intersections

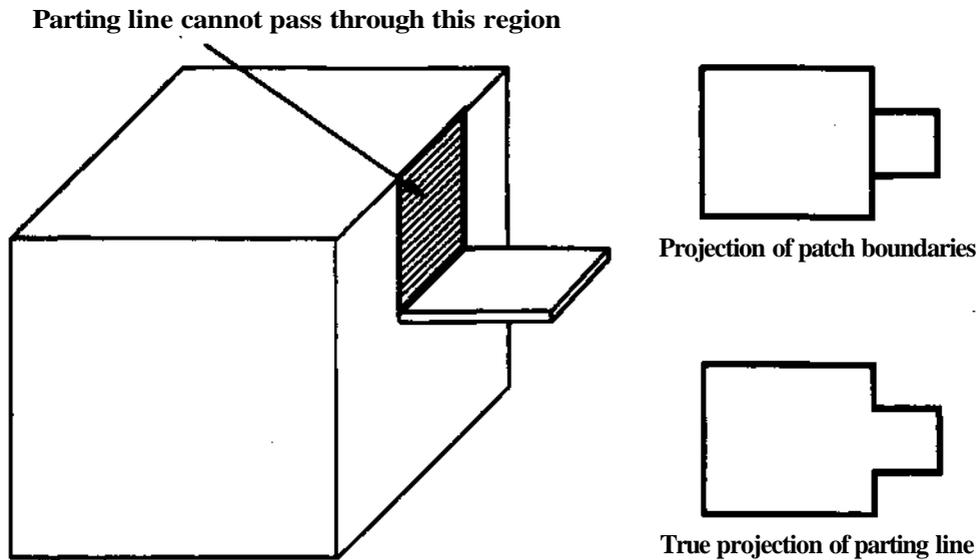


Figure 5: Projection of parting line

series of nodes⁶, which are connected by straight lines. This projection is the same for *all* possible parting lines in the part. However, this is a projection in $3\mathbb{f}^2$ space, whereas the actual parting line is a closed, connected curve in $3\mathbb{f}^3$ space. To transform this projection into the three dimensional representation of the part, we need to fix a value for the z-coordinate of each node in the projection of the parting line.

This is a problem with a non-unique answer, because each of the nodes can take a *set* of values for the z-coordinate. This becomes possible due to the presence of zero patches, which map into straight lines in the projection but offer an *area* in the $3\mathbb{f}^3$ representation for the parting line to pass (fig 6). However, if there are no zero regions, like in the egg shaped object shown in fig 6, one does not have a choice of many parting lines. In such a case the boundary of plus and minus patches is *the* parting line.

⁶Characterized by their x, y positions; Assuming Z to be the draw direction.

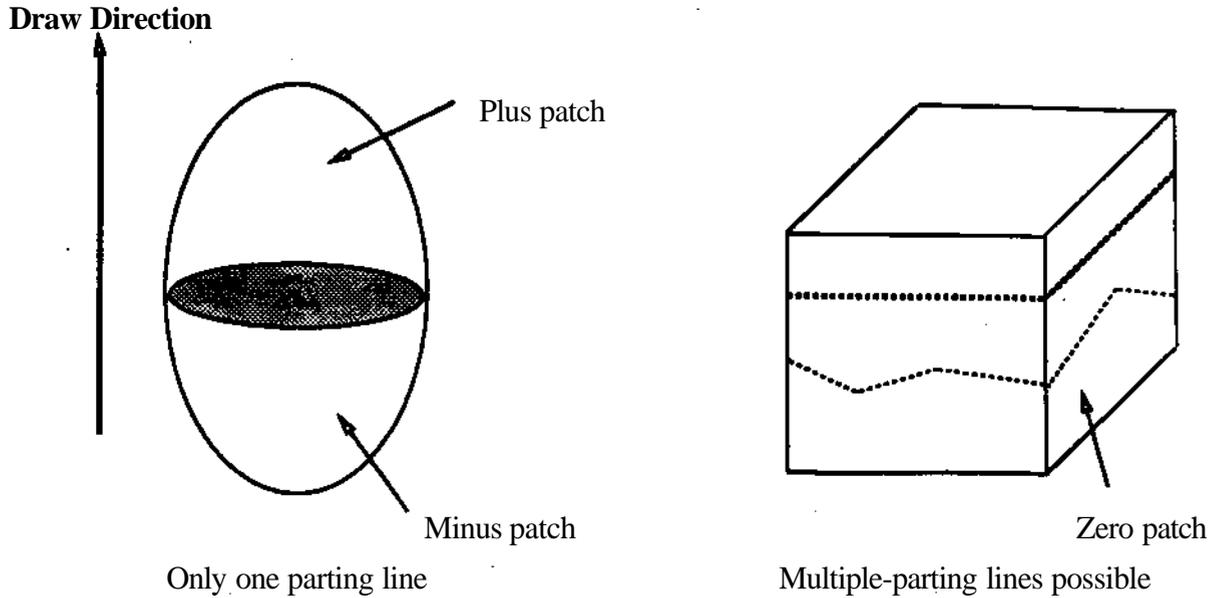


Figure 6: Non-unique parting line problem

3.1 Concept of Ranges

As illustrated in the previous section, a part containing zero patches may have a number of different parting lines in a particular draw direction but these parting lines have a common projection in a plane perpendicular to the draw direction. This brings out the fact that the variation in position of parting line nodes, along the draw direction is what forms the various parting lines. Hence the decision to keep parting line as an ordered list of nodes. Now by assigning a **range** [*highdow*] of positions (along the draw direction, say *Z*) to every node, the entire gamut of possible parting lines is covered. This is shown in fig 7.

The part shown in fig 7 has two small cubes cut out at the top and bottom. The true projection of all possible parting lines is shown by a dark line. The nodes of the parting line are shown with black dots. Node 1-4-5-6-7-8-9-10 are sufficient for obtaining the projection of parting line but they are *not* sufficient to cover all the parting lines by themselves. For example a line between the lowest positions of node 1 and 4 is physically not possible. For this reason

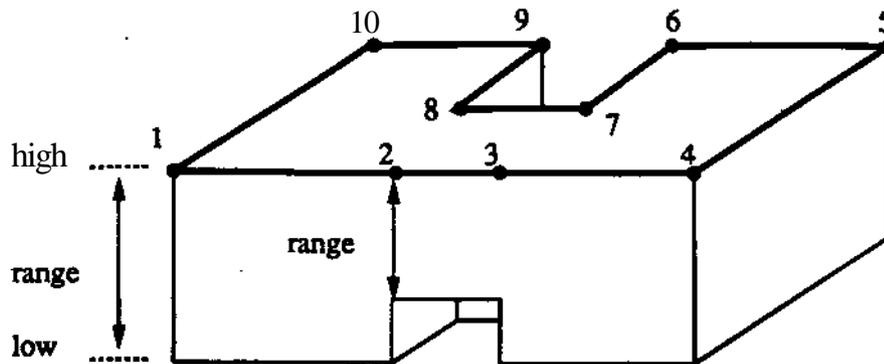


Figure 7: Assigning ranges to each node of the parting line

node 2 and 3 are included in this list of nodes. Now the range of these two nodes will prevent parting line from falling off into the cut out portion of the part.

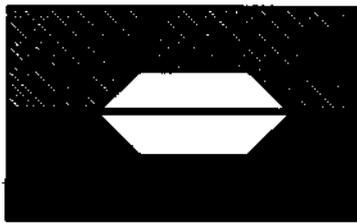
To obtain all these nodes, projections of both plus and minus patch boundaries are needed. As mentioned earlier both these projections are *same* in terms of shape but the actual number of nodes in each projections may be different depending on the shape of the part. e.g. in fig 7 node 2 and 3 do not occur in the projection of plus patch boundaries but do appear in projection of minus patch boundaries. These two projections are combined to provide bounds on the position of the parting line by assigning range to every node of these two projections.

3*2 Development of a Parting Line

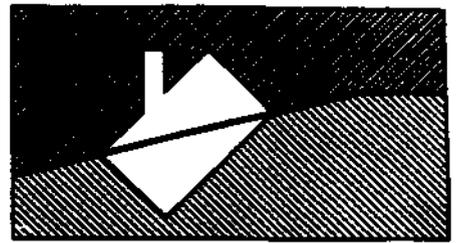
After assigning ranges the next step is to select a position for each node such that it lies within its defined range. This can be done in several ways to adapt to the kind of parting line desired. Various kinds of parting lines (fig 8) are used in mold making with each having its specific advantages.

However Flat parting lines and surfaces are preferred in most cases. The molds with flat parting line are easy to manufacture as well as maintain. Hence this kind of parting line is attempted first.

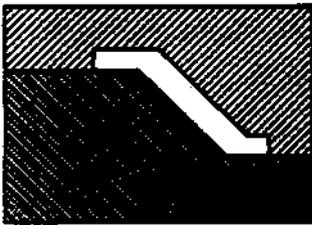
As noted earlier, the parting line design problem has a non-unique answer



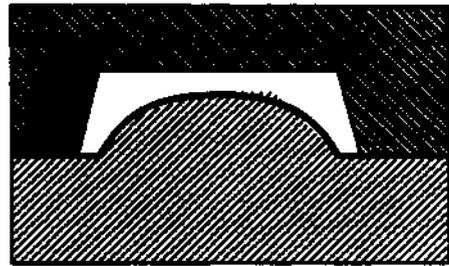
(a) Flat Parting Surface



(c) Angled Parting Surface



(b) Stepped Parting Surface



(d) Profiled Parting Surface

Figure 8: Various kinds of parting surfaces

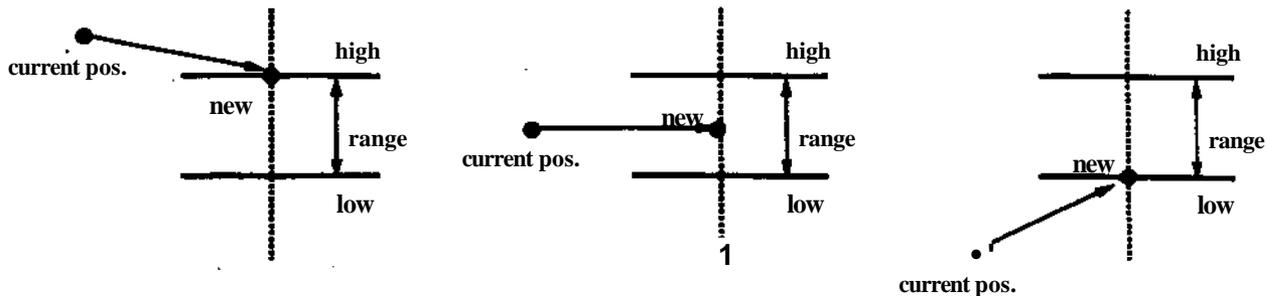


Figure 9: Development of parting line

due to the multitude of parting lines offered by presence of zero patches. However, in practice, not all nodes of the parting line are expected to have non-zero ranges because most surfaces will have drafts instead of being perfectly vertical. This means that the **parting band**⁷ is composed of line segments and areas. The line segments indicate the nodes which have zero range.

To design a flat parting line, we start with the node which has minimum range, called the primary node. As discussed in the preceding paragraph, in most cases the range associated with the primary node will be zero. Hence this node (primary node with zero range) has to be on the parting line and if there is another node in parting line whose range does not permit the same position⁸ as that of primary node, a flat parting line *cannot* be obtained. If all nodes can take positions same as primary node along the draw direction then a flat parting line is obtained. In case the range associated with primary node is not zero, it implies that primary node's position is not fixed but can be changed. In these cases the starting position for the primary node is chosen as the midpoint in its range.

In situations where a flat parting line is not possible, an attempt is made to get as close to it as possible by minimizing the deviation (along the draw direction) of a node from the previous node (fig 9).

This essentially tries to minimize the total length of the parting line by minimizing the segment length at each step. Stepped or locally stepped parting surfaces (fig 8) will result due to this approach. Options to obtain the

⁷The set of all possible parting lines

⁸along draw direction

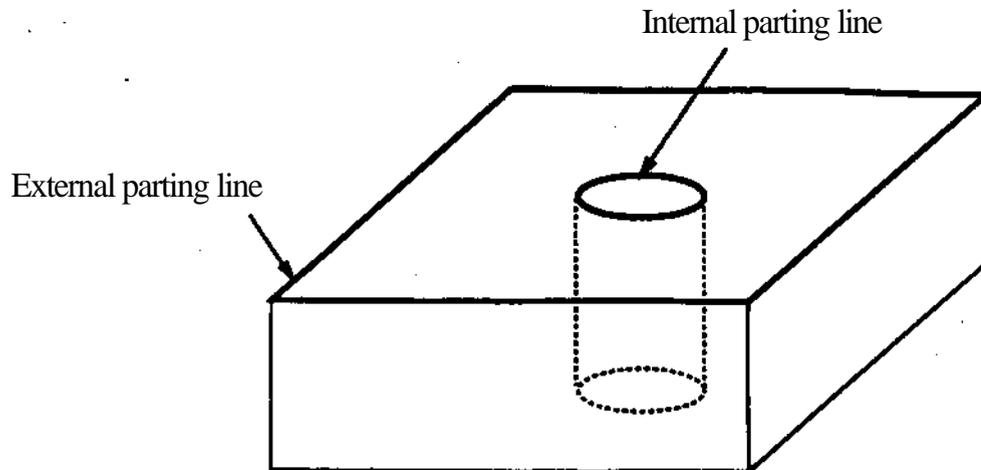


Figure 10: Internal parting lines

highest/lowest parting lines are also available. The highest parting line is obtained by fixing all node positions equal to the top of their ranges while lowest parting line fixes the positions equal to the bottom of the respective ranges.

Internal parting lines are possible in parts whose genus is greater than zero as shown in fig 10. In such parts the internal parting lines are handled in exactly the same way as the external (i.e. the outermost) parting line since they are also represented as a series of nodes joined by line segments.

➤ Sometimes it is desirable to shift the parting line by a small amount, up or down, to intentionally create an undercut. This produces a self locking of the part inside the mold to assure that the part stays with the mold half which contains the knock-out pins when the mold is separated. This option has **also** been incorporated by using the information contained in the parting line. The shifting of parting line, by the desired amount, is accomplished by recalculating positions of the nodes with *zero* range (fig 11). This is so because these nodes lie at the boundary of plus and minus patches and simply shifting their position up or down will make them lie *outside* the part, which is a physically impossible situation. Hence these nodes are shifted in such a manner that they lie *on* the part even after the shift.

Other nodes are left as such since shifting them does not necessarily create

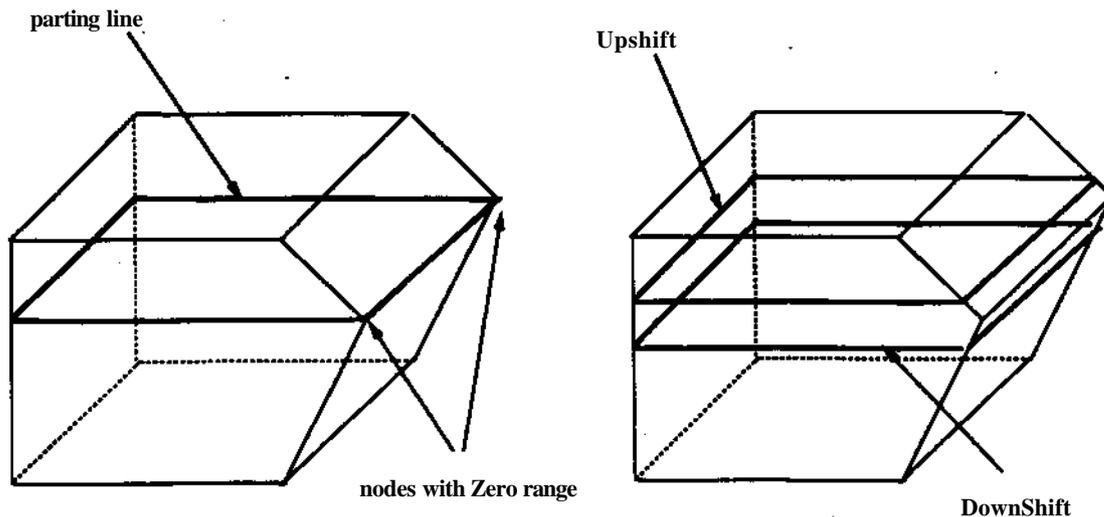


Figure 11: Shifting of parting line

an undercut. However, if a flat parting line is shifted, effort is made to restore its planarity at the new level.

4 Parting Surface Design

The next important step in this system is to design *parting surfaces*, which serve to connect the parting line to the base frame of the mold. This problem is trivial for a flat parting line since in that case the parting surface is the frame itself. However, in most of the practical situations, the parting line happens to be a three dimensional closed curve. In this situation, there are several demands that can be made on the parting surfaces. The parting surface is generally required to be at a particular angle⁹ with respect to the draw direction, **for** ease of ejection. This is more important in the RTM system, since these surfaces also need to be sprayed with metal and the difficulty as well as quality of spray is related to the angle at which the spraying is done.

Thus we define this problem as follows:

Design a set of planar faces which connect the parting line to a flat

⁹This angle may vary from 0° to 90°

base i.e. frame, while making an angle θ with the draw direction.

This essentially is a problem of sweeping down the parting line *outward* at an angle onto a flat base frame which is at a level that is less than or at least equal to the lowest node's position, along the draw direction, in the parting line.

4.1 Theory of Cones

The approach to solve this problem is to consider a series of right circular cones centered at each node of the parting line such that—

- Apices of these cones coincide with the respective nodes of the parting line.
- Half angle of each cone is θ , as defined earlier.
- Base of each cone lies on the flat surface, called **base plane**, of the frame.

Thus, different cones along the parting line may have different heights due to non-planar nature of parting line. The idea behind using a cone at each node is motivated by the fact that all surfaces which make an angle of θ with the vertical and pass through that particular node of the parting line will be *tangential* to a right circular cone which is defined at this node in the manner described above.

Now the original problem of parting surface design reduces to finding planes which are tangential to two adjacent cones as shown in figure 12. A series of such planes then form the entire parting surface around the parting line.

As is clear, this approach requires the distinction between internal and external tangential planes i.e. the planes that would lie *inside* or *outside* the volume generated by sweeping the parting line straight down onto the base plane. The parting surface can only be composed of external planes. Also the two adjacent tangential planes at a given cone may:

1. not intersect at all.
2. intersect along a line which is tangential to the cone.

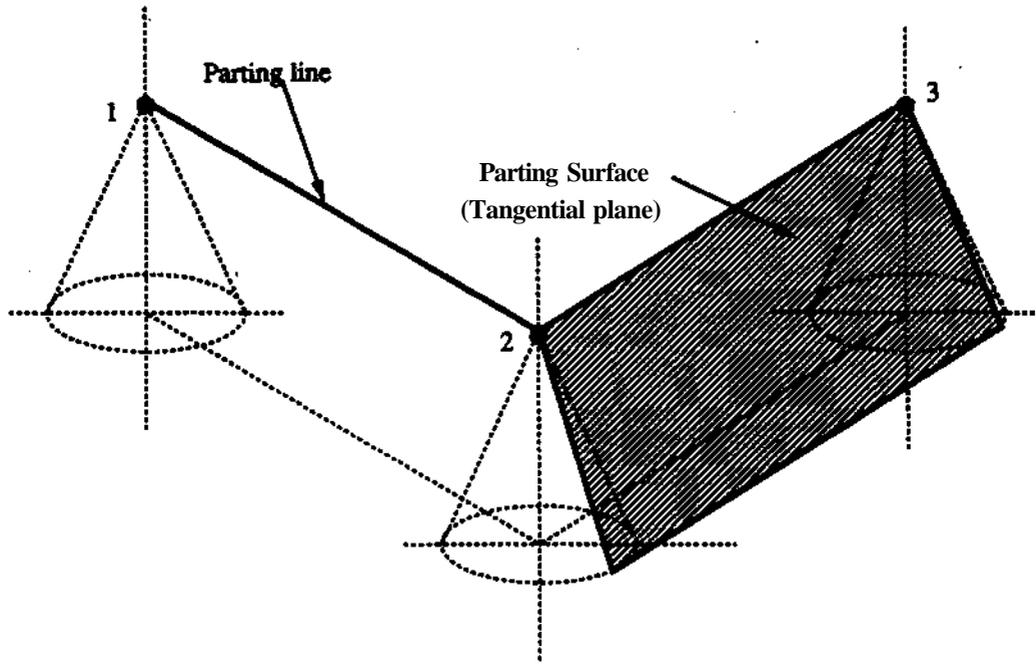


Figure 12: A Parting Surface facet

3. intersect along a line *before* making tangential contact along the cone. Thus the intersection line is *not* tangential to the cone.

4-2 Transformation to $3\mathbb{R}^2$ space

Fortunately, one can easily deal with all these cases in a $3\mathbb{R}^2$ space. If we consider each **tangential** plane as a *line*, along which it intersects the base plane, **and the cones as circles** on the base plane, the lines have to be tangential to the circles. Since two non-concentric circles have at most four tangents (fig. 13), **one has to** choose a tangent to get the desired parting surface.

Clearly the tangents that cross the center line between the two circles are not admissible and these are eliminated from consideration. Out of the two remaining tangents, we choose the tangent which has greater length lying *outside* the bounded polygon formed by taking the projection of the parting line on the base plane (fig 14).

This ensures that the parting surface formed using this tangent will lie

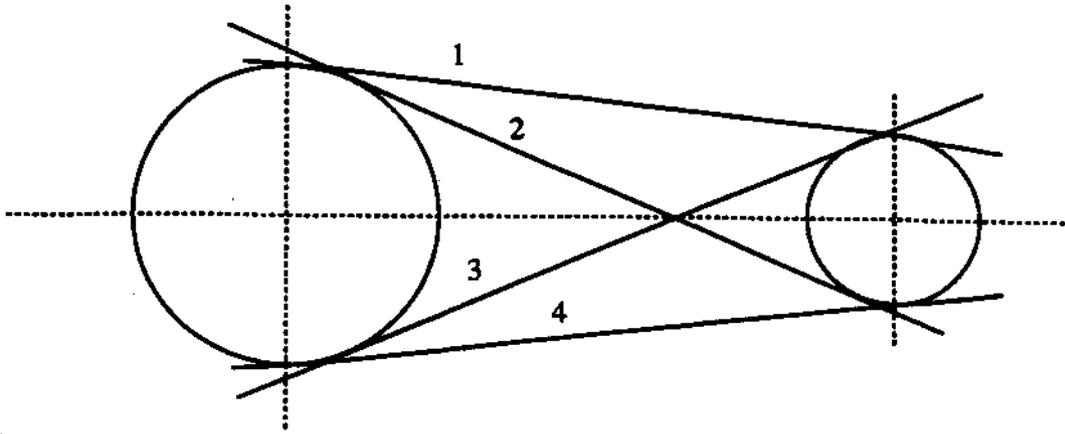


Figure 13: Common tangents for two circles

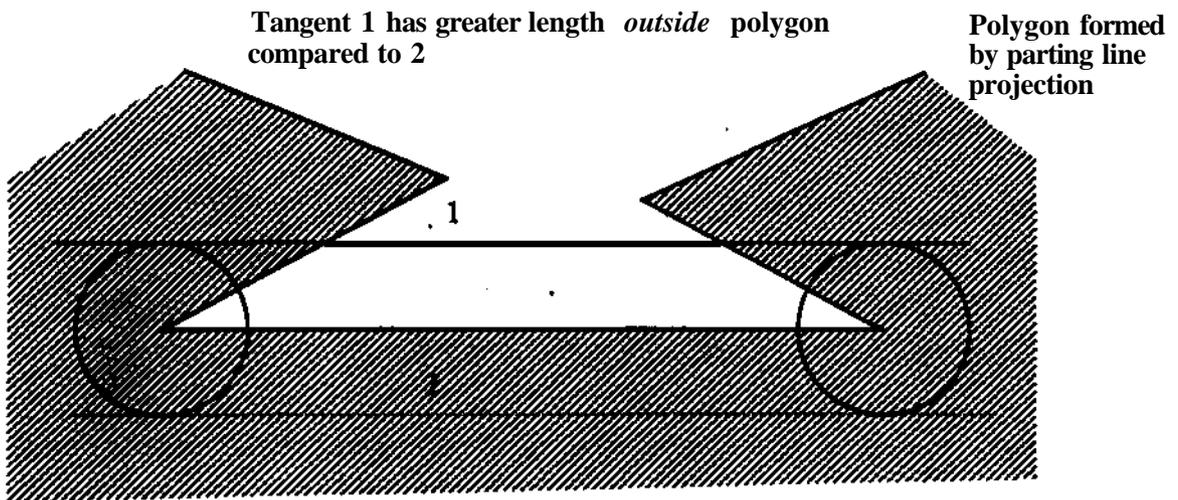


Figure 14: Choosing a tangent

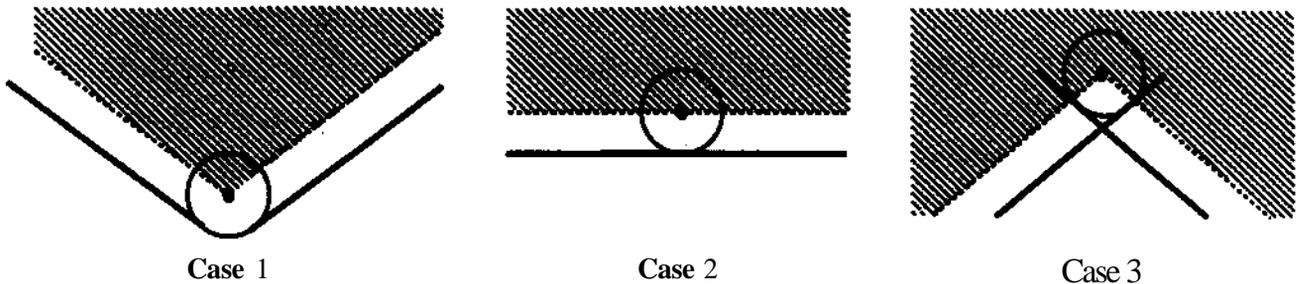


Figure 15: Transforming the cases in $3\mathbb{f}^2$ space

outside the swept volume of parting line.

Now, once the circle tangents are identified, we need to look at three cases which were outlined earlier. In the $3\mathbb{f}^2$ space, the cases are reformulated in terms of two tangents incident on a circle which may behave as follows—

1. They may not intersect at all.
2. Their intersection point lies on the circle boundary.
3. They intersect before making a tangential contact at the circle.

These cases are shown in fig 15.

First two cases are well behaved with respect to our design goals for the parting surfaces. The first case requires a portion of the circle in order to make a smooth transition to the next tangent. This is readily interpreted in $3\mathbb{f}^3$ space as portion of the cone's curved surface. Such a situation is in fact desirable since it smoothes out the sharp corners. This is particularly helpful for metal **spraying** in the later stages of the RTM system. The second case is a perfect **though** rare case, which requires no post processing. The third case, however is a problem case.

Here creation of parting surfaces which satisfy the angle criterion is impossible. The user can be informed that the guarantee of parting surfaces being at a particular angle with respect to the draw direction will be violated here. A more practical solution to this problem is to tackle this problem during actual creation of parting surfaces. Each tangential plane is actually created in terms of two triangular faces which are adjacent to each other along the diagonal of

the plane. In case 3 situations, consider a line l joining the intersection point of the two tangents to the node i.e. apex of the cone. Now when the triangles are created around this line l , the two triangles on either side have an angle different than θ with respect to the draw direction. However, in most practical cases this deviation is negligible and thus by compromising a bit on the angle requirement, a feasible parting surface can be obtained.

Another important feature of the parting surface design includes the ability to detect if a parting surface has run into some other surface created earlier. This is due to capabilities provided by the geometric modeling system which notifies the user of such inconsistencies during the creation of the model of parting surfaces. In such situations, the designer is advised to try again with a reduced angle requirement.

4.3 Special Cases

When the angle requirement on the parting surfaces is $\theta = 0^\circ$, the parting surfaces can be trivially generated by sweeping the segments of parting line straight down. Here the cone at each node degenerates to a straight line with base having a zero radius.

Another special case is for $\theta = 90^\circ$. This can be supported in case of flat parting lines only. In such cases, the parting surface turns out to be a flat plane perpendicular to the draw direction. For a three dimensional parting line it becomes a degenerate case of a right circular cone whose half angle is equal to 90° , which is not possible.

4.4 SLA Pattern Creation

Once the parting surface is designed, it exists as a free standing structure. The surfaces and the frame can be merged together with the part taking advantage of *nODdes* non-manifold capabilities and a solid pattern ready for spray can be generated. It can also be treated as a pattern for a mold cavity. However, runner and gating system needs to be integrated into the pattern. Current plans for runner and gating system include creation of a library of

standard runner and gate shapes. User would be able to pick a particular type of runner and gate at various locations and develop the entire system. In future, it is expected that a lot of process and geometry constraints would be incorporated to automatically decide the best runner and gating system for a particular mold.

Some examples are presented in the next section which illustrate the concepts presented here. The parting surfaces and patterns generated for some complex parts are shown.

5 Examples

Figure 16 shows a fan which is used in a variety of small scale cooling applications. Here a flat parting line is impossible and hence a parting line is generated which minimizes the variation (in height) from one point of parting line to the next as explained earlier in fig 9. This parting line is fairly complex as it follows the contours of fan blades. Parting surface model is generated from the parting line and is then merged with the original model to form the pattern for thermal spraying in the Rapid Tool Manufacturing System[5]. Figure 16 shows the fan, its parting line and finally the pattern.

Another example is presented in figure 17. It is a sidemarker lamp housing of a car. The original data for the part is a set of NURB¹⁰ surfaces which is linearized for use in *nODdlts*. These complex industrial parts tend to have inconsistencies in directions of face normals, called noise, due to errors in original data generation and representation. This noise predominantly consists of a *very small* plus (or minus) patch surrounded by a big minus (or plus) patch. To eliminate this noise, these small patches¹¹ are merged into a surrounding bigger patch which has the longest adjacency with "noise". Care is taken to avoid treating valid patches as noise. The parting line and pattern, ready for spray, are shown in figure 17.

¹⁰Non-Uniform Rational B-splines

¹¹whose projected areas are of the order of 1 mm^2

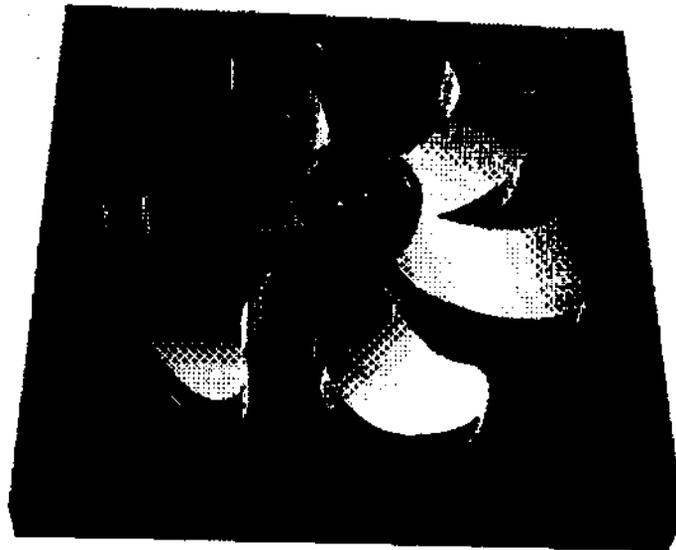
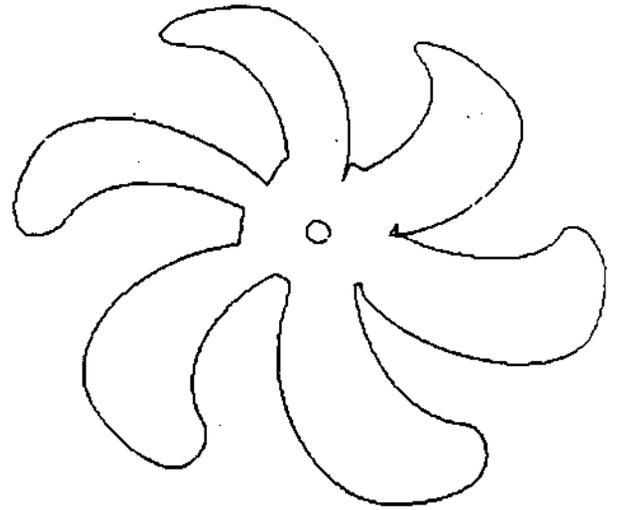
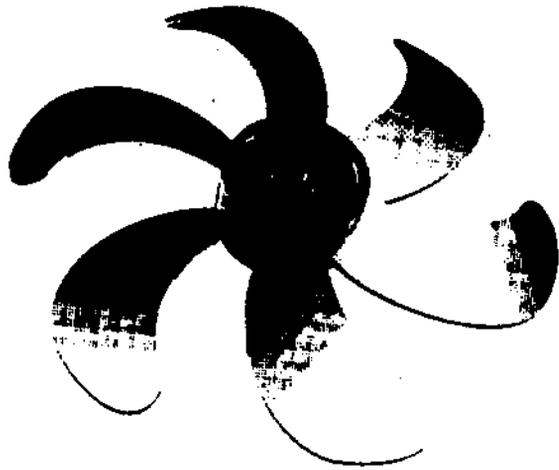


Figure 16: Parting line and surfaces for a fan

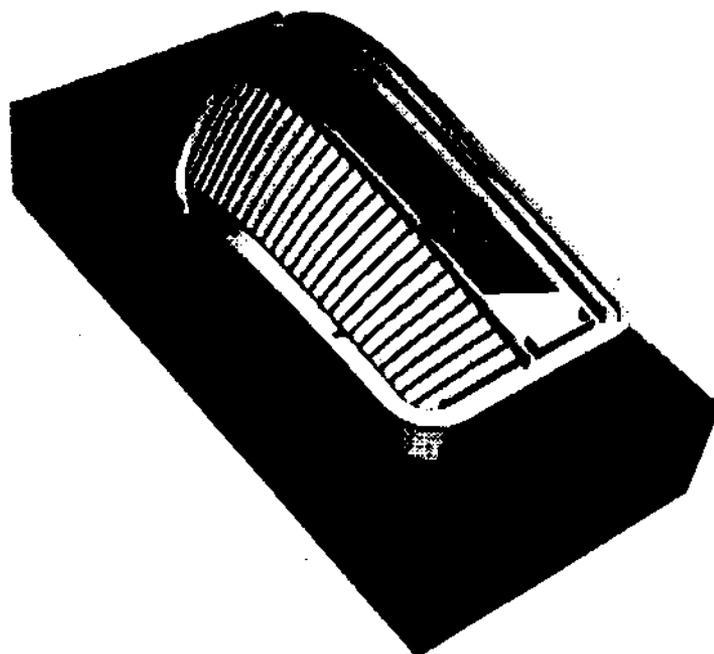
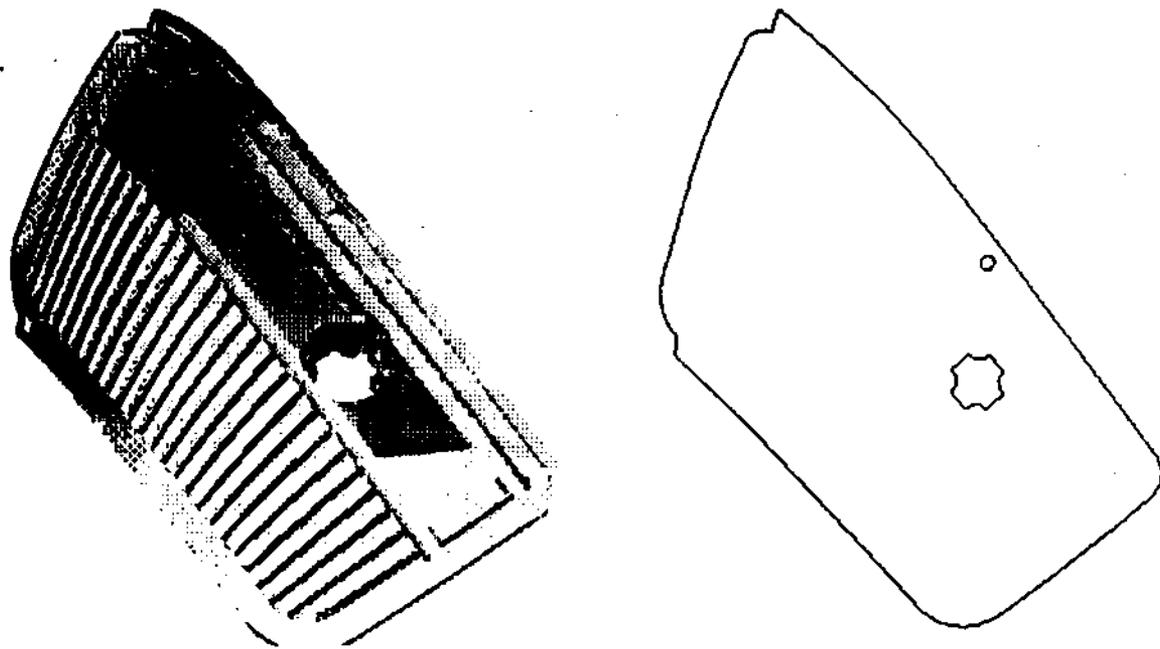


Figure 17: Parting line and surfaces for Side Marker Housing

6 Conclusions and Future Work

This report presents an approach to analyze ejectability for components manufactured in molds or dies and to automatically **design parting** line and surfaces. At present molds are supposed to have two **mold halves** with no moving parts i. e. undercuts are not allowed in ejectable **parts**. Application of this work to a rapid tool manufacturing system has also been illustrated. Future work will include analysis of slide actions in case of parts with undercuts. Since the problem is localized by identifying the patches which cause unejectable situations, one should be able to develop on this information. Integration of process constraints in the design of runner and gating system as well as other parts of the program is also highly desirable.

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