RAPID PROTOTYPING BASED ON CNC MACHINING

A Thesis

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by

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CHAPTER I

RAPID PROTOTYPING TECHNIQUES: A SURVEY

1.0 Introduction

An activity that is critical during the stages of design and production is prototyping. Though technically the term prototype could be interpreted as "the first of its kind", prototype has come to mean many different things. For the developer of commercial satellites, the prototype may be the final product. At the other extreme, the development of a new ballpoint pen may involve more than 10 prototypes before the design is finalized. Prototypes may be used to assess styling, to perform life testing, or to verify fit. In most cases though, prototypes are used differently at different stages. At the design stage, a prototype might be made to help visualize a product, to predict its performance characteristics, or to check sources of interference. For manufacturing, a prototype is used to test and verify a process; in fact, the manufacturing process itself may become a prototype at some point. Thus, a prototype must fulfill a particular need at a particular time.

In recent years, the term Rapid Prototyping has been used to refer to those techniques that permit the rapid reproduction of conceptual designs into three-dimensional objects. Today, the commercially available systems can be classified into two major approaches: photopolymer-solidification systems, pioneered by 3D Systems (stereolithography); and material-deposition techniques, such as fused deposition. These processes are highly automated and relatively fast. The prototypes produced by them provide good visualization tools and in some cases can be used to fabricate tooling.
1.1 Rapid prototyping methods

Over the years, engineers have used scaled models built by craftsmen to predict the performances of their designs. These craftsmen can still be found in places such as foundries where patterns for molds are made out of wood and clay. This is the most traditional way of prototyping. Perhaps it is also the slowest and, without a doubt, the most difficult to master. Recently, this task has been given to the computers, in the form of CAD solid modeling. However, the term Rapid Prototyping surfaced with the advent of a series of techniques, which use a shaping deposition process to build three dimensional shapes by the incremental material buildup of thin layers. Today there are at least eight commercial firms that offer rapid prototyping systems (see Appendix A). Conceptually, the market can be split roughly into two major approaches. In widespread use are the photopolymer-solidification systems pioneered by 3D Systems and a variety of competing methods. A second approach is made up of various materials deposition techniques to fabricate parts, such as Fused Deposition. Among the most important techniques are:

a) Stereolithography;
b) Laminated Object Manufacturing;
c) Selective Laser Sintering;
d) Fused Deposition;
e) Three Dimensional Printing;
f) Ballistic Powder Metallurgy;
g) Photochemical Machining;
h) Light Sculpting;
i) Spray Deposition;
j) Shape Melting;
k) Rapid Prototyping via CNC Machining.
The first ten techniques will be reviewed in this chapter, while the last one will be reviewed in the following chapters. As will be shown, each one of these techniques has its own advantages. Furthermore, it will be evident that, in the end, the purpose of the prototype will define which technique is best for a certain application. Rapid prototyping via CNC machining will be treated in detail in the following chapters because it is the technique that best matches the purpose of our prototypes. This purpose will be defined at the end of the chapter.

1.1.1 Stereolithography

Perhaps today's leader in the rapid prototyping business is 3D-Systems Inc. Founded in 1986 by Raymond Freed and Charles Hull, 3D-Systems engineered the ultraviolet laser/photopolymer-based process technology during 1987. By 1988 shipments of the first Stereolithography Apparatus (SLA) began and by 1990 revenues had reached $30 million. Impressed with this growth and attracted by the potential of the technology, Ciba-Geigy Ltd. (Basel, Switzerland), a chemical company that is a major supplier of photopolymer resins, ventured into the market. Today they own 38 percent of 3D Systems.

According to 3D Systems, about 300 SLA systems have been ordered by business in the automotive, aerospace, medical, and electronics industries. Approximately 250 of them are operational. An SLA system consists of a vat where photosensitive liquid resin is held and where the model is to be fabricated, an elevator system which lie inside the vat, and a Laser light source (Fig. 1). The motions of the elevator and the laser are controlled by a computer.

Stereolithography starts with a solid or surface CAD model of an object that is down loaded to a slicing algorithm, which cuts the CAD model into layers between 0.005" and 0.020" thick. The sliced model is then used to program the actual fabrication of the part.
The fabrication starts with the elevator platform resting just below the liquid surface, allowing a thin film of resin to lie on the surface of the platform (the thickness is equivalent to that of the slices of the CAD model). An ultraviolet laser beam is then deflected in the x-y axes by galvanometer-driven mirrors in such a way as to reproduce the shape of the corresponding slice in the CAD model. The resin solidifies when exposed to light. After a layer is built, the elevator drops a programmed distance so that a new coating of liquid resin covers the solidified layer. A wiper blade then sizes the coating depth. Next, the laser draws a new layer on top of the first one. The process of stacking layers is repeated until the whole part is completed from the bottom up. The diameter of the laser beam (0.010") is usually small compared with the cross sectional area of the part, therefore, in order to speed up the process, not all of the resin which composes each layer is initially solidified. Rather,
the final part is more like a honeycomb which traps liquid resin within solid walls. After processing in the SLA, the part is cured in an oven to complete the solidification of the resin. The whole process takes on the order of hours to complete. During the whole operation, humans are required only to define the best position for the part to be manufactured. This is done before the part is sliced. After this, the SLA can work unattended. Depending upon the complexity of the part, a prototype 3 X 6 X 4 inches can be completed in 6 to 8 hours. Post curing usually takes less than 30 minutes.

According to some sources (2), the achievable tolerances by the early models was rather poor: +/- 0.010" for the first inch and +/- 0.005" per inch thereafter. The most important factors which affected the accuracy were the curing discrepancies (which include the error that the size of the laser beam introduces, as well as the need for excess material to support the part at the bottom), and the material shrinkage in the post curing operation which is on the order of about 6% in volume (1.8% linear). However these figures could be improved by fine tuning the process (which requires some experience), by increasing the material hardened in the initial stage, or by finishing the part by conventional processes.

Recently, 3D Systems introduced a new part building technique called Weave, which improves dimensional tolerances (up to +/- 0.005" overall). With this technique, more resin is solidified in the vat to reduce distortions due to post-curing.

Several sources claim different properties for the solidified resin (see Appendix A). Although these parts are good for visualization, the reality is that today they are too brittle for most end-use applications. Perhaps the most important practical application is that of the quick development of prototype tooling using patterns created by Stereolithography. Types of molded tooling that work well with SL masters are epoxy tooling, tartan tooling, silicone rubber tooling and Acrylic tooling. A promising technique is being developed right now at Carnegie Mellon University using an SL model along with sprayed metal to produce dies
(3). This technique has been used at the Westinghouse Science and Technology Center (45). In all cases, the SL prototype is used as a pattern and is covered by different materials in order to produce dies.

The two major issues around this technique are thus the improvement of the achievable tolerances and the development of new resins to provide better physical properties. A considerable amount of research is focused on these two topics, and in the near future major developments are expected in these areas. In fact, chemical companies have shown a great deal of interest in the development of these techniques, due to the fact that they see a potentially large market for new materials. This has caused them to invest in the field in ventures such as 3D Systems-Ciba Geigy.

Several other vendors offer systems that are very similar in principle: DuPont/Somos Venture, Quadrax Laser Technologies, and Light Sculpting Inc., all of them in the United States. The similarities in their systems has caused a series of law suits for violations of the patents claimed by 3D Systems. The uncertainty that this has created has stopped the introduction of similar systems by Sony Corp. and Mitsubishi Corp. (Tokyo) in the United States.

Another commercial system that is worth mentioning is the one developed by Cubital Ltd., an Israeli/German company formed in 1987. The system that they have developed is said to be robust and capable of high throughputs, making it well suited to high volume use. The basic principle is the same as the one used in Stereolithography, as far as the material and its photosensitivity are concerned. Ultraviolet Light is provide by a Lamp in 2 seconds-bursts. The process though, is a little different, in that it involves an extra stage after the slicing of the CAD model. This stage calls for the creation of a "negative" reproduction of each slice in what is called a Mask Generator. Another difference is that wax is added after each layer is created in order to support the structure being built. Finally,
the surface of the part is milled after each layer is created in preparation for the next layer. No post curing of the finished model is needed. Tolerances of 0.1% of the dimensions in X-Y-Z are achievable by this technique. By the end of 1991 four systems had been sold in the United States.

Summarizing, stereolithography provides a means for the physical representation of parts. Among its advantages are that the process is fast and highly automated, and almost any geometry is achievable. On the other hand, the achievable dimensional tolerances are rather poor, and the materials are too brittle to allow the parts to have significant functional properties. These problems, along with the potential to produce tooling with SL prototypes, are the major areas of research for the near future.

1.1.2 Laminated object manufacturing

Laminated Object Manufacturing (LOM) is a Rapid Prototyping technology which builds 3-Dimensional parts by Laminating and cutting material in sheet form. LOM is under development by Helisys, Inc. of Torrance, CA (formerly Hydronetics). A similar process, still far from commercialization is being developed by Landfoam Topographics of Needham, Massachusetts (5).

As with most other systems, the Helisys software slices 3-D CAD models into thin cross sections. The slices correspond to the thickness of the sheets that will be stacked to form the object. To manufacture parts, the LOM system sequentially bonds a layer of 0.002 to 0.010 inch rolled sheet material (plastic, paper, foil, or glass or fiber composites) to a stack of previously formed laminations and then cuts it to shape with a 40-watt carbon dioxide laser beam that is tuned to a depth of one lamination. The scanning beam follows the perimeters of CAD-generated part cross sections like a laser cookie cutter. Parts of up to
15 X 10 X 15 inches can be constructed with accuracies of +/- 0.005 inch. The use of sheet materials means that models do not shrink or distort.

![Diagram of LOM machine](image)

Fig. 2: Schematic of laminated object manufacturing machine (From ref. 5).

Figure 2 shows a schematic of an LOM machine. Sheet material is supplied from a continuous roll on one side of the machine and taken up on the opposite side. Beneath the sheet is a platform on which the block is fabricated and which can be moved vertically under computer control. The beam from a continuous-wave CO2 laser is reflected sideways by a mirror and down toward the material surface by a moving head. The head, containing a mirror and focusing optics, moves along both horizontal axis (parallel to the layer) under computer control. A heated roller is located above the paper on a linear stage.
Not shown are a device for measuring the height of the block and the computer that slices the CAD model and controls the process.

When material is to be cut out of the center of the part, it can be removed immediately by an automated vacuum after each layer is formed or the material can be left inside to support subsequent laminations.

The vendor of this system claims the following advantages of LOM over other Rapid Prototyping Techniques:

a) *Low production times:* The reason is that LOM uses a subtractive method of layer formation. Material is removed to create a layer with the required cross sections, whereas all other systems create layers by addition of material. The effect is more noticeable when building parts having a high ratio of volume to surface area.

b) *Parts are less fragile and more dimensionally precise:* Since the part is supported by a form fitted block of material, the entire geometry is stabilized during building and is prevented from distorting under its own weight. There is no need for specialized supports when making "islands". In addition, the laser is X/Y staged and not directed by rotating mirrors, thus reducing distortions. Additionally, shrinkage is not an issue, and dimensional changes produced by the heat of lamination can be reduced by using low expansion, low moisture content materials.

c) *Materials are cheaper:* Usually materials tend to be inert and non-toxic. Given suitable adhesives, materials ranging from paper to plastic to metals can be utilized.

Finally, layers of different materials can be bonded to produce one part.

The most important disadvantages of this system are:

a) *Unwanted adhesion:* Cleanup is a manual process needing care to ensure that only waste material is removed and delicate sections of the part are not fractured.
b) Material removal: Because of excess material trapped within the walls, a hollow structure with closed surfaces cannot be fabricated as a single piece.

c) Waste: Typically, the majority of material consumed by LOM does not contribute to the part itself. Rather, it remains with the original continuous sheet or ends up as support material, to be scrapped after building.

d) Safety: Laser cutting produces smoke and/or fumes, depending on the material. Therefore, a good filtration system or external venting is required.

e) Laminar structure: Since parts are made from alternating layers of material and adhesive, many of their physical properties are inhomogeneous and anisotropic. Further, delamination of the finished part under stress is possible, because of failure of either the material or the adhesive.

Today, beta units cost $75,000; future commercial versions will be priced at $100,000. The attention is now focused on the solution of the shortcomings of the technique. To avoid unwanted adhesion, several methods for applying adhesives are under investigation; parts which trap support material can be assembled from multiple pieces. In order to reduce waste, software that will reduce the space between parts is also being developed. Better materials with stronger adhesives can be developed specifically for LOM. Finally, new ideas on multi-colored aesthetic and visualization models are being surveyed.

1.1.3 Selective laser sintering

Originally developed at the University of Texas, the license for its commercialization belongs to DTM Corp. from Austin, Texas. In this technique powder particles adhere to each other under the influence of external energy. This energy becomes heat, which causes the viscosity of the particles to drop. When this happens, surface tension overcomes viscosity, thus allowing particles to adhere to each other.
What makes this technique so unique is the rather wide variety of materials that can be bonded by sintering, such as polycarbonate, poly-vinyl chloride, investment casting wax, and soon nylon and acrylonitrile butadine stirene plastic (ABS). In the near future it is expected that composite materials made out of metals and ceramics might also be processable by this technique.

Fig. 3: Schematic of operation of model 125 SLS system (From ref. 6).

Figure 3 shows a schematic of the Model 125 Prototype System, which is being improved for commercial application (6). As in other processes, the SLS system starts with a CAD model of the piece, which is sliced into thin layers and, if needed, it can be scaled to
fit in the workspace volume of the equipment. This work space is defined by an empty cylinder with an open top. A piston furnishes a single layer of powder; following this, a roller spreads the powder evenly on the surface of the cylinder. At this point, infrared heaters remove thermal induced stresses from the powder, and an inert gas fills the chambers in order to control laser-induced powder combustion. The powder is then raster scanned by a high power laser beam in such a pattern as to reproduce that of the lower layer in the CAD model. Temperatures reach 150 °C during the fusion of the particles. After this layer has been solidified, the process is repeated for each subsequent layer, until the part is finished. When the process is completed, the unsintered material is removed to expose the finished part. Models are usually built in layers of 0.005", and DTM claims that accuracies of +/- 0.001" are achievable through this process. The SLS system shown in Figure 4 costs between $300,000 and $400,000.

The most important applications for SLS are expected to be in three areas: model making by designers, batch manufacturing of low volume parts, and production of molds and patterns for large production of castings.

Currently, a version of the system, capable of fusing metal and ceramic powders, is being designed at the University of Texas. The purpose is to expand the range of materials that can be processed by SLS. Among the materials under investigation one can find copper-tin alloys and an alumina-ammonium phosphate powder which forms a glassy ceramic composite which could be used for investment casting molds.

Future work will focus on powders made out of aluminum and tungsten carbide-cobalt. Work will also have to be concentrated on the improvement of the surface finish of the prototypes as well as in the reduction of the porosity of these prototypes.
1.1.4 Fused deposition

The commercial system based on Fused Deposition is called 3D Modeler and is being sold by Stratasys Inc. at a price of approximately $180,000. The system consists of a modeler, slicing software and a Silicon Graphics Unix workstation, and is capable of producing parts of up to 12 X 12 X 12 inches size.

The system is capable of slicing 3D wireframe, surface, or solid CAD models into layers of between 0.001" and 0.050" thick. Each layer is reproduced as follows: a spool of 50 mil thermoplastic filament feeds into the unit's heated extruding head, just like a wire would feed into an automatic welder. Inside, the filament is melted by a resistance heater at a temperature of about 180 °F. The head moves in the X-Y plane according to a CNC program generated by the software; at the same time it delivers the thermoplastic material
through its nozzle. Again, each new layer is deposited on top of the previous one after the
surface is lowered in the Z direction.

Currently, the available materials for processing are machinable wax, smooth
investment casting wax, and tough nylon-like thermoplastic material with a proprietary
formulation. The achievable tolerances are claimed to be of +/- 0.005", however, speed is a
function of the degree of precision required, therefore, longer processing times are needed
for better accuracies.

Currently under development is a new set of materials which includes a silicone rubber
sealing type, an automotive body foam type, and a transparent version of the nylon-like
type. Future work will also include the improvement of the surface finish and strength of
the prototypes.

1.1.5 Three dimensional printing

Three dimensional printing is a rapid prototyping technique currently being developed
at the Massachusetts Institute of Technology. The process has also been called Free-Form
Fabrication.

The fabrication of a prototype starts again with a computer model that is sliced. The
resulting 2D geometries are then reproduced using a technology similar to that of ink-jet
printing. A schematic of the process is shown in Figure 5. The manufacturing process of
the physical object starts when a layer of a powder is laid on the surface of a piston head.
Following this, a binder material is applied in a raster-way as to reproduce the shape of one
of the layers in the computer model. The piston is lowered and the operation is repeated
until a stack of layers forms the complete part (7).
Fig. 5: Schematic of three-dimensional printing process (From ref. 7).

Typical powder materials include silica, alumina, zircon, zirconia, and silicon carbide. A typical inorganic binder could be colloidal silica (8). The two most important potential applications of this process are:

a) Fabrication of ceramic cores and shells for metal castings;

b) Fabrication of porous ceramic preforms to be infiltrated with liquid metal to produce metal-ceramic composite parts.

The research team at MIT reports to have produced parts of up to 40 X 40 X 15 mm (1.57 X 1.57 X 0.59 in) (8). The achieved part bending strength ranged between 12.3 and 18.7 MPa, which is considered suitable for investment casting. For a piece of 38 mm, part
to part dimensional control was within +/- 20 micrometers, and dimensional variation was within +/- 13 micrometers overall (these figures are only good for reference, since the parts are relatively small).

In order to increase knowledge on the process as well as enhancing the equipment design, the team is currently investigating several topics, such as the interaction of binder and powder, print modulation technology, printhead transport, powder decomposition, and automation control. A goal is to produce a version with a 100-nozzle print head capable of building parts up to 12 X 12 X 24 inches.

The commercialization of this process has already begun. Soligen Inc., of Northridge California, has obtained a license to investigate the application of this process for metal casting.

1.1.6 Ballistic manufacturing process

Currently under development by Perception Systems Inc. this system resembles inkjet printing. The basic principle is the same as in all of the other techniques. The system interprets the CAD model cross sections and reproduces them by spraying their patterns onto a worksurface with fine jets of molten wax. Each layer is deposited on top of the previous one until the part is created. As the wax layers are created, support structures for overhangs and voids will be built from polyethylene glycol. The part is washed in a warm water bath that will dissolve the supports away.

The system is expected to be used by investment casters and design engineers. A working prototype is scheduled to be available within eighteen months, and its commercial version is expected to cost about $50,000.
1.1.7 Photochemical machining

This was perhaps the first of all the Rapid Prototyping Processes to be researched. Battelle of Columbus, Ohio, and Formigraphics Engine Corporation of Berkley, California, investigated this technique during the 70's. However, Formigraphics discontinued all of its work on this technique during the 80's, and Battelle concluded that several years of extensive research would be required to bring this process to the market. Apparently, no sponsor for further research has been found.

The process is very similar to Stereolithography, but it uses two laser beams instead of one. The idea is to polymerize the material on two different planes, XY and YZ, in order to produce three dimensional solidification of the polymer.

The major topics for research are the quality, speed and efficiency of the laser beam. Along with this, new polymers that do not cure when exposed to a single light have to be developed.

Although this process offers a tremendous potential, the technological barriers imposed on its development will keep a commercial photochemical machining system off the market in the near future.

1.1.8 Light sculpting

This process was developed by Light Sculpting Inc. (Milwaukee) in 1986 and is similar to the Stereolithography technique. In light sculpting a liquid polymer is solidified, one layer at a time, by irradiating an entire layer of polymer through a photomask.

The commercial system is labeled LSJ-069MA. It consists of a 140 watt ultraviolet lamp which irradiates an entire layer of liquid acrylate photo-polymer through a photomask, in a process which is similar to the printed circuit board (PCB) fabrication: the mask, which is a negative image of the slice cross section, is produced by using a photoplottter to transfer
the inverse image from a solid or surface CAD model to the masking plate. Transparent and opaque patterns on the photomask correspond to the solid and hollow portions in the slice respectively. The irradiating surface is supported from above by a rigid glass plate, positioned below the mask. A key to this technology is a proprietary material on the bottom surface of the glass plate. When this plate is placed in contact with the unexposed liquid surface of the photopolymer, the material preserves the cross linking capability of the surface polymer so that the subsequently deposited polymer layer adheres to the irradiated surface. The special material also assures that the glass can be removed without distorting the solidified slice.

The functional properties of the part are the same as those of a part made by stereolithography. The resolution of the system is claimed to be within 0.0025" and 0.0015" for a 0.001-0.050 " thick layer. The LSI-0690MA can make parts up to 6 X 6 X 9 inches and costs about $75000.

1.1.9 Spray deposition

This method is in reality an application of stereolithography and is currently being developed at Carnegie-Mellon University. Its purpose is to build prototype dies and molds that can be used in test runs.

In this process, a part previously made by stereolithography is used as a pattern to create a cavity. A metal is sprayed on the part until a shell thick enough to support itself is formed around the pattern. At this point the part and the shell are separated. The shell is placed in a container in such a way as to expose the cavity on one of its faces. The container is then filled with an epoxy or a ceramic that provides a support for the shell. At the same time this backing material provides a body for the die or mold.
At present, zinc and zinc alloys are used to produce the shell, while a process using a ferrous material is under development. Tolerances are expected to lie between 0.001” and 0.020”. The molds this process makes are useful for small quantity production or for wax pattern making in investment casting.

1.1.10 Shape melting technology

At present, shape melting technology is at a development stage at Babcox & Wilcox. This technique proposes arc welding as a means to produce a part, in such a way that a component can be made entirely out of weld metal. The weld deposits are applied continuously to provide layers of material. Allegedly, multimaterial parts can be fabricated with this process, and any weldable material is a candidate to be used for this purpose.

1.2 Remarks

Rapid prototyping is a technology that has gained importance over the past four or five years. The system that pioneered this field was stereolithography in 1987, but since then a great variety of vendors have developed a number of processes. Today, all of them compete for a share in an increasing market.

All of these systems are similar at least in one aspect: the extensive automation through computers, from the slicing of the CAD models to the actual fabrication of the parts. This is perhaps their greatest asset, since most manufacturing firms are moving towards full automation of their processes. A variety of materials can also be processed by different techniques, from photopolymer resins, to paper and metals. Another important advantage of these systems is the short time it takes them to produce prototypes. Finally, and perhaps the best quality that these processes offer is that complex geometries can be achieved with relative ease.
On the other hand, two major shortcomings are also common to all techniques. First, the achievable tolerances are usually worse than those required by today's standards in most fields. Second, the functional properties of the parts are rather poor, mainly because of the types of materials that can be processed by these techniques. This has reduced the practical applications of the prototypes to visual purposes only. As a result, most research is being conducted in these two directions, development of new materials with better properties and improvement in the processes to obtain better accuracies without slowing the processes. Following these trends, 3D Systems has introduced two new materials to improve prototype performance: a tough, machinable resin labeled Cibatool XB-5143 which is supposed to be stronger and more ductile than older resins and a safer, more accurate resin, labeled Exactomer 2201. Cubital has also developed a series of photoresins for special purposes with elongations of up to 55%, while DTM announced the introduction of a new nylon material for use in its selective laser sintering process. Reports on their use in industry are not available yet.

Today, the most important practical application being implemented is that of the use of the prototypes as patterns for investment casting molds and tooling, such as dies (3). The processes used for the production of these patterns are Stereolithography and 3D Printing, and they are under research at Carnegie Mellon and MIT respectively. A third process, Selective Laser Sintering offers an important potential for new materials ranging from ceramics to metals, and is currently being researched at the University of Texas.

In conclusion, if the objective of the prototype is to provide a physical model of a product, for the purpose of visualization, and in some cases interference checks, rapid prototyping technologies offer a fast, reliable solution. On the other hand, if the objective is not only to provide a functional prototype of a part, but also to simulate to some extent the actual manufacturing process that produces this part, then an alternative approach must be
chosen. This idea is the motivation to investigate the potential of CNC machining as a prototyping technique. In the following chapters attention is devoted to this technique.
CHAPTER II
RAPID PROTOTYPING VIA CNC MACHINING

2.0 Introduction

In the previous section, a survey of today's most important rapid prototyping techniques was presented. Attention was centered in prototyping methods based on slicing approaches. Although other potential applications are being researched, it was concluded that as of today these techniques provide prototypes that are good only for visualization. Also, the question has been raised as to what is meant by prototype, and it was explained that its definition is a function of the purpose of the prototype. In this chapter, a method whose objective is to overcome the limitations of the rapid prototyping techniques is presented. It is proposed that this method be implemented in the form of an expert system. The most important characteristics of such a system are also explained in this chapter.

2.1 Prototype objective

In our context, we think of a Rapid Prototyping Technique (RPT) as a tool not only for the rapid construction of a prototype part, but also as a means of simulating the actual manufacturing process that leads to the successful production of the part. The idea is to reproduce not only the parts that can be used for visualization, but also to reproduce the actual process that can be used to fabricate the final product. So, what are the alternatives? What RPT could we use to reproduce prototypes and finished parts? Evidently, if the final product is going to be made out of a solidified resin, wax, or some nylon powder, we
should consider using some of the RPT processes previously described. However, in reality, the range of products that are actually made out of these materials is very limited. Therefore, another technique capable of processing more materials has to be developed.

In response to the need for the development of a more accurate prototype of a part and the process required to produce it, we have proposed the implementation of a system for rapid prototyping that uses CNC machine tools. This is done in spite of the fact that the development of new materials has given birth to a whole new era of manufacturing processes and techniques (of which all the aforementioned RPT are examples). However, the capabilities of the traditional machine tools have been enhanced to allow them to process many of these new materials. New ranges of spindle speeds are available; multiaxis control has been introduced; high achievable accuracies and repeatabilities are being improved; new materials for tools have been developed; and finally, almost full automation is possible.

A further argument in favor of such a system is the importance that machine tools play in the development of the economy. A figure that has been used lately to measure not only the competitiveness of the manufacturing industry of a country, but that has been correlated to the standard of living of its society, is the number of machine tools per capita in this country. A proof of the versatility of some types of CNC machine tools is given the widely accepted fact (which is also far from being scientifically proven) that the only machine that can reproduce itself is the milling machine (actually, it can only make its composing parts).

2.2 Strategy for rapid prototyping via CNC machining

Traditional pattern making provides a good example of what a prototyping technique involves. As can be seen in foundries, the pattern maker, will receive a blueprint of the final product which usually represents a complex geometry. Based on his past experience, he will decompose the final geometry into a certain set of features that can be manufactured
in lathes, milling machines, or whatever equipment he has available (Fig. 6). Then he will make these parts out of, for instance, wood. Once the composing parts are finished, he glues them together to form the desired pattern. In most cases, he will complete the part by adding clay to reproduce those features that he could not manufacture in the machine tools. This pattern is then used to make molds for castings. After a trial cast is made, a dimensional checkup is performed in order to obtain information and to make any necessary adjustments to the pattern. This process is repeated until the final cast is within specifications.

![Diagram of part decomposition](image)

**Fig.6**: Representation of part decomposition. A complex part is divided into elements that can be manufactured in the available equipment. These are later assembled to form the part.

Our concept for rapid prototyping is based on the methodology followed by these craftsmen. The basic idea is to create a program that, given a part, will provide alternatives for the rapid reproduction of a finished model of this part. The system should provide a solution constrained by the following parameters:

a) Type of equipment available;
b) Time needed to fabricate parts;

c) Comparison of tolerances between model and final product.

To accomplish this, our system would emulate the process that the pattern maker follows through the use of automatic equipment. Table 1 relates the process that the pattern maker would follow, and the corresponding action that our system would perform.

From this table, we can describe the process that is to be followed for the completion of a part. The sequence starts with a computer model of the finished object. An expert system analyzes the geometry and recognizes those features that are manufacturable by CNC equipment. The system then decomposes the part into these features and assigns proper dimensions and tolerances to them to achieve the required dimension on the final product. At this stage, the proposed solution has to be evaluated to compare it with other possible solutions, in terms of cost, for example. Once the best solution is found (if one exists) the parts can be manufactured in available equipment. The part is completed by assembling the different pieces.

From this discussion, we can extract the issues that will affect the proposed rapid prototyping technique. They are:

a) Computer representation of a part, feature recognition, and extraction of manufacturable features;

b) Automatic assignment of economically achievable tolerances;

c) Machine tool related issues, such as CNC program generation, number of setups, and fixturing requirements, all of which affect the time and consequently the cost of implementing such a solution.

To effectively reduce the development time of a solution, the proposed method requires the use of knowledge based techniques (or expert system techniques). A computer program will then be responsible for extracting the manufacturable shapes, thus trying to imitate the
process that a craftsman would follow. The output of this research should then be such a computer program.

Table 1: Comparison of tasks performed by a craftsman and the corresponding actions taken by an automated system.

<table>
<thead>
<tr>
<th>STEPS BY PATTERN MAKER</th>
<th>AUTOMATIC ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Blue print of part is issued to human</td>
<td>A computer model of part is furnished</td>
</tr>
<tr>
<td>2) Identification of those features that can be made on available equipment</td>
<td>Feature recognition and extraction from model; Automatic part decomposition as a function of available equipment; Assignment of tolerances to features, limited by cost and finish dimensions of part;</td>
</tr>
<tr>
<td>3) Process plan is designed</td>
<td>Process plan is generated</td>
</tr>
<tr>
<td>4) Fabrication of elements</td>
<td>CNC fabrication of features</td>
</tr>
<tr>
<td>5) Assembly</td>
<td>Assembly</td>
</tr>
</tbody>
</table>

Once this system is complete, it could easily be modified to be used in the development and fabrication of EDM electrodes or even in the manufacture of patterns for casting. In the case of the electrodes, they can be used to produce dies and molds, which can in turn be utilized for an actual production run. This is an example of how a prototyping of the process may be accomplished. Researchers at Carnegie Mellon University have used a similar approach by combining stereolithography and sprayed molten metal (3).
At this stage, this method offers the following advantages:

1) Flexibility to use any machinable material;
2) Tolerances comparable to those of the real component can be achieved;
3) Comparable surface finishes should also be achievable;
4) Multiple prototypes of the same part should be interchangeable;
5) CNC coding for the prototype might be used for production of the actual part;
6) The use of available equipment reduces the need for capital investment and training.

2.3 Characteristics of the expert system

An expert system that is capable of performing the tasks for rapid prototyping should have the following characteristics.

2.3.1 Input information

The input to the expert system will be a CAD model of the component. There are available many different representation schemes, and these will be explained in a later chapter. However, regardless of the type of representation scheme used, the CAD model is expected to fulfill the following requirements:

a) The CAD model should be easy to generate.
b) The decomposition of the model must be accomplished with relative ease.
c) Assembly or union of models must be possible.
d) CNC code generation for the part presented by the CAD model must be possible.
e) Modifications to the CAD model must be possible, due to the fact that the expert system will be part of the development process, and therefore frequent changes are anticipated.
f) Geometrical information retrieval from the component model will be needed since the application of rules to divide the component requires geometric information.

2.3.2 Division/Decomposition of part

The decomposition process that divides a solid model requires geometrical and topological data from a CAD model of the component. Surfaces and sections of the component that are not machinable by the available equipment must be recognized. Then, the model should be decomposed in such a way that the resulting parts can be reproduced in the available machine tools. Decomposition is thus a function of the manufacturability of the recognized features. In turn, manufacturability is related to the types of achievable geometries by a given machine tool, and their effect on the selection of the required tooling and fixturing. In Chapter 5 some of this will be explained for the case of a milling machine.

2.3.3 Joining of the parts

In order to preserve the dimensional integrity of the component, a method for joining the different composing elements must be developed. If needed, the system must provide adequate joining features to the different parts in such a way as to guarantee that the dimensions and surface finishes of the finished component are accomplished. Therefore, a thorough knowledge of the joining method must be provided to the system before the actual decomposition of the part takes place so that the system can take the necessary steps to fulfill this objective.

2.3.4 CNC Program generation

The system must provide the means to reproduce the CNC programs that will actually manufacture the defined parts. This does not necessarily mean that the system must
automatically generate the process plan and CNC coding of the part, but at least it should provide the information in a manner that is understandable by a CAM system. The topic of automatic part program generation is in itself a research issue.
CHAPTER III
ISSUES AFFECTING THE IMPLEMENTATION OF THE METHOD: SELECTION OF
A REPRESENTATION SCHEME

3.0 Introduction

Originally, CAD and CAM evolved independently of each other. As a result, contemporary geometric modelers usually are not integrated directly into CAM systems. In other words, tasks such as manufacturing process planning or group technology (GT) classification cannot be performed automatically by relying on traditional CAD software. The reason for this is that there is a mismatch in the level of abstraction between the information that CAD systems offer and the information that a CAM system requires to perform its tasks.

This fact directly affects our rapid prototyping technique. During the first stages, our program must decompose a complex part into manufacturable features, and to do so, it must be able to extract certain information from the CAD database. The problem of feature extraction and recognition by computer is thus apparent. To perform these tasks, the model of the part must provide a realizable, complete and unambiguous representation of a part. Further, this representation must allow significant querying about important geometric aspects of the object for manufacturing.

Over the years, several types of representations have been used in CAD systems (11). A summary of them is now presented.
3.1 Two-dimensional representations

Traditionally, the information of a part would go from the designer to the production floor in the form of a drawing. These drawings are printed on paper so that two dimensional shapes are the entities utilized to represent objects on a blue print. When CAD systems appeared, their capabilities were adjusted to match these type of representations. Initially, only this traditional form of representing objects was expected from CAD.

Two dimensional drawings (Fig. 7) are still the most common type of representation. A 2D, three-view drawing is usually composed of a plan view and front and side elevations. A part is interpreted as a physical object by simultaneously examining the three views. Today, most commercial systems offer part representation by this technique and, although a person can obtain all the information for a process from these drawings, the reality is that most of the data is not explicitly available. For example, the coordinates of a point cannot be given in simple (x,y,z) coordinates, since the data base contains its location in either XY, YZ or XZ at best.

This type of representation does not suit our demands since the information describing the characteristics of the object cannot be extracted from the data that a 2D database can provide. That is, a drawing represents an object only in the mind of the person who visualizes an object by simultaneously combining the features described by the three different views.

3.2 Three-dimensional representations

As more was required from CAD databases, a new form of representation, 3D drawings, appeared. Basically, two types of 3D representations were adopted: Wire Frame Geometry, and Surface Models.
Fig. 7: Two-D drawing. Three orthographic views plus an isometric view (from ref. 11, pp. 96).

3.2.1 Wire Frame Geometry

In this method, vertices are specified in terms of the three axes (x, y, z). These vertices are connected by lines (usually straight). As opposed to 2D orthographic views, the edges and vertices have three-dimensionality, and the user can inquire about the coordinates of the vertices and the lengths of the edges. However, wire frames are far from being complete representations of physical objects. For one thing, surface geometries and their corresponding impositions, are not present. It is not possible to provide a wire frame of an object with hidden surfaces removed, since there are no surfaces. Important information
that can be used for manufacturing is thus lacking. In fact, in most cases wire frames are ambiguous, and they do not even provide a good visualization aid. In essence a wire frame is just a collection of points and lines which define the edges of objects.

3.2.2 Surface Models

In an attempt to overcome some of the disadvantages of wire frames, some modeling schemes add surface information to the parts. The user enters the vertices and edges as above, but in an ordered manner, outlining or bounding one face at a time. Plane and sculptured surfaces can be selected. Even cylinders and spheres can be chosen as surface examples. In the case of sculptured surfaces, irregular shapes can be used to fit legally connected vertex-edge loops. Although surface modelers provide an enhancement over wire frames, they still present several drawbacks. The modeler contains definitions of surfaces, vertices and edges, however, it does not store the connectivity (topology) of these entities. The modeler has no information on the part inside or outside. It cannot store the surface normals, and so it cannot establish which face of a surface is looking towards the air and which one is facing the material. Because of this, a surface modeler cannot calculate volumes, moment of inertia, and other mass properties. In fact, a surface modeler cannot guarantee that the designer has described a realizable object.

From this discussion, we conclude that none of the previously discussed techniques provide the information that our system requires. Basically, all of them depend upon human interpretation to describe an object. To overcome the disadvantages that other forms of representations brought about, Requicha from the University of Rochester (12), successfully implemented the concept of solid modeling in the form of mathematical models during the 70's. A description of the techniques that evolved from his development is now given.
3.3 Solid modelers

The purpose of a solid modeler is to provide a computer representation of an object from which mass properties such as volume, surface area, weight, etc. can be obtained. As a result of the work of several researchers, it has been established that a representation must mathematically capture certain properties, in order to qualify as a solid model of an object (13). These properties are:

1. Rigidity: The shape of the solid model must be invariant, and must not depend on the model location or orientation in space.

2. Homogeneous three-dimensionality: Solid boundaries must be in contact with the interior. No isolated or dangling boundaries should be permitted.

3. Finiteness and finite describability: The former means that the size of the solid is not infinite, while the latter ensures that a limited amount of information can describe the solid for computational purposes.

4. Closure under rigid motion and regularized boolean operations: Ensures that manipulation of solids by moving them in space or changing them via boolean operations must produce other valid solids.

5. Boundary determinism: The solid must be bounded, and therefore its interior must be distinctly determined.

Several representation schemes are available (a representation scheme is defined as a relation that maps a valid point set into a valid model). The representation schemes must have certain properties, which will determine its usefulness and validity in geometric modeling. They are:

1. Domain: The class of objects that the scheme can represent.

2. Validity: The set of valid representations or models it can produce. Several types of checks for validity exist.
3. Completeness: Determines the ability of the scheme to support analysis and other engineering applications.

4. Uniqueness: Required to determine object equality.

There are other properties of representation schemes such as conciseness, ease of creation, and efficacy in the context of applications. However, they are not considered formal. There are several representation schemes, some being more popular than others; among them: Half spaces, Boundary Representation (B-Rep), Constructive Solid Geometry (CSG), sweeping, analytic solid modeling, cell decomposition, spatial enumeration, octree encoding, and primitive instancing. Each of them has its own properties, advantages and disadvantages, and most existing solid modeling packages or systems use one or more of the known schemes. Nevertheless, the most widely used are B-Rep and CSG; Sweeping is a distant third. Table 2 shows a comparison of the schemes utilized by several of the available solid modelers. As can be seen, all of them use only one representation scheme, although some of these systems provide two options for the input of the data. The following is a brief description of the most common representation schemes.

3.3.1 Cell Decomposition (CD) and Spatial Occupancy Enumeration (SOE).

Solid objects are decomposed into primitives, or "cells", that may have several types of shapes. However all shapes are topologically equivalent to a sphere. The only combination operator available is "glue". On the other hand, spatial occupancy is a cell decomposition which uses cubic cells of predefined size in a fixed spatial grid. A refinement of a cell size leads to a higher resolution which approaches the definition of the solid body as a series of fixed points in space as the limiting case. The difference between the two is that SOE starts with a 3D space that is divided into small volumes which are classified as empty, full or
Table 2: Comparison of commercial solid modelers. ASM stands for Analytic Solid Modeling (from ref. 13, pp. 350).

<table>
<thead>
<tr>
<th>Modeler</th>
<th>Vendor</th>
<th>Primary representation scheme</th>
<th>User modeling input based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMOD</td>
<td>Auto-trol</td>
<td>B-rep x</td>
<td>B-rep x</td>
</tr>
<tr>
<td>CATIA</td>
<td>IBM</td>
<td>B-rep x</td>
<td>B-rep x</td>
</tr>
<tr>
<td>CMOD</td>
<td>Auto-trol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDM SOLIDS</td>
<td>GE Calma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUCLID</td>
<td>Maita Datavision</td>
<td></td>
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<tr>
<td>GEMSMITH</td>
<td>Vulcan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEOMED</td>
<td>SDRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEOMETRIC MODELING SYSTEM</td>
<td>Graflex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICEM</td>
<td>COC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICM GMS</td>
<td>iCM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Phoenix Data Systems</td>
<td>B-rep x</td>
<td>B-rep x</td>
</tr>
<tr>
<td>MEDUSA</td>
<td>Prime Computer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PADEL-2</td>
<td>Cornell University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PATRAN-G</td>
<td>PDA Engineering</td>
<td></td>
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<tr>
<td>ROMULUS</td>
<td>Evans and Sutherland</td>
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<tr>
<td>SOLID DESIGN</td>
<td>Computervision</td>
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<tr>
<td>SOLIDS MODELING II</td>
<td>Applique</td>
<td></td>
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<tr>
<td>SOLID MODELING SYSTEM</td>
<td>Intergraph</td>
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<tr>
<td>SYNTHVISION</td>
<td>MAGI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIPS-1</td>
<td>CAM-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNIS-CAD</td>
<td>Sperry Univac</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNISOLIDS</td>
<td>McDonnell Douglas</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.2 Half Spaces

By combining half-spaces (using set operations) in a building block fashion, various solids can be constructed. Half-spaces are usually unbounded geometric entities; each one of them divides the representation scheme into two infinite portions, one filled with material
and the other empty. The most widely used half-spaces (unbounded) are planar, cylindrical, spherical, conical, and toroidal half spaces. The main advantage of this representation is its conciseness in representing objects as compared to other schemes. However, it can lead to unbounded solid models, and it is usually difficult to learn and understand.

3.3.3 Sweep Representations

These are generated by the locus of the path of curves and surfaces. Typically their algorithms use translations or rotations for modeling objects. Sweep representations are very effective in modeling constant cross-section or axisymmetric parts. They are unique and unambiguous, but are almost always used in conjunction with other schemes for design representations.

3.3.4 Boundary Representations

One of the two most important and widely used schemes is boundary representations (B-Rep). A B-Rep model is based on the topological notion that a physical object is bounded by a set of faces (Fig. 8). These faces are regions or subsets of closed and orientable surfaces: closed because they are continuous, and orientable because the sides of the surface are distinguishable from each other because of their normals. Each face is bounded by edges and each edge is bounded by vertices. Thus, topologically, a boundary model of an object is comprised of faces, edges, and vertices of the object linked together in such a way as to ensure the topological consistency of the model. Topology is created by performing Euler operations and geometry is created by performing Euclidean calculations.
Euler operators (Fig. 9) provide designers with drafting functionality, at the same time that they ensure the validity of the B-Rep model. Solid models can be built up graphically by incrementally adding individual vertices, edges, and faces to the model in such a way as to obey Euler's Law (Appendix B). Volumetric properties can be computed by virtue of the Gauss divergence theorem. B-Reps are closely related to traditional drafting. In practice, the main advantage of this scheme is that it is very appropriate for solid models of unusual shapes, that are difficult to build using primitives. Examples are aircraft fuselage and automobile body styling. In addition, it is
Fig. 9: Euler's operators used for the creation of topology. See Appendix B for explanation of symbols (From ref. 13, pp. 380).
very simple to convert a B-Rep into a wire frame model, and its algorithms are reliable and competitive with those of CSG. On the other hand, its major disadvantages are the need for large amounts of memory required, because it stores the explicit definition of the model boundaries; and the fact that it is a very verbose scheme for describing the part. Additionally, an interface to CSG is usually required in order to avoid the use of the slow and inconvenient Euler operators that are considered of a lower level than Boolean operators.

Finally, the part data stored in a B-Rep must be interpreted before tool paths for machining can be generated. This process is commonly called feature extraction.

3.3.5 Constructive Solid Geometry

A CSG model is based on the topological notion that a physical object can be divided into a set of primitives that can be combined in a certain order following a set of rules (boolean operations) to form the object (Fig. 10). Primitives themselves are considered CSG models. Each primitive is bounded by a set of surfaces, usually closed and orientable. The primitives' surfaces are combined via a boundary evaluation process to form a boundary of the object, namely its faces, edges, and vertices. A CSG model differs from a B-Rep in that for its topology, CSG does not explicitly store faces, edges, and vertices. It evaluates them whenever they are needed. Although two schemes of CSG are available, one based on bounded solid primitives, and the other one based on generally unbounded half-spaces, the former is by far the most widely used.

The CSG scheme provides an easy way to construct models out of primitives and boolean operations. It is concise and requires minimum memory to store part definitions, by means of a graph. On the other hand, models are slowly retrieved because the graph
has to be read. It is also slow to generate wireframes, that is, line drawings, since the CSG model has to be converted first to a B-Rep. Perhaps its major disadvantage is its inability to represent sculptured surfaces and half spaces. However, intensive research is being done in this area. Finally, CSG has proven to have important application in the design and manufacturing areas. During design, models built by this technique can be checked for interference before a final dimension is established. In manufacturing, the results of the machining operations can be simulated by subtracting from the model of an object those primitives that correspond to features that are manufacturable in milling or turning operations.

References (11), (12) and (13) provide detailed information about the implementation of these computer techniques, that is, about the mathematic concepts behind them.
3.3.6 Hybrid schemes

Hybrid, or nonhomogeneous, representation schemes may be designed by combining the different approaches that have already been described. CSG/B-Rep, CSG/Solid Sweep, and CSG/General Sweep, are examples of hybrid schemes.

3.3.7 Feature based representation: the Pro/Engineer system

A feature is a set of information related to a part description which can be used for design, manufacturing, inspection or administrative purposes (14). Mechanical applications and design processes demand a connection between the geometric and topological information in the geometric model, and the various processes and materials information of features. A feature based representation can have any of the previously discussed geometric shape representation schemes with information of individual features.

An example of such a system is Pro/Engineer, a CAD software which allows feature based design. Pro/Engineer provides a way to explicitly capture design knowledge through the use of parametric relations. These relations are user-defined mathematical equations which capture design relationships within a part or between component parts of an assembly. For example, in an assembly, the diameter of a hole in one part can be defined as the diameter of a shaft plus a certain clearance, in order to guarantee assemblability.

The Pro/Engineer CAD system is a hybrid model of B-Rep, CSG and sweep representations. It defines different features in relation to CSG primitives. These primitives are in turn defined in B-Rep and sweep representation schemes, thus combining the advantages of all three representation schemes. The database of this software contains data which describes the boundary of the surface and contains a pointer
to the primitive surface on which it lies. The primitive surfaces are three dimensional geometric surfaces parametrized by two variables (u and v). The surface boundary consists of closed loop (contour) of edges. Each edge is attached to two surfaces, and each edge contains the u and v values of the portion of the boundary which it forms with both surfaces. Surface boundaries are traversed clockwise around the outside of a surface, so an edge has a direction in each surface with respect to the two dimensional domain, the three dimensional surface, and a flag indicating whether the surface normal points towards the inside or outside of the part. The user data is intended for run time use only, and this information is not stored with the surface.

In addition, Pro/Engineer provides a collection of C functions to access geometric and display information from its database. These functions have been gathered in the Pro/Develop module. For more information on this system the reader should refer to the Pro/Engineer manuals.

3.4 Related work

By comparing the advantages and disadvantages of all the different techniques of computer modeling of objects, it is evident that Solid Modeling provides the best computer representation of objects available today. Consequently, a great deal of attention has been given to the potential applications of solid modeling for the purpose of linking CAD/CAM. However, different techniques offer different advantages, and different researchers have used different techniques according to their own particular needs. Many research efforts are concentrated in either obtaining features from a commercial CAD database, or the use of features in design to capture the purpose behind the design. The first approach is called feature recognition and extraction, while the second approach is known as feature based design. A feature based design communicates maximum
information for a particular purpose, and if the same model is used for other purposes, the related features can be extracted from this model.

Rogers and Shah (14), contend that the key to CAD/CAM integration are features, which they define as "a set of information related to a part's description", and classify them as form, precision, material, technological, and assembly features. Furthermore, according to them, there are three potential ways of supporting features, namely:

a) Human assisted feature definition: used for preparing input for process planning. However, it defeats the purpose of automation;

b) Feature recognition and extraction, in which a pattern recognition algorithm is applied to the geometry database. Algorithms for pattern recognition are usually very complex.

c) Feature Modeling, in which features are incorporated directly at the beginning of the part definition.

Recently, Pratt (15) reviewed a number of papers in order to determine which is the best approach to form feature modeling, and concluded that, in general, form features are best modelled by B-Reps. He surveyed three topics that are related to the problem of Part Decomposition for Rapid Prototyping: Design by features; Classification and Coding (as in Group Technology); Computer Aided Process Planning (CAPP); and Automatic Dimensioning and Tolerancing. These topics have in common the need for the support of features.

Examples of such applications are the work by Ames (21) who developed a system that automatically generates group technology (GT) from B-Rep solid model data; and the work by Grosse and Sahu (22) who have tried to develop a system that predict manufacturability of a part while it is being designed through a 3D system. In later chapters work related to CAPP will be described.
3.5 Remarks

Without a doubt solid modeling provides the best CAD representation of an object. At the same time, the two most important approaches for the storage of solid model data are B-Reps and CSG. B-Reps offer explicit model representation and implicit feature representation, while CSG offers implicit model representation and explicit feature representation. By all accounts, it has been recommended to use B-Reps to support machining operations.

During the past few years a feature-based approach has been used to facilitate both design and manufacturing operations. Pro/Engineer presents this type of system. This type of approach is being investigated for application in our system.
CHAPTER IV
ISSUES AFFECTING THE IMPLEMENTATION OF THE METHOD: THE TOLERANCING PROBLEM

4.0 Introduction

According to our scheme, the first step for rapid prototyping of a part is to decompose it into a set of primitive features. Above all, these features must have two characteristics:

1) Each feature must be economically manufacturable.

2) After assembly, they must guarantee a certain dimensional accuracy of the prototype with respect to the finished part.

In both of these cases, the tolerancing of each individual feature will determine how well these objectives are met. On the one hand, the cost of manufacturing a part is a function of the tolerances that must be achieved (Fig. 11). Tight tolerances require longer processing times in more sophisticated equipment than loose tolerances. Costs are accordingly higher. On the other hand, tight tolerances are required to assure better fits during assembly. Better fits produce more predictable part dimensions. One is tempted to believe that tightly tolerated features will necessarily produce more accurately finished parts than loosely tolerated features. In reality, there is very little knowledge available as to how different tolerances affect the final output, particularly when the tolerance stacking is nonlinear (the usual case). Therefore, attention must be given to balance cost and functionality of the prototype.
Fig. 11: Cost of achieving tolerances (From ref. 13, pp. 771).

It is thus necessary to introduce into our system a means of assigning tolerances to the decomposed features in such a way that the final prototype part (which is formed by assembling these features) is dimensionally and economically acceptable. This can be done in either of two ways: by allowing the program to interact with an experienced designer, or by creating a system which can automatically assign tolerances. The first solution obviously defeats the purpose of automation of the process, while the second one imposes a formidable task. In the following paragraphs, some of the details of the tolerancing problem will be discussed.

4.1 Tolerancing techniques

Tolerancing practices arose directly from manufacturing basics. Experience shows that it is physically impossible to manufacture parts of exactly equal dimensions. Physical limitations on the manufacturing processes (such as cutting conditions, tool wear, software and hardware accuracies, skills of machine operators, etc.) as well as assembly
techniques and material properties are responsible for such variations. Designers have accounted for these variations by assigning tolerances to the features of a part. Tolerances are thus a range of values within which suitable sizes of parts must lie in order to be considered acceptable. If a part size and shape are not within the minimum and maximum limits defined by the tolerances, this part is not acceptable. Thanks to tolerancing, it is possible to guarantee the dimensional integrity of a finished part, or the interchangeability of the elements that form an assembly.

During design, two approaches are used to specify the dimensions and tolerances of a part: by means of traditional tolerancing, or by geometric tolerancing. In both cases, dimensions and tolerances are assigned according to the required basic sizes, the chosen fits and the required surface quality. Traditional tolerancing is the most widely used dimensioning method. It is very easy to understand and is particularly useful when all the dimensions are given in only one direction. This method has, however, some major shortcomings. For one thing, it is incapable of supporting physical variability, that is, it assumes only perfect shapes. The concept of datums which is so useful for manufacturing and inspection is not supported either. These facts are evident when one looks at the case exposed in Figure 12. The tolerances assigned to the coordinates of the center of the hole when measured from the perfect edges, allow its position to reside between the boundaries of a square. This would then permit the center of the hole to be at the corner of the square and still be considered an acceptable location, even though the distance to the basic (targeted) center is larger than the specified tolerance. This in itself might not be wrong at all, depending on the situation. However, such an awkward condition worsens in the case of 3D drawings. Thus, this type of tolerancing cannot be used for computer solid models, since it cannot in itself support a congruent physical interpretation.
Fig. 12: Ambiguities of traditional dimensioning techniques (From ref. 13, pp. 776).

Geometric tolerancing, although more difficult to understand, provides an alternative for a physical representation of tolerances. It introduces the concept of datums, which represent support surfaces in real manufacturing or inspection conditions; it also provides interpretation for size, location and form tolerances, thus allowing parts to be imperfect. ANSI and ISO have developed a set of standard symbols and rules for the purpose of representing real objects. Experience has proved that these techniques are very effective, particularly when high accuracies are required. Furthermore, it provides a better option than traditional tolerancing for applications in solid modeling. Figure 13 shows an example drawing of a part that has been dimensioned using geometric tolerancing rules and symbols.

Reference (35) provides the details of the ANSI standard for dimension and tolerancing using Geometric Tolerancing.
Fig. 13: Application of some of the ANSI standard symbols in geometric tolerancing
(From ref. 13, pp. 794).

4.2 Tolerance modeling

As stated before, geometric modeling is the best available tool for the representation of solids in CAD systems. To successfully utilize these solid models in CAM systems, the CAD systems must supply tolerancing facilities. Otherwise, full automation of the manufacturing activities through CAD/CAM cannot be achieved. The task of assigning tolerance information to geometric models has not been easy; however, several approaches have been used for this purpose. For example, one of the first attempts to add tolerancing information to nominal geometric models was to treat these tolerances as a mixture of text and graphical data which users could insert as modifiers of dimensioning commands. This approach was used with wire frame models and applied only to
conventional tolerancing. Its primary emphasis was to add tolerances as texts to engineering drawings. For full automation, this approach is far too limited, and therefore the solid modeling theory should be utilized in tolerance modeling and representation. An explanation of this problem, however, goes beyond the scope of this report. For a more complete explanation of this problem, reference (13) provides a good analysis of such a task. In it, two approaches for dimensioning and tolerancing of B-Rep and CSG solid models are defined. They are labeled "evaluated" and "unevaluated" D&T Models respectively. By means of them, dimension and tolerancing of solid models can be achieved. Also, Ranyak and Frisdaahl (36) developed a set of rules for the implementation of tolerancing a model based on features and used the ANSI Y14.5 M standard for this purpose.

4.3 Current work

Tolerance analysis refers to the process of predicting the effect of the accumulation of tolerances on the final dimensions of the assembled part. Theories such as the worst case arithmetic method, worst case statistical method, monte carlo simulation and others, have been developed for this purpose. Recently, Greenwood and Chase (37, 38) have developed new techniques for mechanical tolerance analysis of assemblies. Pandit (42) used a statistical procedure to perform tolerance analysis with B-Rep models.

Tolerance synthesis is the opposite process. In this case, the allowable tolerance of the design function is known, and the dimension tolerances of the individual components must be determined. Spotts (39), Peters (40), and more recently, Speckhart (41), have contributed to the study of tolerance synthesis with cost as the variable to be minimized.

Probabilistic methods similar to those used by the researchers mentioned above can be used for one-of-a-kind parts. Our approach will call for a process of synthesis and
should at least resemble their concepts in one respect, that is, the statistical variability of the manufacturing process must be taken into account.

4.4 Remarks on tolerancing for our prototyping system

If our system is to be fully automated, a set of rules that have the purpose of assigning dimensions and tolerances to the individual features will have to be implemented. The developed rules must be responsible for providing toleranced features that will not only be economically manufacturable with the available equipment, but that will also provide a valid finished part after assembly.

Geometric tolerancing must be supported by the system in order to provide a link between the different CAD/CAM functions.

Finally, although much attention has been given to the problem of tolerance analysis and synthesis, its primary objective has been to reduce costs in high production runs. Although this work can be useful, some research will have to be done in order to develop techniques that are oriented towards the problem of developing one-of-a-kind parts.
CHAPTER V
IMPLEMENTATION OF A PROTOTYPING SYSTEM BASED ON MILLING:
CAPABILITIES OF THE PROCESS

5.0 Introduction

Machine tools and the processes they perform constitute the basic element of our prototyping method. As an initial step towards the implementation of a prototyping system based on machining, the capabilities of the particular machining process must be understood. In this chapter the characteristics of a milling machine are analyzed. In particular, the two machining processes that were used in our system at its initial state are described.

5.1 Justification of the use of 3-axis milling.

As a first step, it has been proposed to implement a prototyping system based on milling. Along with lathes, milling machines are the most common types of manufacturing equipment found on the shop floor. Milling machines are capable of performing a wide variety of machining operations including end and face milling, drilling, reaming and boring. The addition of computer numerical controls makes milling machines even more versatile. These characteristics make milling machines a good foundation for the initial implementation of a prototyping system.
With the development of machining and turning centers, traditional differences among the machines have disappeared. However, fundamental differences exist between turning, drilling, milling, tapping, etc. A description of the milling and drilling processes is given in the following paragraphs.

5.2 Drilling

Drilling is a machining process by means of which a hole is produced or enlarged. In drilling the material is removed in the form of chips by the relative motion of the tool and workpiece. Although drilling is a fast and economical process to generate holes, its process is inefficient. Cutting speeds vary from a maximum at the tools outside diameter to a minimum at the center of the tool, thus varying the loads on the cutting edges. Chip ejection and flow of the cutting fluid are restricted by the arrangement of the different elements during the drilling operation.

5.2.1 Achievable tolerances

Many parameters affect the accuracy of the drilling operation, among them the rigidity of the setup, workpiece and drill material, process parameters, and types of drill and machine tool used. Table 3 shows an estimate of the accuracies that are obtained through the drilling process. Errors in hole shape, location, roundness and size as well as burrs should be expected. Straightness of holes is also a problem, although concentricities within 0.0002" per foot can be achieved with special gun drilling operations. By the same token, surface finishes obtainable thru drilling range from about 100-250 micro inches or more. When better surface finishes or better geometries are required, subsequent reaming, boring, grinding, honing or burnishing is performed.
5.2.2 Manufacturable features

The only feature that is manufacturable by drilling is a cylindrical hole with a cone-shaped tip. However, the dimensional accuracy of drilled holes remains a concern. Figure 14 shows the types of true shapes that are commonly achievable by drilling.

Table 3: Average accuracy of holes produced with twist drills (from ref. 54 pp.9-3)

<table>
<thead>
<tr>
<th>Drilling Condition</th>
<th>Diameter, in (mm)</th>
<th>Oversize in (mm)</th>
<th>Location in (mm)</th>
<th>Oversize in (mm)</th>
<th>Location in (mm)</th>
<th>Oversize in (mm)</th>
<th>Location in (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.Centr-drilled hole or bushing</td>
<td>1/8-1/4 (3-6)</td>
<td>0.003 (0.08)</td>
<td>+/-0.007 (0.18)</td>
<td>0.006 (0.15)</td>
<td>+/-0.008 (0.20)</td>
<td>0.008 (0.20)</td>
<td>+/-0.009 (0.23)</td>
</tr>
<tr>
<td>Center-drilled hole, no bushing</td>
<td>1/4-3/4 (6-9)</td>
<td>0.003 (0.08)</td>
<td>+/-0.004 (0.10)</td>
<td>0.003 (0.08)</td>
<td>+/-0.004 (0.10)</td>
<td>0.004 (0.10)</td>
<td>+/-0.005 (0.13)</td>
</tr>
<tr>
<td>With drill bushing</td>
<td>3/4-1 1/2 (19-38)</td>
<td>0.002 (0.05)</td>
<td>+/-0.002 (0.05)</td>
<td>0.003 (0.08)</td>
<td>+/-0.002 (0.05)</td>
<td>0.004 (0.10)</td>
<td>+/-0.003 (0.08)</td>
</tr>
</tbody>
</table>

5.2.3 Drilling methods

The diameter of the hole as well as the ratio of hole diameter vs hole length play an important role in the type of drilling process that is to be performed. Small hole drilling is performed in holes of diameters of less than 1/32 inches. The major problem under these circumstances is presented by the delicate rigidity of the tools used in this process. Holes of less than 0.001 inches may be generated with special microdrilling machines. Holes with larger diameters and small length to diameter ratios (l/d <3) can be generated without special care and in general purpose equipment (milling machines, machining centers, etc.). For length to diameter ratios between 3 and 6 special drilling strategies are commonly used.
An example is a strategy called "peck-drilling" in which the tool is retracted at regular intervals to allow for chip disposal.

For the case of larger length to diameter ratios, special types of drilling processes, machines and tools may be required. Gun drilling, gun boring and trepanning are examples of drilling processes in which self-guided tools that use high-pressure cutting fluids to generate deep holes. Special machine tools are also available for deep hole drilling applications.

Fig. 14: True shapes achievable by drilling (from ref. 54 pp. 9-3).

5.2.4 Types of tools

The most basic type of drilling tool is called a "twist drill". Twist drills are defined as rotary end-cutting tools that have one or more cutting lips and one or more helical or straight flutes for the removal of chips. These tools are not intended to be precision cutting
tools. Instead, they are designed to generate holes rapidly and economically. Twist drills can be classified according to the type of shank (straight or taper), number of flutes (single, two, and three or four-flute drills), and cutting rotation (right or left handed). Figure 15 shows a twist drill along with its associated terminology. ANSI standard B94.11M-1979 establishes nomenclature and dimensions for twist drills. Twist drills can have different geometric attributes for special applications (such as the subland drill or combination drill-countersink). They may also be coated in order to accomplish specific cutting conditions.

Other types of drilling tools are also available for specific application such as spade drills (see ANSI Standard B94.49-1975) used for large holes, indexable insert tools and gun drills used for deep holes, and trepanning tools, used for creating large diameter holes in single passes.

Fig. 15: Terminology associated with a twist drill (from ref. 54 pp. 9-15).
5.2.5 Drilling machines

The drilling operation can be performed in a variety of machine tools that range from hand drills to machining centers. The common dedicated-drill machine configurations include the bed-type drilling machine (very similar in appearance to the bed-type milling machine), gang-type drilling machine, radial drilling machine, multipindle drilling machines, turret drilling machines. Special machines allow deep hole drilling and small-hole drilling.

General purpose machines can also be used for drilling operations. Milling machines, lathes, and machining or turning centers are capable of performing drilling operations.

5.3 Milling

One of the most efficient and versatile machining processes is milling. It is also one of the most widely used. In this process material is removed by the relative motion between a part and a cutting tool. The cutting tool has multiple cutting edges and turns at relatively high speeds with respect to the workpiece. The milling operation is performed in a milling machine, which is capable of holding and moving both elements, the tool and the part.

Several arrangements are available for accomplishing the relative motion of the tool and part:

- The tool is stationary while the part is moved with respect to the tool axis.
- The part is stationary while the tool moves around the part.
- Both, the tool and the part are moved with respect to each other.

Although the part may move with respect to the tool, the part remains stationary with respect to the table of the machine tool, as it must be firmly clamped to it. The type of relative motion arrangement depends upon the design of the machine tool.
The amount of machine tool configurations, workpiece movements and types of tools make the milling process one of the most complicated ones. Consequently most milling rules and practices are empirical, the result of many years of experience with this process.

5.3.1 Process Capabilities

The tolerances and surface finishes that are achievable by milling depend on many factors. Type of milling machine, milling strategy, workpiece geometry and material, type of cutter used, cutting conditions and rigidity of setup are some of the parameters that affect the quality of the milling operation.

In general, achievable tolerances range between +/-0.002" and +/-0.005". Under normal conditions +/-0.001" is the best obtainable tolerance. Similarly, surface finishes as smooth as 10 micro inches or less may be produced in steel, while 60 micro inches or less can be achieved in cast irons. Other geometric characteristics such as flatness, perpendicularity, and parallelism are heavily dependant upon the rigidity and quality of both the machine tool and the workpiece clamping to the table (normally referred to as fixturing). The rigidity of the cutting tool also affects these geometric characteristics. While most milling machines are capable of maintaining tool trajectories that can be either parallel or perpendicular to the machine tool table within +/-0.005" per foot traveled, the uncertainty regarding the stiffness of the setup makes it very difficult to guarantee tolerances of less than +/-0.001". In practice, it may be necessary to perform experimental trials with variations to the different parameters before a given tolerance and surface finish can be guaranteed.
5.3.2 Manufacturable Shapes

The importance of part manufacturability has been established in previous chapters. In the end, several issues will affect a criteria defined for the purpose of evaluating part manufacturability. Number of setups, required tooling, physical characteristics of the material, and even availability of equipment and time will affect in the evaluation of part manufacturability. In the context of rapid prototyping via CNC milling, if the cost-based rules for tolerancing of features can be linked to the part decomposition routines, the problem of evaluating the relative manufacturability of two parts reduces to the comparison of the geometric characteristics of each part.

As previously explained, the milling process calls for the removal of volumes of material by the tool as it describes a trajectory into the workpiece. The tool provides a cutting edge that rotates around the axis of the spindle. As the tool moves, a volume of material is "swept" away from the workpiece. The cross section of the swept volume is identical to the cross section of the volume that the tool describes as it rotates around its axis. Cross sections with a constant depth (referred to as 2 1/2-dimensional shapes) constitute the easiest features to machine. One has to bear in mind, however, that sharp inside corners cannot be reproduced. In fact, the smallest inside radius that can be machined is just as big as the radius of the tool. Further, an inside corner will produce a concave feature; it is not possible for the tool to produce a swept volume that has sharp corners. Another restriction is imposed by the relation of thickness vs depth of the feature. Long, narrow features, are more difficult to reproduce than short, wide ones. In the first case, long tools must be utilized. This causes dynamic instability of the tool, presented in the form of deflections and vibrations, which in turn contribute to poor surface finishes.
Sculptured (3-D) surfaces present a different problem. For one thing, specially sharpened ball-end milis must be provided. The part surface must then be precisely modeled in order to program the coordinates that will permit the tool to follow the exact contour of the part. Surface finish is strictly a function of the closeness of each individual pass, and therefore, of the time it takes the tool to describe its whole path. As in the case of 2 1/2-D shapes, the radius of the smallest inside sphere that can be reproduced is limited by the size of the tool.

Another important concept is that of reachable features. Basically, if a feature is to be manufactured in a 3 axis milling machine, it has to be placed on a plane that lies perpendicularly to the axis of the spindle. Only those features that are visible (reachable) from the spindle's point of view are candidates to be manufactured. One can think of the perspective of the spindle as the perspective that a draftsman has when he looks at a plane view of a part in a 2D drawing. Two views from two different positions would be different from each other. The view that shows fewer hidden lines would potentially be the one that is most easily manufacturable. Some hidden features could still be reached from a given position, but they would require special tooling, which would also take some time to be fabricated.

Closely related to this problem is the number of setups. When an object is to be produced, the process designer has to decide the different positions in which the part is to be set with respect to the spindle in order to complete the whole part. A certain position requires certain fixturing. Each position is called a setup. The number of setups also affects the cost of the final part, since setup time implies machine idle time. The cost of this time goes directly into the cost of the part. Therefore the objective should be to machine as much as possible in each setup (nevertheless, one must make sure that the
final number of setups is the minimum required, regardless of how much is done in each setup).

With these guidelines in mind, we can classify features according to descending manufacturability as follows:

2 1/2-D Shapes, no hidden lines

These types of features are the easiest to manufacture since they can be done in one set up, or in one position with rearrangement of the holding clamps. Thanks to numerical control, almost any shape of a given thickness can be generated. Again the only restriction is imposed by the tool itself. Internal corners which are smaller than the tool radius cannot be manufactured. Figure 16 shows some features of this type.

2 1/2-D Shapes, with hidden lines

Next in simplicity, are the geometries of a given profile and depth, which hide features from the sight of the spindle. The same limitations apply as in the previous case. In some cases, hidden features can be machined by means of special tooling. However, these features are very limited in size and shape, and usually more than one set up will be required. Counterbores in Figure 17 represent some of the feature that show hidden lines but that can be machined in a single setup.

3D Shapes

Molds for glass bottles fall into this category. In general, sculptured surfaces can be milled, but specially shaped end mills are required, as well as long processing times (surface finish is mainly a function of time in this case). Furthermore, the smallest internal radius must be greater than the radius of the tool. Although the presence of
hidden lines when the sculptured surface is analyzed implies more setups, the major problem is still presented by the sculptured surface itself. Spheres and cylinders are not easily manufacturable even though they would not show hidden lines.

Fig. 16: Features that are easily manufacturable by milling (from ref. 13, pp.990).

5.3.3 Milling Methods

Basically, there are two milling methods: peripheral milling and face milling. A relatively large number of related methods that are a variation of these two are also available. By combining these methods the different features can be generated.
Fig. 17: If the diameter of the counterbore on the right is too large it will need to be machined in a different set up (From ref. 13, pp. 991).

Peripheral Milling

In peripheral milling, sometimes referred to as slab milling, the milled surface that is generated by the cutting edges of the tool lies on a plane that is parallel to the tool axis. Surfaces generated by form relieved tools (tools that have a particular shape that lies along the axis of the tool), and whose outline correspond to the contour of the tool, are also included in this type of milling. Figure 18 shows some of the trajectories that a tool may follow during peripheral milling.

Face milling

In this type of operation, the milled surface lies flat on a plane perpendicular to the tool axis. The generated surface is flat and its shape is unrelated to the contour of the tool, except perhaps on those portions that lie parallel to the tool axis (usually called shoulders).
The material removal rates for face milling are usually higher than those achievable by peripheral milling. Consequently, face milling is preferred to peripheral milling whenever possible.

**Additional milling methods**

Although the following methods can be classified as either peripheral or face milling, they are considered separately because of the type of tool used or the kind of part being machined:

- **End Milling**: End mills have cutting edges on both their end faces and their peripheries, therefore they can be used for both face and peripheral milling.
- **Side and Straddle Milling**: In side milling the surface is machined perpendicular to the milling machine arbor by a side cutter. Straddle milling implies the use of several side cutters to generate simultaneously several parallel faces.
- **Gang Milling**: Similar to straddle milling, except that cutters can be of different types.
- **Gear milling**: Performed under very specific circumstances. Machines must be equipped with dividing heads while standard gear tooth cutters must be used.
- **Cam milling and thread milling**: Enhanced by the use of CNC machine tools, these are intricate part shapes generated by the simultaneous motion of several machine tool axis.
- **Diesinking**: This operation generates sculptured surfaces commonly found in dies and molds. Special tools with semi-spheric tips (called ball end mills) are used in this type of applications. This type of operations are performed by copier machines or CNC machines.
Fig. 18: Tool paths and coordinates in peripheral milling (from ref. 13, pp. 1010).
There are other types of operation which are less common, among them plunge, planetary and crankshaft milling. References (54) and (57) provide a good explanation of such processes.

5.3.4 Types of cutters

Many different types of milling cutters are available in the market. All of these types however have the same conceptual design: a body that provides one or more cutting edges which intermittently engage the workpiece and remove material, plus a shank or other kind of shape that allows the tool to be held by an adapter which in turn is mounted on the spindle of the milling machine.

Cutters may be described as a function of their application, the shape and position of the cutting edges, or even the type of workpiece produced. The most common types of cutters are:

- Plain milling cutters: Their shape is cylindrical and they have straight or helical cutting edges only in their circumferences.
- Form milling cutters: Modified versions of plain cutters, that have cutting edges shaped to perform specific applications.
- Side milling cutters: These cutters have cutting edges on their peripheries and on one or both faces. Staggered-tooth cutters are a variation of side milling cutters.
- Shaped profile cutters: Similar to form cutters, their main purpose is to generate splines, gear teeths and similar features. Hobs are considered in this type of cutters.
- Face mills: Designed to machine surfaces parallel to the face of the cutter, they have teeth that cover relatively large areas.
- End Mills: Perhaps the most versatile milling cutters, they have cutting edges along their longitudinal axis and in most cases, at the bottom of the tool. End mills may be sharpened to specific shapes according to the requirements of slotting, profiling or engraving operations.

Figure 19 shows the nomenclature and geometry associated with end mills. Terms associated with general characteristics of the tool (length, diameter) as well as those associated with cutting angles (rake, relief) are commonly used with other types of milling cutters. Different values of these parameters have different effects upon the performance of the tools.

Fig. 19: Nomenclature of end mills (from ref. 54, pp. 10-39).
Figure 20 shows some of the most common types of milling cutters, while Appendix C shows a summary of the tolerances on standard milling cutters as defined in the ANSI Standard B94.19-1977.

The fact that the tool is held by an adapter was mentioned before. Many different designs and configurations are available for the purpose of attaching a tool to the spindle, from the conventional straight-shank or taper-shank tool integral holders to the more sophisticated modular systems such as Sandvick’s Varilock system. All designs must however suit the standards for spindle dimensions, tool shanks, and draw-in bolt ends for milling machines presented in ANSI Standard B5.18-1972. Figure 21 shows some standard integral vs modular tool holders, while Appendix C presents some of the standard dimensions and tolerances for selected adapter elements.

5.3.5 Configuration of a milling machine

Although milling machines are designed to perform milling operations, the introduction of computer numerical control technology has broadened the amount of machining processes that a milling machine can generate. Processes such as reaming, boring, tapping, planning, slotting, cam profiling, gear profiling and drilling can be performed by a machine that has the basic configuration of a milling machine. In this section, this basic configuration is discussed.

Figure 22 shows a schematic of a three axis vertical milling machine. In practice, the number of axis refers to degrees of freedom that the spindle has and that are controllable at any one moment during a milling operation. Spindle rotation around its own axis is not considered a degree of freedom for the purpose of machine denomination. The term "vertical" indicates that the spindle axis is vertically lined up (and is thus perpendicular to the worktable).
Fig. 20: Common types of milling cutters (from ref. 54, pp. 10-25).
Fig. 21: Standard integral and modular tool holders (from ref 59, pp. 242).

For the purpose of workpiece processing, two non-structural elements are of vital importance. The first one is the spindle. In the schematic shown in Figure 22, the spindle is located at the bottom of the vertical head. The spindle performs three basic functions:

- It locates the cutting tool very accurately with respect to the rest of the machine tool, in particular, to the table.
- It firmly holds and supports the tool.
- It provides the rotating power that allows the cutting tool to cut through the material.

The second element is the table. The table provides a surface upon which the workpiece can be firmly clamped and accurately located.
The configuration shown in Figure 22 is known as "knee and column type" milling machine. The three axis (or degrees of freedom) are provided as follows:

- **X axis** (horizontal motion as seen from the point of view of the spindle) is provided by the table.
- **Y axis** (vertical motion as seen from the point of view of the spindle) is provided by the saddle.
- **Z axis** (along the spindle axis) provided by the knee.

In this particular arrangement, the vertical head can be moved to different locations along the column. However, this is not considered an additional axis, since the position of the head cannot be independently controlled during cutting operations. A motor provides power for the different axis and the spindle. Depending upon the type of machine, one or more independent motors may be available for each of the different degrees of freedom and the spindle. Finally, the machine shown in the figure provides handles for manual controls of the different axes. At some point during operation, the motor may be engaged in order to provide motion to the axis upon which cutting is taking place, thus allowing for a smoother, stronger feed than what could be manually provided. Not shown in the figure are the coolant pumps and nozzles that supply the coolant during the cutting operations.

Usually more automation implies a change of denomination from milling machine to machining center. Machining centers have a structure that is identical to that of an equivalent milling machine. What makes a machining center different is that a computer control allows for the control of a series of peripheral devices such as chip conveyors, automatic tool changers, tool magazines, and pallet (table) changers that enhance the capabilities of the milling machine. In fact, the difference between a CNC milling machine
Fig. 22: Basic configuration of a milling machine (from ref. 54, pp. 10-10).
and a CNC machining center resides only in their peripheral devices, and not in the machining processes that can be performed by each one.

Manufacturers of milling machines provide a wide range of configurations and designs that make the machines more suitable for particular operations. From the structural point of view some additional types of milling machines are the "bed type" milling machine, the "fixed bed saddle type" milling machine, the "gantry type" milling machine, the "ram type" milling machine and the "traveling column type milling machine. ANSI Standards B5.45-1972 and B5.18-1972 provide dimensions for some general features of milling machines.

**Basic elements of a milling machine**

From the previous discussion, the basic elements of a milling machine can be grouped as follows:

a) Work holding system: A table is provided for the purpose of locating a part for processing. The table is sometimes larger than the actual workspace, or range, of the machine (the workspace of the machine is the volume where the spindle can reach a part). Devices such as fixtures and tools allow the machine spindle to process the parts that are located on the table.

b) Axis motion system: A set of motors is supplied to provide 3 or more degrees of freedom. All points in the machine workspace can be reached by the spindle through the motion of the table, the spindle structure, or both. Its arrangement usually depends upon the size of the workspace.

c) Spindle system: This system provides a device that precisely locates and holds the tool at a controllable position. In addition, it provides the power to the tool by means of a motor that rotates the spindle. The rated horsepower of the machine refers to the power that can be exerted by the spindle motor while the tool cuts.
d) Control system: The most important function of this system is to provide accurate control of the position of the tool with respect to the part. In conventional equipment, this control is provided by a set of handles and knobs which allow a human to control axis feeds, spindle speeds, and related functions. CNC technology has introduced computer control of these and other functions.

e) Hydraulic system: Lubrication of the machine is usually accomplished through the hydraulic system. Depending on the machine type, this system can also provide control for certain other functions.

f) Support structure: This system holds all the different systems together in order to form the machine. The support system may take different forms (gantry type, knee type of support, etc) but must provide mechanical rigidity. In most cases, thermal stability and damping capabilities are also introduced in the design of the support structure.

f) Miscellaneous: Depending on the level of sophistication of the machine tool, other systems might be available, such as coolant pumps, tool magazines, tool changers, etc.

5.3.6 Additional comments on the control of milling machines

The type of control plays a major role in the capabilities of a milling machine. It is therefore customary to provide a classification of milling machines based on the type of controls available to these machines. Based on this criteria, milling machines are classified as:

- Manually controlled: handles are provided for the independent control of each axis.
- Tracer controlled: the tool path motion is coordinated with that of a tracer that follows the contour of a master model.
• Programmable controls: provide feature pushbutton programming by means of manual data input into electronic controls.

• CNC controlled: computer numerically controlled machines. Control is provided by a computer which interprets a code made up of a combination of numbers and letters. During the early years of this technology, codes used only numbers in specific locations to generate tool motion commands; thus the name "numerically controlled" (NC) was used. Computer controls later replaced tape readers, giving its way to today's CNC technology.
CHAPTER VI
IMPLEMENTATION OF A PROTOTYPING SYSTEM: PROCESS PLANNING

6.0 Introduction

The most important objective of all rapid prototyping methods is that of reducing the time it takes to generate an accurate model of a product or part. For this reason, all of these methods make extensive use of computers.

In milling, the generation of part process plans and CNC programs along with machine and setup preparation accounts for a great percentage of the time it takes to fabricate a single part. A recent study performed at MIT shows that for typical parts CNC programming and debugging accounts for 40% to 50% of total production time, setup time accounts for similar figures, and actual machining accounts for less than 10% of total production time. These data was obtained from rapid prototyping applications, in which very low volume production is the rule. If a prototyping method based on machining operations is to be successful, the time for process plan generation and setup creation must be reduced.

In this chapter an overview of the most important tasks involved in the development of process plans for machining operations is presented. The order in which these tasks are arranged intends to follow a logical sequence of events. In practice, the process is highly iterative, and assumptions made at earlier stages must be reevaluated as the process approaches its completion. The guidelines provided here are common practice in general industry. However these rules may not apply for certain cases, for example the aerospace
industry. Figure 23 shows a schematic of the process that is followed to generate a process plan.

Fig. 23: Steps in process planning.

6.1 Steps in process planning

In general, rules are given for two scenarios: low volume vs high volume production. Intermediate scenarios require a combination of the given guidelines. Ultimately, personal experience and careful analysis will dictate the approach that is to be followed. In the following discussion, tasks that are more closely related to milling will be discussed in more detail.

6.1.1 Task 1: Obtain part information

Before any operation can be performed, sufficient part data must be gathered. The most important information and their sources are the following:

- **Physical Information of part**: Obtained from CAD databases, blueprints or drawings, the physical characteristics of the part must be clearly defined. Part
material, general geometric shape of the part (prismatic or nonprismatic, cylindrical etc.), part dimensions and tolerances, surface finishes and hardness are the kind of data that will affect the choice of equipment and machining process as well as the sequence in which they are used.

- **Production Information**: The quantity of parts and the required lead time are obtained from the people in charge of programming the production. This data will determine the type and amount of resources that are to be spent in the production of the part. For example, if a part is made out of steel, for large volume production as well as with long or mid-term commitments with the customer the development of cast models may well be justified. The investment in the development of such raw material infrastructure will be more than offset by the savings in machining time and resources. Further, dedicated equipment such as new machine tools and fixtures may be economically justifiable, thus affecting the routing of the part. On the other hand, low volume production and short lead times with short term commitments implies the use of generic raw material (such as round stock or plates, or even blocks) and may introduce the need for further processes such as welding or assembling in order to finish the part. Routing through the available equipment will have to be programmed. Modular fixturing must also be available for each setup. These are perhaps the extreme cases as far as production information is concerned. Different scenarios will call for the use of different approaches.

6.1.2 Task 2: Define raw material and part routing

Based on the part and production information, raw material and part routing has to be determined. The following considerations must be kept in mind for each case:
6.1.2.1 Raw material

In general, raw material for machining operations is available in two forms:

- Generic raw material (blank) such as plates, round stock, blocks, and sheet metal. Generic raw material is used whenever the time or production volume constrains do not permit the development of casting models. When this type of approach is used, longer machining times and high amounts of wasted material which result in higher costs may be expected. The advantage of using generic raw material resides in the short time needed to obtain this material, or seen from a different perspective, in the savings that arise from not having to keep a stock of generic blanks.

- Castings. The use of castings guarantees that machining times and wasted material will be kept a minimum. However, the use of castings requires an initial investment for the development of patterns for the casting process. Further, lead times for castings may be at least on the order of weeks. Therefore, the need for castings has to be anticipated or cast material for a given part must be kept in storage; either case implies cost. Consequently, castings are used to full advantage when high volume production and long lead times are expected.

In particular applications these guidelines may be overruled by other criteria. For example, its not uncommon to make structural components of high volume-long, lead time assemblies out of generic materials.

6.1.2.2 Define Routing

Part routing refers to the sequence of processes through which a part must go before it is completely finished. Part routing depends on several factors including size of part envelope, feature dimensions and tolerances, production requirements and availability of equipment. The effect of these factors on part routing is now explained.
Production requirements and availability of equipment

These two factors are closely related. For example, high volume production of a part may justify an investment in new, dedicated equipment. Tailor-made drilling machines are commonly used in high volume production. If this is the case, presently available equipment may be liberated from these tasks, and can be used for other operations. On the other hand, low volume production would not justify an investment. A case in point is a splined cylinder, for which a new hob (outside spline) or broach (inside spline) may not be justified. In this case, milling machines may have to be conditioned to perform such tasks. The production floor has to be equipped with flexible machines, either manual (conventional) or CNC to perform such tasks. Special operations such as heat treatments may have to be done in outside facilities.

Size of part, general geometry, and feature dimensions

The size and general geometry of the part as well as feature tolerances and dimensions affect the selection of the equipment. Prismatic features such as slots and round or squared pockets and bosses are candidates to be machined in milling machines. Long, cylindrical parts can be turned. Holes can be milled or drilled, depending upon their number and geometric arrangement. Splines and gears call for special machines such as gear generators or hobbing or broaching machines. The general dimensions of these features and their locations in the part envelope affect the choice of the machine tool size, since their workspace of the machine tool is finite.

Feature tolerances and surface finishes and hardness

The last of the factors affecting part routing is feature tolerances and surface finish. Poor surface finishes allow cheaper machining processes than tighter finishes. A hole
whose surface finish is 1000 micro inch or larger can be generated by flame cutting. On the other hand, the same hole with a 63 micro inch finish will require at least a drilling operation. Tight tolerances may require the need for intermediate operations such as stress relief after heavy cuts. Grinding operations might also have to be performed as a result of small surface finishes or a combination of high hardness and tight tolerances. Tight tolerances might be met only with automatic equipment, such as CNC machine tools. Thus, depending on feature tolerances and surface finishes, different machine tool and processes have to be included in a part routing.

All of these factors affect in one way or the other the definition of raw material and part routing. As has been mentioned, special attention must be given to specific cases.

6.1.3 Task 3: Define setups and fixtures

As the part goes through each one of the machine tools during its route, the part might need to be machined in more than one position at one particular machine. The reason for this is that not all part features may be reachable from a certain position. Similarly, the part has to be firmly clamped to the table in each particular position. Each one of these positions along with the devices that clamp the part to the table constitute a setup (Fig. 24). In particular, the clamping device is called a fixture.

6.1.3.1 Setups

Before any cutting operation is defined, the different setups must be determined. The process planner will establish what features are to be machined in each particular setup. The tendency is always to reduce as much as possible the number of setups, in other words, to machine as many features as possible in each setup. The reason for this is that each new
setup requires the particular machine tool to remain idle while the fixture is mounted on the table.

Fig. 24: Setup for an injection molding plate.

Reachability is not the only factor that determines whether or not a feature can be totally machined in a given setup. Tolerance requirements may force certain operations to be performed before others. Thus, all the features that are reachable in one setup may not be finished at a particular time, but instead they may have to be rough machined first and then finish machined at a later stage. The need for intermediate stress relief operations may also require that a feature be finished in a different setup than when its roughed. These factors, combined with the experience of the process planner, will determine the number of setups that are needed to machine a part.
6.1.3.2 Fixturing

A Fixture is a type of tool utilized for adequately locating and holding a workpiece that is being subjected to a manufacturing operation (24). Machining, assembly, and inspection are examples of operations that make extensive use of fixturing devices. Due to the nature of our research, attention will be confined to machining applications.

As with any other tool, the main objective of a fixturing device is to reduce overall manufacturing costs, maintain quality and increase productivity within a framework of maximum flexibility (25). Traditionally, fixtures have been responsible for fulfilling certain requirements (26):

a) Positive Location; that is, the fixture must hold a part and inhibit its motion in any possible direction.

b) Deterministic workpiece location; which means that identical parts should be located by the fixture exactly in the same place for processing.

c) Rigidity; the fixture must provide enough support against the cutting forces, and clamping forces should not upset the part.

d) Interference; ease of loading and unloading of part, as well as accessibility of part to the cutting tool must also be provided by the fixture.

In addition to the above functions, a special type of fixture, called a Jig, provides tool guidance. In recent years, the introduction of CNC equipment has diminished the use of this type of fixtures. Nevertheless, jigs are still used, particularly when extreme conditions are encountered. Figure 25 shows a schematic of a typical fixture.
Fig. 25: A fixture with its most important elements (from ref. 22).

**Dedicated vs Modular Fixtures**

As production techniques change, fixturing practices also go through changes. Traditional dedicated fixtures have been tailor-made for a specific part only. This type of fixture is very accurate but, at the same time, it can take weeks to be designed and manufactured, it is very expensive, and it is not very suitable for engineering changes and dimensional variations. Thus, this fixturing concept is effective when large quantities of the same part are produced.

With new production techniques, dedicated fixturing may not be the best approach. Currently, frequent design changes require frequent manufacturing modifications. To take advantage of techniques such as group technology and flexible manufacturing, setups must be constantly modified. Similarly, job shops usually work with small lots of different parts and short lead times. In these cases, modular fixturing provides a better
option. In modular fixturing, common fixturing elements have been standardized, and are available “off the shelf”. Consequently, these standard components can be mass produced by outside manufacturers. Cost can thus be reduced, while quality is improved. Although modular fixturing usually requires long setup times and a great deal of experience for complex parts, it still offers a good solution when frequent part changes are the rule.

Figure 26 provides a guideline as to when to use each approach. It was extracted from a brochure provided by Qu-Co, a vendor of modular fixtures. At present, there are at least six major manufacturers who specialize in modular fixturing in the United States.

Design of Fixtures

In general, the design of a fixture involves a given set of steps, regardless of the adopted approach. Certain information must first be available: workpiece data (such as geometry), machine tool data (i.e. available workspace and constraints), and process data (operations sequence, tools, approximate cutting forces). Once these parameters have been defined, a fixture designer will follow the next steps:

1) Locating and Restraining Motion: A fixture must locate the part at a predetermined location with respect to the machine tool. Additionally, since the workpiece has six degrees of freedom, the fixture must inhibit the motion of the part in all directions. Two approaches are the most widely used: The 3-2-1 rule and the 4-2-1 rule. They refer to the number of points at which a locating feature is provided in three orthogonal planes, with the purpose of blocking the motion of the part. The 3-2-1 rule provides the minimum number of points needed for this purpose. The 4-2-1 rule is a variation which provides for a more stable support.
Fig. 26: Costs of modular vs dedicated fixtures (From ref. 60, pp. 11).

2) Use of clamping elements: Not necessarily equal in number to the locating points, the clamping elements will provide the forces needed to overcome the effects of the machining operations. They must be applied as directly as possible, and without causing deformation of the part.

3) Providing support: Locators are used only to provide geometric stability of the part, and they do not by themselves guarantee proper support of all loads without deformation of the part. The supports must be sufficient in number and strength to absorb all acting loads, and they must not interfere with the locating of the part.

4) Cutter guidance: In the case of jigs, proper guidance must be provided. Drill bushings are examples of jig elements.

5) Completion of body: The basic idea is to provide the structure that will carry all the composing elements with sufficient strength and rigidity. It must accommodate the part, have clearance for loading and unloading, and for easy removal of chips; it must also provide some sort of supporting surface to be clamped to the machine.
table, and, at the same time, it must also provide some sort of locating feature for quick alignment.

As established before, the design process is the same regardless of the approach taken. When designing a dedicated fixture, many of the elements are commonly picked from among those available in the market. However, the body is usually an original design, which must be created and manufactured from scratch. On the other hand, modular fixtureing implies a process of selection of the elements that will perform the required functions. In both cases, experience plays an important role for the design of a proper fixture.

Requirements for ease of fixtureing

From the above discussion, it can be inferred that certain geometries will be easier to fixture than others. In general, flat surfaces can be used for all fixtureing purposes - positioning, locating and holding - and should be used as much as possible. Curved and irregular surfaces are not as good as flat surfaces, specially for clamping purposes. A wide range of modular fixtureing elements that can be combined to hold different geometries is available in the market.

Vendors

There are at least six major vendors of fixtureing systems in the United States. Among the most important ones are Carr-Lane, from St. Louis; Qu-Co, from Union, Ohio; Stevens Engineering, from Phoenix, Az; Hurko, from East Granby, CT; and Jergens, from Illinois. OTC Power Team Division (Owatoma, Mn), and Enerpac (Milwaukee, WI) provide hydraulic clamping systems.

In general, the fixtureing elements that these vendors provide are classified as follows:
a) Base elements: Where all locating, supporting and clamping elements are attached.
b) Supporting elements: Used for supporting the parts, such as V-Blocks.
c) Locating elements: Such as pins;
d) Clamping elements; and
e) Miscellaneous elements: additional elements used for the construction of the fixture.

Recently, many vendors have implemented their catalogs in the form of 2D and 3D packages which can interact with commercially available CAD software to help during the design process.

6.1.4 Task 4: Establish tool and cutting strategies

Once a setup is defined, tools must be selected and cutting strategies must be defined. This is perhaps the task that is most affected by the personal experience of the process planner. The type of feature, its tolerances and its material are the driving factors for the proper selection of tools and cutting strategies.

6.1.4.1 Tool selection

There is a finite number of machining processes and tools associated with each type of machine tool. A case in point, lathes are used primarily for turning (although operations such as drilling and roller burnishing can be performed for certain part geometries), and tools can be chosen from among the universe of "single-point tools".

Our discussion will be centered in milling operations, however. In the previous chapter the capabilities of milling machines as well as some of the available tools were described. The first factor that affects tool selection from the universe of tools available to milling is the type of feature being machined. Although several tools can generate similar features,
certain tools are generally associated with certain features. For example, holes are usually produced with drills. Slots are done with end mills or slotters, while pockets are done with end mills. Large plane surfaces are generated with face mills. The second factor that affects tool selection are the feature tolerances and/or surface finishes. For example, good surface finishes in holes may only be accomplished with the use of reamers. On the other hand, tight hole straightness or cylindricity may require the use of boring bars or even end mills for the finishing operations.

It must be kept in mind that some features require the creation of auxiliary features. In the following chapters it will be shown that in order to generate slots of some sizes, holes must first be drilled. In this case, the holes are the auxiliary features that are not shown in the CAD model or the blueprint of the finished part. Experience of the process planner is what ultimately determines what kinds of auxiliary features are needed in order to accomplish certain feature geometries or tolerances.

Once a tool is chosen, it must be defined in terms of its type, material, size, and holder. Special attention must be given to the geometries of the cutting edges. In general, when cutting soft materials (such as some types of aluminum) high radial and axial rake angles should be used, while low angles should be used for material such as cast iron. Specialized literature (see references 54, 58 and 61) provide guidelines for the proper selection of angles for different combinations of tool and part materials.

**Tool sequence**

The sequence in which the different features are machined along with commonly used practices determines the order in which cutting tools are used. The general criteria in establishing tool sequence is summarized in the following guidelines.
• Reference planes are done first: Usually parts and features will be located with respect to these planes, therefore they must be available for subsequent operations.

• Auxiliary features are done after reference planes and before finished features: Included in this case are the combination drill-countersink tools (spot drills) that generate holes that will later guide drills. Holes drilled in preparation for end mill entry are also included here.

• Heavier cuts are done before lighter finish passes: The reason for this is that heavier cuts generate high residual stresses that might later distort the part. It is thus customary to take heavier cuts, stress relieve the part, and then finish machine the part.

6.1.4.2 Cutting Strategies

Tool paths, depths of cut and cutting conditions (feeds and speeds) are included in what is called cutting strategy. The cutting strategy is a function of the production objectives. Under normal circumstances the main objective is to reduce the cost of each functional part. The term functional implies that the part is within the required quality parameters. To accomplish the main objective of the cutting strategy, a balance among tool paths, depths of cut and cutting conditions must be found. The problem one faces while trying to accomplish this objective lies in the fact that it is difficult to quantify the actual efficiency of a given strategy. For example, a strategy in which deeper cuts and higher feed rates are used will certainly reduce machining time. At the same time tool wear will also increase. Again, experience will usually dictate what strategy may be more successful.
Tool paths

For all conditions remaining the same, tool paths must be programmed in such a way that the tool finishes its trajectory in the least amount of time. This requires that the sum of the time of rapid motions (when the tool is not cutting material) plus feed motions (in which the tool engages the part) be a minimum.

The most important factors affecting the definition of the tool paths are:

- Part geometry, which determines the relative location of the features.
- Set up geometry, which determines what obstacles the spindle must clear in order to reach these features.
- Roughing vs finishing pass. In roughing passes, the most important thing is to remove as much material as possible in the most cost effective manner. Since finish dimensions are not accomplished, the trajectories do not have to follow the exact contour of the part, and thus there is some liberty in defining the paths that have to be described. In finish machining tool trajectories must match the contour of the part, thus reducing the options for different tool paths.

There are commercial CAD/CAM packages that are capable of defining automatically the tool trajectories based on the geometry of the tool, geometry of the part, and the geometry of the blank material. In particular, CATIA provides a very powerful module for the definition of cutting trajectories for mold cavities. This module is capable of defining cutter paths for roughing and finishing passes with relatively little operator intervention.

Conventional vs Climb milling

Depending on the direction of tool motion and rotation with respect to the part, a cutter will encounter either full chip thickness (climb milling) or minimum chip thickness (conventional milling). Figure 27 shows a schematic of these two cutting strategies.
Significant differences exist between these two cases in terms of the magnitude and direction of cutting forces, tool wear and failure, and dimensional accuracy and surface finish achievable by each. Climb milling requires a strong setup and stiff machine (no backlash may be allowed). Conventional milling does not have these requirements. However, conventional milling results in higher power consumption, lower metal removal rates, and shorter tool life than climb milling.

![Diagram of conventional and climb milling](image)

Fig. 27: Conventional (a) and climb (b) milling.

**Cutting conditions**

The selection of cutting conditions depends primarily on the following parameters: part material, tool material, machining case (roughing or finishing), available tool horsepower, and rigidity of the setup. Except for the rigidity of the setup, all parameters are known.

Machining handbooks contain information regarding optimum cutting conditions as a function of tool material, part material and machining case. These conditions are given in
terms of surface speeds (usually surface feet per minute) and feed per revolution (inches per cutting edge per revolution). The parameters that are intended to be optimized with these conditions are surface finish and tool life (or time between resharpening operations). Appendix D shows a typical chart used for obtaining these figures. From these tables, spindle rpm's (revolutions per minute) and feeds (inches per minute) may be calculated by the formulas (1) and (2).

\[
\text{rpm} = \frac{\text{sfpm} \times 12}{(3.1416 \times \text{diam})} \quad (1)
\]

\[
\text{ipm} = \text{npe} \times \text{rpm} \times \text{fpi} \quad (2)
\]

where

- \( \text{rpm} \) = revolutions per minute of spindle
- \( \text{sfpm} \) = surface feet per minute (feet/min)
- \( \text{diam} \) = tool diameter (in)
- \( \text{npe} \) = number of cutting edges (edge)
- \( \text{fpi} \) = feed per cutting edge (in/edge)

Available horsepower sets a limit to the amount of material that can be removed per unit time. Complicated formulas have been developed to calculate the amount of power being consumed during a cutting operation. However, a simplified formula is accepted throughout the machine tool industry and is based on the premise that 1 hp is required to remove 1 in\(^3\) of mild steel with a sharp, positive rake cutter in one minute. This formula is stated as follows:

\[
\text{hp} = \text{ipm} \times \text{area} \times k \times 1.3 \quad (3)
\]

where

- \( \text{hp} \) = horsepower required at spindle.
- \( \text{ipm} \) = feedrate, inches per minute.
- \( \text{area} \) = width*depth of cut, in\(^2\).
\[ k = \text{material machinability factor.} \]
\[ 1.3 = \text{30\% dull tool safety factor.} \]

Machinability factors for some materials are given in Table 4. Since available horsepower (hp), machinability factor \( k \), and feedrate (ipm) are known, the area of cut (width \(*\) depth) can be calculated. In most cases, width of cut can be calculated from the available cutting trajectories, therefore, depth of cut can be determined by dividing the area of cut by the width of cut. It is apparent that after this, all parameters are known. In reality, the values that were obtained from this formulas and the charts may not be correct at all. The reason is that up until this moment, the rigidity of the setup has not been taken into consideration. The lack of rigidity makes itself present in the form of chatter or vibration, and poor surface finishes are evidence of it.

Unless an accurate estimation of the rigidity of the setup is known in advance, the parameters that have been calculated constitute only starting values of the cutting conditions. In actual practice cutting parameters are defined on a trial and error basis under actual operating conditions at the machine tool, since it is very difficult to predict the true rigidity of the setup (58). The fact that all parameters (spindle speeds, feeds and depth of cut) may have to be modified until optimum settings are found indicates that rigidity of the setup cannot be quantified in a single parameter that could be plugged back into any of the equations (1,2,3). Although the net effect of setup rigidity (or lack of it) could be quantified as an increase (or reduction) in the horsepower that can be exerted at any given moment, it would be difficult to predict where this change in horsepower should be accounted for (rpms, width of cut, depth of cuts, feeds). For these reasons, it is customary to define the final cutting conditions at the machine tool.
Table 4: Machinability factors (From ref 55, pp. 60)

<table>
<thead>
<tr>
<th>Work Material</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>0.3</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.3</td>
</tr>
<tr>
<td>Copper</td>
<td>0.5</td>
</tr>
<tr>
<td>Brass</td>
<td>0.4</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.5</td>
</tr>
<tr>
<td>Malleable Iron</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Cast Irons</strong></td>
<td></td>
</tr>
<tr>
<td>Ferritic</td>
<td>0.7</td>
</tr>
<tr>
<td>Pearlitic</td>
<td>1.0</td>
</tr>
<tr>
<td>Chilled</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Steels</strong></td>
<td></td>
</tr>
<tr>
<td>Up to 150 Bhn</td>
<td>1.5</td>
</tr>
<tr>
<td>300 Bhn</td>
<td>1.7</td>
</tr>
<tr>
<td>400 Bhn</td>
<td>2.0</td>
</tr>
<tr>
<td>500 Bhn</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Stainless Steels</strong></td>
<td></td>
</tr>
<tr>
<td>Free machining</td>
<td>1.0</td>
</tr>
<tr>
<td>Other</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Titanium Alloys</strong></td>
<td></td>
</tr>
<tr>
<td>Under 100,000 psi (689.5 MPa)</td>
<td>1.3</td>
</tr>
<tr>
<td>100,000-135000 psi (930.8 MPa)</td>
<td>1.7</td>
</tr>
<tr>
<td>135,000 psi and over</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>High Tensile Alloys</strong></td>
<td></td>
</tr>
<tr>
<td>180,000-220,000 psi (1241-1517 MPa)</td>
<td>2.0</td>
</tr>
<tr>
<td>220,000-260,000 psi (1517-1793 MPa)</td>
<td>2.5</td>
</tr>
<tr>
<td>260,000-300,000 psi (1793-2068 MPa)</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>High Temperature Alloys</strong></td>
<td></td>
</tr>
<tr>
<td>Ferritic Low Alloys</td>
<td>1.7</td>
</tr>
<tr>
<td>Austenitic</td>
<td>2.0</td>
</tr>
<tr>
<td>Nickel Base</td>
<td>2.5</td>
</tr>
<tr>
<td>Cobalt Base</td>
<td>2.5</td>
</tr>
</tbody>
</table>
The formulas presented here are the simplest available for computing cutting conditions. Appendix D shows a table in which more formulas of this type are presented. For a more comprehensive study, references (11) (12) (13) should be consulted.

Economic considerations

The type of production has an important effect upon the selection of cutting conditions. Figure 28 shows the effect of tool speeds upon the cost per piece, while Figure 29 shows how speed affects time per piece. In Figure 28 the cost per piece is a function of machining cost, tool change cost, and tool cost. As speed is increased machining time is reduced, while the number of tool changes and tool wear increase. Figure 29 shows total time per piece as a function of both machining and tool change time. In high volume production, these parameters must be optimized to achieve minimum costs. However, in the case of rapid prototyping, the machining time to accomplish a given surface finish may be more important than any other factor. These facts may affect the determination of the cutting parameters during the trial stage.

Determination of cutting parameters by trials at machine tool

Different parameters have different effects on tool life. The following guidelines should be considered when cutting conditions are modified at the machine tool:

- Changes of depth of cut have the least effect in tool life. Figure 30 (a) shows that a 50% increase in depth of cut reduces tool life by 15%.
- Changes in feed rate have an intermediate effect on tool life. Figure 30 (b) shows that an increase of 50% in feed per revolution decreases in 60% the tool life.
- Changes in spindle speeds have the most dramatic effect on tool life. Figure 30 (c) shows that an increase of 50% in spindle speed causes a 90% reduction of tool life.
Fig. 28: Tool speed vs cost per piece (from ref. 61, pp.6).

Fig. 29: Speed vs time per piece (from ref. 61, pp.7).
Fig. 30: a) Change in tool life vs change in depth of cut, b) change in feed per rev. vs change in tool life, c) change in spindle speed vs change in tool life (from ref. 61, pp. 4).
Additional considerations

In addition to the rigidity of the setup, two factors that affect the dimensional integrity of the finished part are the deflection of the cutting tool and/or the deflection of the part. These two factors are directly related to the cutting forces that appear during the cutting operation. Figure 31 shows the different scenarios for the case of end mills. Although the deflection of an end mill can be predicted by using the analogy of a cantilever beam, the final dimension of the workpiece may be more difficult to predict because of the complexity in the calculation of the dynamic forces. In conclusion, cutters should be as short and wide as the application allows it to be. Finish passes should be done in lighter cuts at smaller feed rates than roughing passes.

![Diagram showing possible deflection scenarios when end milling.]

Fig. 31: Possible deflection scenarios when end milling.

Finally, in the case of mold and die cavities, surface finish is a function of the scallop height, which in turn is a function of the distance between consecutive cutter passes (see Fig. 32: Smaller distance between passes implies longer tool paths. Consequently, during
Fig. 32: Effect of pitch size on surface finish. As consecutive passes are done closer, the scallop height is reduced. Surface finish is improved accordingly.
cavity finishing operations a compromise between surface finish and processing time must be reached.

6.1.5 Task 5: Generate CNC programs

Numerical control (NC) is a technology that enables the automatic operation of machine tools through a series of commands given in the form of coded instructions. These codes include numbers, letters and other symbols. The origin of this technology dates back to 1952, the year in which a three axis milling machine equipped with an analog-digital control unit that used a binary perforated tape as the means for storing the machining program was built at Massachusetts Institute of Technology. The instructions for these machines were given in the form of a numerical code, form which the term Numerical Control arose. The code was available to the control in the form of a perforated tape. This control was capable of controlling the motions of the three axes of the machine tool. The development of computer technology during the 1960's gave rise to new controllers that were denominated CNC (Computer Numerical Controls). These types of controls had the capability of storing programs in their own memory. At that time, several commercial companies had invested in this technology and were producing their own controls. Today, CNC technology is widely used in the machine tool industry.

Through the years machine tool builders developed their own controls, each of which introduced variations to the basic codes that enhanced the capabilities of the machine tool, thus giving a competitive advantage to the machine tool builder. To avoid the proliferation of languages, NC codes have been standardized by the international organisms. Standard ISO 6983/1 is an example. The basic purposes of this standard are to:

- To allow portability of CNC programs between different controls.
- To avoid the user's need to learn different languages.
Machine tool builders and control manufacturers have not completely adhered to these standards. Differences in machine tool and control capabilities are the reason why different codes are introduced by different manufacturers. The codes supported by the different controls are very similar, however, and users can easily interpret the codes of different manufacturers. Portability is not fully accomplished though.

Thanks to the recent technological advances reached in control architecture, a new modality has been adopted by control manufacturers. Controls are now able to read two different codes: a code that adheres to a certain standard (ISO), and a code defined by the manufacturer of the control. While the standard allows users familiar with CNC programming the capability of writing programs for these controls, the code developed by the particular manufacturer is more powerful, since it is tailored to the capabilities of the particular machine tool. This type of language is generally denominated "conversational", because a program is generated by answering a series of questions or screen prompts. Conversational codes provide automatic tool cycles that are more powerful and sophisticated than those supported by the standard codes. These tool cycles are predefined tool trajectories that commonly appear during program generation and that have been parametrized for the purpose of reducing the amount of program instructions. In the standard ISO codes they are commonly referred to as "canned cycles". The standard supports canned cycles for drilling, counterboring and similar operations. On the other hand, the conversational cycles are usually called "macros". In addition to the standard canned cycles, macros support more complex geometries such as pockets and cavities. Further, in the case of threaded holes, these macros include the preliminary drilling cycles needed before a tapping operation. The advantage of conversational programming are that it reduces the size of the programs and facilitates programming. The major drawback for conversational languages is the fact that they differ among vendors, and since controls are
incapable of translating a conversational code into a corresponding standard code, portability is virtually impossible.

Some of these controls provide databases and calculators of cutting conditions, which simplifies the task of computing the cutting parameters. In the past conversational programming and cutting conditions calculators would not have been a great advantage since controls themselves would not be used to generate CNC programs. Programs would be written off-line instead, thus allowing the machine tool to work. Today's controls however can be used to generate programs while the machine is working. This provides great flexibility, in particular for applications such as rapid prototyping.

Structure of a program

A CNC program consists of a series of statements (commonly called blocks) arranged in sequential order. Statements give specific commands to the control. Both conversational and standard ISO programs have the same basic structure:

- A declaration for program identification usually a number in ISO codes and a string of characters in conversational programming.
- Statements that define the origin of the coordinate system and kind of coordinates (absolute or incremental) used to describe the tool trajectories.
- Statements that define operations other than tool motions, such as turning spindle and coolant, changing tools, setting speeds and feeds etc.
- Statements that define the actual tool trajectories.
- Statements that tell the control that the program is finished. In some cases statements that instruct the control to call subprograms are also used.

A statement or block is made up of words that represent specific information that the control needs to perform its tasks. The line
N01G00X20;

is composed of the words "N01", "G00", "X20" and ";". Lines start with a sequence number ("N01") and finish with a terminating character (";"). The intermediate words represent instructions that have different effects depending on the type of word and numerical figure used. Figure 33 shows a typical NC program along with its explanation. Reference (NC) provides a thorough explanation of the ISO code used by a specific control.

Programming off-line

CNC programming can be performed off-line in either of two ways: manually or computer assisted.

Manual programming is better suited for those cases in which the geometries are very simple and the amount of features is not too large. When geometries are complicated and/or the number of features is large, program generation should be aided by computers. In cases where information is only available in blueprints or a similar means, a system that supports some conversational programming might be very helpful.

The steps required in creating a successful program are the following:

Step 1. Establish a coordinate system for the part.

Part coordinate systems should always be consistent with machine coordinate systems. For each setup, the exact location and geometries of all features must be known in order to generate the tool motions. Although several coordinate systems may be used for one single setup, it is customary to define all geometries with respect to a single coordinate system, since in reality the part is located with respect to entities that form one single coordinate
<table>
<thead>
<tr>
<th>NC PROGRAM</th>
<th>MACHINING PLAN No. 0001</th>
</tr>
</thead>
<tbody>
<tr>
<td>G0001;</td>
<td>Step 1: Place the tool at the center of the workpiece, 1.5&quot; above the surface. Use absolute coordinates, in inches, to define a tool position (statement N1).</td>
</tr>
<tr>
<td>M1620X0Y0Z1.5;</td>
<td>Step 2: Move the tool horizontally to the lower left corner of the part ((x = -1.375, y = -1.5)) and turn on the spindle. Set the spindle speed at 20% of the maximum speed (statement N2).</td>
</tr>
<tr>
<td>N2G00X-1.375Y-1.5M03S20;</td>
<td>Step 3: Move the tool down rapidly to the point ((z = 0.05)) and then lower it to the desired depth ((z = -0.55)) at a speed of 4 in./min (statements N3 and N4).</td>
</tr>
<tr>
<td>N3S1.375;</td>
<td>Step 4: Cut the periphery of the part (statements N5 to N8).</td>
</tr>
<tr>
<td>N4S1.375;</td>
<td>Step 5: Move the tool up rapidly (statement N9). Return to the starting position and turn off the spindle (statement N10).</td>
</tr>
<tr>
<td>N5G00Z1.5;</td>
<td>Step 6: End of this machining process plan (statement N11).</td>
</tr>
<tr>
<td>N6X1.375;</td>
<td></td>
</tr>
<tr>
<td>N7Y-1.375;</td>
<td></td>
</tr>
<tr>
<td>N8X-1.375;</td>
<td></td>
</tr>
<tr>
<td>N9G00Z1.5;</td>
<td></td>
</tr>
<tr>
<td>N10X0Y0Z0S;</td>
<td></td>
</tr>
<tr>
<td>N11M30;</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 33: Program for NC machining center (from ref. 56, pp.16).

system (see fixturing principles). Although some controls support other kinds of coordinate systems, rectangular coordinate systems are simpler to understand and relate better to the common machine coordinate systems.

Step 2. Generate tool motions and auxiliary operations

Once all tool trajectories, feeds and speeds have been calculated (see task 4), a set of instructions that indicate the corresponding tool motions have to be generated. These instructions have to be codified in the language that the control is able to interpret. Special attention must be given to auxiliary functions such as tool changes and supply of coolants.
Step 3. Test and debug program

A program is not released to the production floor unless it has been tested. Many computer systems are capable of simulating the tool motions. The quality of the information that can be obtained from this simulation varies with the sophistication of the program. However, regardless of simulation results the program must be tested at the machine tool before it is used in full production.

6.1.6 Task 6: Document process

This is an important step whose value is sometimes overlooked. After the process is finished and debugged, all final parameters and strategies must be recorded for later use or reference. Drawings and schematics of fixtures and setups must be saved too. This record constitutes actual experience that must be saved. Most importantly, if the part has to be manufactured in the future, good documentation will save the time and effort that interpreting a simple set of CNC instructions require.

6.2 Related work

In the past few years, considerable work has been done in the field of computer aided process planning (CAPP). The introduction of artificial intelligence techniques has enhanced the capabilities of the latest systems. Work in this area is divided into three major topics: automated process planning, automated fixture design and optimization of cutting conditions. Most CAPP systems incorporate each one of these elements up to a certain degree, either as part of their output (the most sophisticated case) or in their input.

Henderson and Chang (16) continued the work done by Anderson and Henderson (17) and applied it in the development of a CAPP system. The system combines Feature Extraction and Recognition from a B-Rep model with Artificial Intelligence concepts to
generate a manufacturing process plan. In his work, Henderson contends that although manufacturing features can be more easily extracted from a CSG tree, their use in the system will put a burden on the designer. Therefore, they choose B-Reps and their explicit model representation, even though features must be interpreted from the geometry database. Bond and Chang (18) utilizes UCLA's CADLOG system and a Knowledge Base for the same purpose. CADLOG creates a 3D Model of the part out of a 2D engineering drawing. Miller, Waldran, and Wang developed a similar system for the process planning of rotational parts (19) in which the user responds to a series of questions to define the features that are to be manufactured. Sakal and Chow (20) linked two commercial packages, AUTOCAD and MASTERCAM, with Artificial Intelligence techniques, to develop a CAPP system. Their system extracts features from a wireframe representation of an object. Cutkosky and Tenenbaum (46) worked on the principle that design for manufacturability is best accomplished by the simultaneous generation of the part design and manufacturing process. They developed a system that links both operations by specifying raw stock and a sequence of manufacturing steps that transform it into the desired form. Brooks, Hummel and Wolf (47) have developed a rule-based CAPP system for prismatic parts and multi-axis milling. Iwata and Sugimura (48) present a system that is capable of generating process plans based on the accuracies of the part. Dallam (43) developed a system that facilitated the definition of manufacturable features for milling with PADL-2. Dewaele implemented a CNC program simulator with IDEAS (44).

In terms of fixturing, Gandhi (26) has pointed out that current trends point towards the development of automated fixture designers. In his article, he claims that the average age of the designers of fixtures in industry is 55 years, and that the number of such personnel is diminishing rapidly. Therefore, the intention is to capture their knowledge
and implement it in computerized systems before these skills are lost. Gandhi has worked in the development of a program which relies on Artificial Intelligence Techniques, Solid Modeling Systems, and Commercially Available Fixturing Systems (27), with the purpose of reducing the need for a skilled fixture designer. It is worth mentioning that, although his system allows the addition of original fixtures to its database, he tries to take advantage of the commercially available elements as much as possible.

Darvishi (25) and Miller (28) have published articles in which they explain how some of the rules used in the successful implementation of an expert system that helps the designer during the development of the fixture. Chou (29), has developed a system which is capable of determining the point of application, magnitudes and directions of the clamping forces required to hold a prismatic part in place based on screw theory and engineering mechanics. Mani (30) used kinematic constraint synthesis to determine the clamping points of 2D shapes. Hayashi (31) et al. are involved in the development of a system similar to Gandhi’s, and they have implemented FEM analysis to predict the rigidity of their design. Youcef-Toumi et al (32), and Markus (33) have also worked with automatic generation of modular fixtures. Nevertheless, Youcef-Toumi is mostly concerned with the design of fixtures to be assembled by robots. Finally, Lee (34) presents a system designed to analyze Flexible Fixturing Systems using an FEM approach.

Optimization of cutting conditions is perhaps the topic that has been more thoroughly studied. Wysk et al. (49) developed mathematical models for the selection of optimum cutting conditions in terms of the tool life. Before that, Field et al (50) worked in the determination of costs and production rates for several machining operations. More recently Kirksharian and Masory (51) have performed similar work. Melkote and Taylor (52) introduced knowledge based techniques for the selection of cutting parameters for
milling cutters. Commercial vendors have implemented machinability data bases for particular applications. One example is the work performed by Zdeblick et al (53).

In the case of rapid prototyping in which process planning accounts for a considerable percentage of the delivery time, attention will have to be given to the interaction of the three factors: process planning, fixturing and cutting conditions. Future systems will have to predict setup rigidity in order to provide process plans that will not require fine tuning,

6.3 Application of Pro/Engineer to process planning tasks

Several tests were performed with Pro/Engineer to determine the advantages of its application to the tasks involved in process planning. Appendix E shows a summary of the results of these tests.

6.4 Concluding remarks

Process planning is a complex task that in most cases requires iterations through trial and error test runs. The guidelines provided here are intended to provide some background on the tasks that are involved in process planning. From our discussion it is evident that the type of production has an important effect on the outcome of the different tasks. In the next chapters our discussion will be centered in process planning for rapid prototyping purposes.
CHAPTER VII

DEVELOPMENT OF A PROCESS PLANNER

7.0 Introduction

As already mentioned, the objective of this research is to implement a system that overcomes the problems of the most important rapid prototyping techniques. Two modules of this system were developed. In this chapter, the details of the implementation of a process planner are presented.

7.1 Justification of system for process planning

The main objective of rapid prototyping via CNC milling is that of producing functional prototypes as fast as possible. Prototyping falls in the category of one-of-a-kind-type production, in which case non-machining time accounts for an important fraction of the total production time. Figure 34 shows a scheme that represents the contribution of the three most important tasks to the total fabrication time for a particular prototyping application. As can be seen, process planning and setup generation account for up to 90% of the time while machining accounts for roughly 10% of the total production time. This data was obtained from a study performed by Wall, Ulrich and Flowers at MIT (1). Although particular cases may not behave as it has been shown in Figure 34, this distribution is typical of many prototyping applications.

To reduce prototype production time a method for speeding process planning and setup generation must be found. Within this frame, we intended to investigate how a feature based approach can be used for reducing process planning time.
7.2 The feature parametrization approach

The term feature has been defined as "a higher level clustering of dimensional, material-related, and shape information which implicitly contains a specific functionality" (19). The feature parametrization approach for process planning is based on the premise that certain features can be associated with certain machining processes and cutting strategies. Strategy refers to the sequence of tools and the trajectories that each tool may describe in the work envelope to generate a feature.

![Diagram](image)

Fig. 34: Distribution of time in a particular prototyping application.

In the feature parametrization approach, the tool trajectories have been parametrized in the form of CNC "macros" that may be combined to generate the required feature. Macros are the equivalent to functions or subroutines used in programming languages. Macros are widely used in conversational languages to reduce CNC programming effort. Traditional canned cycles (drilling cycles, tapping cycles, etc.) are also a form of macros. In our
approach, macros take a certain number of parameters, perform certain calculations with them, and deliver a code that describes tool trajectories, cutting depths and cutting conditions. Macros may define a code used with one or more tools depending on their level of sophistication. Ultimately, the sequence of tools, their trajectories and their cutting conditions constitute the information required to machine a feature.

Potentially this approach can be used in two different scenarios:

- In those cases that suit Group Technology approaches, in which a finite number of features are frequently manufactured and for which CNC macros may be developed to satisfy the requirements of the user.
- In the rapid prototyping via part decomposition method. In this case, features that are frequently used to facilitate assembly may be parametrized.

This approach may reduce the time it takes to generate a process plan by automatically performing certain tasks that are straightforward but time consuming such as:

- Selection of tools.
- Calculation of the tool paths and depths.
- Calculation of cutting conditions
- Generation of CNC programs.

To investigate the feasibility of implementing this approach, a system that handles two types of features was implemented. The features are a side-blind slot and a round boss. The objective was to compare the different approaches for two different types of features: a void (slot) and a solid (boss).

7.3 Implementation procedure

Once the features were chosen, the next step was to establish how they could be machined. Two experienced machinists were interviewed for this purpose. A questionnaire
that contained the two principal features, the slot and the round boss, plus an auxiliary feature, a hole, was presented to them. The reason for including the hole was that personal past experience indicated that certain types of slots were started by drilling holes at the extreme ends of the slot. In this context, holes were not considered principal features due to the fact that they were not needed to define the attributes of the slot, but were needed to manufacture it instead. Appendix G shows an example page of the questionnaire.

Two facts were very apparent when interviewing the machinists though:

- Answers were accompanied by "ifs", in particular concerning the depths of cut and number of passes, despite the fact that features were presented in an isolated, unambiguous form. It was obvious that some of these doubts arose from the lack of information regarding the rigidity of the setup.

- Answers were totally based on personal experience and style.

Despite these facts, the information that they provided was grouped as follows:

- Tools needed to machine each feature.
- Sequence in which they were used.
- Depths of cut and trajectories associated with each tool.

A particular group of this information constitutes a strategy.

At this stage, two questions had to be answered based on the information provided by the machinists:

1) What is the optimum "size" of a macro, in other words, how many different tools and trajectories should be included in a particular macro?

2) What are the most important feature attributes for the selection of a particular strategy?
7.3.1 Definition of macros

Figure 35 illustrates the type of questions that arise during the definition of a macro. The feature in question is a hole. Its most important characteristics are its geometric shape (a cylinder), the fact that it is a void (as opposed to being a solid), its size (diameter and depth), its dimensional tolerances, surface finish and the material in which it is made.

![Diagram of a hole with coordinates]

HOLE 1
X = 1 +/- 1/32
Y = 1 +/- 1/32
D = 0.75 +/- 1/32

HOLE 2
X = 1 +/- .01
Y = 1 +/- .01
D = 0.75 +/- .002

Fig. 35: Two possible scenarios for the definition of a strategy for a hole.

For the values of hole 1, a spot drill and a drill will be needed to create it in a milling machine. The second case is denominated hole 2. All attributes remain the same except for its dimensional tolerances. In addition to the spot drill and the drill, a reaming operation will be required to bring the hole to the specified tolerances. The difference in tolerance makes it necessary to develop two different strategies.

To determine the optimum size of the macro feature interaction must be considered in addition to the geometric information of the feature. Going back to Figure 35, a macro for the first hole may be defined as follows:
1) Load a spot drill onto the spindle.
2) Drill a lead hole.
3) Load a drill onto the spindle.
4) Drill full hole.
5) Unload tool.

For the second hole, two more operations must be performed:
1) Load a spot drill onto the spindle.
2) Drill a lead hole.
3) Load a drill onto the spindle.
4) Drill full hole.
5) Load a reamer.
6) Ream the hole.
7) Unload tool.

In our context, macros could be created for each isolated feature in this manner. However, if both holes were to be machined in the same setup, it is obvious that it would be better to use a tool that is needed for both holes at the same time. In other words, a spot drill would be used for both holes before a drill was used on either one. Further, instead of parametrizing the whole process for each type of hole (that is, the five or seven steps), a natural way to save programming effort would be to parametrize each different operation performed (drilling cycle, tool change cycle, etc.).

**Feature Attributes**

By analyzing the information provided by the machinists, it was concluded that the most important attributes and their effects were:
a) The overall size of the feature. Machine tool and cutting tool size are affected by this.

b) The material that is being machined. Tool trajectories and setups are affected by this because of chip removal problems.

c) Tolerances. In general tighter tolerances require more passes, with more complicated tool trajectories. Surface finish is almost always consistent with the tolerances, and can be addressed by the proper selection of cutting parameters.

Based on these conclusions, the different strategies for the different cases can be established. Table 5 shows a summary of these strategies. The arrangement shown allows for a natural isolation of the macros that are needed to machine the features.

"Feat" column

Refers to the types of feature being handled. Two basic features were considered: slot and round boss. Three variations of the slot were defined because of their different attributes. In the following descriptions, refer to figures 36 and 37.

- Slot, the most basic slot, it is open only in one direction and its bottom surface is flat.
- Slot2, similar to Slot1, the difference being that it is open in two directions along its depth (i.e it is a "thru" slot)
- Slot3, also similar to Slot2, it is open in one direction only, but its bottom surface follows the contour of the top surface at a constant depth. Its cross section is a semisphere at the bottom, thus allowing the use of a ball end mill.
- RBoss, plain round boss.
Table 5: Summary of the definition of the machining strategies.

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Condition columns

Based on the answers given by the machinists, these conditions were the feature characteristics that had the greatest impact on the definition of a machining strategy:

- Matl: The material in which the feature is created. Two variations were considered "Al" for aluminum and "Cl,S" for cast iron or steel.
- Tol: The type of tolerance that must be held. This tolerance is associated with the geometric attributes of the feature, regardless of the feature location tolerance.
- Attr: Refers to the attribute that had the most important effect on the machining strategy:
  - T: In the case of the slots, thickness was the most important attribute.
  - D: In the case of the round bosses, their diameter was the most important attribute.

"Strat" column

Indicates the strategy number. A strategy is made up of a sequence of tools that move in certain trajectories. In all, 13 different strategies were needed to cover the different possibilities of feature characteristics.

"Seq" column

Indicates the tool sequence number.

"Desc" column

Gives a short description of the machining operation taking place. This operation could be:

- Rough: For a rough milling operation.
- Finish: For a finish milling operation.
Fig. 36: Types of slots supported by system: a) Slot1, b) Slot2 and c) Slot3.

Fig. 37: Round Boss.

- SDrill: For a spot drill.
• Drill: For a drilling operation.

The reason for the introduction of this column was to anticipate the need for the development of parameters for different options within a CNC macro.

"Tool" columns

A description of the tool is given in these columns including:

• Type: Which could be "emill" for an end mill, "fmill" for a face mill, "bmill" for a ball end mill, "drill", or "sdrill" for a spot drill.

• Matl: Cutting edge material, which could be "HSS" for high speed steel and "C" for carbide.

• Diam: Which indicates the outside diameter of the tool.

• Flutes: Which gives the number of cutting edges.

CNC macros columns

After analyzing the different tool trajectories that were needed to create each of the features, it was determined that six different CNC macros could account for the different tool paths.

• C.Cut: Stands for "center cut". In this macro, the trajectory of the tool is a straight line between two points. The tool plunges into the material at one of the points and moves at constant depth until it reaches the other point. In the final macro, this operation is repeated until the final depth is reached.

• CD Cut: This macro is associated only with a Slot3 type feature. It stands for "center at different depths of cut". It is similar to a center cut except that a group of points that lie in different planes constitute the path that the tool will follow.
• **Drill2**: This macro drills auxiliary holes in preparation for the milling operations in a slot. Two drilling cycles are performed by this macro at the extreme locations of the slot.

• **InSlot**: Stands for "interpolated slot". In this case, the internal periphery of a slot is interpolated by an end mill. Approach and exit trajectories are provided to avoid tool marks. This trajectory can be repeated at different depths.

• **R.Boss**: A round boss is roughed out by this macro. A conventional milling operation is performed by this routine.

• **F.Boss**: This macro finishes a round boss in a climb milling operation.

The information contained in Table 5 constitutes the foundation of the system that performs the process planning operations.

### 7.3.2 Development of the program

The tasks that must be performed during the definition of a machining plan are:

• **Obtain information.**

• **Establish raw material and part routing.**

• **Define setups and fixtures.**

• **Establish tools and cutting strategies.**

• **Generate CNC programs.**

• **Finish trials and documentation of process.**

Different capabilities and systems must be built into a computer program that handles these tasks automatically. A program that can handle all these tasks must be composed of at least:
• A consistent representation scheme. This representation scheme must be able to support both, the geometric information required for manufacturing purposes and the production data that is associated with the model of the part.

• A system capable of addressing geometric reasoning questions. This system would be responsible for extracting, arranging and distributing the required geometric information for the production expert. At the same time, this system will support operations such as setup and fixture design and the definition of raw material.

• A production expert. This system would be able to define part routing based on geometric and production data. This system would have to interact with the process planners for each individual manufacturing operation involved.

• A manufacturing processes expert. This system would interact with the production expert in order to define part routing, and would ultimately define the strategies for a part fabricated in a particular machine. A process expert must be devised for each particular operation that is to be supported.

• A system for the analysis of dynamic problems. This system would address questions such as fixture and setup rigidities as well as cutting forces. With its help, machining trials would be diminished or even avoided.

• Tooling, fixturing and machinability databases. This would provide the information needed for the definition of tools, cutting conditions, fixtures, etc.

• CNC program generator. Once all information is defined, process plans would have to be translated into instructions for the machine tools.

To this date, there is no system known to handle all of these tasks. Instead, the usual approach is to concentrate on a manufacturing process and then develop a system that can handle some of these tasks for that process. In particular, systems that analyze dynamic
performance (i.e. rigidity) require so much computing effort that the quality of their solutions in most cases does not justify the time needed to generate them.

As already explained, our efforts were concentrated in one process (milling) for two features (slot and round boss). Three questions were addressed during the development of this program:

- What range of attributes of the features should be supported?
- What should the output of our program be and how should it be presented?
- What information is needed in order to generate this output?
- How is this information processed?

7.3.2.1 Range of attributes

Dimension, material and tolerances are the attributes that whose ranges were defined for this system.

a) For Slots of type 1 and 2, a low precision thickness tolerance (>+/−0.010", surface finishes not better than 32 min), and a high precision tolerance (between +/− 0.009" and +/− 0.002", surface finishes between 16 and 32 micro inches rms) are supported.

b) For Slots of type 3, a thickness tolerance between +/− 0.005" and +/− 0.002", and surface finish between 32 and 64 micro inches is supported.

c) For round bosses, two tolerances in boss diameter are supported: tolerance greater than 0.010", and a tolerance between +/−0.010" and +/−0.002". The same surface finishes as in the case of slots 1 and 2 are supported.

d) Slot thickness must lie within .125" and 1.5".

e) Data for aluminum, steel and cast iron is available.
7.3.2.2 Output of the program

Depending upon the sophistication of the program, the output could take the form of a simulation on a computer screen, printed tool sequence data, a CNC program or a combination of all of them.

In our case, the output of the program includes the number of tools, their basic description, the sequence in which they are used, their cutting conditions and their cutting trajectories. We chose to present this information in two parts, a tool sequence plan and an APT program that can be used to generate a CNC code for milling the part.

The choice of using an APT code as an output is supported by several facts. The APT program can describe all tool trajectories and cutting conditions needed to fabricate the part. Unlike CNC codes that vary between different controls, APT programs are a standard way of representing machining instructions. The APT code of a part can be processed by different post processors to generate the CNC programs for machine tools of similar type, even if these machines are supplied by different manufacturers or equipped with different controls. Second, APT programs are far more readable by the human than other forms of representation such as CL files. Finally, APT codes are supported by a variety of commercially available computer aided manufacturing (CAM) systems.

Since the output was intended for a three axis milling machine, each output APT program works for a particular setup only. After this, the part must be refixtured, an a different program will be executed.

One of our objectives was to simulate the tool paths in CATIA’s machining module, and use IBM’s postprocessor to generate CNC codes for either a T-10 Cincinnati Milacron machining center or an Okada model maker, both available in our facilities.

Figure 38 shows what this system is capable of doing within the frame of a system that is capable of supporting all the tasks that a process planner performs.
7.3.2.3 Input information

In general, the type of input data required by a process planner depends upon two things: the type of output required from the program, and the type of operations that the program is intended to support.

![Diagram of the Master Process Planner with interconnections between Tooling & Fixturing Databases, Geometric Reasoning System, Machinability Database, Stresses and Dynamics Expert, Manufacturing Process Expert, Production Expert, Representation Scheme, Machinability Data for Milling, Machinability Data for Al, St, Cl, and Strategies for Slot & Boss.]

Fig. 38: Frame within which our system works.

As already mentioned, our intention was to relieve the user from the tasks of calculating trajectories, calculating cutting conditions and generating the CNC programs for milling the given features. On the other hand, tasks that involve geometric reasoning were not intended
to be supported, since they would be handled by a program that was being developed in parallel with this system. Consequently, the information that must be available to the program is:

- Geometric information of the part. This information is given in terms of the features that compose the part. Due to the effect they have on the definition of the milling strategies, tolerances and surface finishes must also be accounted for. For this purpose, good surface finishes (16 min) were assumed to be associated with close tolerances (<+-0.002”). The geometric information needed for each of the features is the following (refer to Figure 39):
  a) For a Slot1 or Slot2: Center coordinates (x,y,z) of the arcs that bound the slot on each side. Coordinate z corresponds to the surface where the slot is machined. Depth and thickness of the slot must also be defined.
  b) For a Slot3: Depth and thickness of the slot, plus the coordinates (x,y,z) of the bottom surface of the slot.
  c) For a Round Boss: Height and diameter plus the coordinates (x,y,z) of the center of the boss at the top. The maximum and minimum coordinates (x,y) of the plane upon which this boss is built are also given.
  d) In addition, a plane of safety must be given for each feature. This plane establishes a height that the tool must clear when approaching the feature from any possible direction.

- Material data. The type of material being machined affects both, the definition of the cutting strategy and the computation of the cutting conditions. Although there are tables of cutting conditions for many different materials, cutting strategies are affected more by the fact the hardness of the material. The way the program was
Fig. 39: Input information for slots and boss.
implemented, cutting data is available for three types of material: aluminum, steel and cast iron.

- Details of feature interaction. Features must be grouped according to the setup in which they are being machined. Feature interaction must be accounted for by establishing if features must be machined in a particular order. This information was handled in the form of a priority number which tells the processor whether a feature must be machined before, simultaneously with, or after another feature. An example of the application of the priority number is shown in Figure 40. In this case, the larger slot is machined before the smaller one. By doing this, the need for long, special tools is avoided.

- Additional information. Information that is not essential for the definition of the strategies such as a part identification number, must also be provided.

![CROSS SECTION A-A](image)

Fig. 40: Application of priority number. Large slot has priority 1, small slot has priority 2.

7.3.2.4 How information is processed
The final step was to define how the information would be processed. At this stage both the expected output and the available information had been defined. In summary, the main tasks that had to be performed were defined as follows:

a) The geometric data and the information regarding priorities and precisions must be read and sorted into a specific format that may allow us to handle them properly.
b) For each setup, all the tools needed to machine the features that are associated with that particular setup must be determined.
c) Each tool must be associated with a particular set of machining operations. Tool trajectories and cutting conditions are included in these operations.
d) The sequence in which the tools are used must be defined.
e) The output of the program must be arranged in two forms: a list of tools and the sequence in which they are used, and an APT program that can be used to generate the CNC code for the setup.

To perform these tasks, a program that consists of five major functions was developed. The program was written in C and runs in an IBM Risc/6000 workstation. Figure 41 shows a scheme of the most important elements of the program. Appendix F contains the program documentation as well as a description of the syntax required in the input data.

The major functions and their description are:

Traffic

This is the principal routine of the program. The only function that this routine performs is to coordinate the actions of the other routines by calling them in a specific sequence.
Fig. 41: Scheme of how the information flows within the program.
Loadinfo

This is the first routine that is called by Traffic. The main function of Loadinfo is to read the input data from a file that contains all the geometric information of the part. The input must be in the syntax shown in Appendix F. This routine prompts for the name of the input file, reads the information from it, and sorts this information in a preestablished manner. The following is the output of this routine:

- A structure that contains all the information for each feature including its most important geometric attributes (see Fig. 39), the precision with which the feature must be machined, and the priority that determines in which order the features must be machined.

- A series of variables that store information such as part identification number, material of the part, number of setups, reference coordinates of each setup and number of features for each setup.

The format of the structure in which the input data is arranged is the following:

```
feature[a][b].xxx=yyy
```

where

- a=associated with a setup number
- b=associated with a feature number
- xxx=attribute in question
- yyy=attribute value

and "feature[1][1].depth=1.000" indicates that the depth of the first feature (b=1) of the first setup (a=1) equals 1.000.
Tools

The next routine called in this program is named Tools. The input for this routine is the structure that Loadinfo created for each feature. Based on the feature geometric data and its precision, Tools defines the following data:

- The type of tools needed to machine each feature. The characteristics of the tools are also defined in terms of the material of the cutting edge, the type of cutter, the number of cutting edges, and the diameter of the cutter. Whenever possible, standard tool sizes as established by ANSI standards B94.19-1985 (end mills) and B94.11M-1979 (drills) were used. The user can change the size of the tool if the program's choice is not available.
- The macro with which each tool is associated.
- The type of cut and pass. When the tool is engaged in cutting the part at an angle of more than 90 degrees cut is assumed to be full, if angle is less than 100 degrees but more than 12 degrees cut is assumed to be partial, otherwise cut is assumed to be light. The angle is measured between a line drawn from the center of the cutter to the point in the periphery of the tool at which the tool engages the part, and a line drawn between the center of the cutter and the point in the periphery of the tool at which the part is disengaged. Pass can either be a roughing or a finishing operation. This information is later used to determine cutting directions as well as depths of cut, feeds and speeds.
- The sequence in which each tool is used.
- Number of tools for each feature.

To accomplish its function, Tools is provided with a full description of all this data for each one of the possible cases that it may encounter. In all, 14 different strategies of tool selection and sequences were required to cover all the possible combinations of materials
and tolerances for the two types of features that were being analyzed. The most important factor in the definition of each strategy was the required tool trajectory. It was determined that six different trajectories could be combined with certain tools to produce any of the features. These trajectories will be explained in the section that deals with the Editor.

In general, the definition of the possible combinations was affected by:

- Whether the material in question was soft or hard.
- Whether the required precision was low or high.
- The type of feature being analyzed.
- The attributes of the feature being analyzed.

For the case of the slot, 12 different scenarios were developed: Slot1 and Slot2 types of slot were covered by 8 strategies while Slot3 was covered by 4. Slot1 and Slot2 were covered by the same strategies because as far as the definition of the cutting strategies was concerned, the only difference between them was in the final depth of cut at which the tool had to be used. Every other condition related to cutting strategy or tool selection remained the same. The next factor that affected the number of strategies associated with Slot1 and Slot2 was the width of the slot. Under certain circumstances, slots whose width is smaller that 3/4" can be machined by taking only center passes. Slots wider than 3/4" were invariably interpolated. The largest slot thickness supported by the system is 1 1/2". Finally, the levels of precision (that is, loose -1- or tight tolerances -2-) and types of material (soft -1- or hard -2-) did affect the definition of the strategies. Consequently, Slot1 and Slot2 were covered by 8 strategies: 2 widths by 2 materials by 2 precisions. Slot3 presented a different situation. Here, two determining factors were considered: width of slot (critical value was again 3/4") and type of material. Since only center cuts would be taken, the level of precision achievable is fairly uniform (+/- 0.002) and is determined only
by the precision of the tool diameter and the number of passes. The possible combinations were thus 4: 2 widths by 2 types of material. Each combination was covered by a strategy. From the discussion with the experienced machinists it was concluded that the type of material had very little effect upon the definition of the cutting trajectories in the case of the round boss. The reason is that as opposed to the slot, the round boss does not present so many problems with chip removal. This could be taken care of by the proper selection of cutting conditions. Geometry of the boss affected only tool definition and depths of cut. Consequently, only two strategies had to be defined for the slot: one for high precision (tolerances < +/- 0.010") and another one for low precision.

The format of the structure in which the tool sequence is stored along with the information associated with it is:

```
feature[a][b].tool[c].xxx=yyy
```

where

- `a` = associated with a setup
- `b` = associates with a feature
- `c` = sequence or operation number
- `xxx` = attribute being defined
  - `type` = spot drill, drill, end mill, face mill.
  - `material` = high speed steel or carbide.
  - `flutes` = number of cutting edges.
  - `pass` = roughing (1) or finishing (2).
  - `cut` = (1) light, (2) medium or full (3).
  - `macro` = Macro number for this operation.
- `yyy` = value
and "feature[1][1].tool[1].type=s" indicates that the tool type used in the first operation of the first feature of the first setup is a spot drill ("s" is the value assigned to represent a spot drill).

A subroutine within Tools determines what group of information (that is, what strategy) is chosen for each feature. The selection is based on the feature data provided by Loadinfo. Except for the cut and pass information, all this data is shown on Table 5.

**Toolmanager**

Summarizing, the information (and source) available to Toolmanager is:

- The steps in which the part is to be manufactured. Each step constitutes a setup (from the input data through Loadinfo).
- In each setup a certain number of features will be machined according to a predefined priority (from the input data through Loadinfo).
- In order to be machined, each feature has been assigned a number of tools, in a given sequence. This sequence number will be referred to as "operation number" (from Tools).
- Each tool is associated with a machining trajectory, referred to as "macro" (from Tools).

The Toolmanager combines this information to generate a milling process for each setup of the part. Each setup is assumed to be independent of the others, and therefore all the features that are present in each setup can be finished before changing to another setup. The functions performed by Toolmanager are:

- Determine what tools are needed to finish all the features that are going to be machined in a single setup.
• Sort and arrange all these tools starting with face mills, then spot drills, then drills and finally end mills. Tools are not repeated when placed in this list. This order corresponds to the sequence in which tools are generally used. This information can be used for the purpose of instructing the tool room about the tools that need to be supplied.

• Specify the machining sequence based on the priority number. This sequence is generated according to the following rules:
  i) Features are machined in sequence according to their priority number (1,2,3...).
  ii) Features of the same priority are machined in parallel, that is, within the same priority the first operation of all features must be performed before the second operation of any feature is initiated.
  iii) When the program encounters two identical operation numbers for two different features within the same priority and the tool for each operation is different, the original sequence of tool arrangement (face mills, spot drills, drills, end mills) is followed. If both tools are of the same kind (that is, two drills) but the different size, the tool is chosen randomly.
  iv) Features of zero priority are machined last under rules (ii) and (iii).

• Keeps track of what has been done and what needs to be done until all features are finished.

Toolmanager prepares all this data in the form of 4-dimensional arrays. These arrays are arranged in a way that allows us to know the feature and the operation number being executed at any given moment. The form of this information is the following:

\[
\text{feature}[a][b][c][d]=x
\]

\[
\text{setup}[a][b][c][d]=y
\]
tool[a][b][c][d]=z

where
a=associated with a setup number
b=associated with a priority
c=associated with a tool number
d=associated with a feature operation number

"feature[1][1][1][1]=x" indicates that the operation in question is "the feature whose first operation (d=1) is to be machined by the first tool (c=1) in the first priority (b=1) and in the first setup (a=1) is 'x' ". Similarly, the setup number and the tool number associated with this operation are known since they are arranged in the same way. In the end, we can tell what sequence of tool (z), of what feature (x), and of what setup (y) is being used at a given moment by a declaration of the form:

"the tool type in use is"=feature[y][x].tool[z].type

In addition the geometric data can be obtained from the input data that Loadinfo created, and the macro information created by Tools is also identifiable, since we know the feature, setup and operation number that is being machined at any given moment.

Editor

The Editor is the last routine of the program. At this point, the tools and the macros associated to them have been arranged in the form that has been explained. The major functions performed by Editor are:

• Calculate the cutting conditions associated with each tool. At this point the "cut" and "pass" information is utilized.
• Calculate the necessary parameters that are to be used in each of the APT macros.
• Print an APT program that handles tool trajectories, tool changes and cutting conditions.

Calculation of cutting conditions: depths, feeds and speeds

Several routines within Editor calculate the depths of cut based on the cut and the type and size of tool being used. In general, these rules are heuristic in nature. At this point, no provision has been made to calculate the horsepower being consumed by the cutting operation, however, these rules give rather conservative values of depths of cut, so that it is safe to assume that horsepower does not become a limiting factor. When the depth of cut is smaller than the full depth of the feature, consecutive passes at different depths are programmed.

In the calculation of the cutting conditions, the first thing considered is the type of tool being used. Depth of cuts for spot drills and drills are only determined by the depth of the hole. If the hole is deeper than twice the diameter of the drill, a peck-drill cycle is programmed. In the case of end mills, depth of cut depends upon whether the cut is full, partial or light and upon the diameter of the tool. These cases are summarized as:

• For full cuts, maximum depth of cut equals the tool diameter divided by three.

• For partial and light cuts, the maximum depth of cut equals the diameter of the tool, as long as it is less than or equal to 1".

Again, these values are obtained from practical experience, and the objective is to reduce tool deflection.

Finally, the maximum depth of cut for face mills is set at 0.200". The most common type of face mills used is the indexable insert type. In this case, depth of cut is limited by the size of the insert and the geometry of the body of the cutter. This depth is usually less than 1/4". Power capacity is more important in this case than in any other case. For this reason, a conservative 0.200" was chosen.
Cutting conditions are calculated based on surface feet per minute and feed per insert data. Routines within the Editor make these calculations based on the formulas given in chapter 5. Machining data is available for the three types of materials, the four types of tools and the two types of pass, either roughing or finishing.

APT macros

A macro is a group of tool trajectories that has been parametrized. Macros are commonly designed for trajectories that appear frequently during machining operations. Their purpose is to reduce programming effort. Once a set of trajectories have been isolated, the APT commands needed to generate these trajectories are created. Coordinate values within these commands are replaced by variables whose values are calculated once the necessary parameters are defined. In our case, it was determined that six macros were needed. By combining these macros in different orders, the four different types of features could be machined. Figures 42, 43 and 44 show a scheme of each of these macros. In the following explanation the term "move" indicates a rapid motion, while "feed" and indicates a feed motion in the X-Y plane, while "plunge" means a motion involving a change in the Z plane. Operations that are repeated do not include motions to and from points in the z clear plane unless otherwise specified.

"Center cut"

This macro is associated with features type "Slot1" and "Slot2" and assumes a flat end mill is used. In this case, the tool follows a straight path between two points located in the same plane (X-Y). In this sequence the tool:

a) Moves to the (x,y) coordinates of the first point at a height equal to z clear.

b) Moves to a plane 0.100" above the z coordinate of the initial point.
c) Feeds to its first depth.

d) Feeds to point two.

If final depth has not been reached, the tool plunges to its next depth, and feeds back to the initial point. This operation is repeated until full depth is reached. At this point the tool moves to the initial z clear coordinate and moves to the initial point (x,y).

"Center cut at different depths"

This macro is associated with a "Slot3" type of slot and assumes a ball end mill is used. In this case the tool

a) Moves to the (x,y) coordinates of the first point at a height equal to z clear.

b) Moves to a plane 0.100" above the z coordinate of the initial point.

c) Feeds to its first depth.

d) Plunges to each of the next points at a constant depth with respect to the surface until the point at the opposite end is reached.

If final depth has not been reached, the tool plunges to its next depth, and plunges into each of the other points in a direction opposite to the initial one, again at a constant depth. This operation is repeated until full depth is reached. At this point the tool moves to the initial z clear coordinate and moves to the initial point (x,y).

"Drill at two points"

This macro is associated with all types of slots and assumes the use of either a spot drill or a drill. In this macro the tool:

a) Moves to the (x,y) coordinates of the first point at a height equal to z clear.

b) Moves to a plane 0.100" above the z coordinate of the initial point.
c) Feeds to its final depth unless a peck drill is executed, in which case the tool retracts 0.010" to allow for chip breakage after plunging to a predetermined depth.
d) Moves back to the z clear coordinate.
e) Moves to the second point in the plane X-Y.
f) Repeats the previous operation at the second point.

After this, the tool retracts to the z clear plane and moves to the first point.

"Interpolate slot"

This macro is associated with features "Slot1" and "Slot2" and assumes the use of a flat end mill. Its purpose is to cut the inside periphery of a slot. In this macro the tool:

a) Moves to the (x,y) coordinates of the first point at a height equal to z clear.
b) Moves to a plane 0.100" above the z coordinate of the initial point.
c) Feeds to its initial depth.
d) Feeds to a point in the periphery of the slot. To avoid any indentation, the trajectory that the tool describes during this motion is an arc.
e) Completes a cycle around the periphery of the slot that finishes at the same point where interpolating motion started started.
f) Tool feeds back to initial point following a semicircular path.

This operation is repeated until the final depth is reached. Afterwards, the tool retracts to the z clear plane.

"Rough-mill round boss"

This macro is associated with a round boss and assumes the use of either a face mill or a flat end mill. Its purpose is to rough-mill the outside diameter of a circular boss. It leaves 0.020" excess material in the diameter of the boss. In this macro the tool:
a) Moves to a point located away from the limiting coordinates of the plane upon which the boss is located. The coordinates of this point are:

\[
x = (x \text{ min})-(\text{tool radius})-0.100
\]
\[
y = (y \text{ coordinate of center of boss})-(\text{tool radius})-(\text{boss diameter +0.020})/2
\]
\[
z = z \text{ clear}
\]

b) Moves to a plane 0.100" above the z coordinate of the initial point.

c) Feeds to its initial depth.

d) Feeds to x-center coordinate of boss.

e) Feeds around the circle back to point in"d)".

f) Feeds 0.050" in the same direction in which point at "d)" was reached.

g) Moves to initial z coordinate + 0.100"

b) Moves to point in a).

These steps are repeated until the final depth is reached. At this moment, the tool moves to the center coordinate of the boss and to the z clear point.

"Finish mill slot"

This macro is associated with a round boss and assumes the use of a flat end mill. Its purpose is to finish a circular boss to final dimensions. In this macro the tool:

a) Moves to a point whose coordinates are:

\[
x = x \text{ Center coordinates of boss.}
\]
\[
y = (y \text{ Center coordinates of boss})-(\text{Boss Radius})-(\text{Tool diameter})
\]
\[
z = z \text{ clear}
\]

b) Moves to initial z + 0.100"

c) Feeds to initial depth
Fig. 42: Schematics of macros center cut (a) and interpolate slot (b).
Fig. 43: Schematics of center cut at different depths (a) and drill at two points (b).
Fig. 44: Schematics of rough mill round boss (a) and finish mill boss (b).
d) Feeds to the point in the periphery of the boss directly above its present position (path is in the Y direction). A semicircle is interpolated to avoid any indentation.

e) Boss is interpolated around its periphery.

f) Tool feeds to point described in "a)". A semicircular path is followed again.

This routine is repeated until final depth is reached. Climb milling is performed in this pass. In the case in which the boss needs more precision, a semifinish pass is added. The general strategy is the same except for two things: conventional milling is used, and 0.010" in diameter are left for the finish pass.

Print APT program

Editor prints out the APT program for each setup of the part. The output file is named by deleting the string "ipt" from the input file and adding "SETUP@.APT" to it, where "@" represents the setup number. This output constitutes the most important result from this process planner, and can be used to simulate cutter trajectories on a computer screen or create a CNC program for the part.

Editor makes use of the arrangement that Toolmanager provides by printing the information according to the way in which it was defined by Toolmanager. Cutting conditions are calculated and printed for each tool. Finally, the initial motions in each macro depend on whether a tool change was performed before a macro is executed. Editor accounts for all this. Appendix F shows an example output of the process planner, while Figure 45 shows a schematic of the sequence of events that take place before this output is obtained.
Fig. 45: Schematic of the sequence followed to fabricate parts in this system.
CHAPTER VIII

SUMMARY AND CONCLUSIONS

In this research, a survey of the most important rapid prototyping techniques was performed. It has been concluded that the prototypes fabricated by these techniques provide good visual representations of products. However, these prototypes have very limited physical properties. The dimensional tolerances and the mechanical properties of the prototypes are poor. Consequently, these prototypes provide limited functional simulation of actual components. In addition, the manufacturing processes that generate these prototypes offer no insight into the manufacturing issues that affect the fabrication of the actual component.

A rapid prototyping method based on CNC machining has been proposed. The objective of this technique is to fabricate prototypes that meet the expected performance capabilities of a component in a time that is competitive with other rapid prototyping techniques. A rapid prototyping method based on CNC machining could also expose issues regarding component manufacturability. It is also expected that this technique may be applied for the fabrication of parts in low-volume-production situations, such as EDM electrodes.

The rapid prototyping method via CNC machining is based on a part decomposition approach. In this approach, the model of a complex part is decomposed into simpler geometries. These geometries are manufactured in CNC equipment and assembled together to form the final part. This approach is similar to the techniques used in traditional pattern
making. To implement this approach, several questions must be addressed: a consistent representation scheme that supports design and manufacturing issues must be selected; tradeoffs between prototype tolerances vs manufacturing cost must be considered; and the functional issues regarding the implementation of a solution must be analyzed, in particular, the effect of the availability of equipment and the reduction of programming and setup time must be addressed.

It has been established that process planning accounts for a considerable fraction of the time it takes to fabricate a prototype. In this work, a computer system that facilitates the task of CNC program generation was implemented. This system was based on two principles: a certain type of equipment can machine a certain type of features, and any of these features can be created by the proper combination of a finite number of tools and tool trajectories. The system was developed for two types of features: a slot and a round boss.

The type of machine that was chosen is a three axes CNC milling machine. For the development of this system, three issues were addressed: the type of information that is needed by the system, how this information is processed by the system, and how is the output information presented.

The system requires all the information regarding feature geometry and feature interaction that might affect process planning. A format for the file that contains this information has been specified. Geometric information includes feature sizes and their dimensional tolerances as well as type of material being machined. Feature interaction includes the setup in which features are grouped, the order in which the features must be machined within the setup, and the tool clearance planes.

The geometric information of each individual feature is analyzed by the program, and a strategy is chosen form among a number of options. A strategy includes the sequence of tools and tool trajectories needed to generate the feature. The different strategies were
defined after consulting with two experienced machinists. Strategies depend upon the material to be machined, the size of the part, and the dimensional tolerances of the part. A very important factor affecting the definition of a strategy is the rigidity of the setup. However, it is very difficult to quantify, and the rules needed to compensate for this factor constitute a topic of study on their own. Consequently, this system does not make any provisions for setup rigidity. Once all strategies for a given setup are defined, tool sequence is determined based on the priority of each feature. Standard tools are used whenever possible. The program keeps track of the order in which tools are selected to guarantee that all features are finished before a new setup is started.

The output information is presented in the form of an APT code. This form was chosen because the APT language has been standardized and a program written in APT is transparent to the postprocessors of different controls. The tool trajectories were parametrized in the form of macros. These macros are predefined APT commands that have been parametrized. The output program includes tool sequence, cutting conditions and tool trajectories. In addition, the description of the tools that are needed for each setup is also provided by the program.

Conclusions

The APT programs provided by this system are comparable to those that an experienced machinist would chose to fabricate a given part, eventhough strategies vary from machinist to machinist because of such intangibles as past experience and "feel" for the particular machine. Further, the rules for tool sequence selection provided by this system generate sequences that are also comparable to those that an experienced machinist would select.

The approach implemented in this system may be useful in two cases: when group technology is utilized, in which case the parametric entities would correspond to those that
the particular application requires, and for rapid prototyping via CNC machining, in which assembly features can be programmed and reproduced without much effort. In both cases, parametric features may be associated to parametric machining codes.

The most important factors affecting the definition of the cutting strategies for the features are the material in which they are machined, the overall dimensions of the feature and the tolerances associated with these dimensions. Because of the way in which our strategies were defined surface finishes are more a consequence of the strategy than a factor affecting it, since good surface finishes are almost always associated with tight tolerances.

Definition and implementation of strategies is much more simple for void features (i.e. the slot) than solid features (the round boss). The reason for this is that in the case of void features all tool motions are done within the feature. Consequently, the strategies are not greatly affected by the shape of the blank material or by presence of neighboring features.

This approach has some drawbacks. The fact that rules are hard and inflexible has an effect on several issues. First, strategies are applied under very specific circumstances, which may not cover certain cases. Second, when feature characteristics are close to the limits of the criteria of a specific strategy, the strategy may not represent an optimal solution as viewed by a machinist. Finally, although standard tool diameters are used whenever possible, in some cases non-standard sizes are chosen by the program. Although the user can change the diameter of the tool within a range specified by the program, the program will change only the trajectory of the tool (if necessary), but the overall cutting strategy will not be affected. In some cases this may not be the best solution. On the other hand, a human machinist would easily anticipate a case in which the strategy would have to be modified.
Future work

In the future, this program may be enhanced by adding more strategies to machine different features. Again, these features should be tailored for a particular application. By the same token, more machinability data may be added to expand its present capabilities. However, several topics must be addressed to round up this system for the purpose of reducing process planning time:

- The program must be linked to a CAD system to facilitate the generation of the program for machining. This possibility has already been explored for the case of Pro/Engineer and some conclusions are explained in Appendix E.
- A system that helps in the definition of a setup, and that addresses fixturing questions must also be developed and linked to this system.

Finally, a system capable of quantifying setup rigidity could also diminish the process generation time, in particular the time it takes to adjust cutting conditions by a trial an error process could be avoided.
APPENDIX A

DATA RELATED TO RAPID PROTOTYPING TECHNOLOGIES
QUICK REFERENCE FOR RAPID PROTOTYPING TECHNOLOGIES

The following is a list of rapid prototyping developers and the equipment they make, extracted from reference (4). For each system, information indicates model name, process, material used, energy source, maximum part size, equipment price, and availability.

CUBITAL AMERICA INC.
23467 Ryan Rd.
Warren, MI 48091
(313) 754-7557

Soldier 5600; solid base curing; acrylate liquid photopolymers; 2 Kw ultraviolet lamp; 20 X 20 X 14 in; $490,000; shipping 3rd quarter 1991.

* * *

DTM CORP.
8716 Mopac N. Suite 200
Austin, TX 78759
(512)339-2992

SLS model 125; selective laser sintering; polycarbonate, polyvinyl chloride, and investment casting wax powders; 23-W carbon dioxide laser; 12 in dia. x 15 in; $300,000-$400,000; shipping 1st quarter 1992.

* * *

DuPONT/SOMOS VENTURE
New Castle Corporate Commons
Two Penns Way, Suite 401
New Castle, DE 19720
(302) 328-5435

Somos 1000 Solid Imager; solid imaging; acrylate liquid photopolymers; 500-mW argon-ion ultraviolet laser; 12 X 12 x 12; technology licensing available.

* * *

HELYSYS INC.
2301 205th St. Suite 107
Torrance, CA 90501
(213) 782-1949
LOM; laminated object manufacturing; plastic, foil, paper, and composite sheet; 40-W carbon dioxide Laser: 15 X 10 X 15 in; $100,000; beta systems available.

* * *

LIGHT SCULPTING INC.
4815 N. Marlborough Dr.
Milwaukee, WI 53217
(414) 964-9860

LSI-0609 MA; layer at a time fabrication; acrylate liquid photopolymers; 140-W ultraviolet lamp; 6 X 6 X 9 in; $100,000 shipping beta systems.

* * *

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Ave.
Cambridge, MA 02139
(617) 253-5381

No product, three dimensional printing; ceramic powders and colloidal-oxide binders; 3 X 3 X 3 in; no price, system under development.

* * *

PERCEPTION SYSTEMS INC.
Box 8002
1110 Powdersville Rd.
Easley, SC 29640
(803) 859-7518

No name yet; ballistic particle manufacturing; organic wax; resistance heating element; 12 X 12 X 12 in; about $50,000; system under development.

* * *

QUADRAX LASER TECHNOLOGIES INC.
300 High Point Ave.
Portsmouth, RI 02871
(401) 683-6600

Mark 1000 Laser Modeling System; laser modeling; acrylate liquid polymers; 5-W argon-ion visible light laser; 12 X 12 X 12 in; $195,000; shipping.

* * *

STRATASYS INC.
7411 Washington Ave. S.
Minneapolis, MN 55439
(612) 941-5607
3D Modeler; fused deposition modeling; nylon like thermoplastic, machinable wax, investment casting wax filaments; resistance heating elements; 12 X 12 X 12 in; $178,000; shipping beta systems.

* * *

3D SYSTEMS INC.
26081 Avenue Hall
Valencia, CA 91355
(805) 295-5600

SLA-190; stereolithography; acrylate liquid photopolymers; 7.5-mW helium-cadmium ultraviolet laser; 7.5 X 7.5 X 9.8 in; $95,000; shipping.

SLA-250; stereolithography; acrylate liquid photopolymers; 16.0-mW helium-cadmium ultraviolet laser; 10 X 10 X 10 in; $185,000; shipping.

SLA-500; stereolithography; acrylate liquid photopolymers; 200-mW argon-ion ultraviolet laser; 20 X 20 X 24 in; $385,000; shipping.
Table 6: Comparison of Rapid Prototyping Techniques (From ref. 7).

| Name                               | Operation                                                                 | Materials                                                      | Maximum Part Size    | Cost              |
|------------------------------------|---------------------------------------------------------------------------|                                                               |                     |                  |
| Stereolithography                  | 12.5-nW HeCd laser cures a photopolymer in vat, post-process curing.     | photopolymer liquid                                           | 20 x 20 x 24 in.    | $100,000 - $400,000 |
| Selective Laser Sintering          | 25-W CO₂ laser sinters powder material.                                   | ABS, PVC, polyester, nylon, wax, polystyrene, epoxy, metals, ceramics | 13 in. dia. x 15 in. tall | $200,000 - $450,000 |
| Laminated Object Manufacturing     | Sheets of material are laminated with a bonding agent and a 40-W CO₂ laser cures away the unused. | anything which can be sliced into sheets (e.g.: paper, plastic, metal) | 15 x 10 x 15 in.    | under $100,000 |
| Ballistic Particle Manufacturing   | Particles of material are shot at a target by an inkjet printer-like device controlled by a robotic system. | wax, plastic, photopolymers, ceramics, metals                  | no limit             | @ $50,000         |
| Photochemical Machining            | Two lasers are used to cure a photopolymer in a vat.                     | photopolymer liquid                                           | not available        | not available    |
| SOMOS™                             | An argon-ion laser on a razor is used to cure a low-shrinking, flexible resin in a vat post-curing is recommended. | photopolymer liquid                                           | 12 x 12 x 12 in.    | $350,000          |
| Optical Fabrication                | A visible light argon-ion laser with beam diameter and layer thickness control is used to cure a low-shrinking, flexible polymer; system includes software enhancement. | photopolymer liquid                                           | 12 x 12 x 12 in.    | $135,000 - $230,000 |
| Fused Deposition Modeling          | Thermoplastic filament is deposited by an extruding head.               | thermoplastics, machinable wax, nylon, investment casting wax  | 12 x 12 x 12 in.    | $130,000 - $178,200 |
| Solid Edge Curing                  | Photopolymer covered by a photomask is cured with an ultraviolet lamp.  | photopolymer liquid                                           | 14 x 20 x 20 in.    | $500,000          |
| 3-Dimensional Printing             | Powder material is joined by a binder deposited from a raster-like mechanism. | aluminum, oxide, silica, zirconia, zircon, silicon carbide     | 75 mm cu.            | not available     |
Table 7: Properties of material used in SLA (from ref. 3).

For the thermoset acrylic material as reported by Prioleau (3):

Tensile Strength.................7200-10100 psi
Tensile Modulus..................360,000-500,000 psi
Elongation..........................2-3%

According to Bezdiceck (11), other properties of commonly used resins for Stereolithography are:

Table 8: Properties of materials used in SLA (from ref. 11).

<table>
<thead>
<tr>
<th></th>
<th>SLR 802 Commercial</th>
<th>3631-196 Developmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity, cps</td>
<td>1600</td>
<td>550</td>
</tr>
<tr>
<td>Green Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>1200</td>
<td>250</td>
</tr>
<tr>
<td>Secant Modulus, psi</td>
<td>20,000</td>
<td>3000</td>
</tr>
<tr>
<td>Extractables, %</td>
<td>21</td>
<td>53</td>
</tr>
</tbody>
</table>

A gallon of DeSoto's SLR 804 costs $352.00, and 7.8 gallons are needed to fill the Vat of a SLA-250. Resin does not need to be changed, but it has to be added after parts are made. Resin is not recyclable.
Table 9: Comparison of commercial resins used for stereolithography.

<table>
<thead>
<tr>
<th>Properties</th>
<th>SLR-800</th>
<th>SCR-001</th>
<th>SCR-002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity (cps/25 °C)</td>
<td>1300</td>
<td>1000</td>
<td>300</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>1.13</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>Laser Solidification matter (Green Structure)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gel Content (%)</td>
<td>67</td>
<td>67</td>
<td>78</td>
</tr>
<tr>
<td>Elasticity (kg/mm²)</td>
<td>8.2</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>5</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Breaking Strength (kg/mm²)</td>
<td>0.4</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>UV POST CURE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gel Content (%)</td>
<td>95</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Elasticity (kg/mm²)</td>
<td>98</td>
<td>135</td>
<td>90</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>3</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Breaking Strength (kg/mm²)</td>
<td>4.7</td>
<td>6.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>
APPENDIX B

DATA RELATED TO REPRESENTATION SCHEMES
The Euler formula defines a solid in terms of the number of faces (F), edges (E), and vertices (V) as follows:

\[ F-E+V=2 \] (4)

Satisfaction of this equation is necessary but not sufficient for a solid to be a simple polyhedron. For multiple polyhedra, the equation becomes:

\[ V-E+F-H+2P-2S=0 \] (5)

where \( H \) is the number of holes, \( P \) is the number of passageways through the object and \( S \) is the number of connected face sets.

Table 10. Explanation of some symbols used in Euler operations (from ref. 13, pp. 379).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Operator</th>
<th>Complement</th>
<th>Description of operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialize database and begin creation</td>
<td>MBFV</td>
<td>KBFV</td>
<td>Make Body, Face, Vertex</td>
</tr>
<tr>
<td>Create edges and vertices</td>
<td>MEV</td>
<td>KEV</td>
<td>Make Edge, Vertex</td>
</tr>
<tr>
<td>Create edges and faces</td>
<td>MEKL</td>
<td>KEMKL</td>
<td>Make Edge, Kill Loop</td>
</tr>
<tr>
<td></td>
<td>MEF</td>
<td>KEF</td>
<td>Make Edge, Face</td>
</tr>
<tr>
<td></td>
<td>MEKBFL</td>
<td>KEMBFL</td>
<td>Make Edge, Kill Body, Face, Loop</td>
</tr>
<tr>
<td></td>
<td>MFKLG</td>
<td>KFMLG</td>
<td>Make Face, Kill Loop, Genus</td>
</tr>
<tr>
<td>Glue</td>
<td>KFEVMG</td>
<td>MFEVKO</td>
<td>Kill Face, Edge, Vertex, Make Genus</td>
</tr>
<tr>
<td></td>
<td>KFEVVB</td>
<td>MFEVB</td>
<td>Kill Face, Edge, Vertex, Body</td>
</tr>
<tr>
<td>Composite operations</td>
<td>MML</td>
<td>KME</td>
<td>Make Multiple Edges</td>
</tr>
<tr>
<td></td>
<td>ESPLIT</td>
<td>ESQUEEZE</td>
<td>Edge-Split</td>
</tr>
<tr>
<td></td>
<td>KVE</td>
<td></td>
<td>Kill Vertex, Edge</td>
</tr>
</tbody>
</table>
Table 11: Tolerances on standard milling cutters (Indexable cutters not included) from ref. 54, pp. 10-26.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Plus</th>
<th>Minus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameters of Mounting Hole:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All cutters, except shell end mills and screw-slotted cutters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 1&quot; diam hole, if not over 3&quot; long</td>
<td>0.00075 (0.190)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Up to 1&quot; diam hole, if over 3&quot; long</td>
<td>0.0010 (0.25)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Over 1&quot; through diam hole</td>
<td>0.0010 (0.25)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Shell end mills</td>
<td>0.0005 (0.01)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Screw-slotted cutters</td>
<td>0.0010 (0.25)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Outside Diameter:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain milling cutters (all types), side milling cutters, staggered-tooth side milling cutters, vice-side milling cutters, plain metal-slitting saws, metal-slitting saws with side chip clearance, metal-slitting saws (with staggered teeth and side chip clearance), screw-slotted cutters, single and double-angle cutters</td>
<td>0.015 (0.38)</td>
<td>0.015 (0.38)</td>
</tr>
<tr>
<td>Concave and convex cutters, corner rounding cutters (arbored type), gear and sprocket cutters</td>
<td>1 16 (1.6)</td>
<td>1 16 (1.6)</td>
</tr>
<tr>
<td>Shell end mills</td>
<td>1/64 (0.4)</td>
<td>0</td>
</tr>
<tr>
<td>T-slot cutters</td>
<td>0.000</td>
<td>0.010</td>
</tr>
<tr>
<td>Corner rounding cutters, shank type</td>
<td>0.010 (0.25)</td>
<td>0.010 (0.25)</td>
</tr>
<tr>
<td>Woodruff keyseat cutters, shank-type:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1, 4 to 3/4&quot;, inclusive</td>
<td>0.010-0.015 (0.25-0.38)</td>
<td>0.0000</td>
</tr>
<tr>
<td>7, 8 to 1 1/8&quot;, inclusive</td>
<td>0.012-0.017 (0.30-0.43)</td>
<td>0.0000</td>
</tr>
<tr>
<td>1 1/4 to 1 1/2&quot;, inclusive</td>
<td>0.015-0.020 (0.38-0.51)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Woodruff keyseat cutters, arbor-type</td>
<td>0.002 (0.05)</td>
<td>0.002 (0.05)</td>
</tr>
<tr>
<td>End mills, shank-type (2 flutes)</td>
<td>0.0000</td>
<td>0.0015 (0.038)</td>
</tr>
<tr>
<td>End mills, shank-type (4 or more flutes)*</td>
<td>0.005 (0.13)</td>
<td>0.000</td>
</tr>
<tr>
<td>Shank Diameter:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All cutters with straight shanks</td>
<td>0.0000</td>
<td>0.0005 (0.013)</td>
</tr>
<tr>
<td>Width of Cutting Face:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain milling cutters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 1&quot; face</td>
<td>0.021 (0.03)</td>
<td>0.001 (0.03)</td>
</tr>
<tr>
<td>Over 1&quot; to 2&quot;, inclusive</td>
<td>0.010 (0.25)</td>
<td>0.000</td>
</tr>
<tr>
<td>Over 2&quot; to 4&quot;, inclusive</td>
<td>0.020 (0.51)</td>
<td>0.000</td>
</tr>
<tr>
<td>Side milling cutters</td>
<td>0.002 (0.05)</td>
<td>0.001 (0.03)</td>
</tr>
<tr>
<td>Staggered-tooth side milling cutters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 3 1/4&quot;, inclusive</td>
<td>0.0000</td>
<td>0.0005 (0.013)</td>
</tr>
<tr>
<td>Over 3 1/4 to 1&quot;, inclusive</td>
<td>0.0000</td>
<td>0.0010 (0.025)</td>
</tr>
<tr>
<td>Dimension</td>
<td>Tolerance, in. (mm)</td>
<td>Plus</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>---------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Half-side milling cutters</td>
<td>0.015 (0.38)</td>
<td>0.000</td>
</tr>
<tr>
<td>Metal-slitting saws and screw-slotted cutters</td>
<td>0.001 (0.03)</td>
<td>0.001</td>
</tr>
<tr>
<td>Single and double-angle cutters</td>
<td>0.015 (0.38)</td>
<td></td>
</tr>
<tr>
<td>Shell end mills</td>
<td>1/64 (0.4)</td>
<td>1/64</td>
</tr>
<tr>
<td>End mills, shank-type</td>
<td>1/32 (0.8)</td>
<td>1/32</td>
</tr>
<tr>
<td>(except heavy duty)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-slot cutters</td>
<td>0.000</td>
<td>0.005</td>
</tr>
<tr>
<td>Woodruff keyseat cutters, shank-type:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/16 to 5/32&quot; face, inclusive</td>
<td>0.000</td>
<td>6.005</td>
</tr>
<tr>
<td>3/16 to 7/32&quot; face, inclusive</td>
<td>0.000</td>
<td>0.0002</td>
</tr>
<tr>
<td>1/4&quot; face</td>
<td>0.000</td>
<td>0.0003</td>
</tr>
<tr>
<td>5/16&quot; face</td>
<td>0.000</td>
<td>0.0004</td>
</tr>
<tr>
<td>3/8&quot; face</td>
<td>0.000</td>
<td>0.0005</td>
</tr>
<tr>
<td>Woodruff keyseat cutters, arbor-type:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/16&quot; face</td>
<td>0.000</td>
<td>0.0002</td>
</tr>
<tr>
<td>1/4&quot; face</td>
<td>0.000</td>
<td>0.0003</td>
</tr>
<tr>
<td>5/16&quot; face</td>
<td>0.000</td>
<td>0.0004</td>
</tr>
<tr>
<td>3/8&quot; face and over</td>
<td>0.000</td>
<td>0.0005</td>
</tr>
<tr>
<td>Sprocket wheel cutters</td>
<td>0.010 (0.25)</td>
<td>0.000</td>
</tr>
<tr>
<td>Concave and corner rounding</td>
<td>0.010 (0.25)</td>
<td>0.010</td>
</tr>
<tr>
<td>Diameter of Circle:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convex cutters</td>
<td>0.010 (0.05)</td>
<td>0.002</td>
</tr>
<tr>
<td>Concave cutters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 7/16&quot; circle, inclusive</td>
<td>0.002 (0.05)</td>
<td>0.001</td>
</tr>
<tr>
<td>Over 7/16&quot; circle</td>
<td>0.004 (0.10)</td>
<td>0.002</td>
</tr>
<tr>
<td>Corner rounding cutters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 1/8&quot; circle, inclusive</td>
<td>0.001 (0.03)</td>
<td>0.001</td>
</tr>
<tr>
<td>Over 1/8&quot; circle</td>
<td>0.002 (0.05)</td>
<td>0.001</td>
</tr>
<tr>
<td>Angle, minutes:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-angle cutters</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Double-angle cutters, half-angle</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Overall Length:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All shank-type cutters</td>
<td>1/16 (1.6)</td>
<td></td>
</tr>
</tbody>
</table>

* If the shank is the same diameter as the cutting portion of double-end end mills, the tolerance on the cutting diameter is +0.0000", -0.0025" (0.063 mm).
### Basic Toolholder Data

**Standard “V” Flange Taper**  
ANSI (B5.50)

![Diagram of V-flange taper]

<table>
<thead>
<tr>
<th>Std. Cat. Taper</th>
<th>Gagedia D</th>
<th>D₁</th>
<th>D₂</th>
<th>C</th>
<th>Thread (tq inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.252 / 1.268</td>
<td>1.24</td>
<td>1.204</td>
<td>1.875</td>
<td>3/8-13</td>
</tr>
<tr>
<td>45</td>
<td>1.752 / 1.768</td>
<td>1.74</td>
<td>1.704</td>
<td>2.50</td>
<td>5/8-11</td>
</tr>
<tr>
<td>50</td>
<td>2.752 / 2.768</td>
<td>2.74</td>
<td>2.704</td>
<td>3.000</td>
<td>3/4-10</td>
</tr>
<tr>
<td>60</td>
<td>4.252 / 4.268</td>
<td>4.24</td>
<td>4.204</td>
<td>5.000</td>
<td>1-8</td>
</tr>
</tbody>
</table>

### Standard

**MAS 403 BT Taper**  
(Japanese standard)

![Diagram of MAS 403 BT taper]

<table>
<thead>
<tr>
<th>Std. BT Taper</th>
<th>D₁</th>
<th>D₂</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.75</td>
<td>3.937</td>
<td>0.335</td>
<td>0.079</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>2.25</td>
<td>3.937</td>
<td>0.335</td>
<td>0.079</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2.75</td>
<td>3.937</td>
<td>0.335</td>
<td>0.079</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 46: Standard dimensions and tolerances for adapter elements (from ref. 59, pp. 455).
APPENDIX D
DATA RELATED TO MILLING PARAMETERS
Table 12: Typical cutting data (from ref. 54, pp. 10-54).

<table>
<thead>
<tr>
<th>Material</th>
<th>Feed and Speed</th>
<th>High-Speed Steel Cutters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Face Mills</td>
<td>Slab Mills</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.025</td>
<td>0.015-0.025</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.63)</td>
<td>(0.38-0.53)</td>
</tr>
<tr>
<td>Brass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.025</td>
<td>0.008-0.020</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.63)</td>
<td>(0.20-0.38)</td>
</tr>
<tr>
<td>Bronze</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.025</td>
<td>0.008-0.020</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.63)</td>
<td>(0.20-0.38)</td>
</tr>
<tr>
<td>Cast irons:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>soft, 150-180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.025</td>
<td>0.010-0.025</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.63)</td>
<td>(0.25-0.51)</td>
</tr>
<tr>
<td>medium-hard, 180-225</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.000-0.015</td>
<td>0.008-0.015</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.63)</td>
<td>(0.20-0.38)</td>
</tr>
<tr>
<td>malleable, soft to hard, 225-350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.005-0.012</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.13-0.38)</td>
<td>(0.13-0.38)</td>
</tr>
<tr>
<td>Cast steels, soft to hard, 350-450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.015</td>
<td>0.010-0.015</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.38)</td>
<td>(0.25-0.38)</td>
</tr>
<tr>
<td>Steels: 100-150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.015-0.020</td>
<td>0.008-0.015</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.38-0.51)</td>
<td>(0.20-0.38)</td>
</tr>
<tr>
<td>150-250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.010-0.020</td>
<td>0.008-0.015</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.25-0.51)</td>
<td>(0.20-0.38)</td>
</tr>
<tr>
<td>250-350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.005-0.010</td>
<td>0.005-0.010</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.13-0.25)</td>
<td>(0.13-0.25)</td>
</tr>
<tr>
<td>350-450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed per tooth, in. (mm)</td>
<td>0.003-0.008</td>
<td>0.005-0.008</td>
</tr>
<tr>
<td>Cutting speed, sfm (m/min)</td>
<td>(0.08-0.20)</td>
<td>(0.13-0.20)</td>
</tr>
</tbody>
</table>

* Coated cermets can generally be applied at the higher speeds in the ranges given.
** Polycrystalline diamond cutters can sometimes be applied at the higher speeds in the ranges given.
Table 13: Formulas for cutting conditions (from ref. 59, pp. 456).

Formulas for turning, milling and drilling

Symbols

\[ \begin{align*}
D &= \text{Diameter (inches)} \\
L &= \text{Length of Cut (inches)} \\
a &= \text{Depth of Cut (turning)} \\
a_t &= \text{Depth of Cut (milling)} \\
a_w &= \text{Width of Cut (inches)} \\
v &= \text{Cutting Speed (feet per minute, SFM)} \\
n &= \text{Spindle Speed (Revolutions per minute, RPM)} \\
s &= \text{Feed per Revolution (inches per revolution, ipr)} \\
s' &= \text{Feed per Minute (inches per minute, ipm)} \\
s_t &= \text{Feed per Tooth (inches per tooth, ip)l} \\
V_c &= \text{Metal Removal Rate (cubic inches per minute, in\(^3\)/min)} \\
K_c &= \text{Specific Cutting Force (pounds per square inch, lbs/in\(^2\))} \\
z &= \text{Number of Teeth} \\
P &= \text{Power (horsepower, HP)} \\
V_p &= \text{Metal removal (cubic inches per minute per H\(_c\), in\(^3\)/min.H\(_c\))}
\end{align*} \]

Formulas

<table>
<thead>
<tr>
<th></th>
<th>Turning</th>
<th>Milling</th>
<th>Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cutting Speed</strong></td>
<td>( \frac{\pi \times D \times n}{12} )</td>
<td>( \frac{\pi \times D \times n}{12} )</td>
<td>( \frac{\pi \times D \times n}{12} )</td>
</tr>
<tr>
<td><strong>Revolutions per Minute</strong></td>
<td>( \frac{12 \times v \times \pi \times D}{n} )</td>
<td>( \frac{12 \times v \times \pi \times D}{n} )</td>
<td>( \frac{12 \times v \times \pi \times D}{n} )</td>
</tr>
<tr>
<td><strong>Feed per Minute</strong></td>
<td>( s \times n )</td>
<td>( s \times n )</td>
<td>( s \times n )</td>
</tr>
<tr>
<td><strong>Feed per Tooth</strong></td>
<td>( \frac{s'}{(2 \times n)} )</td>
<td>( \frac{s'}{(2 \times n)} )</td>
<td>( \frac{s'}{(2 \times n)} )</td>
</tr>
<tr>
<td><strong>Cutting Time</strong></td>
<td>( L/s' )</td>
<td>( L/s' )</td>
<td>( L/s' )</td>
</tr>
<tr>
<td><strong>Metal Removal Rate</strong></td>
<td>( 12 \times a \times a_s \times v )</td>
<td>( a_t \times a_s \times s' )</td>
<td>( s' \times (\pi \times D) \times 4 )</td>
</tr>
<tr>
<td><strong>Horsepower at Spindle</strong></td>
<td>( \frac{V \times K_c}{33.000} )</td>
<td>( \frac{a_t \times a_s \times s}{V_p} )</td>
<td>( \frac{V \times K_c}{33.000} )</td>
</tr>
<tr>
<td><strong>Torque at Spindle</strong></td>
<td>( \frac{63025 \times P}{n} )</td>
<td>( \frac{63025 \times P}{n} )</td>
<td>( \frac{63025 \times P}{n} )</td>
</tr>
</tbody>
</table>
APPENDIX E

USE OF PRO/ENGINEER FOR PROCESS PLANNING
Use of Pro/Engineer for Process Planning

Several tests were performed on Pro/Engineer to test its possible use in tasks related to process planning. The license at our site does not include all possible capabilities of Pro/Engineer's. Consequently, conclusions were drawn based only on the capabilities of our system.

Our initial objective was to develop a system that helped in two tasks:
1) Representation of fixtures and setups.
2) Generation of machining process.

For these purposes, several capabilities of Pro/Engineer's were tested. The conclusions drawn from these tests are described in the following paragraphs.

General

Pro/Engineer is a solid Modeling system which utilizes a parametric approach for part definition. Pro/Engineer is made up of a variety of modules which allow the user to define a part in different manners as well as perform different types of analysis. The most important modules are:

a) Sketcher: This module allows the user to create two-dimensional sketches of parts. Sketches form the foundation of the features that are created in Pro/Engineer.

b) Drawing: In this module, engineering drawings of parts with orthographic and isometric views are created.

c) Part: This is the module in which models are created. To create parts it utilizes a variety of tools such as predefined, parametrized features, as well as the sketcher. Models created in this module are associated with other modules. Consequently, changes to the model of a part may be performed in any other module.
d) Assembly: In this module parts can be assembled together to form different components. Assembly procedures are relatively simple and straightforward.

In addition, Pro/Engineer's database is open to the user through Pro/Develop, a library of functions written in "C" that allow the user to obtain information from and add information to the database, at the same time that Pro/Engineer is being utilized.

Other modules, including a Manufacturing module, may be purchased from the developer of the system (Parametric Corporation). In this study, attention was centered in the Part and the Assembly modules.

Part Module

Pro/Engineer is one of the most user-friendly systems from the point of view of model creation. The use of parametrized features greatly simplifies this task. A part is created by sketching a base feature. Other features are later added to the base. The features that are added to the base are taken from a menu of features that have been parametrized.

Based on our objectives, two of the Part Module's capabilities were tested. The first one was the "User Defined Features" (UDF) option and the other one was the "Family Tables" option.

User Defined Features (UDF's)

User Defined Features are features that have been designed and parametrized by the user. Relations between parameters may be defined in order to maintain certain proportions. Our intention was to create a menu of UDFs that correspond to those features that facilitate assembly in the context of rapid prototyping. Later, these features would be associated with CNC macros in order to develop machining processes. The major problem in this task is to extract the proper feature information from the database.
Pro/Engineer is capable of providing a "Part Information File" from which general feature data may be extracted. Feature identification number and feature type are the most important parameters that can be extracted from this file. Although geometric information data is also provided, the uncertainty associated with the way in which a feature is defined by the user makes this information useless. The general procedure is to get the feature type and name, and then interrogate the database by using geometry extraction functions based on Pro/Develop.

We investigated if the use of UDF's could allow us to predict accurately the form in which the geometric information is presented in the part information file. To accomplish this we had to analyze how UDF's are defined. In the most simple case, a UDF is created by grouping a series of features (that can be holes, slots, boss, etc.). Then two types of attributes must be defined: those that define the feature size, and those that define the feature location. It was found that the attributes that define the feature size can be chosen by the creator of the UDF in any form, as long as a consistent feature definition was guaranteed. The same geometry may be defined by setting the three lengths of the sides or by choosing a combination of a length and two angles. The depth however can only be defined as such to make it consistent. Once a user adds a UDF to a part, size attributes are identifiable in the part info file. However, part location and orientation proved to be more difficult to predict. In the most usual case, Pro/Engineer only prompts for reference surfaces and edges during the initial creation of a UDF. A user that is later adding a UDF to a part model can arbitrarily chose these reference planes or edges when prompted about the feature location and orientation. The part information file does not provide information regarding where these references are located. This also makes size information useless, since it is impossible to know how a certain attribute is oriented.
To overcome this problem, we tried to associate a UDF to a particular coordinate system which could later be referenced to the coordinate system of a part. Although a coordinate system location is not provided by the part information file, Pro/Develop provides a function that can find where a coordinate system is located with respect to another. If all other attributes within a UDF are known with respect to the UDF coordinate system (and they are known since the UDF can be designed in such a way that the information file can tell the size of an attribute), the geometric information needed for machining purposes can easily be calculated. This would greatly simplify feature extraction tasks.

Up to this point, we have been able to create UDF's as a function of their own coordinate system. Later, these UDF's can be added to other parts by defining the UDF's coordinate systems with respect to the part coordinate system. However, only translations between the two coordinate systems are possible. A UDF coordinate system cannot be rotated with respect to a part coordinate system. The way in which the UDF was initially designed has the most important effect on whether or not it can be rotated. The problem is know to design a way in which a UDF can be not only translated but also rotated, while keeping the information from the coordinate systems.

Family Tables

Family tables is another way of creating a UDF. The only difference is that once a basic feature is defined and parametrized, parameter values may be saved in a file. Further, a particular set of values can be named. Later, a feature of a given size can be extracted from the family table by calling its name.
For our purposes, family tables can be utilized to store commercial modular fixtureing elements, tooling elements, machine tables and spindles, etc. which can later be used for setup representation in the assembly mode.

Assembly mode

The use of the assembly module for setup representation purposes was also investigated. Assembly on the computer screen can be either manual or automatic. Manual assembly is straightforward since the system prompts for assembly constraints until an assembly is totally defined. Automatic assembly can be accomplished in several ways. The automatic assembly method that we studied more closely is similar to the method we tried to implement for UDF definition. In this automatic assembly method, a part can be assembled with another part by making its own coordinate system meet the coordinate system of the other part. Pro/Develop may also be used in the assembly mode.

Figure 24 shows the scheme of a fixture that was represented in the assembly mode. In all, 14 elements were assembled for this representation: 4 clamps, 3 locating pins, 4 parallel bars, 1 base plate, 1 pallet and 1 part. This representation provides an excellent means for checking interference, since the only limiting factor is imposed by the accuracy with which the models were created.

There are two problems with this type of representation:

1) Although simple, manual assembly is a slow process.

2) Any change to the views in the screen may consume a lot of time

These situation get worse as more elements are added to the setup or as more computer resources have to be shared with other tasks. For the case shown in figure 24, a simple reorientation of the setup that would allow a closer examination of a particular location could take from 40 seconds to 1 minute.
The use of Pro/Develop along with the development of specialized software may reduce the time it takes to create the representation of a setup. Speed in changing views can only be improved by the developer of the software or by improving the hardware in which it runs.
APPENDIX F

SYNOPSIS OF PROGRAM FUNCTIONS
INPUT DATA

The input information must be available in the form of a text. The type of data that is needed and the syntax in which it must be presented is now explained. The following rules apply in this description:

1) Strings between quotation marks (") must be written as shown.
2) The character "x" represents an integer number.
3) The characters "x.x" represent a real number.
4) The characters "yyyy" represent a string.

Figure 47 shows an example input file.

Input file

The input file name must finish with the string ".ipt", and it may be at most 10 characters long (excluding the string ".ipt").

Body of input text

The input text must start with a header that is separated from the rest of the information by a line that contains at least eight asterisks ("***********"). A blank line must be given before and after this line. In this header the following information is expected:

Part data follows the header. Part data is divided in different setups. The end of the information is declared by the line:
"END PART"

In the part information, feature data must be given for each setup. Since this program is incapable of performing any reasoning about the geometry of the part, feature information must be associated with a setup. The assumption here is that in general, not all features of a part can be machined in a single setup. The information of all the features that
PART # 1002
MATERIAL 1=AL, 2=STEEL, 3=CAST IRON: 1
TYPE OF MILLING MACHINE: HORIZONTAL
HORSEPOWER: 10

***************************************************

SETUP # 1

PLANE # 1

REF COORD X: 10.0
REF COORD Y: 20.0
REF COORD Z: 30.0

FEATURE # 1
FEATURE TYPE: SLOT1
PRIORITY: 0
PRECISION: 2
GEOMETRIC CHARACTERISTICS
THICKNESS: 0.3000
DEPTH: 0.3500
CLEAN Z: 1.000
COORDINATES C1x: 1.2500
COORDINATES C1y: 1.2500
COORDINATES C1z: 0.0000
COORDINATES C2x: 2.7500
COORDINATES C2y: 2.7500
COORDINATES C2z: 0.0000
END FEAT

END SETUP

SETUP # 2

PLANE # 1

REF COORD X: 10.0
REF COORD Y: 20.0
REF COORD Z: 30.0

FEATURE # 1
FEATURE TYPE: MOUND-BOSS
PRIORITY: 1
PRECISION: 2
GEOMETRIC CHARACTERISTICS
HEIGHT: 0.250
DIAMETER: 3.900
CLEAN Z: 2.000
COORDINATES C1x: 2
COORDINATES C1y: 2
COORDINATES C1z: 0
CUTTING DIRECTION: Y
MAX X: 4
MIN X: 0
MAX Y: 4
MIN Y: 0
END FEAT

END SETUP

END PART

Fig. 47: Example input file.
can be machined in one setup must be available to the program. Consequently, the
description of the part is given in terms of the features that are manufacturable in each
setup.

Setup information is contained between the strings "SETUP # x" and "END SETUP". Between them and the rest of the data blank lines must be present. Reference coordinates that indicate the location of the setup coordinate system with respect to the machine coordinate system must be given in the form:

"REF COORD X: x.x"
"REF COORD Y: x.x"
"REF COORD Z: x.x"

Feature information is given within the lines "FEATURE # x" and "END FEAT". The first line gives the feature identification number. No lines are needed between feature data unless it is specified otherwise. The type of data needed is the following:

- "FEATURE TYPE: yyyy" which may be SLOT1,SLOT2,SLOT3 or ROUND-BOSS
- "PRIORITY: x" sequence number, any integer.
- "PRECISION: x" 1=low precision, 2=high precision.
- "GEOMETRIC CHARACTERISTICS" tells the program that geometric data is next.
- "THICKNESS: x.x", "DEPTH: x.x" thickness and depth of slots;
- "CLEAR Z: x.x" plane at which tool is free to move without risk of collision.
- "COORDINATES C1x: x.x " coordinates of first top point in a slot or top center point in a round boss. Format is similar for y and z.
- "COORDINATES C2x: x.x " used only with slots type 1 and 2. Coordinates of second point. Similar format is used for y and z.
• "HEIGHT: x.x" height of round boss.

• "MAX X: x.x" limit coordinates of base plane of boss. A rectangular plane is assumed.

In addition, Slot3 requires data points of its bottom surface. Data points are given between the lines "DATA POINTS" and "END DATA". A blank line must be given before the "END DATA" line. Between these two, the following information is given:

"COORDINATE X: x.x" contains the x coordinate of the first point at the bottom of the slot. Immediately after it the coordinates for y and z of the same point must be given. Once a point has been completely defined, a blank line must be left before the next point.

Example output.

Figures 48 and 49 show an example output from the system. These figures are intended to show the basic elements of the output, namely: program identification; definition of cutting parameters, tool changes and tool trajectories; and program ending statements.
Fig. 48: Headings and identification of an output. Cutting parameters and the definition of tool trajectories can be seen in this example.
Fig. 49: Finishing statements for an example output.
FUNCTIONS USED IN PROCESS PLANNER

NAME: compare.
SYNOPSIS: int compare (*inptline, *pattern)
DESCRIPTION: This function returns 1 if the string pattern is found in the string
inptline, 0 if not. Any character or blank space is allowed.
INPUTS: char *inptline, char *pattern.
OUTPUTS: None.
RETURNS: 1 if pattern is found, 0 if not.

NAME: getint.
SYNOPSIS: int getint (*inptline, stop1)
DESCRIPTION: This function reads the integer value from a line after the character
"stop1". The remaining characters on the line must thus represent an
integer number for this function to make sense.
INPUTS: char *inptline, char stop1.
OUTPUTS: None.
RETURNS: An integer number.

NAME: getfloat.
SYNOPSIS: float getfloat ( *inptline, stop)
DESCRIPTION: This function reads the value of variable from a line after the character
stop. The characters after stop must be convertible to a float type,
that is, they must be numbers with at most 1 decimal point.
INPUTS: char *inptline, char stop.
OUTPUTS: None.
RETURNS: A float number.

NAME: getstring.
SYNOPSIS: void getstring (*inptline, stop1, *ouptline)
DESCRIPTION: This function get a string value from a line after a character stop1.
The remaining characters on the line must thus be a string for this
function to make sense. The output goes to char *ouptline. The best
way to define the string the string that is going to hold this value is
"char string(150);". This function removes the carriage return
character (\n).
INPUTS: char *inptline, char stop1, char *ouptline.
OUTPUTS: A string containing all characters after the stop character.
RETURNS: None.
FUNCTIONS USED BY LOADINFO

NAME: loadinfo.
SYNOPSIS: void loadinfo()
DESCRIPTION: This function reads feature information that includes geometry and machinability data. The data is scanned from an input file whose syntax must conform to a predefined standard.
INPUTS: Text file.
OUTPUTS: Machinability parameters & geometry data in the form of a structure.
RETURNS: None.

FUNCTIONS USED BY TOOLS

NAME: tools.
SYNOPSIS: void tools()
DESCRIPTION: This function assigns tools in sequence to machine each individual feature.
INPUTS: None, but uses loadinfo's output.
OUTPUTS: Tool information associated with each particular feature, including tool code, pass, cut.
RETURNS: None.

NAME: slotstrat
SYNOPSIS: void slotstrat(i, j).
DESCRIPTION: This function determines what type of strategy must be associated with a slot of type 1 or 2.
INPUTS: int i, int j.
OUTPUTS: None.
RETURNS: None.

NAME: slotcamstrat.
SYNOPSIS: void slotcamstrat(i, j).
DESCRIPTION: This function determines what type of strategy must be associated with a slot of type 3.
INPUTS: int i, int j.
OUTPUTS: None.
RETURNS: None.

NAME: robosstrat
SYNOPSIS: void robosstrat(i, j).
DESCRIPTION: This function determines what type of strategy must be associated with a round boss.
INPUTS: int i, int j.
OUTPUTS: None.
RETURNS:  None.

NAME:  getinserts.
SYNOPSIS:  int getinserts(diam).
DESCRIPTION:  This function determines the number of cutting edges of a face mill based on its diameter. The selection is based on information based on catalogs of cutting tools manufacturers.
INPUTS:  float diam.
OUTPUTS:  None.
RETURNS:  Number of inserts or cutting edges.

NAME:  maxsize.
SYNOPSIS:  float maxsize(maxcoord, mincoord, centcoord, featdiam).
DESCRIPTION:  This function returns the value of the minimum tool diameter needed to cover in one pass the surface of a plane upon which a round boss is located. The largest value that this function returns is 4 inches, since the system does not support a larger face mill. The minimum value that this function returns is 0.375 inches. This value is only calculated for a given axis. Strategy functions compare the values for two possible axes. Plane is assumed to be rectangular in shape. Sides are assumed to be parallel to machine axes.
INPUTS:  float maxcoord, float mincoord, float centcoord, float featdiam.
OUTPUTS:  None.
RETURNS:  Tool diameter needed to cover area.

NAME:  dhratio.
SYNOPSIS:  float dhratio(diam, height).
DESCRIPTION:  This function returns the value of the tool diameter that finishes a round boss. The computation is based on the size of the boss. The maximum value this function returns is 1.5 inches, and the minimum value is .125 inches.
INPUTS:  float diam, float height.
OUTPUTS:  None.
RETURNS:  Tool diameter.

NAME:  chooseflutes.
SYNOPSIS:  int chooseflutes(width).
DESCRIPTION:  This function determines the number of cutting edges of an end mill based on its diameter. The selection is based on ANSI standards.
INPUTS:  float width.
OUTPUTS:  None.
RETURNS:  Number of cutting edges.
NAME: diam.
SYNOPSIS: float diam(i, j, target, upper, lower, flutes, l, m).
DESCRIPTION: This function takes the diameter of a tool and selects a standard size that lies within a certain range around the given diameter. If no standard size is found, the target value is returned.
INPUTS: int i, int j, float target, float upper, float lower, int flutes, int l, int m.
OUTPUTS: None.
RETURNS: Standard tool diameter.

NAME: getspot.
SYNOPSIS: float getspot(max, min, depth).
DESCRIPTION: This function selects a standard spot drill diameter based on given limits. Used only for slots.
INPUTS: float max, float min, float depth.
OUTPUTS: None.
RETURNS: Standard spot drill diameter.

NAME: getdrill.
SYNOPSIS: float getdrill(max, min).
DESCRIPTION: This function selects a standard drill diameter based on given limits. User is prompted if chosen size is available. If not, user can select size.
INPUTS: float max, float min.
OUTPUTS: None.
RETURNS: Standard spot drill diameter.

NAME: getendmill.
SYNOPSIS: float getendmill(max, min, flutes).
DESCRIPTION: This function selects a standard end mill diameter based on given limits. User is prompted if chosen size is available. If not, user can select size.
INPUTS: float max, float min, int flutes.
OUTPUTS: None.
RETURNS: Standard end mill diameter.

NAME: getfacemill.
SYNOPSIS: float getfacemill(diam).
DESCRIPTION: This function selects a standard face mill diameter based on given limits. User is prompted if chosen size is available. If not, user can select size.

INPUTS: float diam.
OUTPUTS: None.
RETURNS: Standard face mill diameter.

NAME: getcode.
SYNOPSIS: int getcode(i, j, k).
DESCRIPTION: This function returns a code for the tool according to the following convention:
For tool type
f=1000000
s=2000000
d=3000000
e=4000000
b=5000000
For tool matl
h=100000
c=200000
For tool diam
    diameter=tooldiam*10000
For number of flutes
    number of flutes.
INPUTS: int i, int j, int k.
OUTPUTS: None.
RETURNS: Tool code.

FUNCTIONS USED BY TOOLMANAGER

NAME: toolmanager.
SYNOPSIS: void toolmanager().
DESCRIPTION: This function sorts tools in the proper sequence to generate all the features associated with a part. Tools and their sequence are grouped.
INPUTS: None. But uses "tools" output.
OUTPUTS: Tool sequence and feature operation associated with each tool.
RETURNS: None.

FUNCTIONS USED BY EDITOR

NAME: editor.
SYNOPSIS: editor().
DESCRIPTION: This function prints an APT program for each setup. The tool sequence has been previously defined by toolmanager. Editor gets this sequence information and adds into the feature geometry information in order to generate an APT code. This APT code can be simulated in CATIA's "NCFILE", and a CNC code for the Okada or the Cincinnati Milacron T10 may be generated by the main frame's post processor.
INPUTS: None.
OUTPUTS: APT code for each setup of the part.
RETURNS: None.

NAME: toolchange.
SYNOPSIS: void toolchange(i, j, seq).
DESCRIPTION: This function prints the APT commands for a tool change. Also the parameters that describe the tool are calculated and printed by this function. This function can be improved by calculating a Z point to which the tool is to be retracted before the tool change command is executed.
INPUTS: int i, int j, int seq.
OUTPUTS: APT code text in output file.
RETURNS: None.

NAME: macroswchange
SYNOPSIS: void macroswchange(i, j, seq).
DESCRIPTION: This function calls an APT macro after a tool change has been performed.
INPUTS: int i, int j, int seq.
OUTPUTS: APT code in output file.
RETURNS: None.

NAME: macroswithout.
SYNOPSIS: void macroswithout(i, j, seq).
DESCRIPTION: This function calls an APT macro after a tool change has been performed.
INPUTS: int i, int j, int seq.
OUTPUTS: APT code text in output file.
RETURNS: None.

NAME: intslotcw.
SYNOPSIS: void intslotcw(i, j, seq, target z).
DESCRIPTION: This function prints the APT commands for an interpolated slot in a clockwise direction. Parameters are calculated based on feature information plus the auxiliary parameters "offset..." previously calculated. Auxiliary function vector is also used.
INPUTS: int i, int j, int seq, float target z.
OUTPUTS: APT code text in output file.
RETURNS: None.
NAME: intslotccw.
SYNOPSIS: void intslotccw(i, j, seq, target z).
DESCRIPTION: This function prints the APT commands for an interpolated slot in a clockwise direction. Parameters are calculated based on feature information plus the auxiliary parameters "offset..." previously calculated. Auxiliary function vector is also used.

INPUTS: int i, int j, int seq, float target z.
OUTPUTS: APT code text in output file.
RETURNS: None.

NAME: compute.
SYNOPSIS: void compute(i, j, seq).
DESCRIPTION: This function returns the four points of tangency of the slot based on the coordinates of the centers of the circles and the thickness of the slot. The coordinates of the points that would locate the tool tangent to these points are also calculated. These points are stored in "...cord.." and "offset..." parameters.

INPUTS: int i, int j, int seq.
OUTPUTS: None.
RETURNS: None.

NAME: vector.
SYNOPSIS: void vector(x1, y1, x2, y2).
DESCRIPTION: This function returns a normalized vector in the direction from P1 to P2. This vector is stored in parameters vx, vy.

INPUTS: float x1, float y1, float x2, float y2.
OUTPUTS: None.
RETURNS: None.

NAME: swap.
DESCRIPTION: This function swaps the target points when cutting a slot in the center.

INPUTS: int i, int j, float *x, float *y, float *z.
OUTPUTS: Coordinated of the next point targeted. Warns when the wrong target was given.
RETURNS: None.

NAME: steps.
SYNOPSIS: void steps(i, j, seq).
DESCRIPTION: This function calculates the number of steps and the size of each step required to reach the final depth during a cutting motion. Parameters stepnum and stepsize[] store these values. These values are good for the cases of end mills and face mills.

INPUTS: int i, int j, int seq.
OUTPUTS: stepnum and stepsize[].
RETURNS: None.

NAME: stepdrill.
SYNOPSIS: void stepdrill(i, j, seq).
DESCRIPTION: This function calculates the number of steps and the size of each step required to reach the final depth during the cutting motion. Parameters stepnum and stepsize[] store these values. These values are good for the cases of end mills and face mills.

INPUTS: int i, int j, int seq.
OUTPUTS: stepnum and stepsize[].
RETURNS: None.

NAME: getrpm.
SYNOPSIS: int getrpm(i, j, seq).
DESCRIPTION: This function calculates the revolutions per minute of a particular tool.

INPUTS: int i, int j, int seq.
OUTPUTS: None.
RETURNS: Revolutions per minute.

NAME: sfpmal.
SYNOPSIS: float sfpmal(toolmaterial, pass).
DESCRIPTION: This function returns the surface feet per minute for aluminum.

INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.

NAME: sfpmst.
SYNOPSIS: float sfpmst(toolmaterial, pass).
DESCRIPTION: This function returns the surface feet per minute for steel.

INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.
NAME: sfpmci.
SYNOPSIS: float sfpmci(toolmaterial, pass).
DESCRIPTION: This function returns the surface feet per minute for cast iron.
INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.

NAME: getfeed.
SYNOPSIS: float getfeed(i, j, seq).
DESCRIPTION: This function calculates the feed in inches per minute for a particular tool.
INPUTS: int i, int j, int seq.
OUTPUTS: None.
RETURNS: Feed in inches per minute.

NAME: fpral.
SYNOPSIS: float fpral(toolmaterial, pass).
DESCRIPTION: This function returns the feed per revolution per cutting edge for aluminum.
INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.

NAME: fprst.
SYNOPSIS: float fprst(toolmaterial, pass).
DESCRIPTION: This function returns the feed per revolution per cutting edge for steel.
INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.

NAME: fprci.
SYNOPSIS: float fprci(toolmaterial, pass)
DESCRIPTION: This function returns the feed per revolution per cutting edge for cast iron.
INPUTS: char toolmaterial, int pass.
OUTPUTS: None.
RETURNS: Surface feet per minute.
APPENDIX G

SELECTED PAGES FROM A SAMPLE QUESTIONNAIRE
Fig. 50: Example feature and attributes defined in questionnaire.
<table>
<thead>
<tr>
<th>MATERIAL FEATURE</th>
<th>SOFT</th>
<th>MEDIUM</th>
<th>HARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLOT WITH GIVEN TOLERANCES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROUND BOSS WITH TOLERANCES REDUCED TO 0.001&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROUND POCKET WITH TOLERANCES REDUCED TO 0.001&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting point?</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Finishing point?</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SLOT WITH TOLERANCES REDUCED TO 0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 51: Sample table for strategy definition.
Sample questions given in questionnaire

Q.1 What kind of tolerances (for surface finish, roundness, perpendicularity, etc.) would force you to ream a 0.500" hole? What sequence of tools would you use for this operation?

Q.2 What kind of tolerances (for surface finish, roundness, perpendicularity, etc.) would force you to bore a 0.500" hole? What sequence of tools would you use for this operation?

Q.3 Under what circumstances (size of slot, tolerance) would you interpolate the slot as opposed to using an end mill the size of the slot width? Is there a critical slot size at which it is necessary to make such a decision?
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