(2)

National Defence / Défense nationale

COMPUTER-AIDED DESIGN OF A NEW PROTOTYPE CB PROTECTIVE GLOVE

by

D.J. Hidson

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

REPORT NO.1054

November 1990
Ottawa

Canada

National Defence / Défense nationale

COMPUTER-AIDED DESIGN OF A NEW PROTOTYPE CB PROTECTIVE GLOVE

by

D.J. Hidson
Chemical Protection Section
Protective Sciences Division

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO.1054

PCN
051LD

November 1990
Ottawa

ABSTRACT

This paper describes the computer-aided design and manufacture of a prototype core model for a new protective glove. The computer system and software are described as are the design processes in geometry and CNC machining. The construction of sculptured surfaces, machine tool paths and postprocessing software for the shape are laid out and the problems of the manufacture of complex geometric parts analysed. The final product was machined on a Matsuura/Fanuc computer-numerical control machine and controller.

RÉSUMÉ

Ce rapport décrit la conception et manufacture par ordinateur d'un noyau de moule pour un nouveau prototype de gant protecteur. L'ordinateur et le logiciel sont décrits ainsi que le processus de conception géométrique et l'usinage par contrôle numérique. La construction de surfaces sculptées, le trajet des outils et le logiciel de conversion pour la forme sont présentés et les problèmes d'usinage de pièces de géométrie complexe sont analysés. Le produit final fut usiné sur une machine-outil à contrôle numérique et contrôlleur Matsuura/Fanuc.

EXECUTIVE SUMMARY

This paper describes the computer-aided design of a core model for a prototype injection-molded protective glove. The computer hardware and CAD/CAM software are described and the design process from inception to manufacture is laid out. The generation of complex surfaces and the machining paths to cut them is tied in with the novel techniques in design required by a CAD/CAM system and the computer-numerical control (CNC) mill characteristics. The unification of the computer design and manufacturing is described with illustrations of the finished products.

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

The Chemical Protection Section at DREO is responsible for providing physical protection for the Canadian Forces against the hazards of chemical and biological agents. This work involves the development of protective equipment such as clothing, gloves, masks, respirators, canisters, etc.

In the past, the development of helmets, gloves, respirators and other articles of clothing and equipment has involved a combination of scientific and artistic techniques. To produce an article such as a new mask or glove, the sizes would be deduced from information gathered by an anthropometric survey. In the production of a face mask, for instance, models would be made up by a sculptor or pattern-maker and compared to the design dimensions derived from the information obtained in the survey. From the model a prototype would be made either by casting or by molding. Subsequent changes in design would require a repeat of all these procedures.

When computers are used in the engineering design process, the models are usually built up analytically as one would use an engineering drawing board. However, computers have the capacity to perform much more demanding tasks, such as building up surfaces from arrays of data points. This second approach is necessitated by the fact that, on many occasions, complex real life objects without regular geometric properties have to be modelled and machined. Examples of this include human body shape data from anthropometry and artificial limb construction, and in the medical field, models of bone structure and the like. The abilities of computers can now be meshed with the stringent requirements of designing protective equipment for humans. This paper describes the development of a prototype CB glove model by means of computer-aided design and manufacturing techniques (CAD/CAM). Data for the general shape was entered into the computer system and from these surfaces were generated to construct the model. With the completion of a computerized model in the database, the computer-aided engineering software (CAE) was used to prepare programs to generate machining files, that is files that contain data and instructions for computer-numerical control (CNC) machines, so that the models could be made.

The eventual manufacture of the CB glove will likely be by an injection-molding process. The present work is devoted to producing a model of the shape of the glove, which would be the core of an injection-mold. This core model is here used to produce latex models by a dipping process for preliminary investigation. It is made this way as a proof-of-concept of the design and because the dipped glove models can be easily tested in dexterity trials. Injection-molds are very difficult and expensive to manufacture so the design should be explored using cheaper methods before a mold is made.

2.0 THE COMPUTER-AIDED DESIGN SYSTEM

2.1 THE HARDWARE

The computer system used for this work consisted of a Data General MV4000 minicomputer, a Megatek D125CE vector-refresh graphics display terminal, a raster scan message monitor, a Calcomp 960 plotter with a Calcomp 907 controller, and a Honeywell VGR4000 screen hard copy unit.

McDonnell Douglas Corporation markets CAD/CAM/CAE software in a variety of forms that will run on a variety of the commonly available minicomputers such as the Digital Equipment Corporation (DEC) VAX-series or the Data General Eclipse series among others. Our current system structure consists of the following:

* Data General MV4000 Central Processing Unit with 2MB 64K Array memory and 73MB Disk subsystem with controller;
* Hard Copy Unit;
* Unigraphics II CAD/CAM software;
* Graphics Mill Module and Multi-Axis Module;
* Machine Tool Data File Generator.

The Unigraphics II CAD software is used by the scientist to produce graphics for the design process. A color graphics screen displays the geometry and a small message screen complements this by presenting the menus and selections. The menu choice is selected from a control panel (the graphics control keyboard, GCK, or "guck") which enables the operator to select functions on the menu and to manage the graphics display by generating different views, changing color, scale, configurations etc.

A Honeywell VGR4000 hard copy display unit provides a black-and-white copy of the raster screen. This produces a readily accessible screen dump.

Other peripherals essential to the system are a band printer, paper tape punch (and/or floppy disk storage device) for CNC machine data, a Calcomp 960 plotter and the operator console for running and managing the AOS/VS operating system on the Data General MV4000 computer. Figure 1 displays a block diagram showing the main components of this system.

2.2 THE SOFTWARE

The usual method for creating geometry in the CAD database is from the control panel and joystick (the GCK). From here, geometric function such as points, lines, arcs, splines, and surfaces are generated. The software is also equipped with its own language, GRIP (Graphics Interactive Programming Language), by means of which the operator may create models in the database, arrange and dimension drawings, and program machining. This capability is very useful in situations where, for instance, a large array of points has to be joined to form a set of spline curves or a set of splines to form a surface. It is also very useful for creating large amounts of repetitive geometry.

The Unigraphics software enables one to create a geometric model in the data base. In order to function properly as the basis of a computer-machined part, the modelled surface data have to be transformed into a set of point-to-point instructions that describe the motion of the cutting tool in three-dimensional space. The various software modules on the package all perform essential parts of this process.

The Unigraphics Design Module will allow geometry to be created in three dimensions in metric or imperial units. As is common in engineering, imperial units have been used throughout this work. The important part of this is that complex surfaces can be constructed from orthogonal sets of spline curves and these surfaces form the basis for the generation of the instruction code for the computer-controlled numerical milling machine. This is a complex process in itself as the geometric information in the CAD model has to be translated into point-to-point motion instructions for a three-axis milling machine by means of a postprocessor. A postprocessor is a piece of software that will perform this conversion task. To be effective it requires a detailed knowledge of the model itself and the capabilities and limitations of the CNC machine. The construction of the postprocessor is described in more detail in another DREO report (1).

Once the data have been produced for the CNC machine, it must somehow be communicated to it. This is done by means of a coded paper tape (punched tape like a teletype) containing all the point-to-point instructions for the geometry and commands for machine speed, cutter dimensions, and a host of other variables that must be specified.

This method of producing a part requires that the scientist possess a good knowledge of machine shop practice and techniques and that the machine operator possess an understanding of the different design techniques engendered by the use of computers.

3.0 GEOMETRIC MODELLING

3.1 DATA ENTRY

The design of any model begins with the generation of points, lines, arcs, conics, i.e. geometric entities. These can be generated at the keyboard or by means of the Graphics Interactive Programming Language (GRIP). If the source of the model is a large point data file, then these data may be read directly from a TEXT file (suffix .TXT). A GRIP program must be written to facilitate this. If, however, the design is of a fairly regular object, then the design process itself will begin at the keyboard.

The engineering task here starts from a previous design found to be unsatisfactory for the purposes assigned to it. The object was to generate a shape for an injection-molded glove that would be suitable for use on either the right or the left hand but would require only one mold. This meant that the design had to be symmetric about the mid-plane of the hand.

The first task was to enter the basic data from which a new design would grow (Figure 2). These figures show a cross-section of the glove. First an origin was selected and important locator points entered and established. These are shown by means of the x- and y- coordinates in the figure. Then the lines and curves are constructed to generate the outline of the cross-section. Since most of the model consisted of axially symmetric parts (as the fingers), these could be constructed using the surface of revolution techniques or by the sweeping of entities along an arc (Figure 3) to produce a sculptured surface.

3.2 CONSTRUCTION OF THE GEOMETRY OF THE PART

3.2.1 Planar Geometry

Figure 4 displays the critical area of the glove, that is, the area between the thumb and wrist. Here, various points are input into the model and a spline curve constructed (see arrow). Since the glove is intended to fit both a left and a right hand, it necessarily follows that it must be symmetric about the cross-section through the mid-plane. This is a design advantage in that only one half of the design has to be modelled. An axis inversion routine will later be used to transform one of the axes (e.g. "y" into "-y") to produce a mirror image which would be the bottom half of the model. This may be performed at the geometry design stage or, much later, at the machining stage by means of commands to the CNC machine controller on the shop floor.

The spline curve construction was performed and the curves and their gradients (i.e. the functions and their first derivatives) were matched where they join other geometric entities to provide a smooth connection. At this point, the planar outline of the model in two dimensions exists.

3.2.2 Surface Geometry

The geometric entities that possess axial symmetry were constructed using the surface of revolution technique. This enables a geometric quantity to be rotated around a specific axis, thereby generating the surface required. In this case, the fingers and the end of the thumb were obvious candidates as Figure 5 shows.

The purpose of the bulge behind the thumb was to accommodate the muscular volume between the thumb and index finger. To accomplish this, the splines were rotated about two independent axes producing two intersecting surfaces of revolution (Figure 6). Then, using a surface editing process, these surfaces of revolution were cut at the intersection curve (Figure 7) and at the points where they crossed the top surface of the hand. Some topological artistry is required to produce the correct number of surface patches because the sculptured surfaces, being constructed from orthogonal sets of spline curves, must have four sides. They can have four very unequal sides but four nonetheless.

Surfaces that match properly at the boundaries produce a smoothly machined model so it was important to accomplish this wherever possible. When several sufaces are tangent to one side or another, then it is not possible to match them all at once. There are techniques to circumvent this: for example, the spline curves that make up all the surfaces can be displayed and reconstructed with matching gradients at their contact points. Alternatively the POINT SET function may be used to generate a set of surface points along the u and w parameters of the cubic splines. Then different surfaces may be generated from these.

Surfaces that do not possess the requisite number of sides (usually three instead of four) can be "massaged" by adding a very small (<0.01 inch) arc between the two of them. This difference will likely be completely screened by the machining process. Further, when constructing surfaces from the two sets of spline curves, all the nodes of one set must match all the nodes of the other set or else continual errors will result from attempting to match splines that do not intersect. In other words, a surface function cannot be multi-valued.

The construction of surfaces from splines can lead to other subtle errors, namely, when gradients are specified for the curves an incorrect sign can lead to the curve slope being totally inverted at the end giving an almost invisible hook-like structure. This may not be readily apparent but such small geometric problems can give rise to huge machining errors when a one-half inch cutter attempts to carve a one-thousandth-inch hole. An example of the type of geometric problem involved is illustrated in Figure 8.

Here, part of the top surface of the hand is shown with an expanded image showing the area in question.

When building complex sculptured surfaces, the spline gradient specification at the ends of the curves is necessary for determining the continuity of the surface function and the first derivative at the edge. Later surface editing may adjust these but more editing leads to problems of spline oscillation and loss of data specificity.

A display of the complete geometry for this model is shown in Figure 9. The small uncut segments at the end of each finger are left so that vibration of the part during the main machining process may be minimized. A final peripheral cut removed this material holding the ends of the fingers to the rest of the block.

4.0 NUMERICAL MACHINING

4.1 CUTTER PATH LAYOUT

A computer-controlled numerical milling machine requires a large quantity of information to carry out its instructions. This is especially true for complex surfaces. When generating this information, care must be taken in considering how the part will be cut by the machine. It is quite possible to generate cutter paths that will produce a final product quite different from the designer's intent.

The PARAMETER LINE milling method was used to generate the cutter paths. This method can be used with one or more contiguous patch surfaces, provided that the boundaries match within a specified tolerance. First, the surfaces to be cut were selected. This number may be more than one but preferably not too large a percentage of the model because errors or unsatisfactory results mean recomputing unnecessarily paths that are good. Further, if several designs are contemplated, and each one involves only a minor modification, then only those parts of the model that require change need be reworked. And only those cutter paths corresponding to those surfaces need further computation.

We began with surface selection. All or any part of a patch surface may be machined: the area to be machined may be delineated by a pair of diagonal points at opposite ends of a rectangle projected onto the patch or by specifying a certain percentage of the patch. Up to 110% of the patch may be machined. The 110% means that the cutter paths will be extended over the physical edge of the work by 10% of the surface edge dimension. This can ensure that no irregularities are left by the cutter at the edge. It is important to note here that the descriptor "patch" refers to one sculptured surface definition in the geometry. Sets of "patches", governed by a specified tolerance, may be joined together and machined as one under PARAMETER LINE milling, but this is a special case.

When surface selection was completed, the first cut was selected. This determined the way the tool travelled over the part surface. Depending on the shape of the surface and the material from which the part is being made, this choice can make a considerable difference to the ease of machining. Figure 10 demonstrates surface selection and definition of the cut boundary.

At this point, the parameters of the machining process had to be considered. The global parameters were defined first. The shape and size of the tool, cutter radius, ball-nose or end-mill, must need be specified as these variables affect the calculation of the cutter location file (CL file). The CL file, when computed, contains the co-ordinate information governing the location of the center of the cutter tip in three-dimensional space. Clearly, its dimensions and properties have to be specified so that these quantities can be included in the calculations of the off-sets of the center of the cutter from the surface of the part.

A work piece size was then chosen. The blank from which the part was to be cut was two by twelve by six inches. Clearance planes were defined above the part (see Figure 11) which define the plane in which the tool would perform its rapid motions between cuts or when returning to the origin. This should be placed no less than one inch above the highest point on the part surface. A lower clearance plane is defined below the part: this will stop the tool travelling beneath the work beyond the specified distance. In this case it was set at one-half inch (the radius of the largest cutter used) beneath the xy-plane.

"BODY INTOL" and "BODY OUTOL" were then set. These quantities define what the tolerance of the cutter will be with regard to the geometry of the model. These are not machining tolerances in the sense that they result from the limitations of any machine, but specified tolerances determining how close the geometry of the cutter path should match that of the geometric model. As the cutter moves over the part, its path is made up from large numbers of small, linear segments. The "INTOL" delineates how much the cutter path may enter the geometric limit of the surface. The "OUTOL" is similarly defined for excess surface left over. Figure 12 shows how these quantities are defined. The smaller these tolerances are, the more point-to-point instructions are required and the larger the resulting CL data files will be. The values chosen for both were 0.001 in.

The tool axis required no specification even though the work was performed on a three-axis machine. In this case the axis was fixed along the z-axis. If a fourth axis is demanded by the work, the vector is defined by direction cosines (e.g. i,j,k= (0,0,1) for a fixed z-axis).

Similarly, the engage vector and the retract vector determine the angles of attack of the tool on the work piece. These must be specified for some three-axis (e.g. roughing-to-depth) work and for all work requiring four or more axes. They were defined as (i,j,k)= (0,0,1) for the engage and (0,0,-1) for the retract indicating opposite motion along the z-axis.

Some essential tool parameters did not need to be fixed immediately. The feedrates, that is, the motion of the tool across the work and the motion of the tool when the cutter is engaging with or retracting from the surface, must be varied depending on the material being used for the final product. Usually, several preliminary cuts would be performed using N/C wax or even wood. Once the paths have been verified, the feedrates may be adjusted to suit the material being used for the final product. This is one of the important functions required of the shop-floor machine operator.

When cutting the model, a complete set of cutter paths may be executed while leaving a very small amount of excess material on the surface of the model. This is known as the floor stock and is equivalent to leaving a small, specified amount of material (maybe five one-thousandths of an inch or 0.13 mm) on the top of the surface of the model. After this first cut, the machining path can be run again and the floor stock removed, that is, reduced to zero. This gives a better surface finish and reduces the amount of polishing of a finished surface.

There are two other important quantities that determine the quality of the surface finish: the step size and the scallop height. The step size defines the chordal deviation between subsequent tool contact points along the tool path (see Figure 13). The scallop height is the maximum height of material left between passes of the cutter, given a particular cutter radius and a particular surface curvature. Figure 13 shows how scallop height is defined. The smaller these tolerances are, the more computation time is required and the larger are the data files that are generated. Here, trade-off between accuracy, computation time and amount of data is a major consideration.

A further parameter, CUT TYPE, affects the style and quality of the finished product. Three choices are available: the zig-zag cut, the zig-zag cut (with lifts) and the area milling option. The zig-zag cut follows the laid-out cutter paths one by one, remaining in contact with the workpiece all the time. The zig-zag (with lifts) means that the cutter lifts off the work at the end of each pass over the surface. The area milling option means that the cutter lifts off the work and moves back to the beginning of the next path. This means that the cut direction is the same for all paths across the surface.

With these conditions satisfied, the paths are calculated for the various surfaces in the model. Figure 14 shows the complex curvature part of the hand including the thumb shape. Figure 15 shows the definition of the first cut and the point distribution that was calculated after the step and scallop parameters were specified.

The model was divided into forty-three surfaces, which resulted in the net generation of 18 different cutter paths. As referred to earlier, the advantage of keeping a substantial number of surfaces means only those that need modification and re-design need be edited. Further, those parts which may be used in a second design without change do not need to be re-worked. A complete list of the cutter paths may be seen in Figure 16, where the filename for the shape is HAND_MOD3 followed by Pn, which denotes the path number, and the "LENGTH" is the file size in bytes. All the tool parameters that need to be specified are summarized in Figure 17. Here, the milling tool information, feedrates, reference coordinate systems etc. are all shown for an example cutter path labelled parameter set 7. Also displayed are the parameters that affect the part surface such as engage/retract vectors, floor stock, clearance planes, step sizes, chordal tolerance and scallop height.

A variety of cutters were used. On the large scale surfaces where there were convex radii of curvature the larger diameter cutters could be used. This gave the same surface accuracy for a fewer number of passes. However, on the finer surfaces, the gouge check avoidance option had to be used. This avoids damage to the surface but at the cost of greatly expanded computation time. An example of this may be seen in Figure 33 where the tool retraction is shown as the tool intersects an area of surface curvature less than that of the tool itself. The complete set of machining paths is displayed in Figures 18 to 35. Also shown in these figures are the clearance planes and the blank geometry.

4.2 POSTPROCESSING OF THE NUMERICAL CONTROL DATA

Once the CL files had been produced, the data in them had to be postprocessed for a particular CNC machine/controller combination. In order to do that a postprocessor was constructed. This is the piece of software that translates the generic point-to-point instructions in the CL file into APT instructions for a specific machine and a specific controller. In this case, the machine was a Matsuura M1000 with a Fanuc 6B controller.

The construction of the postprocessor software is described elsewhere in detail in another DREO technical report (1) and so is only mentioned briefly here. The conversion of the generic CL file data into an extensive list of point-to-point APT instructions depends very much on the exact nature of the CNC machine/controller combination.

The G-codes had to be set for this combination. These codes define how the machine interpolates what units it uses, whether absolute or incremental positioning is required and a variety of other functions. A summary of the machine data file parameters contained in the postprocessor is shown in Appendix A. Also included are the descriptors for the data structures that are needed for the coded tape for the CNC machine. The M-codes define the quantities like coolant spray, direction of tool rotation and various other physical parameters. Once the postprocessor has been set up, the data in the CL file (*.CLS) is ready for postprocessing.

Once the postprocessor has been prepared, it then acts as a compiler for the data stored in the CL file wherein it converts the point information into point-to-point instructions with G-codes and M-codes that tell the CNC machine how to generate and execute instructions to machine the part.

The act of producing postprocessed data involved using the KUT postprocessor to generate the instructions for the CNC machine. This then produces an end file with the suffix ".PTP" indicating that an ASCII file is ready that contains all the requisite CNC data and is ready for punching onto paper tape.

It should be noted that no matter how good the postprocessor, some file editing of the final punch-ready file needs to be done to suit the CNC machine/controller combination which will require some commands that are specific to that workshop. These changes may be accomplished by the execution of a GRIP program, for instance, that contains all the modification data. This was performed here. The program "FILEADDR.GRS" was written to perform these functions and is included as Appendix B. The extra data demanded by the CNC machine for shop preparation are shown in Appendix C.

4.3 TRANSLATION AND PAPER TAPE PUNCHING

The ".PTP" suffix codifies all files that contain information that is ready for the paper tape. These files are stored in ASCII format in the UGFM module (Unigraphics File Manager). The files may be punched directly on paper tape by using the program XLATOR. This is resident on the AOS/VS operating system on the Data General MV4000. It serves only two basic functions: one - to punch numerical control tape files that are generated by the Graphics Postprocessor Module and two - to read paper tape if necessary.

XLATOR translates these files into an ISO MCD (Machine Control Data) format. The data then exist in an ISO MCD image which has an even number of bits. This image may be stored directly in UGFM as a binary file (which cannot be edited) or output directly to the tape punch.

The paper tape punch is set up as a queue on the AOS/VS operating system. To punch, the queue must be started with:

```
CONTROL @EXEC START PTP @CON05
CONTROL @EXEC CONTINUE  @CON05
```

where @CON05 is the descriptor for the particular RS232 console connection on the Data General MV4000. A FACIT 4070 tape punch was used and the connection set up in the following way: pins 4 and 5 looped; pins 6, 8 and 20 looped; IAC pin 2 to pin 3 on the punch and IAC pin 3 to pin 2 on the punch where IAC stands for "Intelligent Asynchronous Controller". Pin 7 on the IAC was connected to pin 7 on the punch. The IACs were the output port structures on the Data General MV4000 computer. These were structured logically in eight- and sixteen-unit IACs and appear physically on the back of the computer as eight- and sixteen-unit RS232 ports.

The paper tape may be punched in ISO or EIA format and in eight- or seven-bits per character. ISO code was used for the Matsuura/Fanuc machine/controller. Parity could be set at even, odd or null.

During the course of the work, the FACIT tape punch was replaced with a CNC Minifile (manufactured by Greco Systems of California), a diskette device that simulates a tape punch as far as the output of the computer is concerned. When the punch-ready files are downloaded via XLATOR, they are ASCII files and as such may be read on to an IBM-compatible formatted diskette. These diskettes can hold up to 360 KB of information, which is equivalent to approximately 5,000 feet of paper tape. As paper tape was bulky, error-prone and takes considerable time to punch, a great saving in effort and time resulted. This work is described in more detail elsewhere (2).

While the preliminary machining was in progress, the material of choice for checking the three-dimensional cutter paths was N/C wax, actually a polyester, that could tolerate machining errors without destroying tools or requiring major repairs to the Matsuura. A further advantage lay in the fact that feedrates and cutting speeds could be much higher when using the wax material. All in all, several forms were cut before all the bugs were removed from the CNC files.

As may be seen from the illustrations, only one-half of the glove form was generated in the geometry and in the machining paths. The model was made from halves joined together at the mid-plane of the hand. As a result of this symmetry, it was not necessary to generate the geometry for the lower part but merely to invert the y-axis of the CNC machine at the time of machining. All that was necessary for this was that the origin of the model be set correctly on the machine bed. A positive to negative y-axis transformation was performed by a switch on the Fanuc controller.

5.0 MANUFACTURE

The final product was made by bolting together the two mirror-images. The machined surfaces were polished smooth to prepare them for the latex dipping process. To make gloves, the model was dipped in latex liquid and withdrawn. The liquid set and the glove form was peeled off. The requisite number of pairs of gloves were made for dexterity testing and the proof-of-principle established.

When the final design is arrived at it will form the core of an injection mold. Then a model will be made by the injection-mold process as a proof-of-principle for production engineering.

6.0 REFERENCES

1. Hidson D.J., "A Postprocessor for a Matsuura CNC machine and a Fanuc Controller", DREO Technical Report, to be published.

2. Hidson D.J., "The Modification of a CAM Facility", DREO Technical Note 90-7, March 1990.

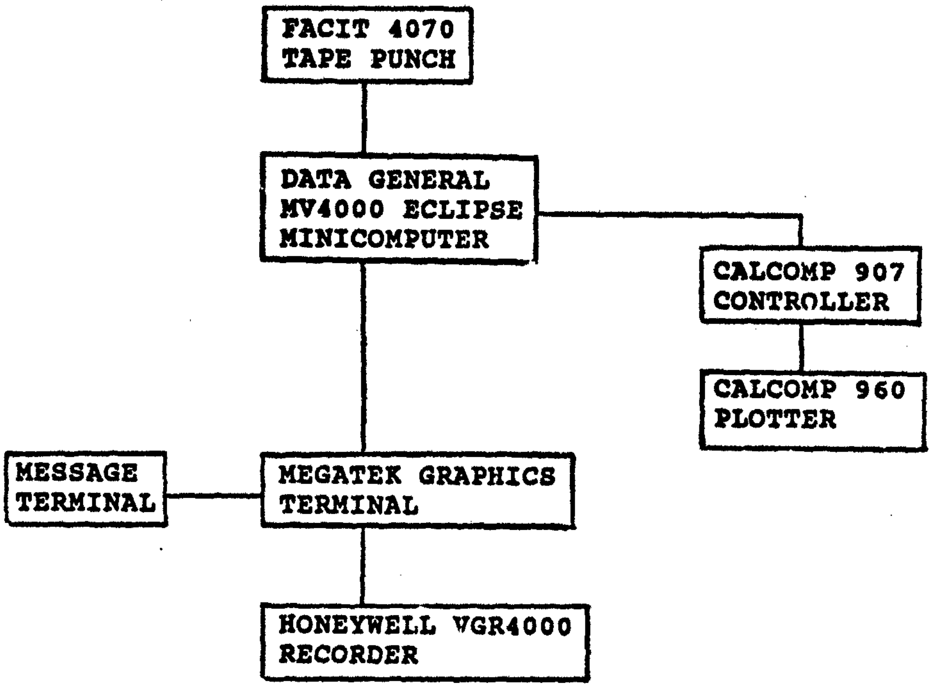

FIGURE 1: Block Diagram of Data General Computer System

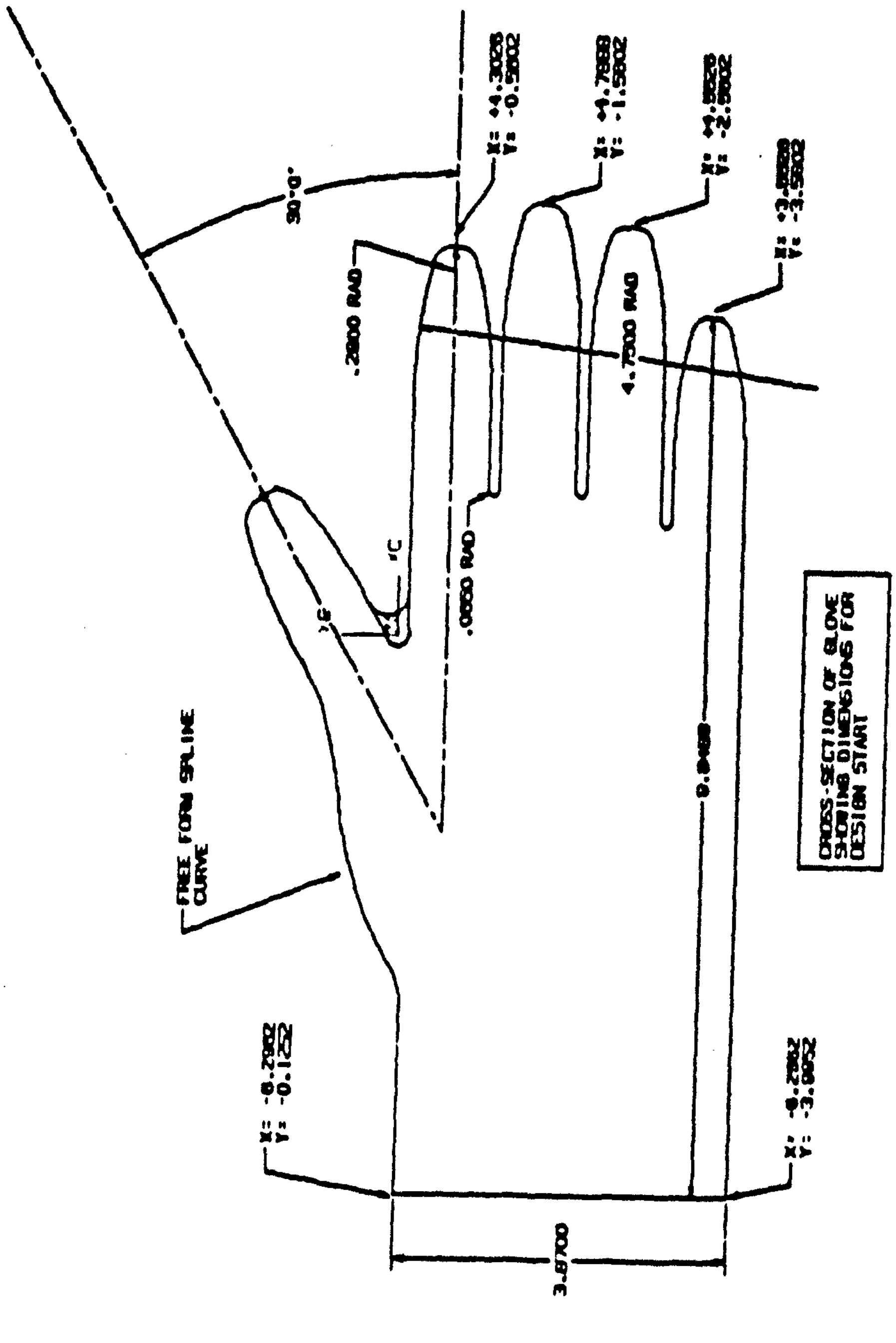

FIGURE 2: Preliminary Geometry Definition

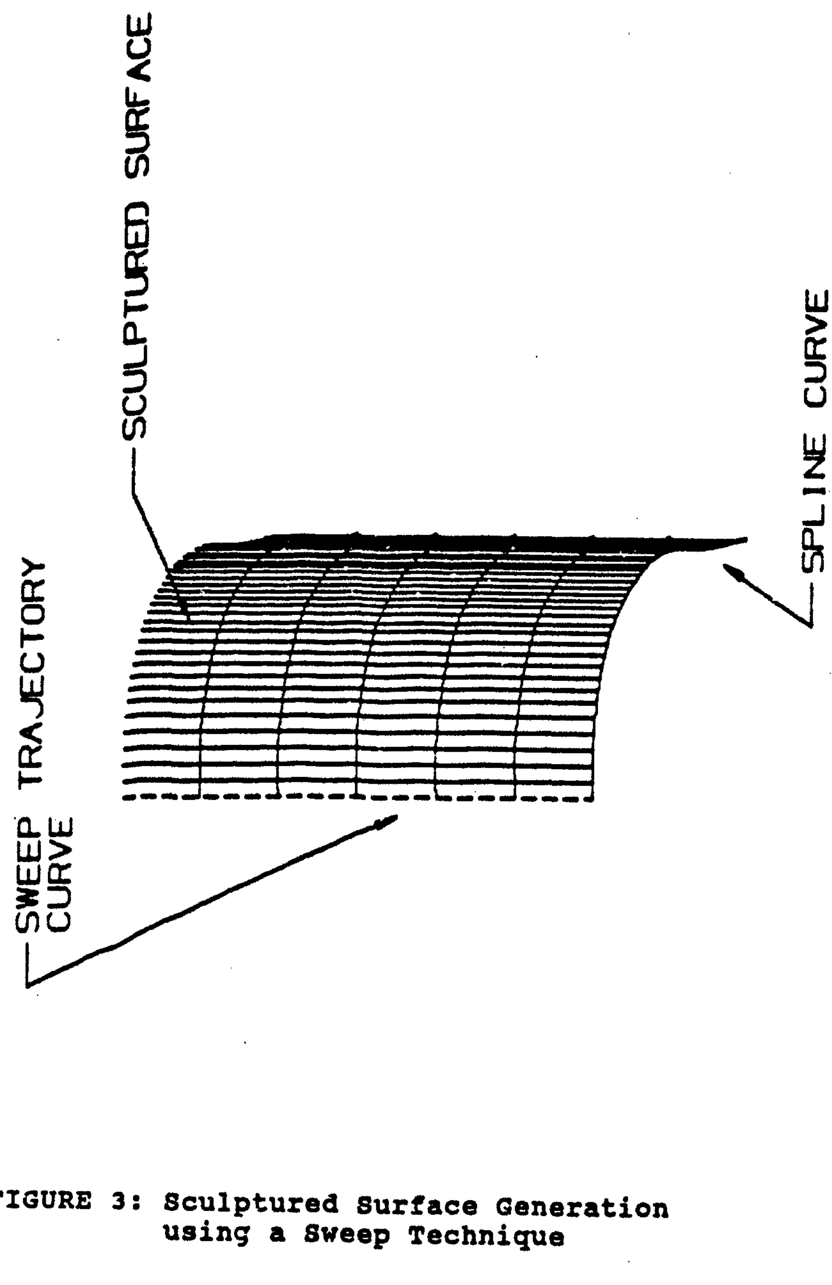

FIGURE 3: Sculptured Surface Generation using a Sweep Technique

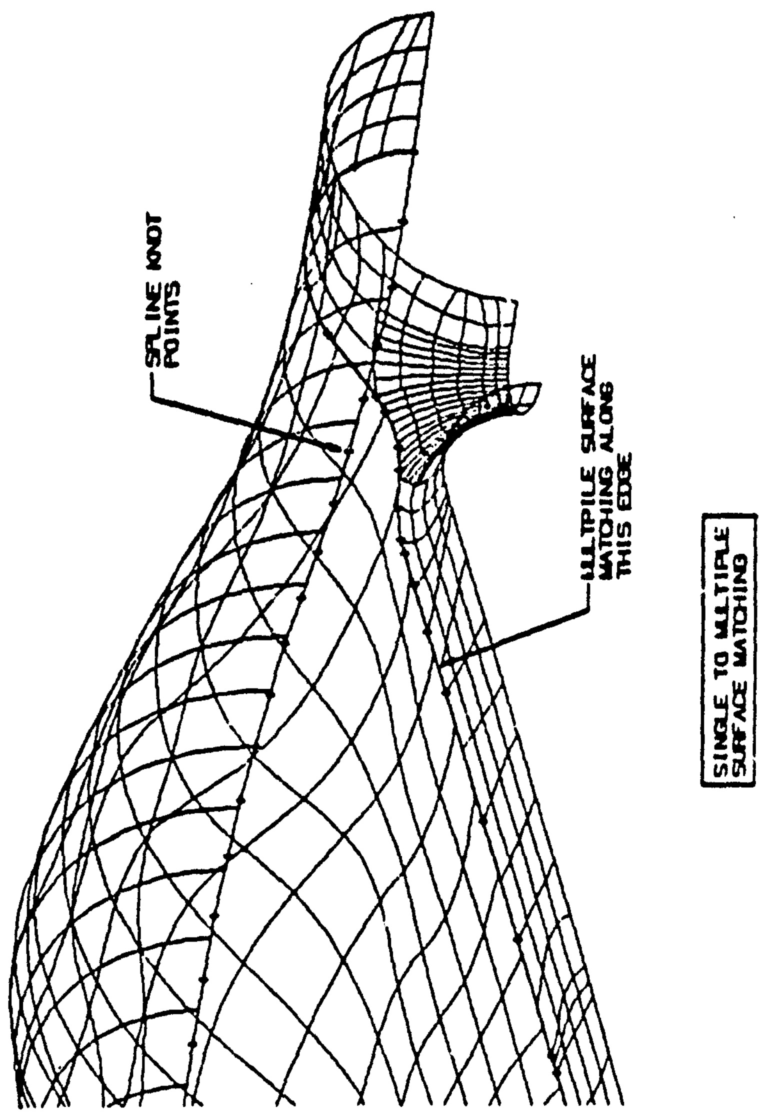

FIGURE 4: Sculptured Surface of Thumb Region

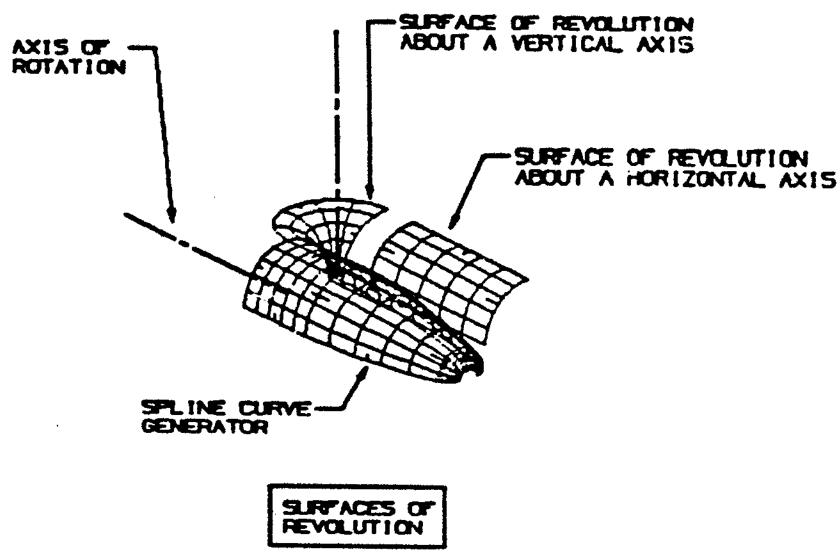

FIGURE 5: Formation of Surfaces of Revolution

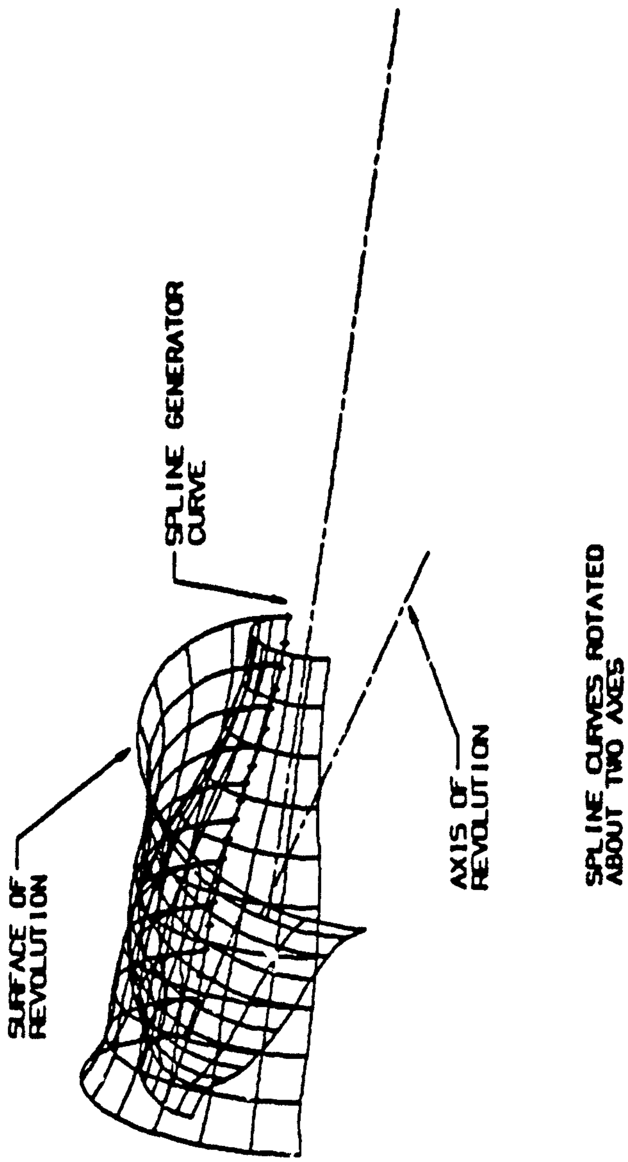

FIGURE 6: Generation of Intersecting Surfaces

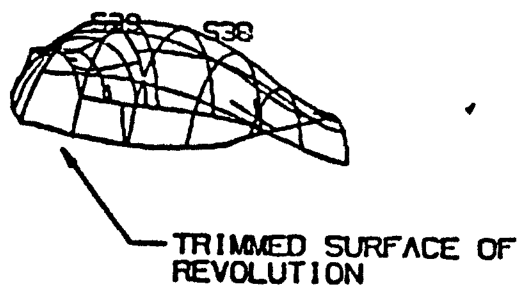

FIGURE 7: Trimmed Surface

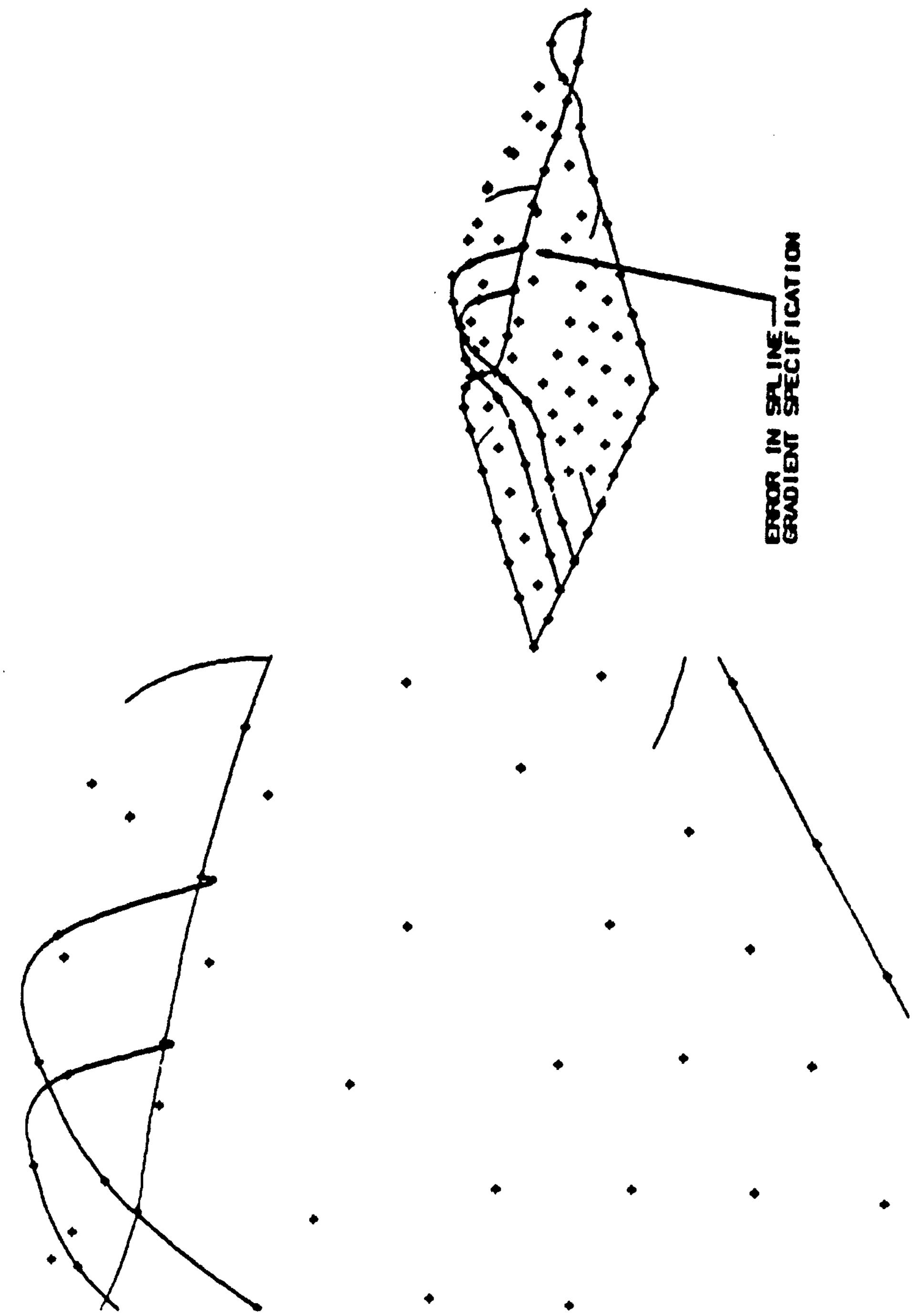

FIGURE 8: Gradient Errors in Spline Curve Formation

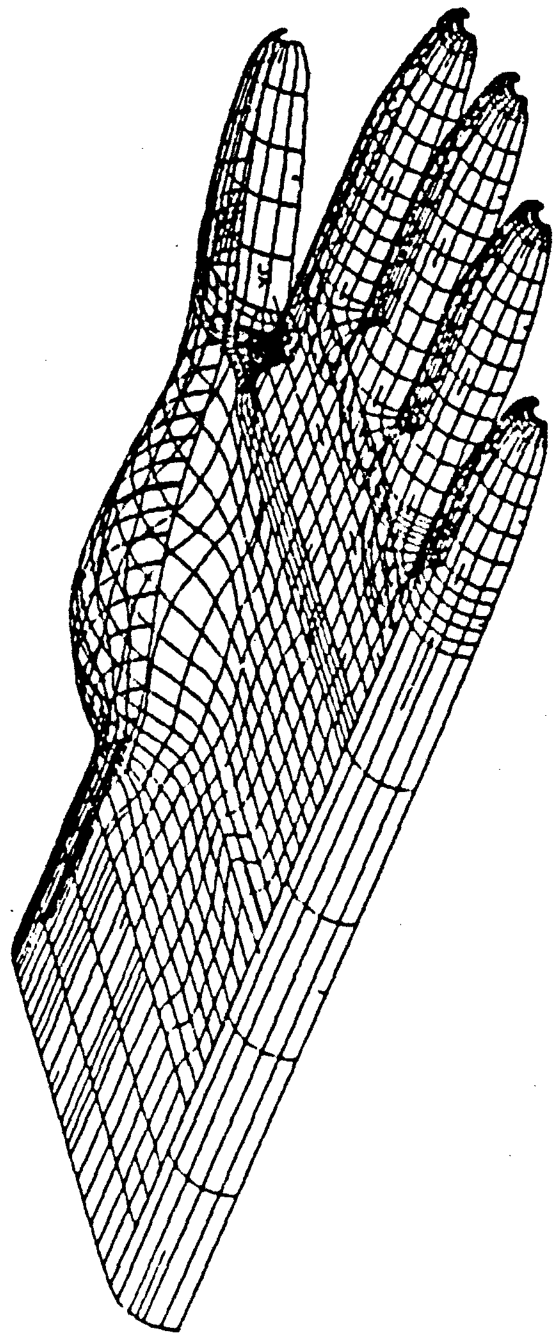

FIGURE 9: Surface Geometry of Model HAND_MOD3.PRT

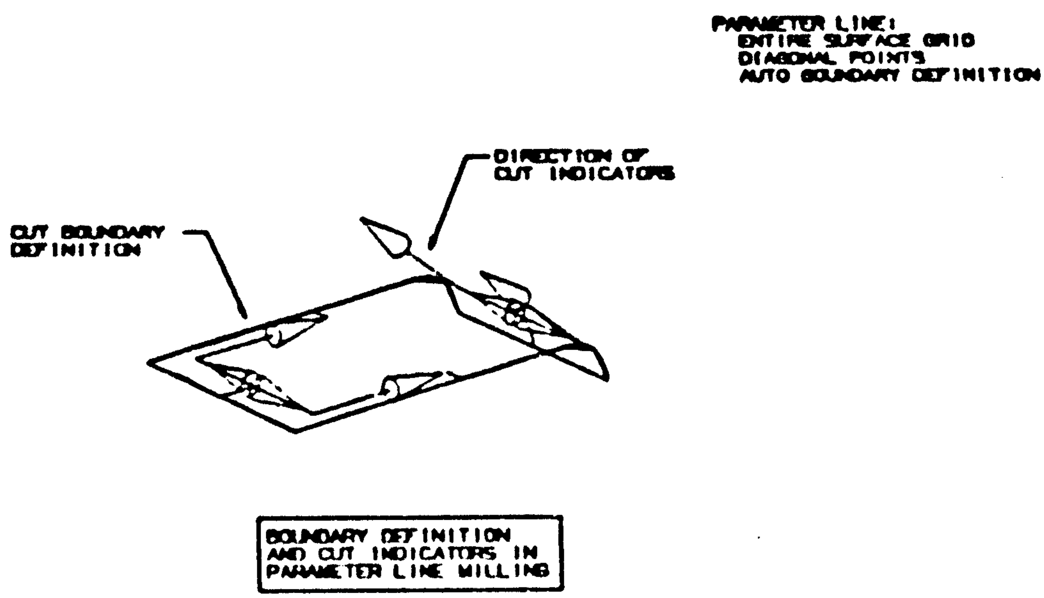

FIGURE 10: Cut Boundary Definition

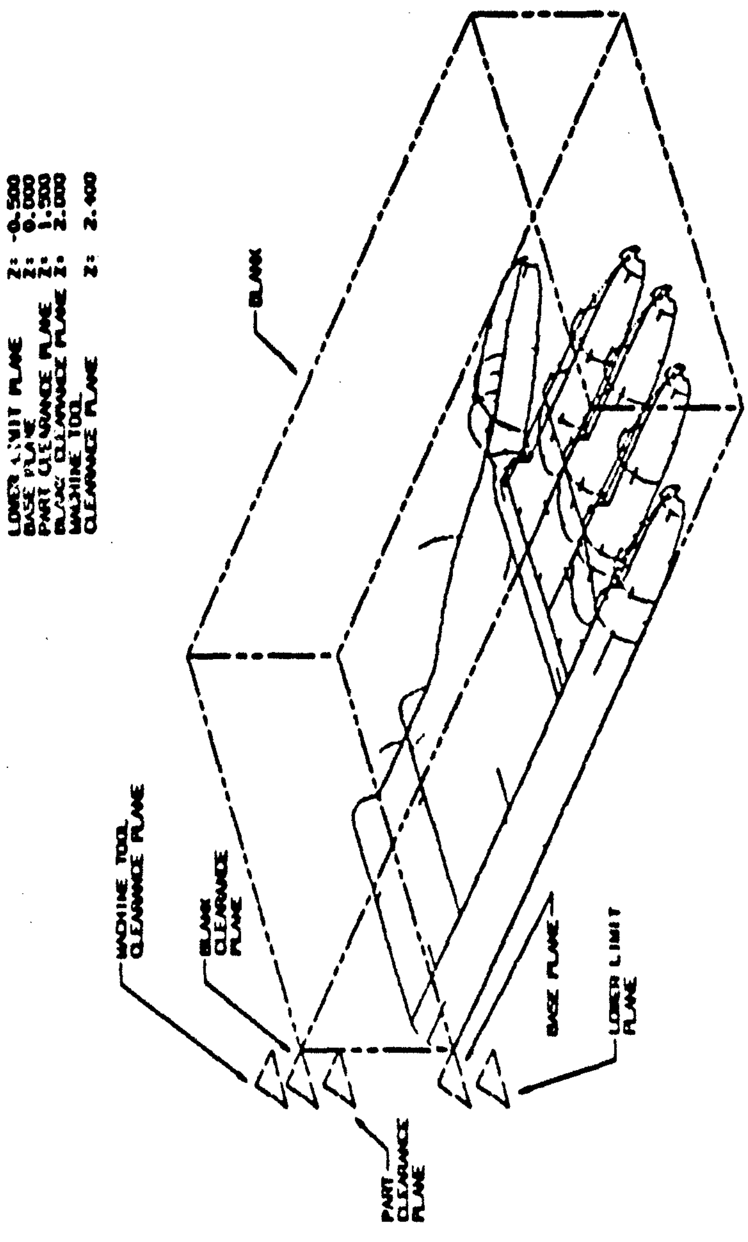

FIGURE 11: Clearance Plane Definition

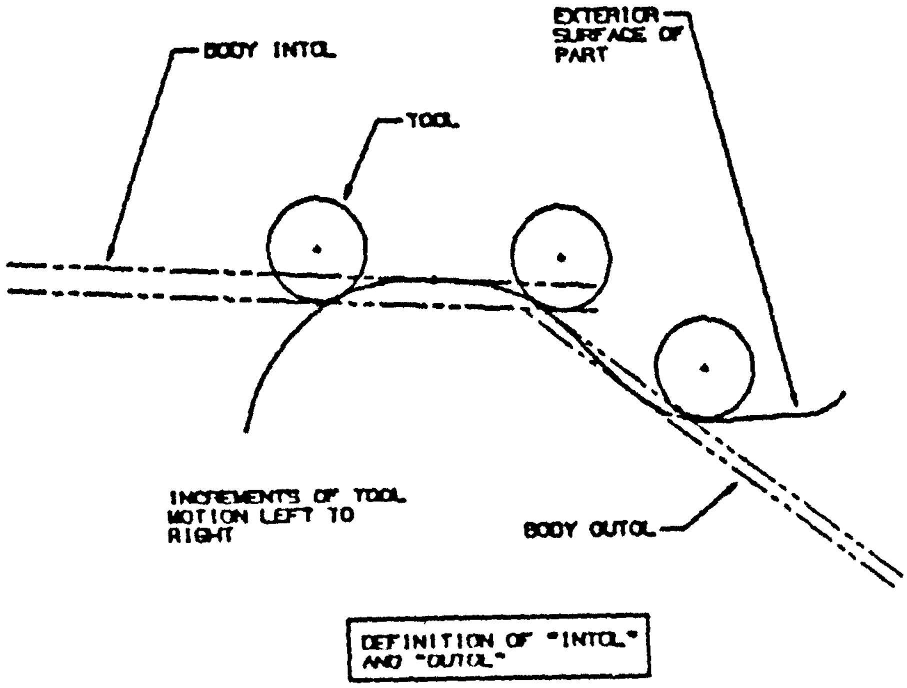

FIGURE 12: Chordal Tolerance Definition

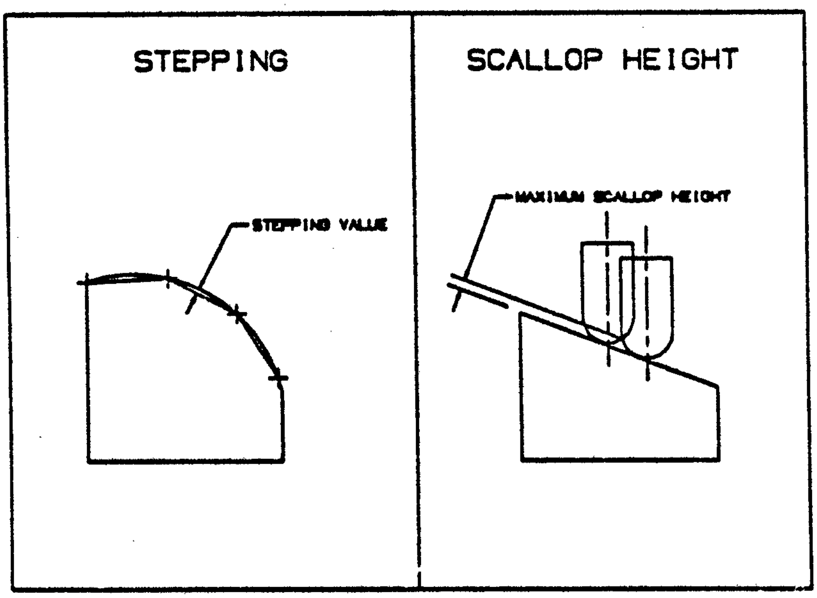

FIGURE 13: Definition of Scallop Height and Step Size

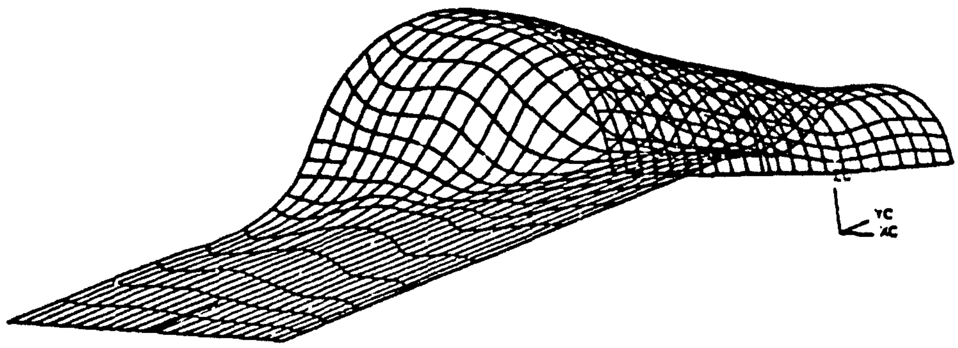

FIGURE 14: Geometry of Thumb Joint

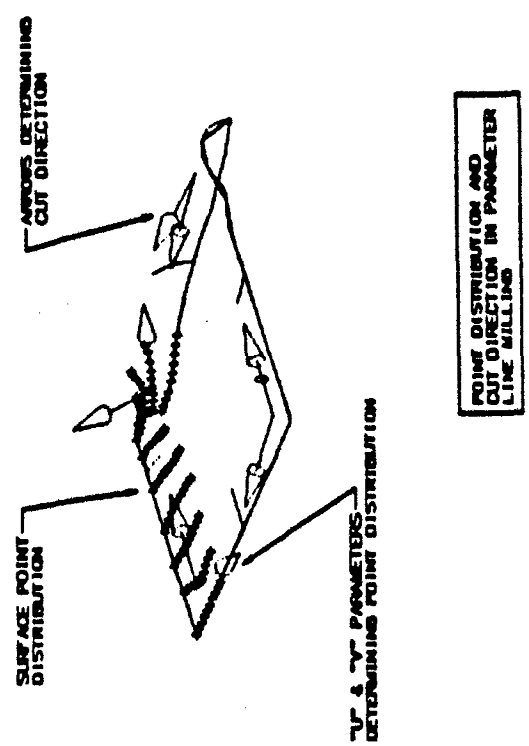

FIGURE 15: Cut Parameter Definition

UNIGRAPHICS DIRECTORY LISTING
DIRECTORY= @UGFMDISK:UGMGR:DAVID

FILENAME	FORMAT	LENGTH (bytes)
HAND_MOD3FLAT.CLS	TEXT	13152
HAND_MOD3P1.CLS	TEXT	9578
HAND_MOD3P2.CLS	TEXT	2680
HAND_MOD3P3.CLS	TEXT	2638
HAND_MOD3P4.CLS	TEXT	8960
HAND_MOD3P5.CLS	TEXT	15332
HAND_MOD3P6.CLS	TEXT	29924
HAND_MOD3P7.CLS	TEXT	29924
HAND_MOD3P8.CLS	TEXT	29924
HAND_MOD3P9.CLS	TEXT	4076
HAND_MOD3P10.CLS	TEXT	8824
HAND_MOD3P11.CLS	TEXT	8310
(no #12.CLS)		
HAND_MOD3P13.CLS	TEXT	4120
HAND_MOD3P14.CLS	TEXT	9128
HAND_MOD3P15.CLS	TEXT	4970
HAND_MOD3P16.CLS	TEXT	10914
HAND_MOD3P17.CLS	TEXT	34130
HAND_MOD3P18.CLS	TEXT	31670
HAND_MOD3PERIM.CLS	TEXT	60498
HAND_MOD3PERIMA.CLS	TEXT	65424
HAND_MOD3THFIN.CLS	TEXT	169806
HAND_MOD3THRUF.CLS	TEXT	46796
HAND_MOD3THUMB.CLS	TEXT	66900

FIGURE 16: Cutter Path Summary

```
PART NAME - HAND_MOD3.PRT
PARAMETER SET - P7
PARAMETER LINE MACHINING

TOOL INFORMATION     -T5
MILLING TOOL
   DIAMETER     = 0.3750
   CORNER RAD   = 0.1875
   HEIGHT       = 1.0000
   TAPER ANGLE  = 0.0000
   TIP ANGLE    = 0.0000
   FLUTE LEN    = 1.0000
   Z OFF        = -939.0000
   NUM FLUTES   = 2
   CATALOG NO.  =

POSTPROCESSOR COMMANDS
   NONE ACTIVE

FEEDRATES
   NON CUT UNITS     -IPM
   CUT UNITS         -IPM
   RAPID        = 0.0000
   ENGAGE       = 0.0000
   CUT          =10.0000
   RETRACT      = 0.0000
   FIRST CUT    = 0.0000
   APPROACH     = 0.0000
   STEPOVER     = 0.0000
   RETURN       = 0.0000

REFERENCE COORDINATE SYSTEM
     ORIGIN     = 0.0000, 0.0000, 0.0000
     MATRIX     = 1.0000, 0.0000, 0.0000
                  0.0000, 1.0000, 0.0000
                  0.0000, 0.0000, 1.0000
```

FIGURE 17: Tool Parameter Sets

```
CLEARANCE PLANE
     NORMAL     = 0.0000, 0.0000, 1.0000
     POINT      = 0.0000, 0.0000, 2.4000

ENGAGE/RETRACT
     ENGAGE TYPE     = NONE
     RETRACT TYPE    = NONE

STOCKING
     FLOOR STOCK          = NONE
     MINIMUM CLEARANCE    = NONE

TOOL AXIS
     TOOL AXIS TYPE       = NONE
```

FIGURE 17: Tool Parameter Sets (Continued)

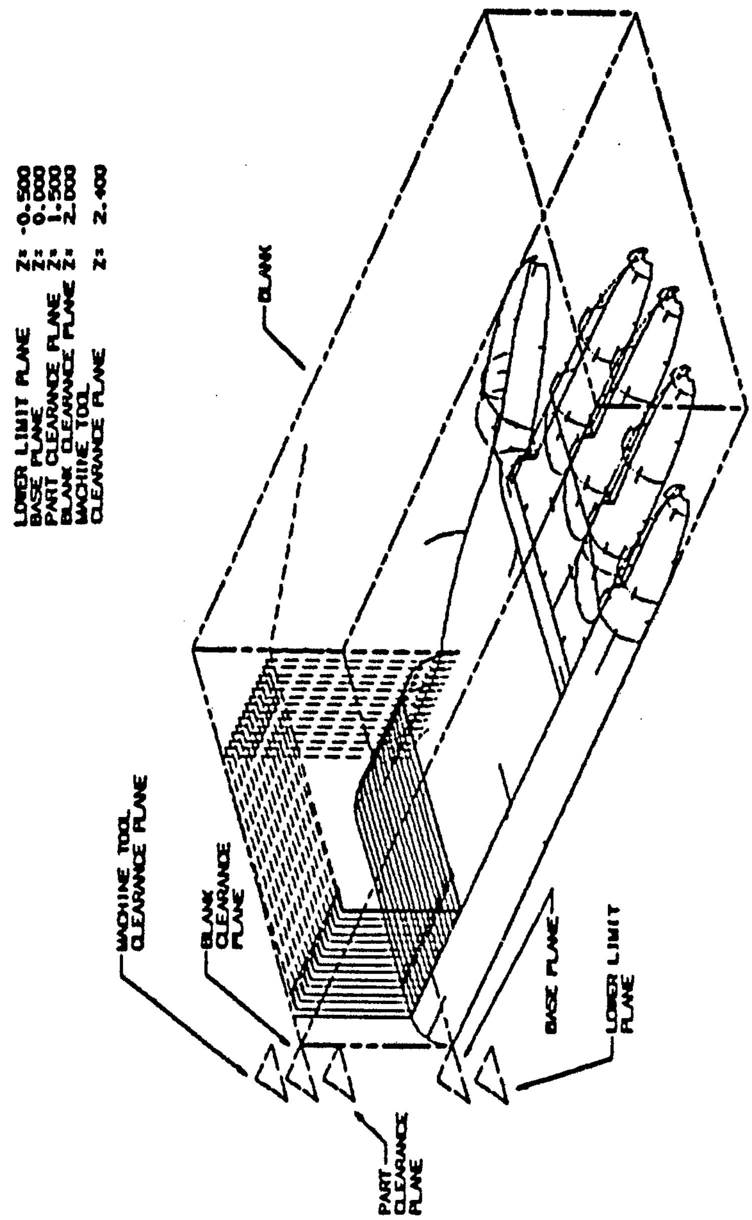

FIGURE 18: HAND_MOD3P1.CLS

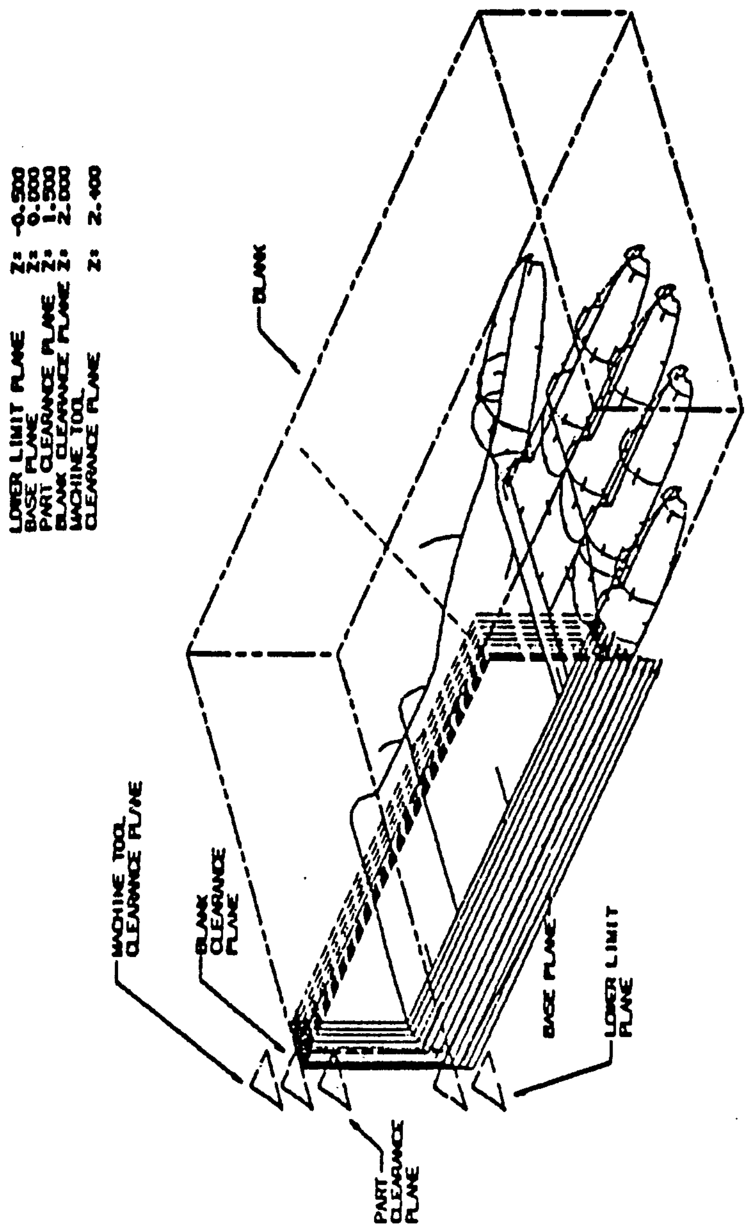

FIGURE 19: HAND_MOD3P2.CLS

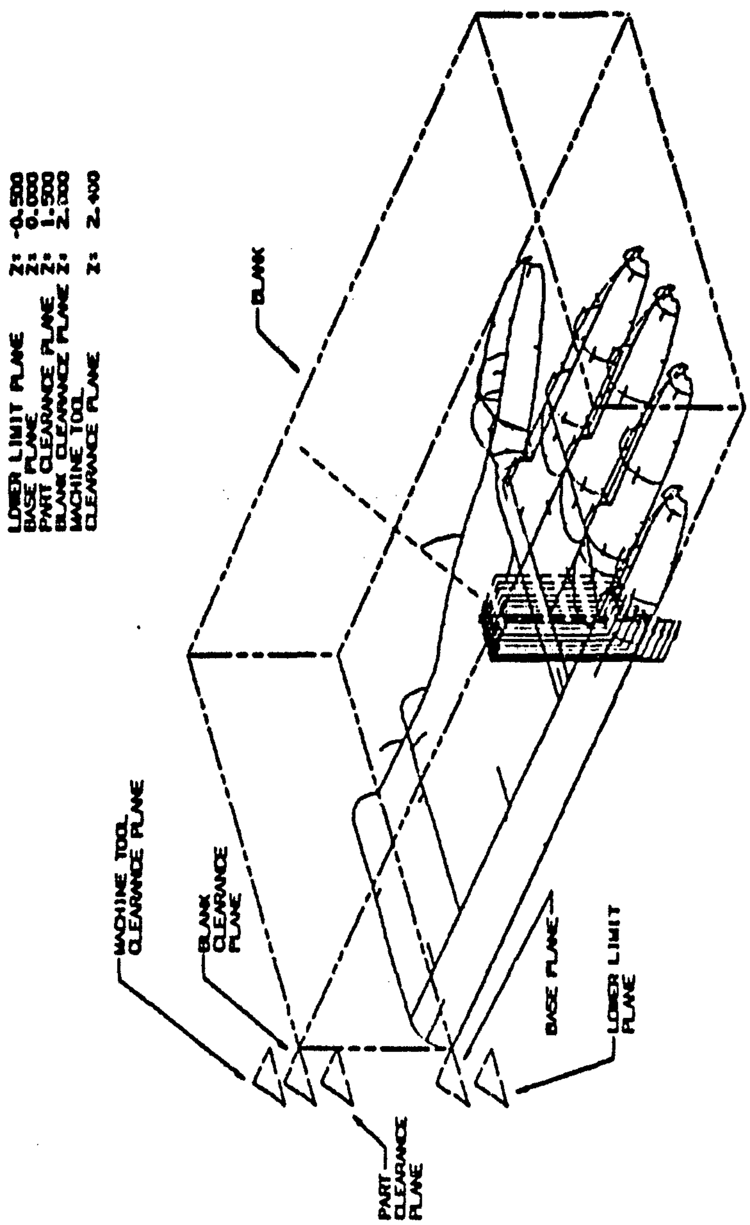

FIGURE 20: HAND_MOD3P3.CLS

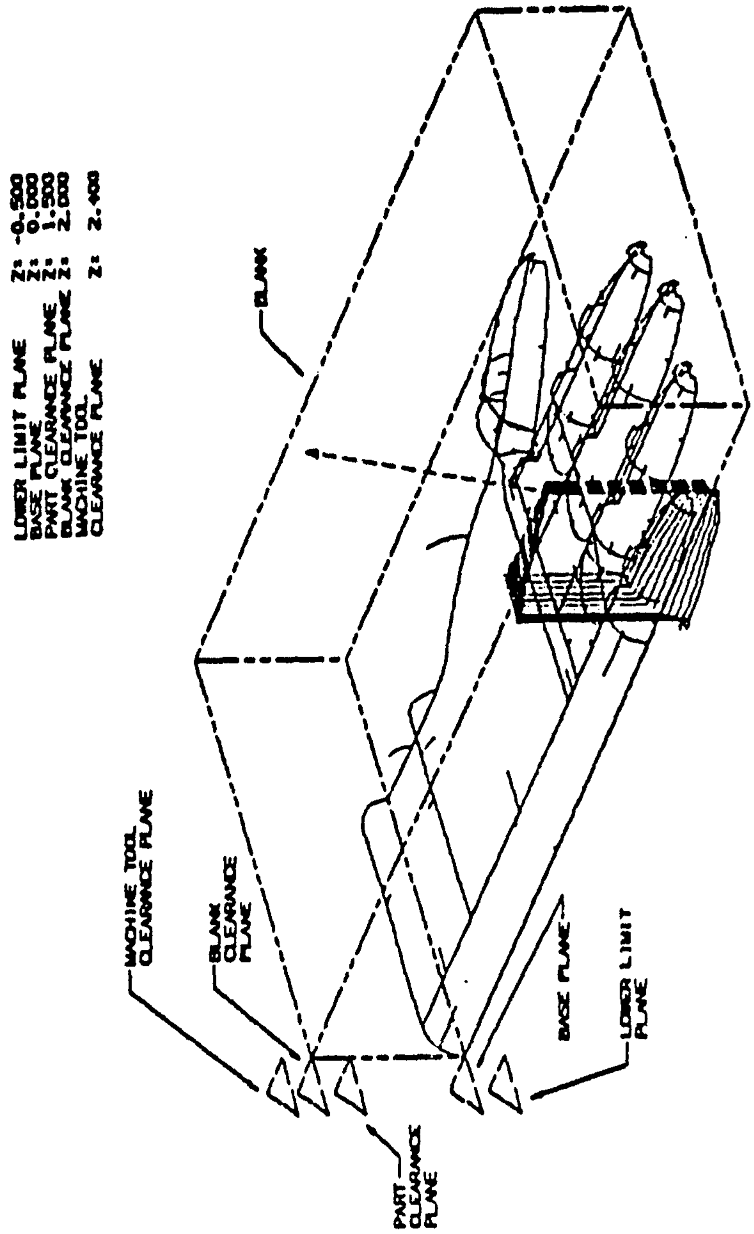

FIGURE 21: HAND_MOD3P4.CLS

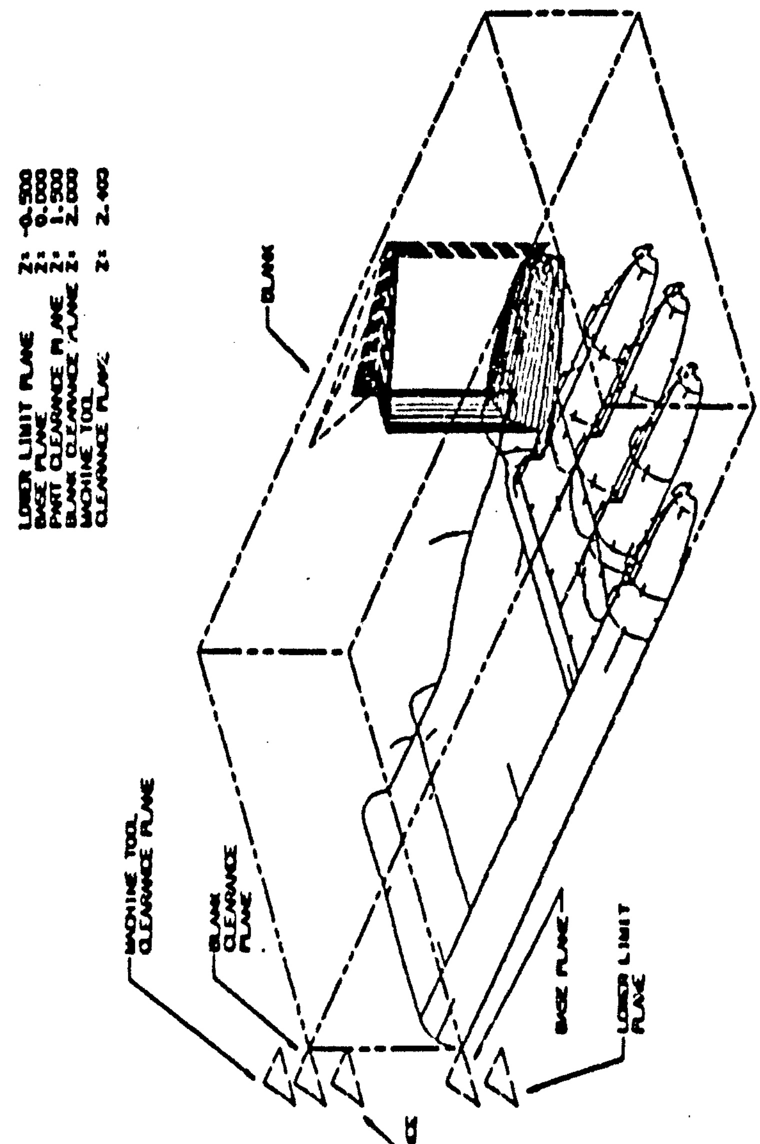

FIGURE 22: HAND_MOD3P5.CLS

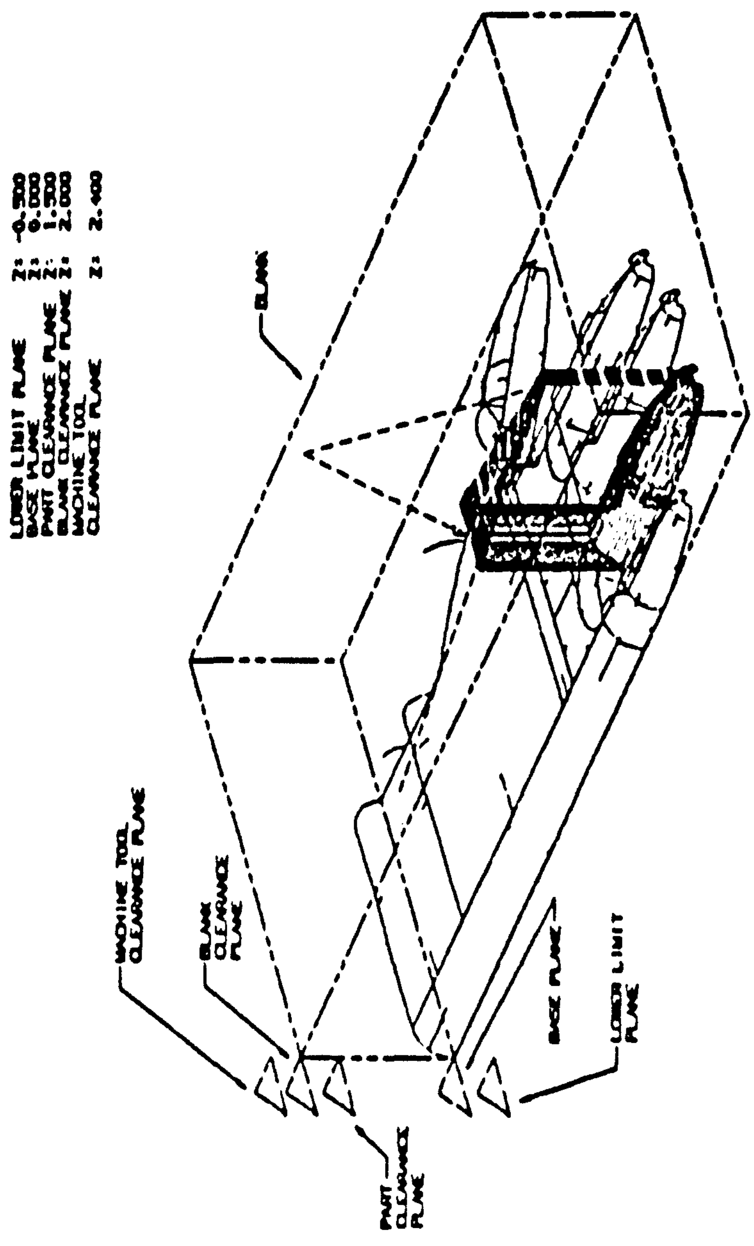

FIGURE 23: HAND_MOD3P6.CLS

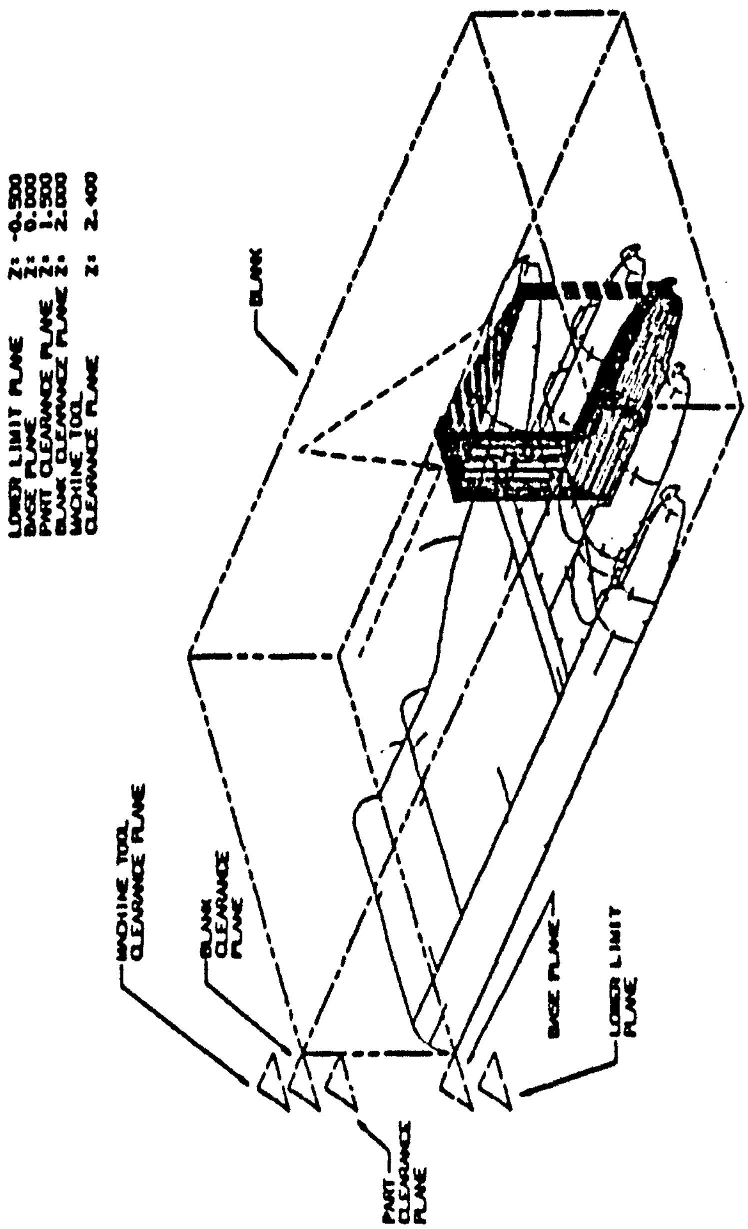

FIGURE 24: HAND_MOD3P7.CLS

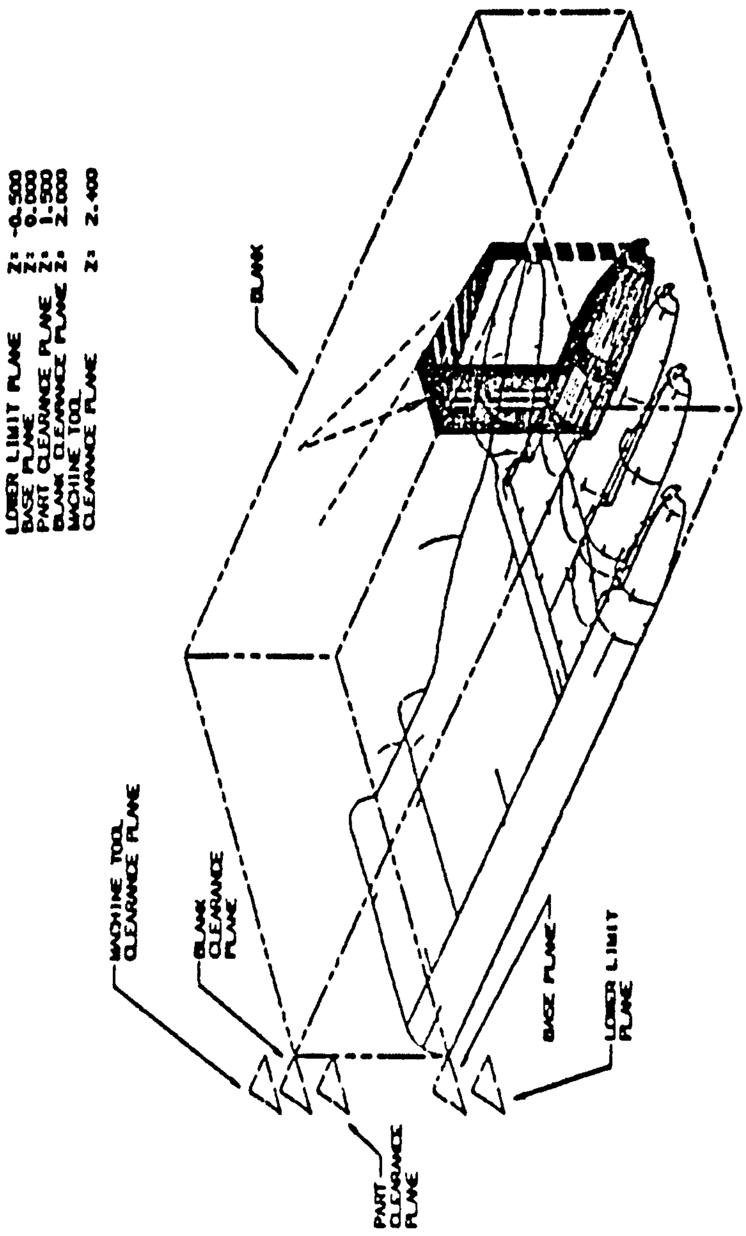

FIGURE 25: HAND_MOD3P8.CLS

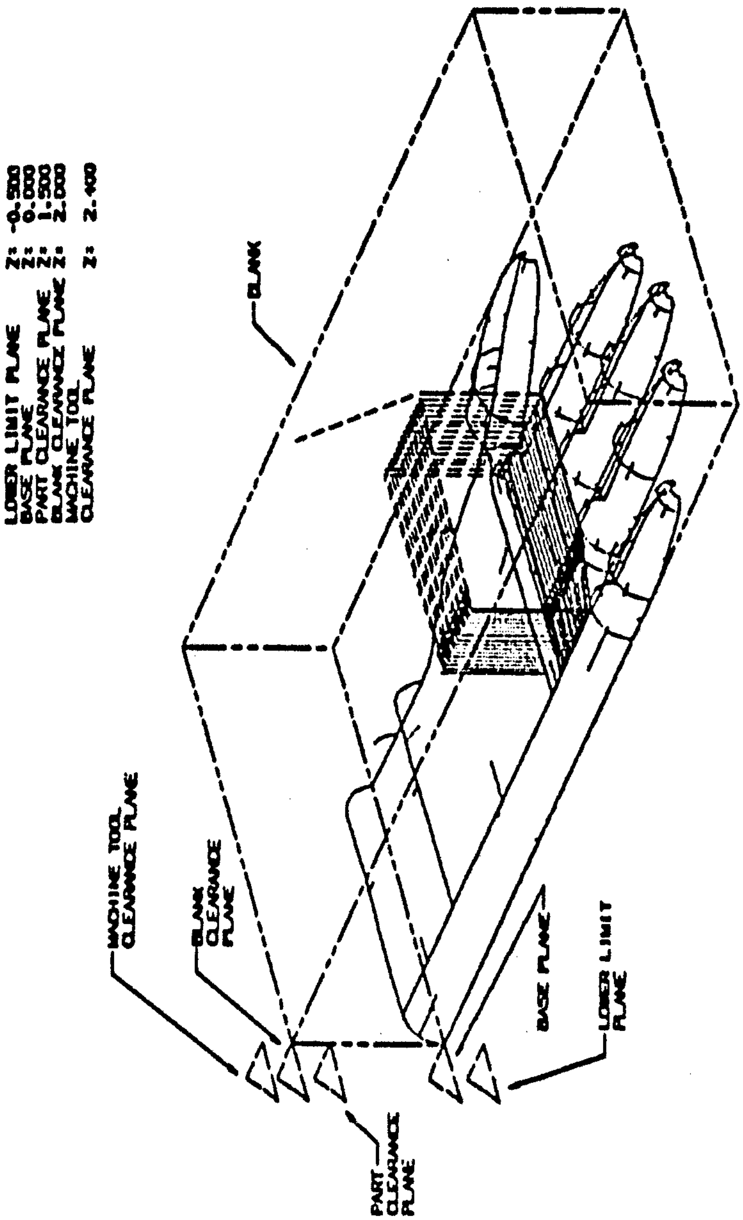

FIGURE 26: HAND_MOD3P9.CLS

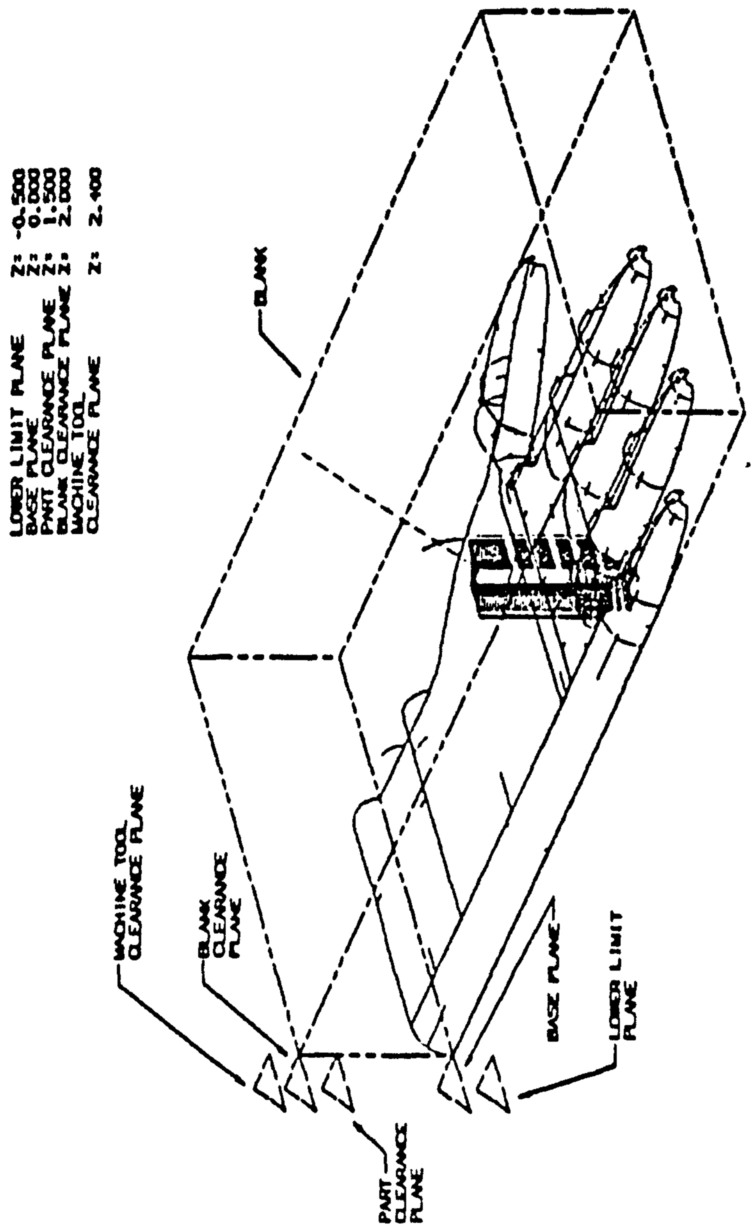

FIGURE 27: HAND_MOD3P10.CLS

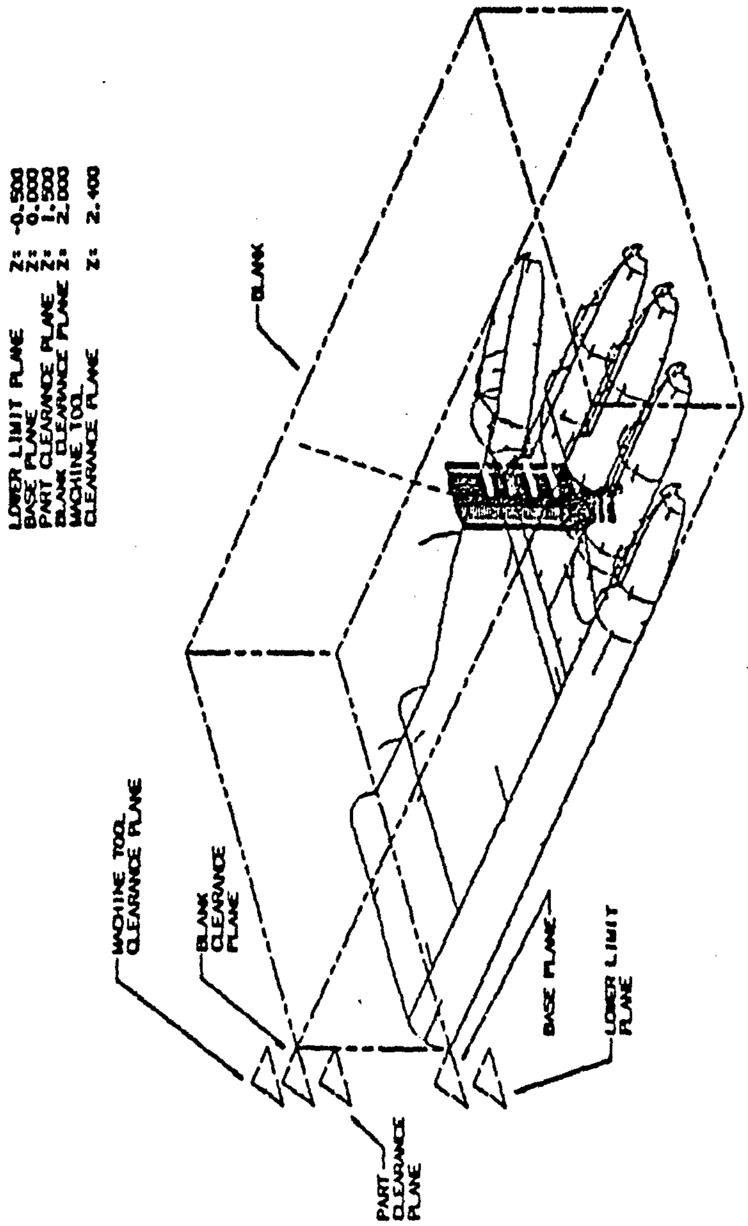

FIGURE 28: HAND_MOD3P11.CLS

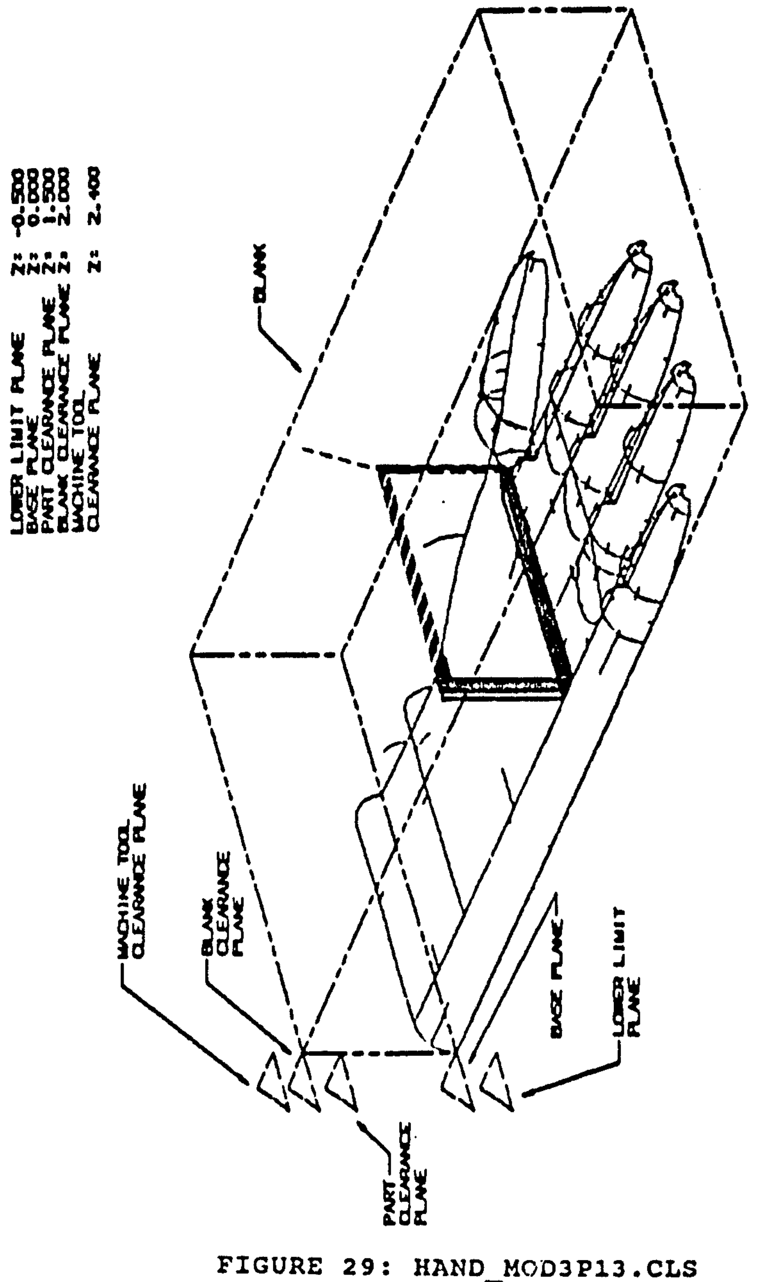

FIGURE 29: HAND_MOD3P13.CLS

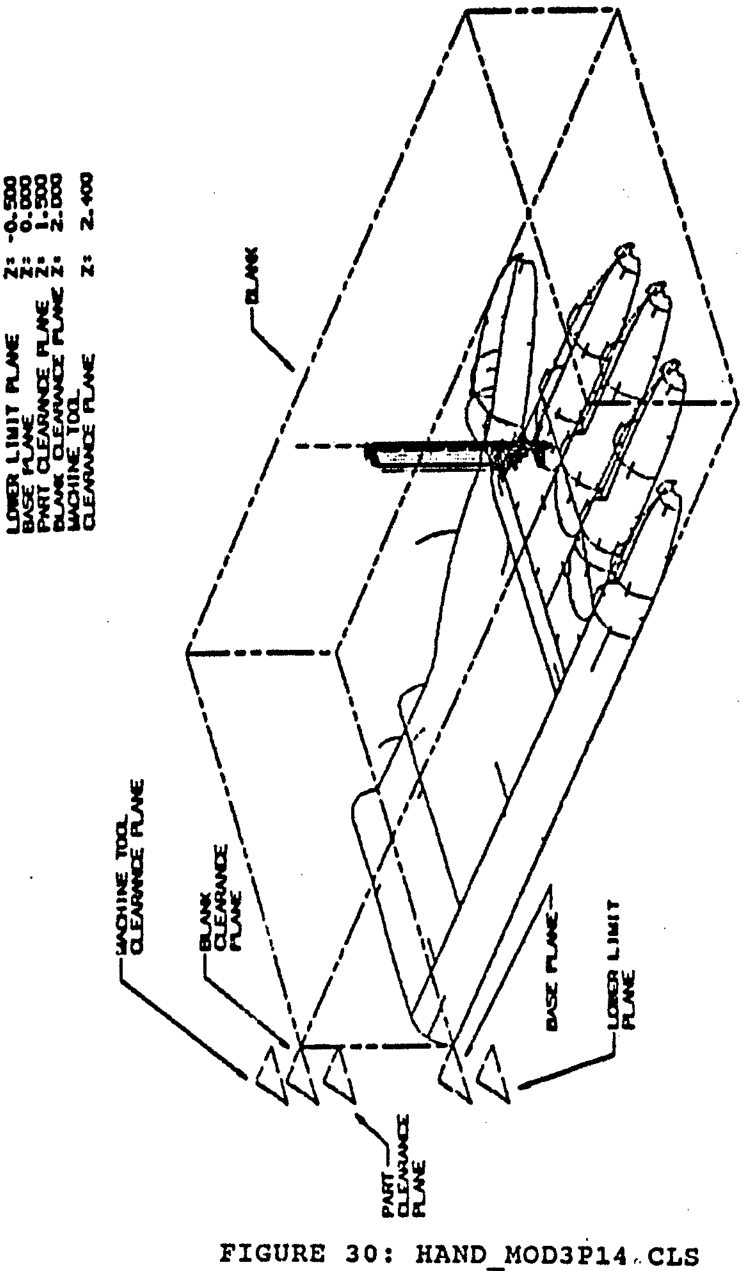

FIGURE 30: HAND_MOD3P14.CLS

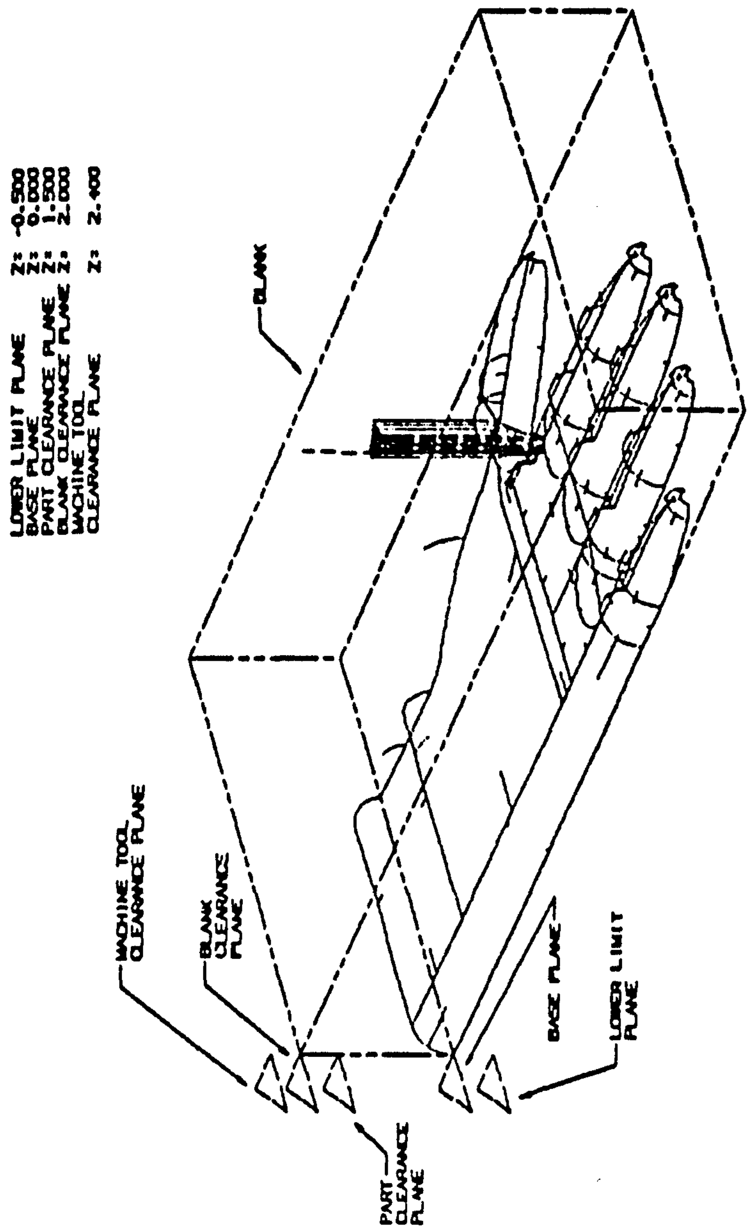

FIGURE 31: HAND_MOD3P15.CLS

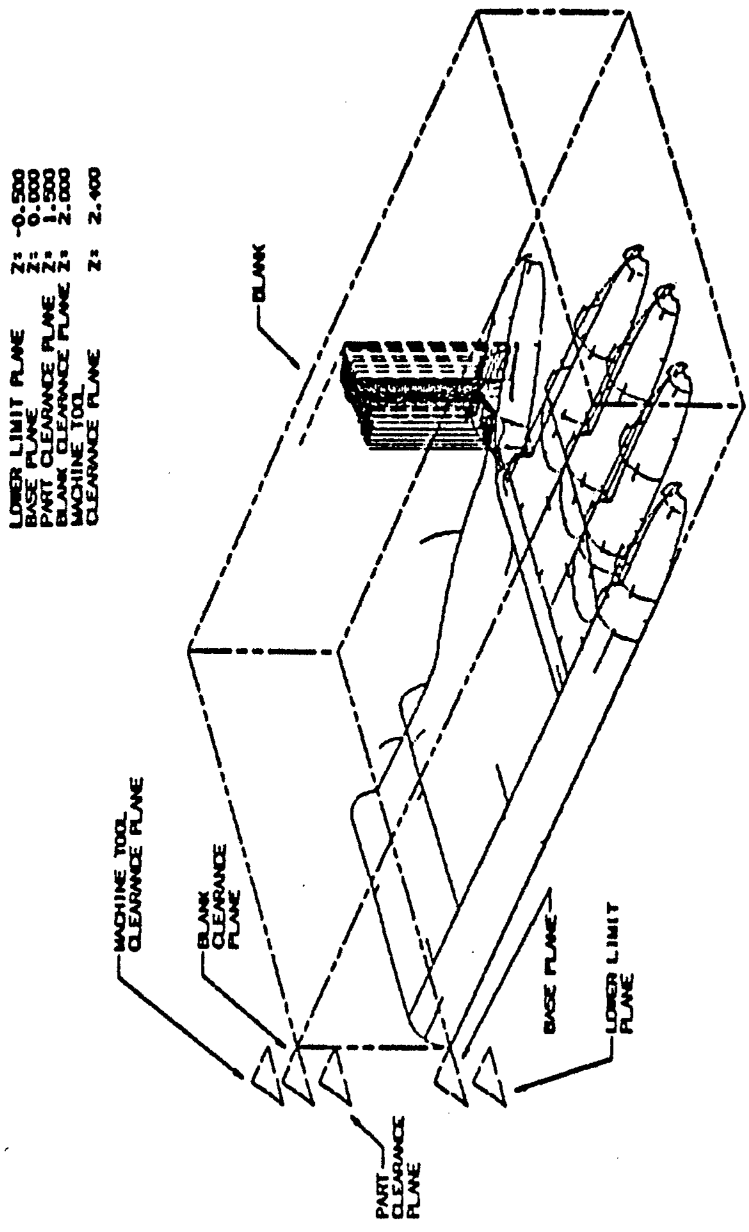

FIGURE 32: HAND_MOD3P16.CLS

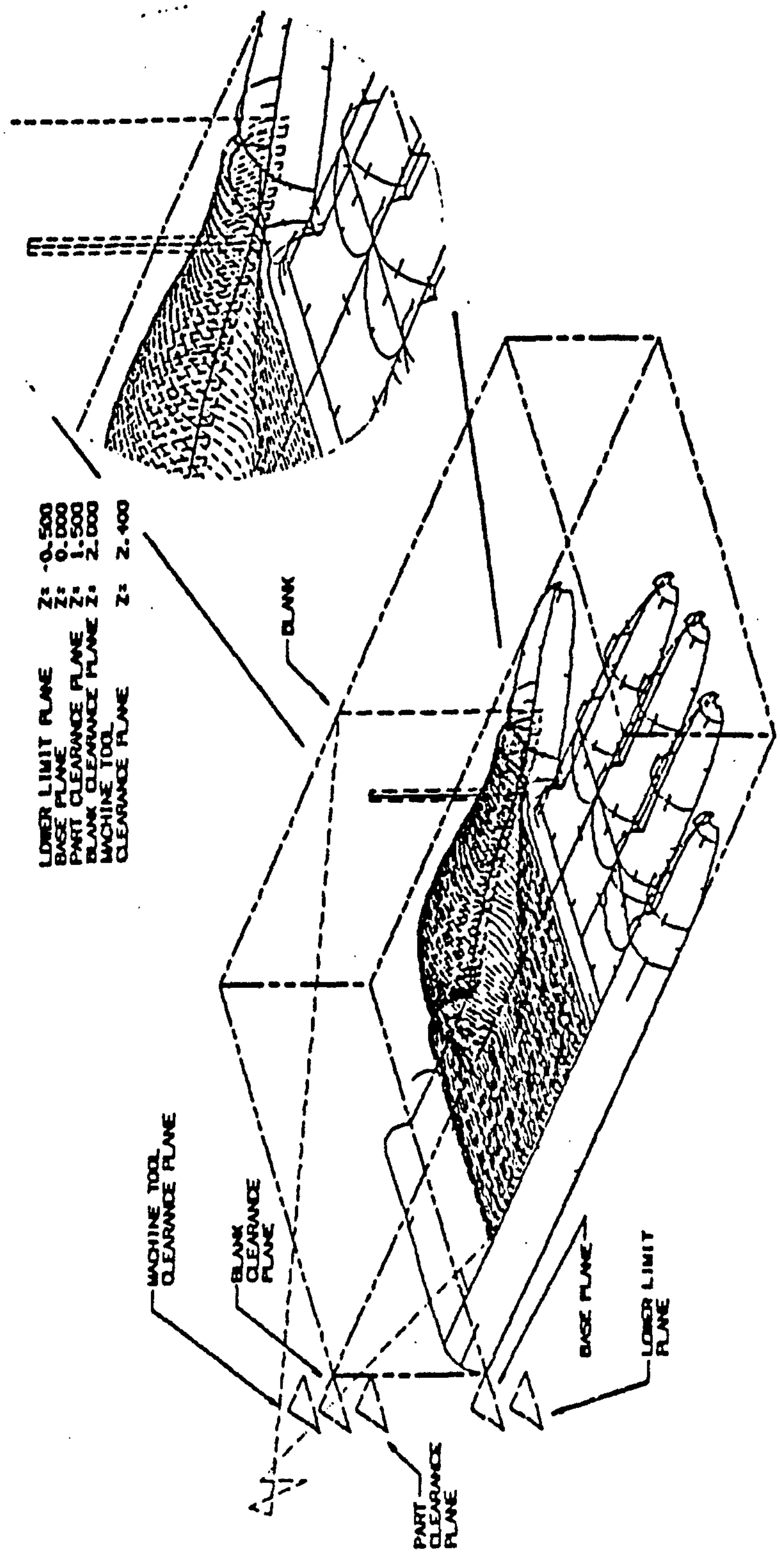

FIGURE 33: HAND_MOD3PTHRUF.CLS

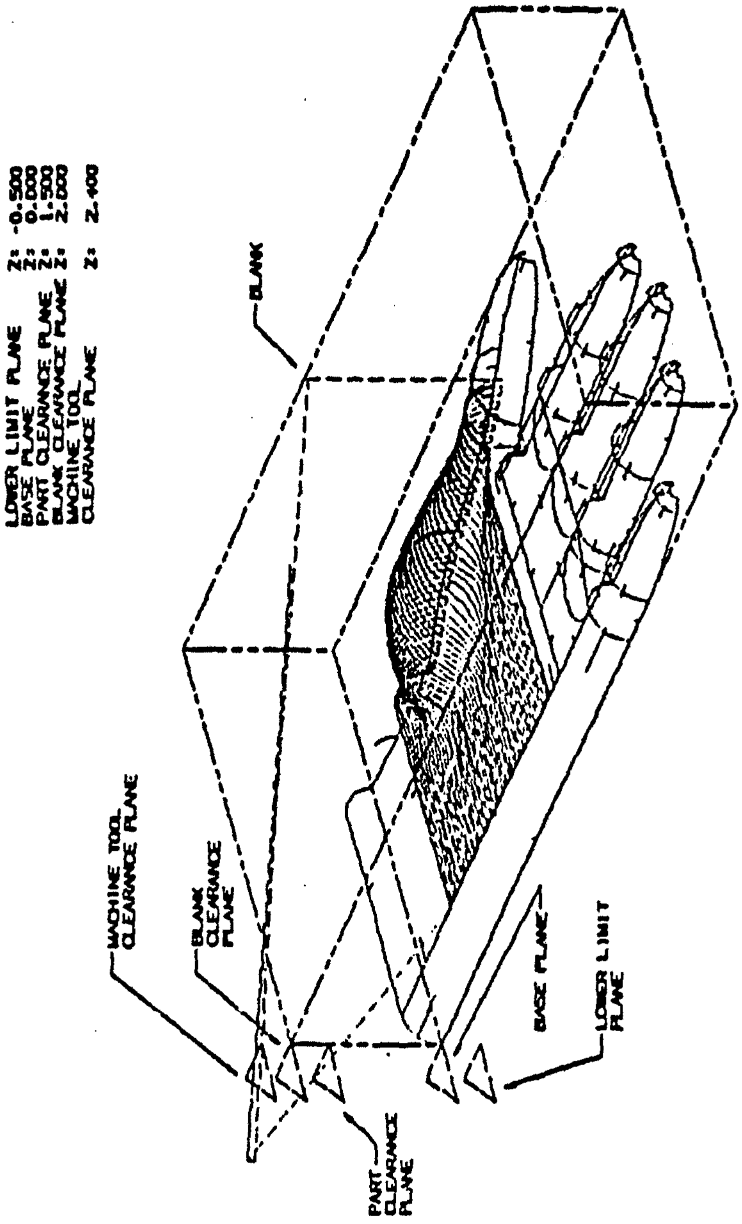

FIGURE 34: HAND_MOD3PTHUMB.CLS

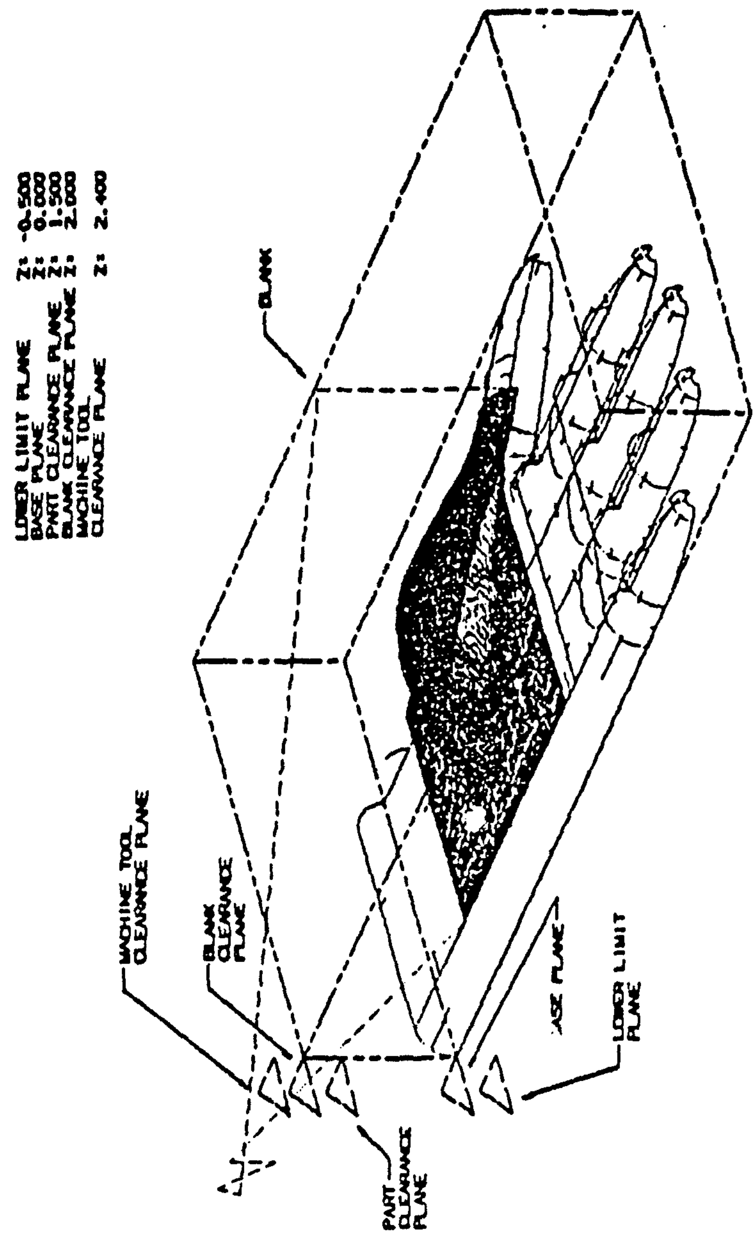

FIGURE 35: HAND_MOD3PTHFIN.CLS

APPENDIX A

ACTIVE POSTPROCESSOR FUNCTIONS

The following contains a summary of the relevant postprocessor functions that are enabled and are active in the software used by Matsuura 1000V CNC mill and the Fanuc System 6B controller. Only those functions that are necessary for the three-axis machining were enabled. The Fanuc controller is able to direct the operations of four-axis machining but the Matsuura mill only possesses three axes.

WORD ADDRESS FORMATS

WORD ADDRESS	DIGITS	DECIMAL PLACES	SURPRESS PLUS	SURPRESS MINUS	SURPRESS LDZERO
N	4	0	YES	YES	NO
G	2	0	YES	YES	NO
X	7	4	YES	NO	YES
Y	7	4	YES	NO	YES
Z	7	4	YES	NO	YES
I	7	4	YES	NO	YES
J	7	4	YES	NO	YES
K	7	4	YES	NO	YES
F	4	1	YES	NO	YES
S	4	0	YES	YES	YES
D	2	0	YES	YES	NO
T	4	0	YES	YES	NO
M	2	0	YES	YES	NO

WORD ADDRESS	SURPRESS TRZERO	OUTPUT DECIMAL	TRAILING CHARACTER	FUNCTION
N	NO	NO	NOT USED	SEQUENCE NUMBER
G	NO	NO	NOT USED	PREPARATORY G CODES
X	YES	YES	NOT USED	X COORDINATE
Y	YES	YES	NOT USED	Y COORDOMATE
Z	YES	YES	NOT USED	Z COORDINATE
I	YES	YES	NOT USED	CIRCLE CENTER X
J	YES	YES	NOT USED	CIRCLE CENTER Y
K	YES	YES	NOT USED	CIRCLE CENTER Z
F	YES	YES	NOT USED	IPM/MMPM
S	NO	NO	NOT USED	RPM
D	NO	NO	NOT USED	TOOL ADJUST NO.
T	NO	NO	NOT USED	TOOL NUMBER
M	NO	NO	NOT USED	MISCELLANEOUS CODE

PREPARATORY FUNCTION LIST

G-CODES	FUNCTION	POSTPROCESSOR COMMAND
00	POSITIONING MODE	RAPID
01	LINEAR INTERPOLATION MODE	GOTO
02	CLOCKWISE CIRCULAR INTERPOLATION	SET/MODE, LINCIR
03	COUNTERCLOCKWISE CIRCULAR INTERPOLATION	SET/MODE, LINCIR
17	XY PLANE	CIRCULAR INTERPOLATION
17		CUTCOM/XY PLANE
18	ZX PLANE	CIRCULAR INTERPOLATION
18		CUTCOM/ZX PLANE
19	YZ PLANE	CIRCULAR INTERPOLATION
19		CUTCOM/YZ PLANE
20	IMPERIAL (INCH) FORMAT	
21	METRIC FORMAT	
90	ABSOLUTE MODE	SET/MODE, ABSOL
91	INCREMENTAL MODE	SET/MODE, INCR
96	SFM/SMM SPINDLE MODE	SPINDLE/SFM (SMM)
97	RPM SPINDLE MODE	SPINDLE/RPM

MISCELLANEOUS FUNCTION CODES

M CODE	FUNCTION	POSTPROCESSOR COMMAND
00	STOP OPERATION	STOP
01	OPTIONAL STOP	OPSTOP
02	END OF PROGRAM	END
03	DEFAULT SPINDLE DIRECTION	SPINDLE/ON
03	SPINDLE CLOCKWISE	SPINDLE/.., CLW
04	SPINDLE COUNTERCLOCKWISE	SPINDLE/..,CCLW
05	SPINDLE STOP	SPINDLE/OFF
06	AUTOMATIC TOOL CHANGE	LOAD/TOOL
00	MANUAL TOOL CHANGE	LOAD/TOOL,...,MANUAL
07	COOLNT MIST CODE	COOLNT/MIST
08	COOLNT FLOOD CODE	COOLNT/FLOOD
08	DEFAULT COOLNT ON	COOLNT/ON
09	COOLNT OFF	COOLNT/OFF
30	END OF PROGRAM, REWIND	REWIND

FEED RATE PARAMETERS

DEFAULT FEED RATE	10 IPM
MAXIMUM IPM/MMPM FEED RATE	400.0 IPM
MINUMUM IPM/MMPM FEED RATE	0.1 IPM
RAPID TRAVERSE RATE	400.0 IPM

MACHINE TRAVEL LIMITS

X AXIS MINIMUM	-1000.0000
X AXIS MAXIMUM	+1000.0000
Y AXIS MINIMUM	-1000.0000
Y AXIS MAXIMUM	+1000.0000
Z AXIS MINUMUM	-1000.0000
Z AXIS MAXIMUM	+1000.0000

RUN TIME PARAMETERS

NUMBER OF MINES PER PAGE OF LISTING	39
NUMBER OF COLUMNS PER LINE OF LISTING	132
COMMENTARY LISTING CONTAINS:	
RECORD NUMBER	
X COORDINATE	
Y CORRDINATE	
Z COORDINATE	
CURRENT IPM/MMPM	
CURRENT RPM	
BLOCK TIME	
NUMBER OF G CODE PER BLOCK	4
LISTING OUTPUT	LINEPRINTER.FIL
LISTING DATA	UNPACKED
PUNCH TAPE OUTPUT TO UGFM TEST FILE	PUNCH.PTP
PAPER TAPE OUTPUT TO SYSTEM LOGICAL	UGPTR
LINEPRINTER OUTPUT	UGII$PRINTER
PUNCH TAPE FORMAT	ISO,RS-358, EVEN PARITY
END OF BLOCK CODE	<CR><LF>
INPUT DIMENSIONS	INCH
OUTPUT DIMENSIONS	INCH
POSTPROCESSOR ERROR MESSAGES	TERMINAL
IF LISTING OUTPUT, ERRORS ON LINE-PRINTER	OUTPUT
LEADER LENGTH	0
TRAILER LENGTH	0
LEADER CHARACTERS	NULLS
SEQUENCE NUMBER INCREMENT	10
NUMBER OF BLOCK PER SEQUENCE NUMBER	1

SPECIAL TAPE CONTROL GUIDES

CONTROL OUT ISO CODE	(
CONTROL IN ISO CODE	)
CONTROL OUT EIA CODE	<032>
CONTROL IN EIA CODE	<112>
INITIAL CODE AT START OF TAPE	REWIND,STOP,END-OF-BLOCK
END OF TAPE CODE	NOT REQUIRED

SPINDLE PARAMETERS

RPM LIMITS	
MAXIMUM RPM, RANGE 1	9999
MINIMUM RPM, RANGE 1	1
SPINDLE DIRECTION CONTROL	M CODES

SPINDLE DIRECTION M CODES OUTPUT FOR EVERY SPINDLE STARTUP
SPINDLE DIRECTION CODE & RPM CODE IN SAME BLOCK

SPINDLE STOP & DIRECTION CHANGE	NOT REQUIRED

TOOL CHANGE PARAMETERS

MAXIMUM TOOL NUMBER	99
MINIMUM TOOL NUMBER	1
TIME FOR TOOL CHANGE	0.20 MINUTES

TOOL CODE WI' L NOT BE CONBINED WITH MOTION

MAXIMUM TOOL . 'UST NUMBER	99
MINIMUM TOOL ADJUST NUMBER	0

TOOL LENGTH COMPENSATION IS ACTIVATED BY OFFSET REGISTER ONLY
TOOL LENGTH COMPENSATION IS CANCELLED BY DO
TOOL LENGTH COMPENSATION CODES OUT WITH Z-MOTION
TOOL CODE OUTPUT IN SAME BLOCK WITH TOOL CHANGE M06
TOOL CODE NOT OUTPUT IF PRE-SELECTED

CIRCULAR INTERPOLATION PARAMETERS

MAXIMUM RADIUS FOR CIRCULAR INTERPOLATION	999.9999
MINIMUM RADIUS FOR CIRCULAR INTERPOLATION	0.0001
PLANES OF CIRCULAR INTERPOLATION	XY, YZ & ZX
ARC CENTER DEFINITION	ABS & INCR MODES

I, J & K REPRESENT THE DISTANCE FROM ARC START TO CIRCLE CENTER
ALL PROGRAMMED ARCS DIVIDED UP INTO SEGMENTS OF 360 DEGREES OR LESS

HELICAL ARCS OUTPUT	LINEARLY

CIRCULAR INTERPOLATION CLW & CCLW G CODES ARE MODAL

LINEAR INTERPOLATION PARAMETERS

MINIMUM MACHINE RESOLUTION (INCH)	0.0001
AXIS OF SIMULTANEOUS MOTION IS	1; X,Y,Z IN SAME BLOCK
ABSOLUTE MODE	G90
INCREMENTAL MODE	G91
VERTICAL DOWNWARDS	-Z AXIS

DEFAULT SPINDLE AXIS FOR WORK PLANE
CHANGE AND CYCLE LOGIC +Z AXIS
POSTPROCESSOR WILL OUTPUT RAPID TRAVERSE MOTIONS IN TWO BLOCKS IF A SPINDLE AXIS MOTION AND EITHER AN X- OF Y-AXIS MOTION OCCURS

COORDINATE CONVERSION PROGRAMMED PART COORDINATES TO MACHINE COORDINATES

COORDINATE DEFINITIONS

XP= PROGRAMMED(X) + TRANS(X) - ORIGIN(X)
YP= PROGRAMMED(Y) + TRANS(Y) - ORIGIN(Y)
ZP= PROGRAMMED(Z) + TRANS(Z) - ORIGIN(Z)
CARTESIAN MILL COORDINATE SYSTEM

MACHINE- X= XP
MACHINE- Y= YP
MACHINE- Z= ZP+ ZOFF

POSTPROCESSOR COMMAND FORMATS

VALID MAJOR WORDS	VALID MINOR WORDS
AUXFUN	N
CHECK	XAXIS,N,N
	YAXIS,N,N
	ZAXIS,N,N
COOLNT	ON
	OFF
	FLOOD
	MIST
END	
FEDRAT	N
	IPM,N
	MMPM,N
	IPR,N
	MMPR,N
GOHOME	X,Y,Z
	XAXIS,N
	YAXIS,N
	ZAXIS,N
INSERT	
LEADER	N
LOAD	TOOL,N
	ZOFF,Z
	MANUAL
	ADJUST,N
OPSKIP	ON
	OFF

OPSTOP		
ORIGIN	X,Y,Z	
PARTNO		
PPRINT		
PERFUN	N	
RAPID		
REWIND		
SELECT	ZAXIS,N	
SEQNO	N	
	INCR,N	
	OFF	
	ON	
	NEXT	
	AUTO	
SET	ADJUST	,N
		ON
		OFF
	MODE	ABSOL
		INCR
		LINEAR
		LINCIR
SPINDLE	N	
	ON	
	OFF	
	RPM,N	
		CLW
		CCLW
		RADIUS
STOP	N	
TIME	SCALE,S	
	NOW	
TMARK	N	
	AUTO	
TRANS	X,Y,Z	

APPENDIX B

CNC FILE MODIFICATION SOFTWARE

The following program ws written in GRIP to prepare the CNC mill for the incoming data from the postprocessed machining files from Unigraphics.

```
$$      PROGRAM:       FILEADDR.GRS
$$
$$      PROGRAM WILL ADD FILE HEADER AND FOOTER
$$      COMMANDS AND EDIT OUT NULL LINES AT FILE END
$$
$$      THE HEADER DATA IS CONTAINED IN FILE
$$      "HEADER.TXT" AND THE FOOTER DATA IN
$$      FILE "FOOTER.TXT"
$$
        STRING/FNAM1(40),GNAM1(40),HNAM1(40)
$$
        DATA/FNAM1,'@UGFMDISK:UGMGR:DAVID:HEADER.TXT'
        DATA/GNAM1,'@UGFMDISK:UGMGR:DAVID:PUNCHFILE.PTP'
        DATA/HNAM1,'@UGFMDISK:UGNGR:DAVID:FOOTER.TXT'
$$
        FETCH/TXT,1,FNAM1,IFERR,ERR1:
        APPEND/1
        FETCH/TXT,2,GNAM1,IFERR,ERR2:
        RESET/2
        LDEL/2.START,10,END,10
        APPEND/2
        N=GETL(2)
        LDEL/2,START,N,END,N
        FILE/TXT,2,GNAM1,IFERR,ERR4:
        FAPEND/TXT,1,GNAM1,IFERR,ERR2:
        APPEND/1
        FAPEND/TXT,1,HNAM1,IFERR,ERR3:
        FILE/TXT,1,GNAM1,IFERR,ERR4:
$$
        TERM:
        HALT
$$
        ERR1:MESSG/'ERR1:',' ERROR OM FETCH #1'
             JUMP/TERM:
        ERR2:MESSG/'ERR2:',' ERROR IN FAPEND: MAIN FILE'
             JUMP/TERM:
        ERR3:MESSG/'ERR3:',' ERROR IN FAPEND: TRAILER FILE'
             JUMP/TERM:
        ERR4:MESSG/'ERR4:',' ERROR IN FILING PRODUCT'
             JUMP/TERM:
```

The program uses the two scratch file areas in GRIP to read, sort and edit the punch files so that the sets of commands in the header and footer files may be added on. The strings FNAM1 etc. contain the file names as character strings so that in order to process another punch file, only one file name has to be changed. It is stored under the original name in the corrected form.

APPENDIX C

PRELIMINARY CNC COMMAND FILE

Preliminary commands contained in HEADER.TXT

```
10    %
20    00000<CR><LF>
30    G00G17G20G22<CR><LF>
40    G40G49G546G4<CR><LF>
50    G80G91G94G98M77<CR><LF>
60    G28 ZO. M38<CR><LF>
70    G28 XO. YO. M48<CR><LF>
80    MOO<CR><LF>
90    (OPTIONAL ACSII DESCRIPTOR)<CR><LF>
100   M06 T<CR><LF>
110   M03 S<CR><LF>
120   G90G00 G43 Z+2.0 H<CR><LF>
130   XO.OYO.OZ3.O<CR><LF>
```

Commands contained in trailing file FOOTER.TXT

```
10    G90 G00 Z+3.0 M09<CR><LF>
20    G80 G40 G49 M05 G28 Z-2.0<CR><LF>
30    M46<CR><LF>
40    M30<CR><LF>
```

Line 90 in HEADER.TXT may be used to insert program names and tool information in man-readable form. Line 20 may also be used for path descriptions e.g. 20 01573<CR><LF>

SECURITY CLASSIFICATION OF FORM
(highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) DEFENCE RESEARCH ESTABLISHMENT OTTAWA National Defence Ottawa, Ontario K1A 0Z4	2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable) UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

COMPUTER-AIDED DESIGN OF A NEW PROTOTYPE CB PROTECTIVE GLOVE (U)

4. AUTHORS (Last name, first name, middle initial)

HIDSON, David J.

5. DATE OF PUBLICATION (month and year of publication of document) NOVEMBER 1990	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 65	6b. NO. OF REFS (total cited in document) 2

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

REPORT

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
National Defence
Ottawa, Ontario K1A 0Z4

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant) 051LD11	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) DREO REPORT 1054	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; further distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availabilty (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

UNCLASSIFIED

SECURITY CLASSIFICATION OF FORM

DCD03 2/06/87

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U). It is not necessary to include here abstracts in both offical languages unless the text is bilingual).

This paper describes the computer-aided design and manufacture of a prototype core model for a new protective glove. The computer system and software are described as are the design processes in geometry and CNC machining. The construction of sculptured surfaces, machine tool paths and postprocessing software for the shape are laid out and the problems of the manufacture of complex geometric parts analysed. The final product was machined on a Matsuura/Fanuc computer-numerical control machine and controller.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

COMPUTER-AIDED DESIGN
COMPUTER-AIDED MANUFACTURING
INJECTION MOLDING
PROTECTIVE CLOTHING