ABSTRACT

An Interactive Computer Graphics Based Off-line AVAIL Programming Environment for Coordinate Measuring Machines

by
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Productivity can be increased by providing computer aided off-line program development environment to operate direct computer controlled Coordinate Measuring Machines (CMM). Such an environment not only results in reduced operational downtime of the CMM but also eliminates the need for the operators to learn and debug the complicated CMM programming language.

An application software was developed to provide a computer based graphical environment for on-the-screen CMM inspection simulation and AVAIL part program development. A comprehensive, menu driven front-end was developed as a foundation for this software. Algorithms were designed and coded to read and interpret CAD software part design information in Initial Graphics Exchange Specifications (IGES) format.

CMM inspection activities can be simulated on the displayed part using various menu options. All user simulation activities are captured and converted to an AVAIL part program, which can be downloaded to a CMM for physical inspection of the part. The output generated by execution of the AVAIL part program can be brought back to the software. Inspection reports can be generated from the output information for further analysis about accept/reject decisions.

AN INTERACTIVE COMPUTER GRAPHICS BASED
OFF-LINE AVAIL PROGRAMMING ENVIRONMENT FOR
COORDINATE MEASURING MACHINES

by
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Off-line AVAIL Programming Environment for
Coordinate Measuring Machines

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CHAPTER 1

INTRODUCTION

The biggest drawback in inspecting a part on a Coordinate Measuring Machine (CMM) using the AVAIL™ [1] computer programming language is that the inspector has to become familiar with this complicated language. The operator has to learn the structure and the language statement syntax to develop a part program. Further, on-line development and testing of the AVAIL inspection program may increase an operational downtime of the CMM, thus resulting in decreased productivity.

If an inspection part program can be developed and tested off-line after a part has been designed in a CAD software system, an inspector can inspect the part without any prior knowledge of the AVAIL programming language. This can result in a better utilization of the CMM for inspection activities. The off-line development of the inspection part programs also eliminates the need for the operator to learn and debug the CMM programming language.

The objective of this thesis is to provide a system with the capability for computer aided off-line development of an AVAIL part program to measure a part on a Coordinate Measuring Machine. This can reduce the time required to program a CMM, and help in integrating the CAD system and Inspection system by a single computer. It can also eliminate a need for the CMM operators to learn and debug AVAIL programming language. Providing such a capability requires reading and interpreting CAD design database information and generating environment to display the part and simulate CMM measurement activities. It also requires to analysis measurement results to generate inspection reports.

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[1] AVAIL is a registered trademark of Brown & Sharp Manufacturing Company

Such a system can be considered as an extension of programmable automation systems. It may serve as a step forward in the direction of the Computer Integrated Manufacturing. It may be considered as a part of Flexible Inspection Systems (FIS). Using such a system can result in virtually no machine time lost in part program development, testing and debugging.

In the course of the work directed towards this thesis an interactive menu driven software was developed. This software provides a graphical environment to simulate the CMM measurement activities. An IGES Processor was developed as a part of the software. In the development of this processor, mathematical algorithms were designed and coded. The IGES processor reads and interprets the file written by the CAD system in the Initial Graphics Exchange Specifications (IGES) format.

After interpreting the IGES file, the part is displayed for on-the-screen simulation of CMM inspection activities. Various entities to be measured can be identified by the users. All the simulation activities performed by the user using different menu options are captured and converted to an AVAIL inspection part program. An AVAIL code generator module was developed to convert the user simulation activities into AVAIL program statements.

The inspection part program generated by the software, can be downloaded to a CMM for physical part inspection. An Output module was developed as a part of the software to provide a capability of reading back the output generated by the execution of the part program for analysis. Inspection reports can be generated to make decisions regarding accepting or rejecting the part.

This software was entirely written in the C language. An extensive use of the Hierarchical Object Oriented Picture System (HOOPS™ [1]) library functions was made in the development of the software. For the user interaction, menus were designed and

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[1] HOOPS is a registered trademark of Ithaca Software

developed using object hierarchy concepts of the HOOPS. The user interaction message library and the help screens were developed to make the software user friendly.

This software runs on a UNIX™ [1] operating system based computers supporting the X Window™ [2] system.

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[1] UNIX is a registered trademark of AT&T

[2] X Window is a registered trademark of Massachusetts Institute of Technology

CHAPTER 2

COORDINATE MEASURING MACHINES

A *Coordinate Measuring Machine* (CMM) is an inspection instrument to measure a workpart according to the design specifications. It consists of a contact probe and a mechanism to position the probe in three-dimensional space relative to the surface and features of the workpart. CMMs have became popular because of their ability to perform accurate and precise measurements. Initially, CMMs were mainly used in the instrumentation labs for measuring critical parts and verifying machine setup. However, now-a-days, CMMs have moved on to the factory floor to become an important part of the Flexible Manufacturing Systems (FMS). CMMs are no longer stand alone units, they may be operated by the central computer system used to control the entire system. Thus they are a part of an integrated designing, machining and inspecting system.

During the part inspection, the probe of the CMM is positioned relative to the features of the workpart. Once the probe is positioned, its location can be accurately and precisely recorded to obtain dimensional data concerning the part geometry.

Most of the CMMs are driven by computer programs, which can be developed on-line or off-line. These programs can be developed to collect timely and cost effective measurement information as well as to make decisions regarding part acceptance or rejection. Measured data can be analyzed immediately while the part is still on the worktable. This analyzed information can be used to provide feedback to CNC machines to reduce manufacturing defects and hence can result in improved productivity. Analyzed data can also be used to provide feedback to the part designers to suggest and implement any design improvements. CMMs have improved the quality and reliability of the measurement data, and have reduced the inspection time and accuracy by as much as 80%.

2.1   CMM Construction

In the construction of a CMM, the probe is fastened to a structure that allows movement of a probe relative to the part. A worktable, usually connected to the structure of the machine is used to locate a part. There are several different physical configurations for achieving the motion of the probe. Following are some of the common construction types of the CMMs.

- **Cantilever Construction**

    In the cantilever configuration, the probe is attached to a vertical quill that moves in a z-axis direction relative to a horizontal arm that overhangs the worktable. The quill can also be moved along the length of the arm to achieve the y-axis motion, and the arm can be moved relative to the worktable to achieve x-axis motion. This construction requires a relatively small floor space and provides a convenient access to the worktable. However, it has a lower rigidity as compared to some other CMM construction.

- **Bridge Construction**

    The bridge configuration is the most common type of configuration used in the industry. Instead of cantilevered arm to achieve the y-axis movement of the probe, the arm is supported on both ends like a bridge. This type of construction provides greater inherent rigidity. This makes the bridge construction more accurate than the cantilevered CMM.

- **Column Construction**

    This type of CMM construction is similar to the construction of a machine tool. Instead of achieving the motion exclusively by moving the probe relative to the worktable, the column-type CMM obtains the x-axis and y-axis relative motion by moving the worktable. the probe quill is moved vertically along a rigid column to obtain the z-axis motion.

- **Gantry construction**

  This construction is generally intended for inspecting large objects. The x-axis and y-axis motions are achieved by a construction similar to a gantry crane. The probe quill (z-axis) moves relative to the horizontal arm extending between the two rails of the gantry.

  Special design features are used in all the above constructions to build the high accuracy and precision into the frame. These features include low-friction air bearings, installation mountings to isolate the CMM and reduce vibrations in the factory from being transmitted through the floor, and various schemes to counterbalance the overhanging arm in the case of the cantilever construction.

  One of the most important aspect in the design of a CMM is the probe. Now-a-days, *touch-trigger* probes are most commonly used. This type of probe use a highly sensitive electrical contact device that emits a signal when the end of the probe is deflected from its neutral position in the slightest amount. As soon as the contact is achieved, the coordinate position of the probe are recorded by the CMM controller. Any limited overtravel of the probe quill due to momentum is neglected by the CMM. After the probe has been separated from the contact surface, it returns to the neutral position.

2.2   CMM Operation and Programming

Either of the manual or computer control method can be used to achieve the probe position relative to the part. Following are the frequently used methods of operating and controlling a coordinate measuring machine:

- **Manual Control Method**

  In this method, the human operator physically moves the probe along the machine's axes to make contact with the part and record the measurements. To permit the easy movement of the probe, it is designed in such a way that it can float freely along the

coordinate axes. The measurements are provided on a digital readout. Any calculations on the data must be made by the operator.

- **Manual Computer-Assisted**

This method provides some level of computer data processing and computational capability for performing data calculations. The types of data processing and computations range from simple conversions between different units of measurement to more complicated geometry calculations. The probe is still free-floating to permit the operator to bring it into contact with the desired part surface.

- **Motorized Computer-Assisted**

In this method, a motor drive is used to power the probe along the machine axes under the operator's guidance. Typically, a joystick or similar device is used to control the motion. To reduce the effects of collisions between the probe and the part, features such as low-power stepping motors or friction clutches are utilized. It is also possible to disengage the motor drive to permit the operator to physically move the probe as in the manual control method.

- **Direct Computer Control**

The direct computer control CMM operates like CNC machine tool. It is motorized and computer is used to control the movement of the probe along the coordinate axes. The computer also performs various data-processing and calculation functions. It also compiles a record of the measurement made during inspection for reporting. The direct computer-controlled CMM is a highly automated inspection machine that operates under program control.

There are mainly two methods of programming the direct computer-controlled CMM. In the first method, a program is developed by a manual leadthrough method. While in the learn mode, the operator leads the CMM probe through various motions, indicating the points and surfaces that are to be measured. This information is recorded in

a program format into the control memory and during regular operations, this program is played back to complete the inspection operations.

In the second method, a program is developed in a conventional method of NC part programming. The program is developed off-line and then downloaded to the CMM controller for execution. The programming statements for a computer-controlled CMM include motion commands, measurement commands and report formatting commands. The motion commands are used for directing the probe to a desired inspection location. The measurements commands are used to control the measurement and inspection functions of the machine. The formatting statements used to document the results of the inspection operations.

2.3   CMM Measurement Capabilities

The basic measurement of the coordinate measuring machine is the definition of the x-axes, y-axes, and z-axes coordinate values where the contact is made with the surface of a workpart. Direct computer-controlled CMMs provides much more sophisticated measurements and inspection capabilities. Following are some of these measuring capabilities [Ref. 4] :

- Dimensions: A dimension of a part can be obtained by taking the difference between the two surfaces defining the dimension.

- Hole location and diameter: By measuring three or more points along the surface of a circular hole , the best-fit center coordinates of the hole and its diameter can be obtained.

- Cylinder axis and diameter: This is similar to above except that the calculations deals with an outside surface rather than an internal surface.

- Sphere center and diameter: By measuring four or more points on the surface of a sphere, the best-fit center coordinates and the diameter can be determined.

- definition of a plane: Based on a minimum of a three contact points on the a plane surface, the best-fit plane is determined.

- Flatness: By measuring more than three contact points on a plane surface, the deviation of the surface from a perfect plane can be determined.

- Angle between two planes: The angle between two planes can be determined by defining each of two planes using the plane definition method and calculating the angle between them.

- Parallelism between two planes: The above function can be used to determine parallelism between two planes. If the angle between two planes is zero, the planes are parallel. The degree to which the planes deviate from parallelism can be determined.

- Angle and point of intersection between two lines: Given two lines known to intersect, the point of intersection and the angle between the lines can be determined based on two points measured for each line.

2.4   CMM Benefits

The direct computer controlled coordinate measuring machines have number of advantages over the manual inspection methods. Some of the benefits resulting from using the CMMs are:

- **Productivity:** Because of the automated techniques included in the operation of a CMM, inspection procedures are speeded and labor productivity is improved. A direct computer-controlled CMM is capable of accomplishing many of the measurement task listed in the above section in one-tenth of the time needed for manual inspection.

- **Flexibility:** A CMM is a flexible and general-purpose machine which can be utilized for inspection of a variety of different part configurations with minimal changeover

time. On direct-computer controlled CMMs, where the programming is performed off-line, the changeover time only involves making the physical setup.

- **Reduced Operator Error:** Because of the automation in the inspection procedure, the human errors in measurement and setups are reduced.

- **Greater Inherent Accuracy and Precision:** A coordinate measuring machine is inherently more accurate and precise than the manual surface plate method of inspection traditionally used.

CHAPTER 3

INITIAL GRAPHICS EXCHANGE SPECIFICATIONS

Initial Graphics Exchange Specifications (IGES) is the standard exchange format developed to address the concept of product data communication among dissimilar CAD/CAM systems [Ref. 10]. Mainly, IGES has been used in the industry for dual purpose: transfer of modeling data within corporate dissimilar systems and digital communications between the company and its suppliers and customers.

IGES defines a neutral database, in the form of a file format, which describes an IGES model of modeling data for a given product. Since, the IGES model can be read and interpreted by dissimilar CAD/CAM systems, the corresponding data can be exchanged among these systems. IGES describes the possible information entities to be used in building an IGES model, the necessary parameters for the definition of model entities, and the possible relationships and associativities between model entities.

The fundamental unit of information in the IGES model and file is an *entity*. All product definition data are expressed as a list of predefined entities with a specific entity type number. Entity number 1 through 599 and 700 to 5000 are allocated for specific assignments. Entity type numbers 600 through 699 and 10,000 through 99,999 are for implementor-defined entities. These entities enable IGES to act as an archiving format where both the sending system and receiving system use the same format.

3.1   Data Representation

IGES has an information structure to describe geometric models. This structure is very similar to the one found in a typical CAD/CAM system. It consists of drawing entities, view entities and property entities. It also describes an information structure for the cross-reference between model entities which is useful in surface representation. With the

information structure of the geometric models captured, the remainder of the data representations consists primarily of specifying the data and parameters of typical geometric entities such as curves, surfaces, and solids, and nongeometric entities such as annotation.

3.1.1 Geometry

IGES uses model coordinate system (MCS) and working coordinate system (WCS) to represent geometric entity types. The MCS defines the model space and WCS defines the working space. The WCS plays a simplifying role in representing planner entities. In such a case, the XY plane of the WCS is taken as the entity plane and therefore only x and y coordinates relative to the WCS are needed to represent the entity. To complete the representation, a transformation matrix is assigned to the entity as one of its parameters to map its description from WCS to MCS. This matrix is defined as entity type 124. Each entity type in IGES has such a matrix. If an entity is directly described relative to the MCS, then no transformation is required and the value of the matrix pointer is set to zero to avoid unnecessary processing.

In IGES, entity numbers 100 to 199 inclusive are reserved for its geometric entities. There is no real scheme in entity number assignment expect that they are even number with the exception of entity type number 125. Entity numbers assigned to various geometric models are shown in table 3.1 on the following page.

Each entity in IGES has two main types of data: directory data and parameter data. Directory data is the entity type number and parameter data is the parameters needed to uniquely and completely define the data. In addition, other parameters related to entity attributes and to the IGES file structure are also specified.

Table: 3.1 IGES Geometric Entity Types

Modeling Type	Entities										
Solids	150 Block	152 Right Angular Wedge	154 Right Circular Cylinder	156 Right Circular cone	158 Sphere	160 Torus	162 Solid of Revolution	164 Solid of Linear Extrusion	168 Ellipse	180 Boolean Tree	184 Solid Assembly
Surfaces	108 Plane	114 Parametric Spline Surface	118 Ruled Surface	120 Surface of Revolution	122 Tabulated Cylinder	128 B-spline Surface	140 Offset Surface	144 Trimmed Surface			
Curves	100 Circular Arc	102 Composite Curve	104 Conic Arc	110 Line	112 Spline Curve	116 Point	126 B-Spline Curve	130 Offset Curve			
Others	106 Copious Data	124 Trans. Matrix	125 Flash	132 Node	134 Finite Element	136 Connect Point	138 Nodal Display and Rotation	146 Nodal Results	148 Element Results		

3.1.2 Annotation

IGES uses annotation entities to represent drafting data. Table 3.2 shows various IGES annotation entities.

Table 3.2 IGES Annotation Entity Types

Entity Type Number	Entity Type
106	Copious Data
202	Angular Dimension
206	Diameter Dimension
208	Flag Note
210	General Label
212	General Note
214	Leader (arrow)
216	Linear dimension
218	Ordinate dimension
220	Point dimension
222	Radius dimension
228	General symbol
230	Sectioned area

Many IGES entities are constructed by using other basic entities that IGES defines such as copious data, witness line, leader (arrow), and a general note via pointers. In association with a given drawing, an annotation entity may be defined in definition space or in two-dimensional space. If a dimension is inserted by the user in the model mode, then a transportation matrix pointer is required when translated into IGES.

3.1.3 Structure

IGES permits a valuable set of product information, besides geometric and annotation information, to be represented via its structure entities. These entities include associativity, drawing, view, external reference, property, subfigure, macro, and attribute entities. Information about line fonts, text fonts, and color definition is included in the attribute entities. Table 3.3 on the following page shows IGES structures entities.

The associativity definition entity (number 302) defines a special relationship between various entities of a given model. The external reference entity (number 416) provides a link between an entity in one file and the definition or a logically related entity in another file. The property entity (number 406) contains numerical and textual data. The MACRO capability in IGES (number 306) allows the family of parts and/or entities grouped by the user for special purpose, which is a common practice on existing CAD/CAM systems to be exchanged. A MACRO entity can be defined only once in an IGES file but can be referenced as many times in the file as required by using the MACRO instance entity (number 600 to 699 or 10,000 to 99,999).

3.2   File Structure and Format

An IGES file is a sequential file which consists of a sequence of records. Depending upon the chosen file format, the record length of the file can be fixed or variable. There are two different formats to represent the IGES data in a file: ASCII format and Binary format. The ASCII form has two format types: a fixed 80-character record length format and a compressed format. In the fixed record length format, the entire file is of 80-character records and divided into sections. Within each section, the records are labeled and numbered. IGES data is written in columns 1 through 72 inclusive of each record. Column 73 stores the section identification character. Column 74 through 80 are specified for the section sequence number of each record. The binary file format is a bit stream binary representation of data.

Table 3.3 IGES Structure Entity Types

Entity Type Number	Entity Type
302	Associativity definition entity
304	Line font definition entity
306	MACRO definition entity
308	Subfigure definition entity
310	Text font definition entity
312	Text display template
314	Color definition
320	Network subfigure definition
402	Associativity instance entity
404	Drawing entity
406	Property entity
408	Singular subfigure instance entity
410	View entity
412	Rectangular array subfigure instance entity
414	Circular array subfigure instance entity
416	External reference
418	Nodal load/constraint
420	Network subfigure instance
600-699 or 10,000-99,999	MACRO instance entity

As shown in figure 3.1 on the following page, there are six section in an IGES file. These sections must appear in the following order: Flag section (optional), Start section, Global section, Directory entry (DE) section, Parameter data (PD) section, and Terminate

section. The identification character or the section codes for these sections respectively are S, G, D, P, and T (excluding the flag section). This character appears in column 73 of each record.

Flag section (optional)
Start section
Global section
Directory Entry section
Parameter Data section
Terminate section
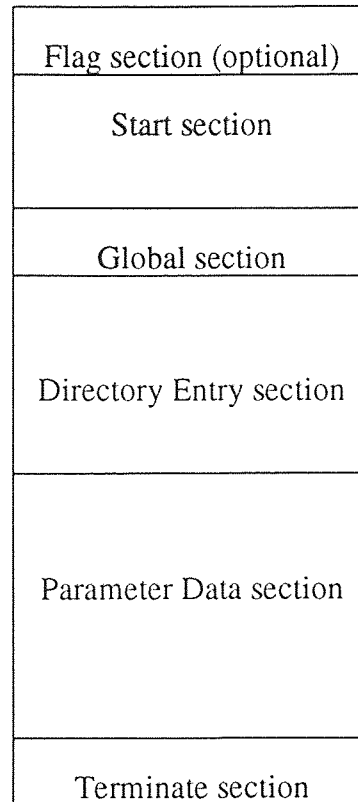
Figure 3.1 IGES File General Structure

- **Flag section**: This section is used only with compressed ASCII and binary format and contains a character C in column 73 to identify the file as compressed ASCII. In binary format, the Flag section is called the Binary information section and the first byte (8 bits) of this section has the ASCII letter B as the identifier.

- **Start section**: This section is a human-readable introduction to the file. It might contain names of the sending and receiving system, a brief description of the product being converted, and some other useful comments. IGES does not specify how this section could be used.

- **Global section**: It includes information describing the preprocessor and information needed by the postprocessor to interpret the file. Some of the parameters that are specified in this section are IGES file name, date and time of generation, model space scale, model units, and vendor and software version of sending system.

- **DE section**: It is a list of all the entities defined in the IGES file together with certain attributes associated with them. Each entity has two 80-character records divided into a total of twenty 8-character fields. The first and eleventh fields contain the entity type number. The second field contains a pointer to the parameter data entry for the entity in the PD section. Information about line font, layer number, transformation matrix, line weight and color is specified as entity attributes in this section.

- **PD section**: It contains the actual data defining each entity listed in the PE section. The number of records needed in each entity in this section varies from one entity to another and depends on the amount of data. Parameter data are placed in free format in columns 1 through 64. The parameter delimiter (usually a comma) is used to separate parameters and the record delimiter (usually a semicolon) is used to terminate the list of parameters. Column 65 is left blank and column 66 through 72 contain the entity pointer specified in the first record of the entity in the DE section.

- **Terminate section**: It contains a single record which specifies the number of records in each of the four preceding sections. The information obtained from this section can be used for cross reference.

The compressed ASCII and binary formats are used to take care of high proportion of the space characters in the ASCII format which may increase the field size significantly. In the compressed ASCII format, the Start, Global, and Terminate sections remain the same as the ASCII form, while the DE and the PD sections are combined into a single Data section. Each record is of variable length to eliminate storing space characters. The binary file format is a bit stream binary representation of data.

A sample of an IGES file is shown in the Appendix.

3.3   Processors

While reading an IGES file, its format must be interpreted, understood, and implemented by a program. This program is called a processor or translator. These processors should provide:

- Translation algorithms between the IGES formats of entities and their formats within specific CAD/CAM systems.

- Read and write routines to access entities stored in IGES files and in the database used by the specific CAD/CAM systems.

Development of a processor has four main components: Design, Implementation, Testing and Verification, and Error Handling.

3.3.1 Design

IGES reduces the database exchange problem to the design of two processors: a preprocessor to map the source database into an IGES file and a postprocessor to map the IGES file to the target processor. A typical database might contain many instances of many types, making the design problem very difficult. Further, many of these entity types involve complex mathematics and complex data structure. A typical IGES processor design process contain following steps.

1. Analyze and tabulate entity characteristics. This requires the study of entity mathematical representations utilized by both IGES and the CAD/CAM system.

2. Define conversion algorithms to convert entities to and from IGES.

3. Develop a complete specification of the processors. This includes the IGES version to be supported, the subset of IGES entities to be supported, and the user interface of the processor.

4. Design verification procedure. IGES processor must be verified by constructing test data, running it through the processors, and comparing the actual results with those expected.

3.3.2 Implementation

In IGES processor implementation, there are two options: implement a full set of IGES entities into the processor or just implement a subset of entities. The first options is preferable over the second. However, in many processors, only a subset of IGES entities that is easiest to understand are implemented.

3.3.3 Testing and Verification

A newly developed IGES processor must be carefully tested before it is used in a production environment. There is an IGES Test, Evaluate, and Support Committee whose function is to provide test data. This committee maintains a library which allows testing of the basic implementation of an entity. This library does not allow variations to be checked that occur in production data due to numerical and computational errors. These variations must be tested by implementors and users themselves.

3.3.4 Error Handling

While processing an IGES file, errors may come from two main sources: program errors in the processor and misinterpretation of the IGES standards itself. These errors should be reported appropriately for correction. The preprocessor should report the entity type, number of uncompressed entries, reasons for unprocessing, and other relevant database information. The postprocessor should report the number of unprocessed entities, their types, their forms, their record numbers in the DE and PD sections, and the reasons for unprocessing. Any invalid or missing data encountered in reading IGES files should also be reported.

CHAPTER 4

ADVANCED VALIDATOR INTERFACE LANGUAGE (AVAIL)

Advanced Validator Interface Language (AVAIL) is an English-like language used to execute various measurements commands on a CMM. As shown in the following figure 4.1, AVAIL follows a set of predefined measurement instructions in a program format to produce measurement reports of the part to be measured.

PART TO BE MEASURED

AVAIL
MEASUREMENT
PROGRAM

MEASUREMENT
REPORT

MEASUREMENT
INSTRUCTIONS
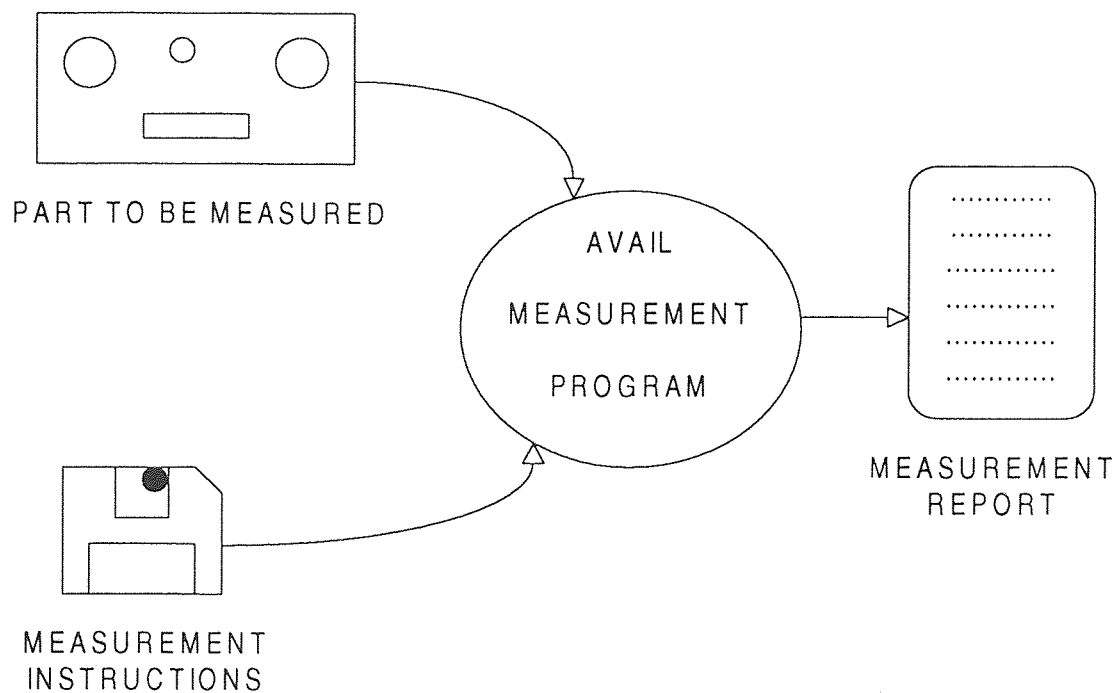
Figure 4.1 AVAIL Operational Structure

AVAIL supports both the beginner and the advanced users. The beginners are guided through a series of menus in order to select the desired measurement instructions and the advanced users can type the measurement instructions directly from the keyboard.

4.1   Operational Modes

AVAIL supports the following Operational Modes:

- Learn Mode: The learn mode is used to create the measurement instructions for the part to be measured. Users use the AVAIL menus to create a permanent list of measurement instructions to be associated with the current part. This list of instruction is saved in the current part folder in a file named llf (learn list file).

- Execute Mode: The execute mode is used to measure previously learned parts. The llf file generated during the learn mode can be executed for any number of parts of the same family.

- Inspect Mode: The inspect mode is used just to check a few dimensions of a part manually. The inspect mode produces the measurement reports, but does not save the measurement instructions.

- Append Mode: The append mode allows for the continuation of the learn mode on a different session. It uses the partially learned llf to add instructions.

- Mixing Modes: A powerful feature of AVAIL is the mixing of various modes. It is possible to jump between Learn, Execute, and Edit modes, all in the same session. User can start the learn mode and jump to edit mode. While in the edit mode, user can make modifications to the program, execute the new changes, and then continue with the learn mode.

4.2   AVAIL Command Structure

AVAIL uses an English-like language as the programming language. The syntax of the AVAIL program statement is as follows [Ref. 1] :

LABEL = COMMAND/OPTION; ARGUMENT LIST

- **Label**: The label must from one to ten characters. It is used as a feature name or as a marker name. Every element measured or constructed by AVAIL is assigned a

feature name. It is also possible to assign a marker in the program and jump to the name of that marker.

- **Command**: The command specifies the measurement instruction to be performed or some other function. The commands are grouped as follows: Measurements, Positioning, Alignment, Orientation, Qualification, Mathematics, Machine, Output, Branching, and End. Under each group there are various types of commands. Commands must be specified with at least the first four characters.

- **Option**: The option describes the specific function of the command. There are some commands that do not have an option.

- **Argument List**: The argument list provides the arguments needed for the selected COMMAND/OPTION. The number of arguments is dependent on the COMMAND/OPTION selected.

- **Delimiters**: Delimiters separate the different fields of the command structure. The equal sign (=) separates the label from the command; the slash (/) separates the command from the option, the semi-colon (;) separates the option from the argument list and the comma (,) separates the arguments within the argument list. All program statements have at least a slash and a semi-colon.

4.3   AVAIL Probe Tip Qualification

The procedure of entering information about *probe tip* into the computer before taking any measurement is known as Tip Qualification. Probe tip qualification tells the computer the probe diameter, location, and the angle of the PH9 probe wrist. The computer then compensates for this information when measuring parts. Qualification procedure is necessary before executing any AVAIL part program.

Before qualifying the probe tips, it should be decided how to measure the part, how to place the part on the table, and how to position the probe. Once various positions

necessary for the probe are decided, tip must be qualified in each of those positions. All this information goes into a qualification file stored in the computer.

Qualification can also be done through an AVAIL part program using *Qualify* command. Following are the various options available to this command.

- Qualify/Change: This option allows the programmer to specify a certain value to be stored as the probe diameter with a given tip. It may be desirable to use a ring gauge or a go-block to determine a custom probe diameter for a given application.

- Qualify/New_Tip: This option is used to qualify a new tip for the first time. This option causes the tip calibration data to be calculated.

- Qualify/Old_Tip: This option recalls a tip that has been previously qualified.

- Qualify/Recall: This option recalls a previously stored qualification file. A qualification file can store upto 500 tips. The file must be recalled before an Old_Tip can be recalled for use.

- Qualify/Save: This option is used to save the current qualified tip data into a specified file name. This option should be selected before exiting a QUAL program.

4.3   AVAIL Command Summary

4.3.1   Alignment Commands

Alignment is a process of relating the XYZ coordinates of a part to the XYZ coordinates of the machine. The machine coordinate system is the set of X, Y, and Z axes that are parallel to the rails of a coordinate measuring machine. The origin (0,0,0 point) of the machine is placed at the position of the probe holder when the machine is homed. This is the end of the Z-axis rail for vertical machines, and the center of the cube head for horizontal arm machines.

Every part has an X, Y, and Z axis, just like a CMM. The operator establishes the coordinate system of the part and its origin in order to measure a specific part feature in

relation to the part's origin. The axes of the part must be related to the axes of the CMM before the actual measurement of the part can begin.

To automatically relate the axes of the workpart to those of the CMM, AVAIL requires users to specify three part features: a plane feature, a plane or line feature and another plane feature. These features are used to determine the part's axes and its point of origin. AVAIL cannot align the part if these features are not measured first.

AVAIL has seven alignment options which are discussed below:

- Alignment/Disable: This option temporarily removes the current part alignment and uses machine coordinates.

- Alignment/Enable: This option puts back into effect a part alignment that was temporarily disabled by the Disable option.

- Alignment/Part: This option must be included in every part program. By this option, user can supply the information the computer needs to realign the part's axes to those of the machine. The point of origin can also determined by the information entered for alignment.

- Alignment/Recall: This option brings back a saved alignment to reuse in the part program.

- Alignment/Rotate: This option rotates a part's alignment by rotating two of the axes around the third by an angle or angle feature. It is possible to rotate by a specified angle in any of the three planes: XY, YZ, or ZX. All features then measured will relate to the rotated axes. The positive rotation is from the reference plane's major axis to its minor axis.

- Alignment/Save: This option names and saves a part alignment. If the part program uses more than one alignment, this option will save the first alignment.

- Alignment/Translate: This option moves the point of origin to another location. Point of origin can be transferred three ways: by feature, by coordinate value, by both

feature and coordinate value. Features which were measured before the translation will report new results based on the translated point of origin.

4.3.2 Automatic Commands

AVAIL has five automatic feature commands to perform the measurement automatically. In these automatic commands, user can specify the starting and ending angle for hit placement as well as the number of hits. During execution, AVAIL will compute the placement of the hits based on the starting and ending angle and the number of hits specified. All automatic commands must be followed by a 'DONE/;' command. Various automatic options are discussed below:

- Automatic/Circle: This option measures circles automatically. Automatic circles are measured with 3 to 100 points equally spaced around the circle. By using the starting and ending angle feature, partial circles can be measured. This option also includes two automatic positional moves. AVAIL will first move the probe tip from its last position along the reference plane to the circle location, and then down into the circle, ready to measure the first point.

    Example:

    CIR1 = AUTO/CIR; XYPL, IS, 4, 8, 1, -0.05, 1, 0, 360

- Automatic/Cone: This option measures cones automatically. Automatic cones are measured with 6 to 100 points on the surface of the cone. This option also includes two automatic positional moves. AVAIL will first move its probe tip from its last position perpendicular to the cone axis, then to the prehit location, ready to measure the first point.

    Example:

    CONE1 = AUTO/CONE; IS, 6, 8, 1, -0.05, 1, 8, 1, -2.5, 2, 0, 360

- Automatic/Cylinder: This option measures cylinders automatically. Automatic cylinders are measured with 5 to 100 points on the surface of the cylinder. This

option also includes two automatic positional moves. AVAIL will first move the probe tip from its last position perpendicular to the cylinder axis, then to prehit location, ready to measure the first point.

Example:

CYL1 = AUTO/CYL; IS, 6, 8, 1, -0.05, 1, 8, 1, -2.5, 0, 360

4.3.3 Calculation Commands

The calculation command allow the user to perform mathematical computations using numeric values or previously measured features. Following are the various calculation options available: Calculation commands requires that the features used in the commands have preassigned names. Discussed below are some of the calculation commands used by the AVAIL program:

- Calculation/Add: This option adds together feature variables or numeric data. This option can be used to calculate a measurement that cannot be measured directly.

  Example:

  DOWN.SC2 = CALCULATION/ADD; PROBE.SC2, 0.05

- Calculation/Copy: This option copies previously measured feature variables, or numeric data, into another feature name. This new feature is then created from the variables of other features. If the feature is created new, the feature type may also have to be copied into the new feature so AVAIL knows what kind of the feature was created.

  Example:

  CIR1.SC2 = CALCULATION/COPY; CIR4.SC2

- Calculation/Divide: This option divides the values of previously measured feature variable or numeric data.

  Example:

  HLF1 = CALCULATION/DIVIDE; DST1.SC2, 2

- Calculation/Multiply: This option multiplies the values of previously measured feature variables or numeric data.

    Example:

    HLF1 = CALCULATION/MULTIPLY; DST1.SC2, 0.5

- Calculation/Powerof: This option multiplies a number a specified number of times. The number can be a feature variable or data.

    · Example:

    SQR.SC1 = CALCULATION/POWEROF; CIR1.SC1, 2

- Calculation/Subtract: This option subtracts previously measured variables or numeric data.

    Example:

    DOWN.SC2 = CALCULATION/SUB; PROBE.SC2, 0.05

4.3.4 Endof Commands

These commands save the part program when a user is finished creating it, or end a subroutine or loop. In the learn mode, AVAIL will not allow the user to exit the mode if all the open loops and subroutines are not ended. Following are the various Endof options:

- Endof/Loop: This option specifies the end of a set of commands that are looped. Every LOOP/TIMES command must have an associated ENDOF/LOOP command.

- Endof/Program: This option ends any.AVAIL part program.

- Endof/Subroutine: This option ends an AVAIL subroutine. This command is required as a last command of a subroutine.

4.3.5 Geometric Elements

There are ten geometric elements in AVAIL - Point, 2D Line, 3D Line, Circle, Plane, Sphere, Cylinder, Cone, Qual Sphere and Set Point. All part features in a part program

can be defined with these elements. The features are either measured as geometric shape or separate features are combined into new geometric shapes. There are basically three modes available to measure geometric elements. In manual mode, the points are taken with the joystick box. In automatic nonvector mode, the points are learned automatically, but positional moves to and from the learned features are required. In automatic vector mode, the points are taken automatically without requiring positional moves.

Following are the various options available to this command:

- Geometric/Circle: This option is used to measures a circle. A circle is from 3 to 100 points measured on the surface of the circle. The center of the circle is assumed to be perpendicular to the reference plane. The circle result is the size and its location.

- Geometric/Cone: This option is used to measure a cone. Cones are measured by taking from 6 to 100 points on the surface of the cone. The XYZ point of a cone is at the apex. The cone results are the apex XYZ and the included angle.

- Geometric/Cylinder: This option is used to measure a cylinder. Cylinders are measured by taking from 5 to 100 points on the surface of the cylinder.. The cylinder results are its size and location. The location of the cylinder is its centroid.

- Geometric/Plane: This option is used to measure a plane. Planes are measured by taking 3 to 100 points on a surface. The location of the plane is its centroid.

- Geometric/Point: This option is used to measure a point on the part's surface. If more than one measurement is taken within a single point name, the result is an average of all points taken.

- Geometric/Qualsphere: This option is used to measure the reference sphere for qualification. Qualisphere is measured by taking from 4 to 100 points around the sphere.

- Geometric/Setpoint: This option is used to group a series of hits, or set of points, into one feature. This allows to measure several features of the part all at the same time and then go back and recall specific points for separate features.

- Geometric/Sphere: This option is used to measure a sphere. Spheres are measured by taking from 4 to 100 points around the sphere. The sphere result is its size and location.

- Geometric/2D Line: This option is used to measure a two-dimensional line that is automatically parallel to the reference plane. A 2D line contains from 2 to 100 points.

- Geometric/3D Line: This option is used to measure a three-dimensional line. A 3D line contains from 2 to 100 points.

4.3.5 Intersect Commands

These commands intersect two previously measured features to form a new feature. These commands are used when it is physically impossible to measure a feature or when it is faster to compute a feature than to measure it. Following are the options available to intersect commands:

- Intersect/Bore: This option uses the center lines from two cylinders to compute the intersection point, the distance between the center lines and the angle between the center lines. The center lines can be cylinder axes or line features that have any orientation to the reference plane.

  Example:

  INT1 = INTERSECT/BORE; CYL1, CYL2

- Intersect/Circle: This option creates a circle from the intersection of a plane and another feature. This other feature can be a cone, cylinder, or sphere. The point location is where the two features intersect.

  Example:

  INT1 = INTERSECT/CIRCLE; PLN1, CYL1

- Intersect/Point: This option creates a point from the intersection of two features. These features can be lines, circles, or planes. If two features do not cross because of

their difference in depth, the XYZ location would be placed halfway between the two features.

Example:

INT1 = INTERSECT/POINT; LINE1, LINE2

• Intersect/Line: This option creates a line from two planes. The direction of the line is determined by the right hand rule - i.e. palm on the first plane, fingers on second, and the thumb points in the direction of the line.

Example:

INT1 = INTERSECT/LINE; PLN1, PLN2

4.3.7 Loop Command

This command is used for repeated execution of a section of the part program. Loops can also be nested inside the other loops upto four times. Loops can be used to inspect a large number of parts without starting the program again, or to easily inspect repetitious or symmetrical features of a part. In the AVAIL program, loops commands are placed directly before the commands that are to be looped. An Endof/Loop command must also be included in the part program to end the loop. Each loop can be executed a maximum of 500 times.

4.3.8 Move Commands

These commands are used to move the probe to a specified location or by a specified distance. The Move/By option moves the probe from its current position by a specified distance, and the Move/To option moves the probe to a certain location by specifying coordinate values or a feature name.

Examples:

MOVE/BY; 4, 0, 0

MOVE/TO, 0, 0, 0

4.3.9   Output Commands

These commands control the format of the measurement output and the sending of measurement results to a specified device. Following are the various output command options:

- Output/Device: This option determines the device to which the part program output should go. The available devices are disk, spool, printer, and file name. For disk, the output is written to a time-tagged file under the current part directory. For spool, the output is written to a temporary file that is deleted after execution of the program. For printer, the data is directed to a line printer fir printing. For file name, the data is written to a file as for disk, but the programmer enters a data storage name and the part program results are overwritten with each execution.

   Example:

   OUTPUT/DEVICE; part1.out

- Output/Print: This option is used with the Output/Device option to print the part program results. This option should be entered at the appropriate place in the program when the output should be sent to the printer.

- Output/User_Form: This option is used to create the output display in the user specified custom format The file name containing the print format must be specified to this option. This file can be created by providing such information as the order of printing, number of decimal places, variables, tabulation and special characters.

   Example:

   OUTPUT/USER_FORM; smpl.fmt

4.3.10 Print Option Commands

These commands control the content and format of the part program output. Following are the various options available to this command:

- Print_Option/Axes: This option permits the user to select which of the features of the element to be reported in the succeeding measurements, reports or calculations.

    Example:

    PRINT_OPTION/AXES; XYZD

- Print_Option/Format: This option permits the user to select the type of reporting to be done. The possible formats are Measured, Full, Out_Tol, User, and None.

    Example:

    PRINT_OPTION/FORMAT; MEASURED

4.3.11 Text Commands

These commands permits programmers to write messages, instructions or reminders to the operator on the computer screen, the printer, or both. They also allows programmers to create menus and report the status of variables as the program is executing. When entering the text, a carriage return with no data typed will exit the Text Mode.

    Example:

    TEXT/DISPLAY; {

    ********   Please Move the Probe Above the Part   ********

    }

CHAPTER 5

SOFTWARE

The primary purpose of the software is to provide an interactive graphical environment for on-the-screen simulation of the part measurement activities of the Coordinate Measuring Machine and generate an AVAIL inspection part program. It was developed in C language using HOOPS (Hierarchical Object Oriented Picture System) library. It runs on a UNIX based computers supporting X Window systems. The software is designed with a modular approach and its flow is controlled by various menus [Ref. 2]. Menu options can be selected by clicking the mouse button while positioning its pointer on the required menu button. When activated, each menu option will present a submenu with series of suboptions or prompt the user with appropriate questions. Help messages are displayed, when necessary, for easy user interaction.

5.1   Software Organization

This software provides an interface link between CAD software systems and Coordinate Measuring Machines. It reads the part design created by the CAD software, displays the part on the screen, allows user to identify the entities to be measured and generates a CMM inspection part program in AVAIL language. This part program can be downloaded on the CMM for execution to perform physical inspection. The software also reads back the output produced by the execution of the part program and performs analysis of this output. The part can be redisplayed on the screen with measured values obtained from the output. A tabular report can be generated listing the designed and measured coordinate values of the entities selected for measurement. Figure 5.1 on the following page shows the organization of the software.

34

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                    ·│   IG E S     │                              ·  O
                    ·│  Processor   │                              ·  F
                    ·└──────────────┘                              ·  T
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                    ·      ▽                                       ·  A
                    ·╭──────────────╮                              ·  R
                    ·│   D ata      │                              ·  E
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      ╭──────────────╮   │                                        ·
      │   C M M      │   ▽            ┌──────────────┐            ·
      │ O utput File │→─│ User         │ Output       │          ·
      ╰──────────────╯  │ Inte rface   │ Analysis Report │       ·
            △     ·      └──────────────┘                        ·
            │     ·      │                                       ·
      ┌──────────────┐   ▽            ╭──────────────╮          ·
      │   C M M      │←──│ A VA IL Part │                        ·
      │              │   │ P rogram     │                        ·
      └──────────────┘   ╰──────────────╯                        ·
                    - - - - - - - - - - - - - - - - - - - - - - -
```
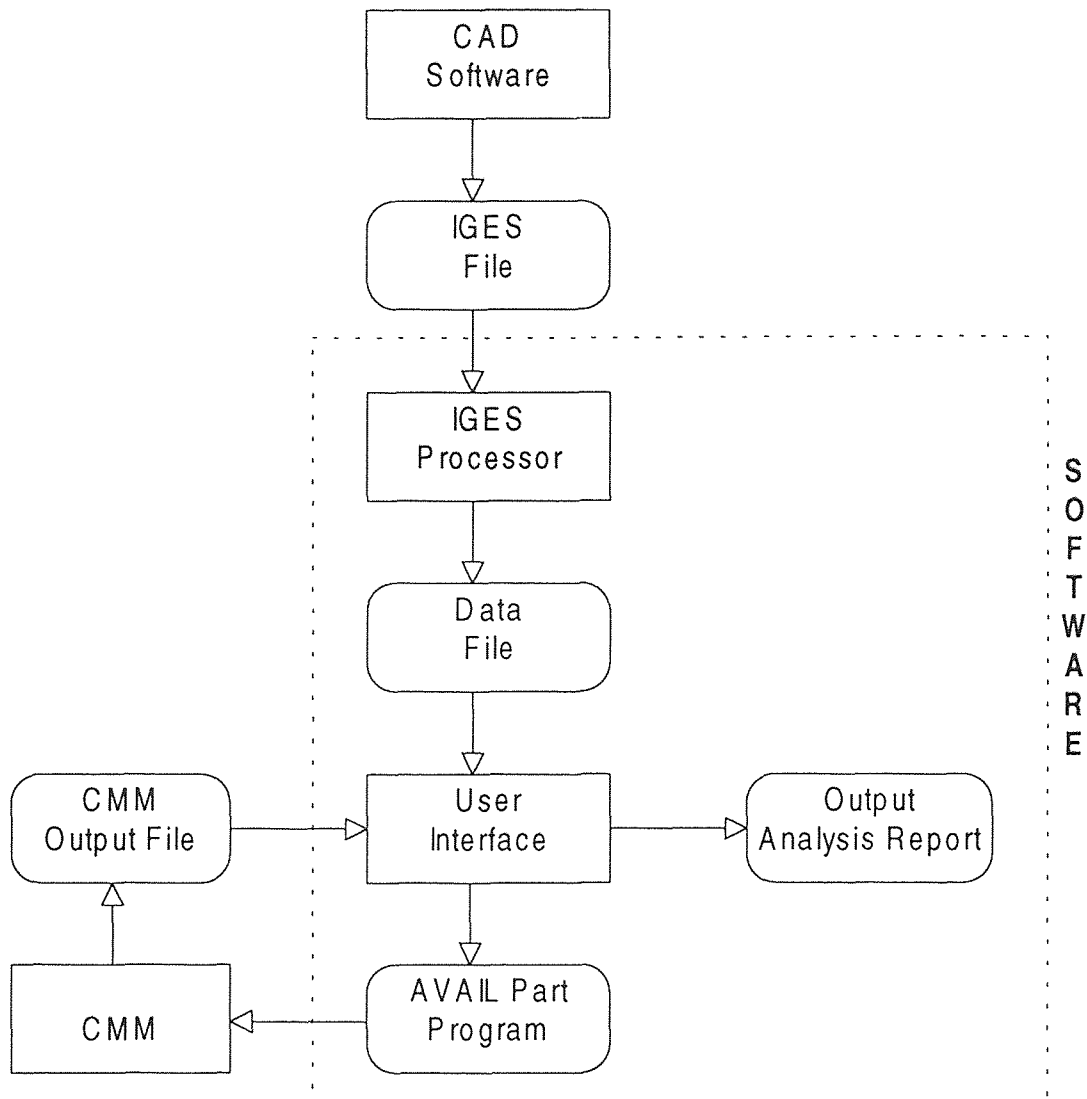
Figure 5.1 Software Organization

5.2   IGES Processor

Most of the commercially available CAD software systems allows writing design database information to an ascii file in IGES format. Once the part is designed in the CAD software, such an ascii file in the IGES format can be prepared by selecting appropriate options. The IGES processor of the software is designed to read this file and interpret the information to generate the part geometry on the screen. Conversion algorithms were designed and coded to map the IGES file entities into the software

database. After conversion, the processor will generate '.dat' file with groups of entities, their corresponding coordinate values, and other pertinent information. The part geometry is constructed from this file.

A sample of IGES file generated by the Pro-Engineer CAD software system and the converted '.dat' file are shown in the Appendix.

5.3   Screen and Menu Organization

The user interface screen is organized into four major components as shown below in figure 5.2.
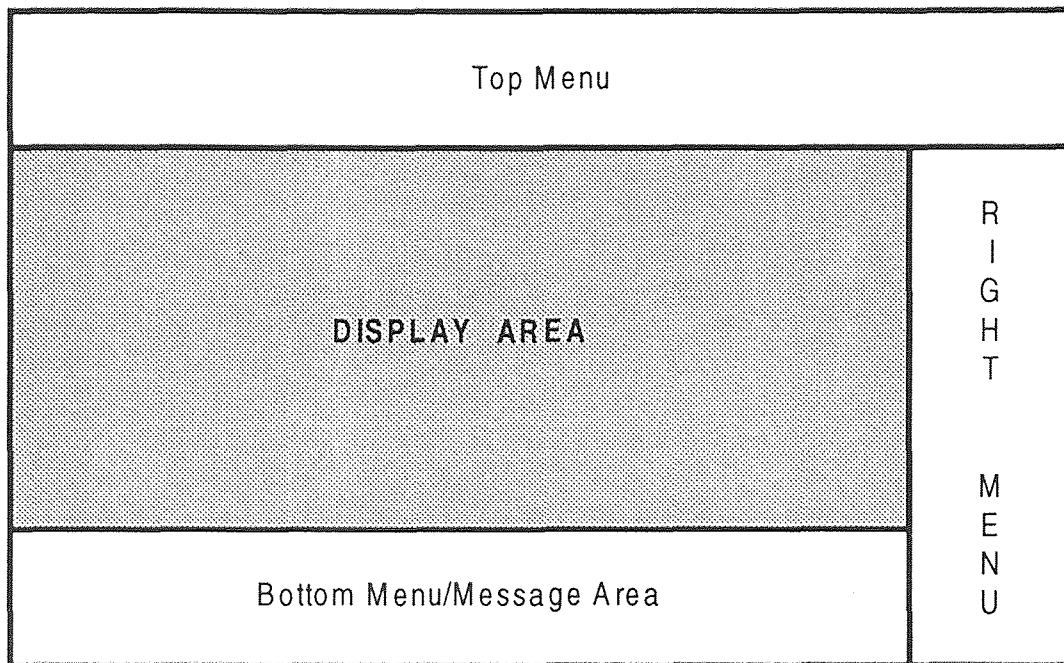
Figure 5.2 User Interface Screen

5.3.1 Display Area

The display area of the screen is used to display the part geometry on the screen once the IGES processor interprets the CAD software part design information. Once the part is

displayed, its orientation can be changed by rotating the object about X, Y, or Z axis. The part can be magnified or decreased in size. Planes can be constructed and shades can be applied. After desired orientation is achieved, users can identify various entities to be measured and included in the AVAIL part program by clicking the mouse button while mouse pointer is on the specific entity. After user is done identifying required entities, CMM measurement activities can be simulated. This area is also used to display the measurement output report generated from the results brought back from the actual execution of the part program on the CMM.

5.3.2   Right Menu

The organization of the right menu is shown in figure 5.3.
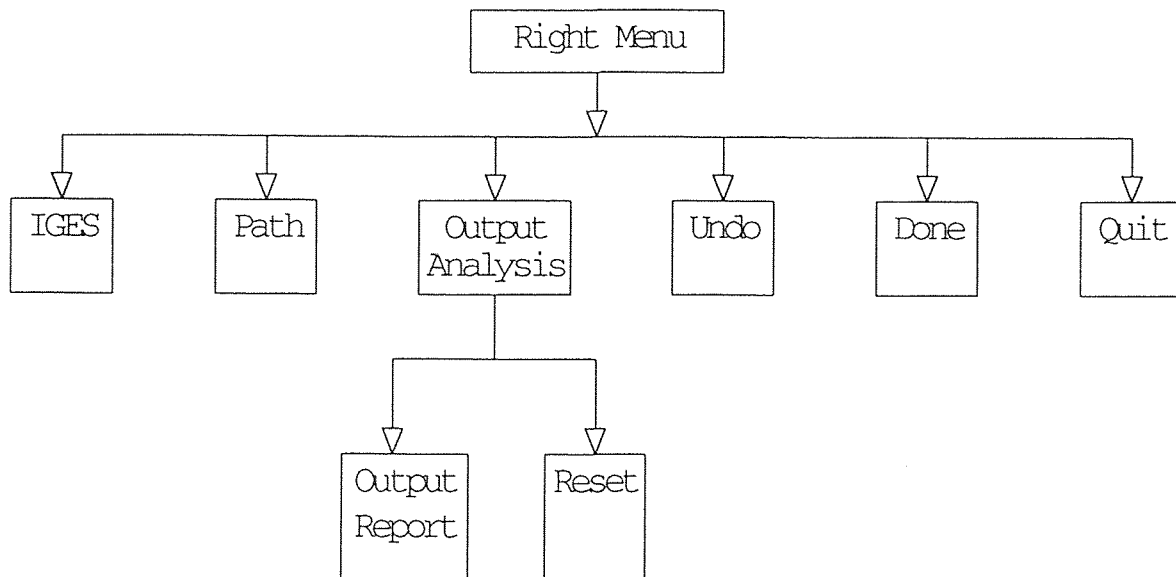
Figure 5.3 Right Menu Organization

- IGES: This option of the menu prompts the user to enter the name of the IGES file containing the part design information written by the CAD software system. Once the file name is verified, it invokes the IGES processor to do necessary conversion. A

converted file is created with the same name of the IGES file, but with '.dat' extension. After complete conversion, the part geometry is displayed on the screen.

- Path: This option of the menu prompts the user to enter the file name in which the AVAIL inspection part program will be written. It then invokes the AVAIL program generator module. The bottom menu is activated for user interaction to perform CMM measurement activity simulation.

- Output Analysis: This option will prompt the user to enter the filename containing the output from the execution of the AVAIL part program. After verifying the filename, it divides the display area into two windows to present the original part in the left window and the part generated from the output values in the right window. The entities selected for measurement are highlighted. Output report can be displayed by selecting the Output Report option. This will tabulate, on the screen, the designed values and measured values of the coordinates of each entities selected for measurement. The measured values not meeting the default tolerance limits are highlighted. By selecting the Reset option, all the output options are turned off and the original part is displayed back.

- Undo: This option allows user to reverse the last action that has produced unwanted changes applied to the part geometry.

- Done: This option allows the user to exit from any submenu.

- Quit: This option allows user to terminate the session and exit from the software.

5.3.3 Top Menu

The top menu is mainly used to modify the part geometry or to alter the part orientation. The organization of the top menu is shown in figure 5.4 on the following page.

- File: This option allows the user to save the part modification information in an ASCII file. It prompts the user to provide the file name in which the modified part

information will be stored. After name verification, a file will be created in the same format as the '.dat' file generated by the IGES processor.
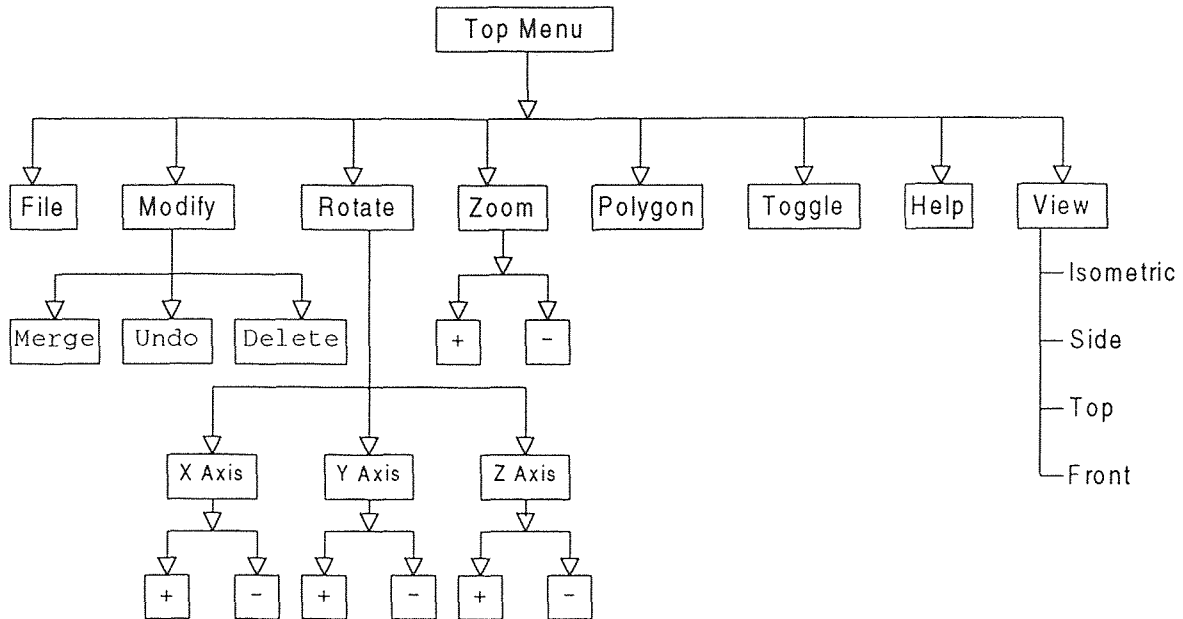
Figure 5.4 Top Menu Organization

- Modify: This option allows users to modify the part geometry displayed on the screen. When this option is selected, a submenu is presented with three options:

  1. Undo - to reverse the last action.

  2. Merge - to merge lines into a curve or a circle.

  3. Delete - to delete a line or a curve.

- Rotate: This option allows users to change the orientation of the displayed part by applying rotation about the X, Y, or Z axis. Rotation can be applied in the steps of +15 or -15 degrees.

- Zoom: This option allows the user to magnify or reduce the part geometry.

- Polygon: This option allows the user to construct a polygon using lines on the same plane. When this option is selected, a submenu is presented with different colors. The

user can select a color to specify the color of the polygon to be constructed. The user is prompted to specify contiguous lines to be used in constructing the polygon. After checking that the specified lines form a closed area, a polygon is constructed with the specified color and lines.

- Toggle: This option allows users to toggle the polygons between wireframe and solid modes.

- Help: This option allows the user to obtain on-line help.

- View: This option allows the users to view the displayed part from different viewing positions. When this option is selected, a submenu is presented with four options to allow the user to generate an isometric, a side, a top, or a front view.

5.3.4 Bottom Menu/Message Area

This area of the screen is shared by the bottom menu and the user messages and interaction prompts. The bottom menu organization is shown in figure 5.5.
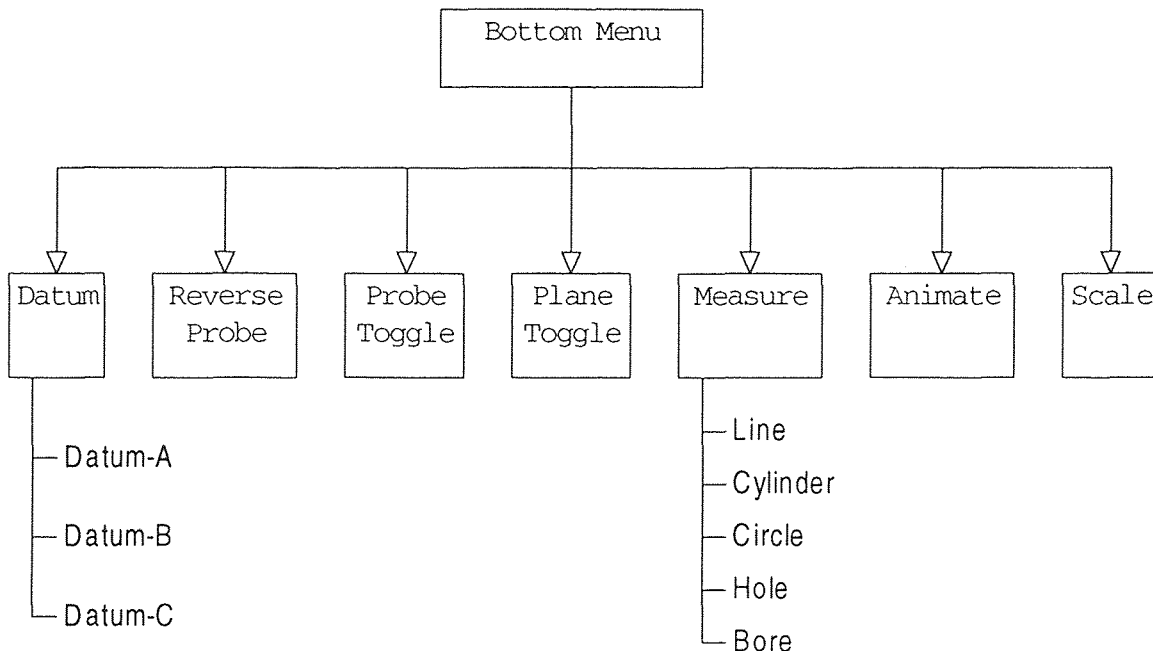
Figure 5.5 Bottom Menu Organization

The bottom menu is mainly used for CMM activity simulation and AVAIL part program generation. Various options of this menu are discussed below:

- Datum: This option allows the user to identify datums for specifying part alignment during physical inspection. For part alignment, a plane datum and two line datums needs to be identified. When this option is selected, a submenu is presented with three options - Datum-A, Datum-B, and Datum-C. Selecting Datum-A will prompt the user to pick a plane on the part. The identification of datum-A establishes one of the axes. It provides the computer with the information needed to compensate for any misalignment between the part's reference plane and the table coordinate system. Selecting Datum-B or Datum-C will prompt the user to pick a line on the part. Datum-B and datum-C will establish the other two axis and provide the information to compensate for misalignment between the axis of the plane and the table coordinate system. The user is forced to identify all three datums. Once all three datums are identified, the part alignment and the part origin is determined.

- Reverse Probe: This option can be used to reverse the direction of the probe.

- Probe Toggle: This option toggles the probe between the wire-frame and the solid models.

- Plane Toggle: This option toggles the datum planes between the wire-frame and solid models.

- Measure: This option allows the user to identify the entities that are to be measured and hence included in the AVAIL part program. Selecting this option presents a submenu which allows the user to specify the type of the entity to be identified. These entities are line, cylinder, hole, circle, and boss. Selecting any of these suboption prompts the user to identify the entity by clicking the mouse button while positioning the mouse pointer on that entity. When an entity is identified, an AVAIL part program is appended with appropriate programming statements.

- Animate: This option allows the user to animate the CMM measurement activities. During the animation sequence, the probe will move to all the entities identified for measurement and perform the measurement sequence.

- Scale: This option allows the user to magnify or reduce the size of the probe.

5.4 Output Analysis

The execution of the AVAIL part program for physical inspection of the part generates an output file giving information about coordinates of each of the entities identified for measurement. This output file can be brought back to the software for further analysis and making decisions about accepting or rejecting the part.

The *Output Analysis* module of the software reads and interprets this file. Once the specified output file name is verified, the display area of the screen is divided into two windows. The left window displays the part with the original design values while the right window displays the part with the measured values obtained from the output file. The entities selected for measurement in the AVAIL program are highlighted for visual on-the-screen inspection. This will allow the user to compare the geometries of the original part and the measured part.

The visual inspection is useful only if measurement errors are significant. It becomes difficult to make a decision when the measurement errors are minor. In this case, an inspection report can be generated. The inspection report lists the designed and measured values in the tabular format along with the tolerance information for each of the entities selected for measurement. The measured values outside the default tolerance limits are highlighted.

A sample of the Output Screen and the Output Report are included in the Appendix.

5.5   Software Usage

Before invoking the software, the user has to design and develop a part in a CAD software (ProEngineer or IDEAS). After developing the part, the user has to write the design database information in an ascii file in the IGES format. The IGES file should be written for the wireframe model only as the software cannot interpret surface model information.

The software can be invoked by typing 'test' at the command line. After initializing the environment, the software presents various on-screen menus with a collection of screen buttons. These menu buttons are accessible with the mouse and can be activated by positioning the mouse pointer into the appropriate button area and then clicking the mouse left button.

Clicking on the 'IGES' button of the right menu invokes the IGES processor to read and interpret the IGES file written by the CAD software. The IGES file should be provided at the prompt. This file is converted and the part is displayed on the screen.. Using the top menu options, the geometry or orientation of the part can be altered as desired.

The next step is to invoke the AVAIL code generator module by clicking on the 'Path' button of the right menu. The bottom menu is activated. Datums are required to be identified for aligning the part coordinate system relative to the machine coordinate system. This also determines the part origin. To identify the entities to be measured, the 'Measure' button should be clicked. A submenu is activated with a list of entity types that can be measured. Selecting an entity type prompts the user to click on the corresponding entity of the part. Clicking on the 'Done' button of the right menu will end the current entity identification session. The CMM activities can be simulated by selecting the 'Animation' option of the bottom menu. To end the AVAIL program generator module and write the part program file, click one more time on the 'Done' button.

The AVAIL part program file can be physically transferred to the CMM using various UNIX utilities. The execution of this part program for physical part inspection will generate an output file. This output file can again be transferred back to the software. The output module of the software can be invoked by clicking on the 'Output' option of the right menu. The output file name should be specified at the prompt. The screen is divided into two windows. Left window will display the original part and the right window will display the part with the measured values. The entities identified for measurement are displayed in different colors.

The output report can be generated and displayed by selecting 'Output Report' option. A tabular report will be displayed on the screen with designed and measured coordinates of each entity identified for measurement. The measured values outside the tolerance limits are highlighted. To turn off all the output options and display the original part, click on the 'Reset' button.

To end the session and exit from the software, click on the 'Quit' button.

CHAPTER 6

CONCLUSIONS

With increasing use of Direct Computer Controlled Coordinate Measuring Machine on the factory floor, the off-line development of inspection part program has gained an increased emphasis. The software developed as part of the thesis provides off-line development of AVAIL part program. Using this software can eliminate a need of a programmer on the inspection site. After a part is designed on the CAD software, the user can identify the features to be measured, simulate the CMM measurement activities, and generate the part program. A skilled CMM operator can execute this program by following the guidelines on the console, to perform the setup of the CMM, establish the Part Coordinate System by identifying necessary datums, and let the part program control the inspection sequences from there on. The results of the part program execution can be sent to an inspection report file. The output generated by the software interpreting the results, can be transferred back to the designer for analysis and to make an accept/reject decision.

In the off-line development of part programming, this software can be considered as a step forward. It can provide an important link in integrating CMM with the Flexible Manufacturing System. The IGES processor of the software makes possible to use part design from any CAD software supporting IGES file creation. It becomes possible for the user to use this IGES file to display the part on the screen and generate an inspection part program without any prior knowledge of AVAIL language. On-the-screen simulation of measurement activities makes it easy for a designer with good measurement skills to use this software to generate the part program and to understand its execution. The output analysis feature of this software can display the inspection results

on the screen to let the user make a decision about accepting or rejecting the part, or for that matter, making changes in the part design.

6.1   Future Work

The software has been designed and developed with a modular approach. The modularity of the software makes possible to add new modules when necessary in the future. Some of the modules of this software can also be used in other related software development projects. Following are some of the areas in which future improvement can be considered:

- Enhance the IGES processor to support IGES files written with surface model information.

- Enhance the AVAIL program generator module to expand the set of entities that can be identified for measurement.

- Enhance the AVAIL program generator module to support incorporation of part tolerance data.

- Allow the users to select different probe tips while simulating CMM activities on the screen.

APPENDIX

IGES File Generated by Pro-Engineer

```
PTC IGES file: FIRST_P.IGS                                    S      1
1H,,1H;,7HFIRST_P,                                           G      1
11HFIRST_P.IGS,                                              G      2
49HPro/ENGINEER by Parametric Technology Corporation,11HRelease 9.0,   G   3
32,38,7,38,15,7HFIRST_P,1.0,1,4HINCH,                        G      4
32768,0.500000,13H931116.193721,0.000100,1000.000000,4Hmasp,,6,0;   G   5
     124    1    1    1    0    0    0   001000001D     1
     124    0    0    1    0              XFORM    1D     2
     100    2    1    1    0    0    1   000000001D     3
     100    0    0    1    0                ARC    1D     4
     110    3    1    1    0    0    0   000000001D     5
     110    0    0    1    0               LINE    1D     6
     110    4    1    1    0    0    0   000000001D     7
     110    0    0    1    0               LINE    2D     8
     110    5    1    1    0    0    0   000000001D     9
     110    0    0    1    0               LINE    3D    10
     110    6    1    1    0    0    0   000000001D    11
     110    0    0    1    0               LINE    4D    12
     110    7    1    1    0    0    0   000000001D    13
     110    0    0    1    0               LINE    5D    14
     110    8    1    1    0    0    0   000000001D    15
     110    0    0    1    0               LINE    6D    16
     110    9    1    1    0    0    0   000000001D    17
     110    0    0    1    0               LINE    7D    18
     110   10    1    1    0    0    0   000000001D    19
     110    0    0    1    0               LINE    8D    20
     110   11    1    1    0    0    0   000000001D    21
     110    0    0    1    0               LINE    9D    22
     110   12    1    1    0    0    0   000000001D    23
     110    0    0    1    0               LINE   10D    24
     110   13    1    1    0    0    0   000000001D    25
     110    0    0    1    0               LINE   11D    26
     110   14    1    1    0    0    0   000000001D    27
     110    0    0    1    0               LINE   12D    28
     110   15    1    1    0    0    0   000000001D    29
     110    0    0    1    0               LINE   13D    30
     110   16    1    1    0    0    0   000000001D    31
     110    0    0    1    0               LINE   14D    32
     110   17    1    1    0    0    0   000000001D    33
     110    0    0    1    0               LINE   15D    34
     110   18    1    1    0    0    0   000000001D    35
     110    0    0    1    0               LINE   16D    36
     110   19    1    1    0    0    0   000000001D    37
```

110	0	0	1	0			LINE	17D	38
110	20	1	1	0	0	0	000000001D		39
110	0	0	1	0			LINE	18D	40
110	21	1	1	0	0	0	000000001D		41
110	0	0	1	0			LINE	19D	42
110	22	1	1	0	0	0	000000001D		43
110	0	0	1	0			LINE	20D	44
124	23	1	1	0	0	0	001000001D		45
124	0	0	1	0			XFORM	2D	46
100	24	1	1	0	0	45	000000001D		47
100	0	0	1	0			ARC	2D	48
124	25	1	1	0	0	0	001000001D		49
124	0	0	1	0			XFORM	3D	50
100	26	1	1	0	0	49	000000001D		51
100	0	0	1	0			ARC	3D	52
124	27	1	1	0	0	0	001000001D		53
124	0	0	1	0			XFORM	4D	54
100	28	1	1	0	0	53	000000001D		55
100	0	0	1	0			ARC	4D	56
124	29	1	1	0	0	0	001000001D		57
124	0	0	1	0			XFORM	5D	58
100	30	1	1	0	0	57	000000001D		59
100	0	0	1	0			ARC	5D	60
124	31	1	1	0	0	0	001000001D		61
124	0	0	1	0			XFORM	6D	62
100	32	1	1	0	0	61	000000001D		63
100	0	0	1	0			ARC	6D	64
124	33	1	1	0	0	0	001000001D		65
124	0	0	1	0			XFORM	7D	66
100	34	1	1	0	0	65	000000001D		67
100	0	0	1	0			ARC	7D	68
124	35	1	1	0	0	0	001000001D		69
124	0	0	1	0			XFORM	8D	70
100	36	1	1	0	0	69	000000001D		71
100	0	0	1	0			ARC	8D	72
124	37	1	1	0	0	0	001000001D		73
124	0	0	1	0			XFORM	9D	74
100	38	1	1	0	0	73	000000001D		75
100	0	0	1	0			ARC	9D	76
124	39	1	1	0	0	0	001000001D		77
124	0	0	1	0			XFORM	10D	78
100	40	1	1	0	0	77	000000001D		79
100	0	0	1	0			ARC	10D	80
124	41	1	1	0	0	0	001000001D		81
124	0	0	1	0			XFORM	11D	82
100	42	1	1	0	0	81	000000001D		83

100	0	0	1	0			ARC	11D	84
110	43	1	1	0	0	0	000000001D		85
110	0	0	1	0			LINE	21D	86
110	44	1	1	0	0	0	000000001D		87
110	0	0	1	0			LINE	22D	88
110	45	1	1	0	0	0	000000001D		89
110	0	0	1	0			LINE	23D	90
110	46	1	1	0	0	0	000000001D		91
110	0	0	1	0			LINE	24D	92
110	47	1	1	0	0	0	000000001D		93
110	0	0	1	0			LINE	25D	94
124	48	1	1	0	0	0	001000001D		95
124	0	0	1	0			XFORM	12D	96
100	49	1	1	0	0	95	000000001D		97
100	0	0	1	0			ARC	12D	98
124	50	1	1	0	0	0	001000001D		99
124	0	0	1	0			XFORM	13D	100
100	51	1	1	0	0	99	000000001D		101
100	0	0	1	0			ARC	13D	102
124	52	1	1	0	0	0	001000001D		103
124	0	0	1	0			XFORM	14D	104
100	53	1	1	0	0	103	000000001D		105
100	0	0	1	0			ARC	14D	106
124	54	1	1	0	0	0	001000001D		107
124	0	0	1	0			XFORM	15D	108
100	55	1	1	0	0	107	000000001D		109
100	0	0	1	0			ARC	15D	110
124	56	1	1	0	0	0	001000001D		111
124	0	0	1	0			XFORM	16D	112
100	57	1	1	0	0	111	000000001D		113
100	0	0	1	0			ARC	16D	114
124	58	1	1	0	0	0	001000001D		115
124	0	0	1	0			XFORM	17D	116
100	59	1	1	0	0	115	000000001D		117
100	0	0	1	0			ARC	17D	118
124	60	1	1	0	0	0	001000001D		119
124	0	0	1	0			XFORM	18D	120
100	61	1	1	0	0	119	000000001D		121
100	0	0	1	0			ARC	18D	122
124	62	1	1	0	0	0	001000001D		123
124	0	0	1	0			XFORM	19D	124
100	63	1	1	0	0	123	000000001D		125
100	0	0	1	0			ARC	19D	126
124	64	1	1	0	0	0	001000001D		127
124	0	0	1	0			XFORM	20D	128
100	65	1	1	0	0	127	000000001D		129

100	0	0	1	0			ARC	20D	130
124	66	1	1	0	0	0	001000001D	131
124	0	0	1	0			XFORM	21D	132
100	67	1	1	0	0	131	000000001D	133
100	0	0	1	0			ARC	21D	134
110	68	1	1	0	0	0	000000001D	135
110	0	0	1	0			LINE	26D	136
110	69	1	1	0	0	0	000000001D	137
110	0	0	1	0			LINE	27D	138
110	70	1	1	0	0	0	000000001D	139
110	0	0	1	0			LINE	28D	140
126	71	1	1	0	0	0	000000001D	141
126	0	0	21	0			B_SPLINE	1D	142
110	92	1	1	0	0	0	000000001D	143
110	0	0	1	0			LINE	29D	144
110	93	1	1	0	0	0	000000001D	145
110	0	0	1	0			LINE	30D	146
110	94	1	1	0	0	0	000000001D	147
110	0	0	1	0			LINE	31D	148
110	95	1	1	0	0	0	000000001D	149
110	0	0	1	0			LINE	32D	150
110	96	1	1	0	0	0	000000001D	151
110	0	0	1	0			LINE	33D	152
110	97	1	1	0	0	0	000000001D	153
110	0	0	1	0			LINE	34D	154
110	98	1	1	0	0	0	000000001D	155
110	0	0	1	0			LINE	35D	156
110	99	1	1	0	0	0	000000001D	157
110	0	0	1	0			LINE	36D	158
110	100	1	1	0	0	0	000000001D	159
110	0	0	1	0			LINE	37D	160
110	101	1	1	0	0	0	000000001D	161
110	0	0	1	0			LINE	38D	162
110	102	1	1	0	0	0	000000001D	163
110	0	0	1	0			LINE	39D	164
110	103	1	1	0	0	0	000000001D	165
110	0	0	1	0			LINE	40D	166
110	104	1	1	0	0	0	000000001D	167
110	0	0	1	0			LINE	41D	168
110	105	1	1	0	0	0	000000001D	169
110	0	0	1	0			LINE	42D	170
110	106	1	1	0	0	0	000000001D	171
110	0	0	1	0			LINE	43D	172
110	107	1	1	0	0	0	000000001D	173
110	0	0	1	0			LINE	44D	174
110	108	1	1	0	0	0	000000001D	175

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110     0     0     1     0            LINE     45D   176
110    109    1     1     0     0     0    000000001D   177
110     0     0     1     0            LINE     46D   178
110    110    1     1     0     0     0    000000001D   179
110     0     0     1     0            LINE     47D   180
126    111    1     1     0     0     0    000000001D   181
126     0     0    21     0          B_SPLINE   2D   182
110    132    1     1     0     0     0    000000001D   183
110     0     0     1     0            LINE     48D   184
110    133    1     1     0     0     0    000000001D   185
110     0     0     1     0            LINE     49D   186
110    134    1     1     0     0     0    000000001D   187
110     0     0     1     0            LINE     50D   188
110    135    1     1     0     0     0    000000001D   189
110     0     0     1     0            LINE     51D   190
110    136    1     1     0     0     0    000000001D   191
110     0     0     1     0            LINE     52D   192
110    137    1     1     0     0     0    000000001D   193
110     0     0     1     0            LINE     53D   194
124    138    1     1     0     0     0    001000001D   195
124     0     0     1     0           XFORM    22D   196
100    139    1     1     0     0    195   000000001D   197
100     0     0     1     0            ARC     22D   198
124    140    1     1     0     0     0    001000001D   199
124     0     0     2     0           XFORM    23D   200
100    142    1     1     0     0    199   000000001D   201
100     0     0     1     0            ARC     23D   202
124    143    1     1     0     0     0    001000001D   203
124     0     0     2     0           XFORM    24D   204
100    145    1     1     0     0    203   000000001D   205
100     0     0     1     0            ARC     24D   206
124    146    1     1     0     0     0    001000001D   207
124     0     0     1     0           XFORM    25D   208
100    147    1     1     0     0    207   000000001D   209
100     0     0     1     0            ARC     25D   210
124    148    1     1     0     0     0    001000001D   211
124     0     0     1     0           XFORM    26D   212
100    149    1     1     0     0    211   000000001D   213
100     0     0     1     0            ARC     26D   214
124    150    1     1     0     0     0    001000001D   215
124     0     0     1     0           XFORM    27D   216
100    151    1     1     0     0    215   000000001D   217
100     0     0     1     0            ARC     27D   218
124,1.,0.,0.,0.,0.,0.,-1.,2.,0.,1.,0.,0.;            1P    1
100,0.,0.,0.,0.4,0.,0.4,0.;                          3P    2
110,-2.45,2.,-0.63,-2.45,2.,0.62;                    5P    3
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110,-2.45,2.,-0.63,4.55,2.,-0.63;                                    7P    4
110,4.55,2.,-0.63,4.55,2.,-0.38;                                     9P    5
110,4.55,2.,-0.38,4.3,2.,-0.38;                                     11P    6
110,4.3,2.,-0.38,4.3,2.,0.62;                                       13P    7
110,4.3,2.,0.62,-2.45,2.,0.62;                                      15P    8
110,-4.2,-2.,0.62,-4.2,-2.,-0.38;                                   17P    9
110,4.3,-2.,0.62,-4.2,-2.,0.62;                                     19P    10
110,4.3,-2.,-0.38,4.3,-2.,0.62;                                     21P    11
110,4.55,-2.,-0.38,4.3,-2.,-0.38;                                   23P    12
110,4.55,-2.,-0.63,4.55,-2.,-0.38;                                  25P    13
110,-4.45,-2.,-0.63,4.55,-2.,-0.63;                                 27P    14
110,-4.45,-2.,-0.38,-4.45,-2.,-0.63;                                29P    15
110,-4.2,-2.,-0.38,-4.45,-2.,-0.38;                                 31P    16
110,-4.2,1.4981955749221,0.62,-4.2,1.4981955749221,-0.38;     33P    17
110,-4.2,1.4981955749221,0.62,-4.2,-2.,0.62;                    35P    18
110,-4.2,1.4981955749221,-0.38,-4.45,1.4265092284824,-0.38;   37P    19
110,-4.2,1.4981955749221,-0.38,-4.2,-2.,-0.38;                  39P    20
110,-4.45,1.4265092284824,-0.38,-4.45,1.4265092284824,-0.63;   41P    21
110,-4.45,1.4265092284824,-0.38,-4.45,-2.,-0.38;               43P    22
124,1.,0.,0.,0.,0.,-1.,0.,0.,0.,0.,-1.,-0.63;                       45P    23
100,0.,0.,0.,1.,0.,1.,0.;                                       47P    24
124,1.,0.,0.,-3.45,0.,-1.,0.,-1.,0.,0.,-1.,-0.63;                    49P    25
100,0.,0.,0.,0.5,0.,0.5,0.;                                     51P    26
124,1.,0.,0.,-3.45,0.,-1.,0.,1.,0.,0.,-1.,-0.63;                    53P    27
100,0.,0.,0.,0.5,0.,0.5,0.;                                     55P    28
124,1.,0.,0.,3.55,0.,-1.,0.,1.,0.,0.,-1.,-0.63;                     57P    29
100,0.,0.,0.,0.5,0.,0.5,0.;                                     59P    30
124,1.,0.,0.,3.55,0.,-1.,0.,-1.,0.,0.,-1.,-0.63;                    61P    31
100,0.,0.,0.,0.5,0.,0.5,0.;                                     63P    32
124,1.,0.,0.,2.55,0.,-1.,0.,0.,0.,0.,-1.,-0.63;                     65P    33
100,0.,0.,0.,0.1875,0.,0.1875,0.;                               67P    34
124,1.,0.,0.,3.55,0.,-1.,0.,0.,0.,0.,-1.,-0.63;                     69P    35
100,0.,0.,0.,0.1875,0.,0.1875,0.;                               71P    36
124,1.,0.,0.,2.55,0.,-1.,0.,1.,0.,0.,-1.,-0.63;                     73P    37
100,0.,0.,0.,0.1875,0.,0.1875,0.;                               75P    38
124,1.,0.,0.,2.55,0.,-1.,0.,-1.,0.,0.,-1.,-0.63;                    77P    39
100,0.,0.,0.,0.1875,0.,0.1875,0.;                               79P    40
124,1.,0.,0.,1.612,0.,-1.,0.,0.,0.,0.,-1.,-0.63;                    81P    41
100,0.,0.,0.,0.1875,0.,0.1875,0.;                               83P    42
110,-4.45,1.4265092284824,-0.63,-2.45,2.,-0.63;                 85P    43
110,-4.45,1.4265092284824,-0.63,-4.45,-2.,-0.63;                87P    44
110,4.55,2.,-0.63,4.55,-2.,-0.63;                               89P    45
110,4.55,2.,-0.38,4.55,-2.,-0.38;                               91P    46
110,4.3,2.,-0.38,4.3,-2.,-0.38;                                 93P    47
124,1.,0.,0.,-3.45,0.,-1.,0.,-1.,0.,0.,-1.,0.62;                    95P    48
100,0.,0.,0.,0.5,0.,0.5,0.;                                     97P    49
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124,1.,0.,0.,-3.45,0.,-1.,0.,1.,0.,0.,-1.,0.62; 99P 50
100,0.,0.,0.,0.5,0.,0.5,0.; 101P 51
124,1.,0.,0.,3.55,0.,-1.,0.,1.,0.,0.,-1.,0.62; 103P 52
100,0.,0.,0.,0.5,0.,0.5,0.; 105P 53
124,1.,0.,0.,3.55,0.,-1.,0.,-1.,0.,0.,-1.,0.62; 107P 54
100,0.,0.,0.,0.5,0.,0.5,0.; 109P 55
124,1.,0.,0.,2.55,0.,-1.,0.,0.,0.,0.,-1.,0.62; 111P 56
100,0.,0.,0.,0.1875,0.,0.1875,0.; 113P 57
124,1.,0.,0.,3.55,0.,-1.,0.,0.,0.,0.,-1.,0.62; 115P 58
100,0.,0.,0.,0.1875,0.,0.1875,0.; 117P 59
124,1.,0.,0.,2.55,0.,-1.,0.,1.,0.,0.,-1.,0.62; 119P 60
100,0.,0.,0.,0.1875,0.,0.1875,0.; 121P 61
124,1.,0.,0.,2.55,0.,-1.,0.,-1.,0.,0.,-1.,0.62; 123P 62
100,0.,0.,0.,0.1875,0.,0.1875,0.; 125P 63
124,1.,0.,0.,1.612,0.,-1.,0.,0.,0.,0.,-1.,0.62; 127P 64
100,0.,0.,0.,0.1875,0.,0.1875,0.; 129P 65
124,1.,0.,0.,0.,0.,-1.,0.,0.,0.,0.,-1.,0.62; 131P 66
100,0.,0.,0.,1.25,0.,1.25,0.; 133P 67
110,-4.2,1.4981955749221,0.62,-2.45,2.,0.62; 135P 68
110,4.3,2.,0.62,4.3,-2.,0.62; 137P 69
110,1.,0.,0.,1.,0.,-0.63; 139P 70
126,17,3,0,0,1,0,0.,0.,0.,0.,0.066666666666667,0.13333333333333, 141P 71
0.2,0.26666666666667,0.33333333333333,0.4,0.46666666666667, 141P 72
0.53333333333333,0.6,0.66666666666667,0.73333333333333,0.8, 141P 73
0.86666666666667,0.93333333333333,1.,1.,1.,1.,1.,1.,1.,1.,1.,1., 141P 74
1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,0.4,0.916515138991170.,0.4, 141P 75
0.916515138991170.-0.025411231153322,0.39530328935621, 141P 76
0.91858997287212,-0.07631090584301,0.37189728673169, 141P 77
0.92847860102843,-0.15502736320976,0.33120727302139, 141P 78
0.94403240467877,-0.22973431374496,0.27392269772613, 141P 79
0.96253764189783,-0.29590479789307,0.20272490499599, 141P 80
0.9802718919714,-0.34855709944173,0.1225626578647, 141P 81
0.99363788801611,-0.38404652672578,0.039414029280745, 141P 82
1.0003092601112,-0.40077763670204,-0.039679494555134, 141P 83
1.0003015372129,-0.40075851428926,-0.12298742755115, 141P 84
0.99359050243508,-0.38392675263755,-0.20327829154216, 141P 85
0.9801589501393,-0.34824692356174,-0.27444550457877, 141P 86
0.96238650915505,-0.29542195049267,-0.33159185376503, 141P 87
0.94389414312642,-0.2291692829388,-0.37209878631337, 141P 88
0.92839548451884,-0.15450964028996,-0.39534710899756, 141P 89
0.9185704384984,-0.0759902873231,-0.4,0.91651513899117, 141P 90
-0.025291194189291,-0.4,0.91651513899117,0.,0.,1.,0.,0.,1.; 141P 91
110,-1.,0.,0.,-1.,0.,-0.63; 143P 92
110,-2.95,-1.,0.62,-2.95,-1.,-0.63; 145P 93
110,-3.95,-1.,0.62,-3.95,-1.,-0.63; 147P 94
110,-2.95,1.,0.62,-2.95,1.,-0.63; 149P 95

110,-3.95,1.,0.62,-3.95,1.,-0.63;   151P   96
110,4.05,1.,0.62,4.05,1.,-0.63;   153P   97
110,3.05,1.,0.62,3.05,1.,-0.63;   155P   98
110,4.05,-1.,0.62,4.05,-1.,-0.63;   157P   99
110,3.05,-1.,0.62,3.05,-1.,-0.63;   159P   100
110,2.7375,0.,0.62,2.7375,0.,-0.63;   161P   101
110,2.3625,0.,0.62,2.3625,0.,-0.63;   163P   102
110,3.7375,0.,0.62,3.7375,0.,-0.63;   165P   103
110,3.3625,0.,0.62,3.3625,0.,-0.63;   167P   104
110,2.7375,1.,0.62,2.7375,1.,-0.63;   169P   105
110,2.3625,1.,0.62,2.3625,1.,-0.63;   171P   106
110,2.7375,-1.,0.62,2.7375,-1.,-0.63;   173P   107
110,2.3625,-1.,0.62,2.3625,-1.,-0.63;   175P   108
110,1.7995,0.,0.62,1.7995,0.,-0.63;   177P   109
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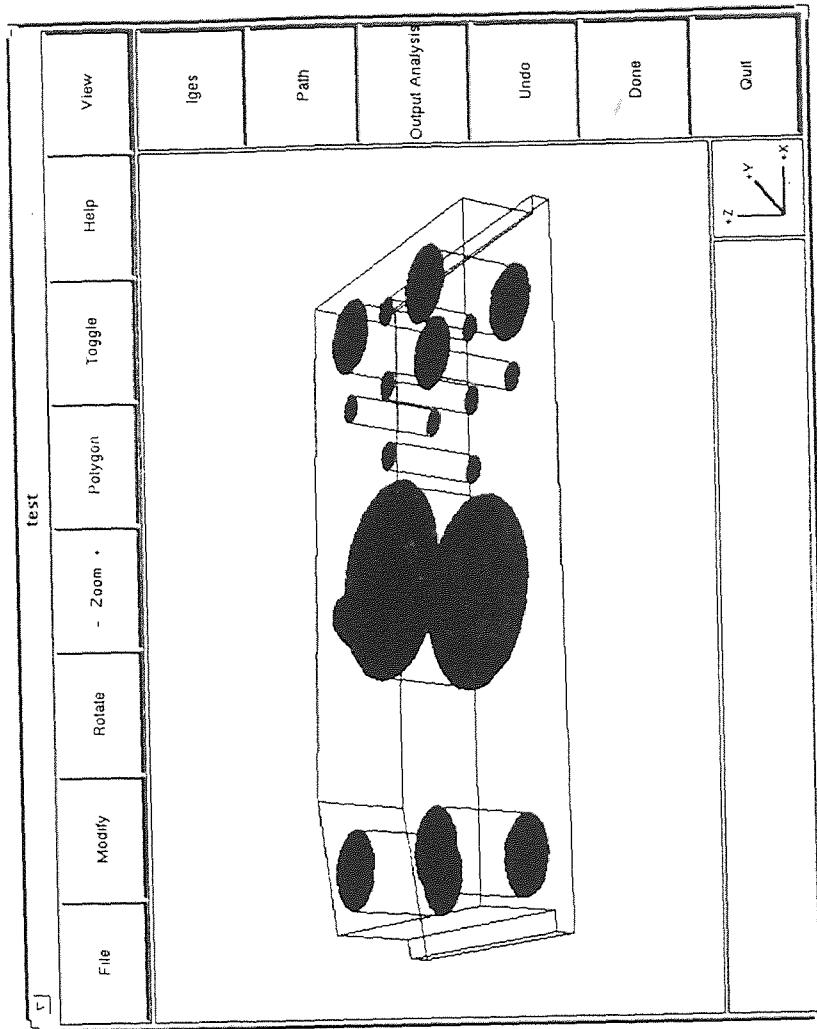-1.250000, -0.000000, 0.620000, -1.250000, -0.000000, 0.000000
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Part Display

test

File Modify Rotate - Zoom • Polygon Toggle Help

View Iges Path Output Analysis Undo Done Quit

+z +y +x

CMM Part Program

```
!                              PC_AVAIL
!
!                           BROWN & SHARPE
!
!              ADVANCED VALIDATOR INTERFACE LANGUAGE
!
!

        VERSION/NUMBER;  2.900000
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        TEXT/PRINTER; {
BROWN & SHARPE AVAIL LAB 3
}
        QUALIFY/RECALL; TIPS
        QUALIFY/OLD_TIP; 1
OUTPUT/DEVICE; DISK
PRINT_OPTION/FORMAT; MEASURED
PRINT_OPTION/AXES; XYZ
DATUM_A    = GEOMETRIC/PLANE;
                MANUAL/; 4
                DONE/;
DATUM_B    = GEOMETRIC/2D_LINE; DATUM_A
                MANUAL/; 2
                DONE/;
DATUM_C    = GEOMETRIC/2D_LINE; DATUM_A
                MANUAL/; 2
                DONE/;
CORNER    =   INTERSECT/POINT; DATUM_B, DATUM_C
                ALIGNMENT/PART; DATUM_A,DATUM_B,CORNER,XYZ
                TEXT/DISPLAY; {
******** PLEASE MOVE PROBE ABOVE PART ********
}
                PAUSE/;
PRINT_OPTION/AXES; XYZR
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                DONE/;
CIR2     = AUTO/CIR; XYPL,IS,4,0.750000,-1.000000,0.000000,1.000000,0,360
                DONE/;
CIR3     = AUTO/CIR; XYPL,IS,4,4.200000,-2.000000,0.000000,2.500000,0,360
                DONE/;
CIR4     = AUTO/CIR; XYPL,IS,4,7.750000,-3.000000,0.000000,1.000000,0,360
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            DONE/;
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            MEASURE/; 0.000000,0.000000,0.000000
            DONE/;
ENDOF/PROGRAM;
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Output Screen
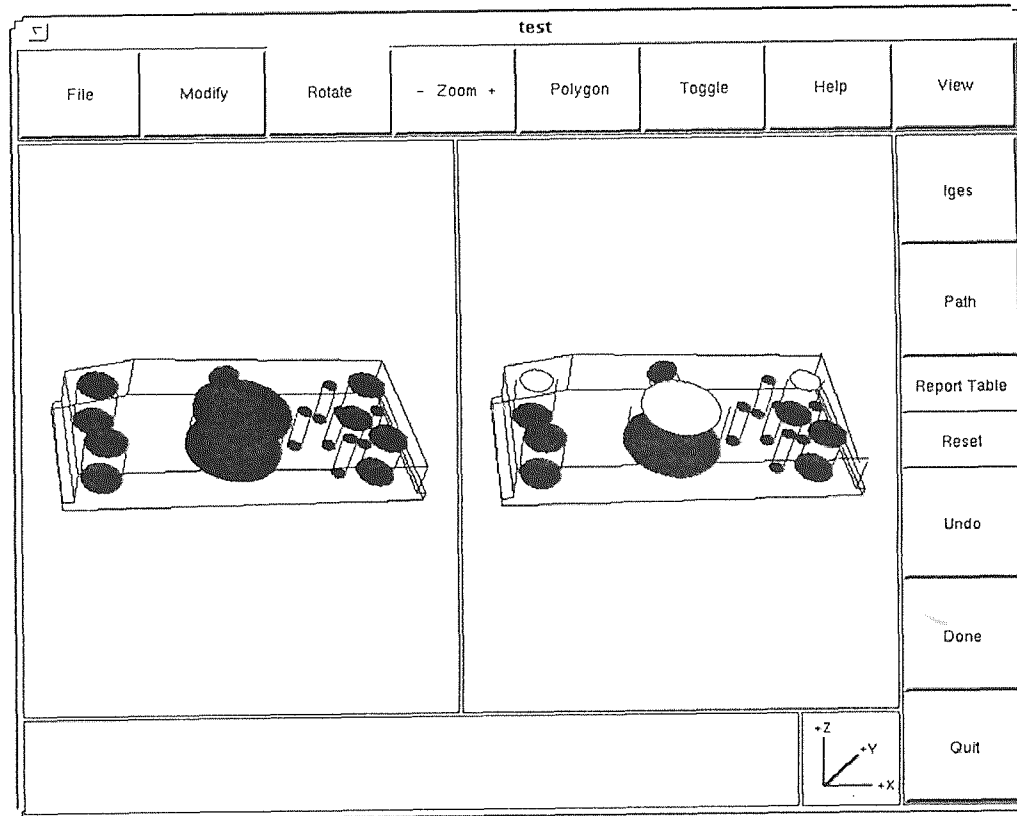
Output Report

File	Modify	Rotate	– Zoom +	Polygon	Toggle	Help	View

Entity	Tol%	X Values		Y Values		Z Values		Radious		Iges
		Des	Mes	Des	Mes	Des	Mes	Des	Mes	
CIR1	5.0	-3.450000	-3.450000	-1.000000	-1.000000	0.620000	0.620000	0.500000	0.400000	Path
CIR2	5.0	3.550000	3.550000	-1.000000	-1.000000	0.620000	0.620000	0.500000	0.400000	
CIR3	5.0	0.000000	0.000000	-0.000000	0.000000	0.620000	0.620000	1.250000	1.000000	Report Table
LINE1	5.0	4.300000	4.300000	2.000000	2.000000	0.620000	0.720000			Reset
		-4.200000	-4.200000	2.000000	2.000000	0.620000	0.620000			Undo
LINE2	5.0	4.300000	4.300000	-2.000000	-2.100000	0.620000	0.620000			
		4.300000	4.100000	2.000000	2.000000	0.620000	0.620000			Done

+Z
+Y
+X

Quit

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