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# Research In The Flexible Manufacturing Laboratory

by

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# OVERVIEW

Systems research in the Flexible Manufacturing Laboratory (FML) consists of two thrust areas, viz.

- Flexible Manufacturing Cell (FMC)
- Magnetic Bearings (MB)

The specific problem areas of research are shown in Figure 1.

The overall objective of the FMC research is concerned with interfacing various activities from design to component manufacturing. This includes such topics as the use of Artificial Intelligence (AI) in process planning, manufacturability evaluation via expert systems, and use of standardization within the cell. The FMC is illustrated in Figure 2.

The research in magnetic bearings is concerned with the control and stabilization of rotors and flywheels at high rotational speeds. Specific topics include the use of magnetic bearing spindles for machine tools, magnetic bearings for attitude control and energy storage in space, and finally magnetic bearings for active vibration control in centrifuges and turbines for industrial use.

Included in this paper are a brief synposis of on-going activities in several of the research areas.

FIG. 1

FLEXIBLE MANUFACTURING LABORATORY

| Magnetic Bearings | | | FMC | | | |
|---|---|---|---|---|---|---|
| M/T Spindles | Space Applic. | Industrial Applications | Design | Integration | Process Planning | Manufacturing |
| • Accuracy enhancement | • Attitude control | • Centrifuge | • Expert system | • System hardware | • AI | • Manufacturability |
| • High speed | • Energy storage | • Turbine | • CAD/CAM | • Interfacing (IGES/M&G) | • Ordered | • Machining |

# FMC Research Objectives

- Add value via machining at least cost and time
- Use AI/Expert Systems based upon algorithmic and heuristic reasoning
- Enhance cell accuracy via advanced control strategies
- Automation from design input to part production
- Compatibility via interfacing with commercial CAD systems

## Magnetic Bearing Research Objectives

- Develop fundamental theories for magnetic bearing design
- Develop control algorithm for robust performance
- Application of magnetic bearing spindles for high speed machining and accuracy enhancement
- Design and laboratory evaluation of high speed composite flywheel energy storage / attitude control space systems
- Design and laboratory evaluation of magnetic bearings for high speed shaft supported systems

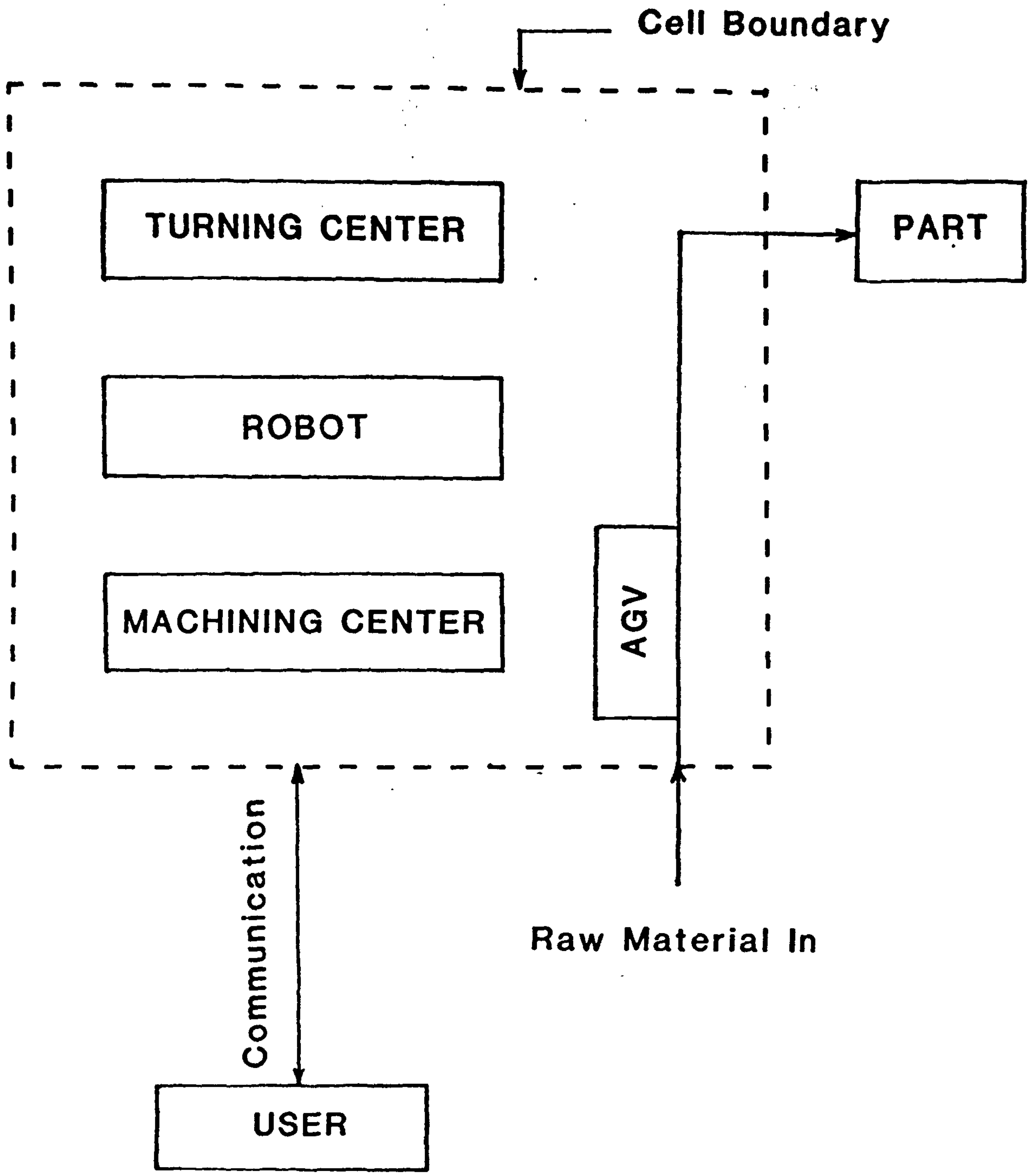



FIG. 2

**Flexible Manufacturing Cell**

# RESEARCH IN MAGNETIC BEARINGS

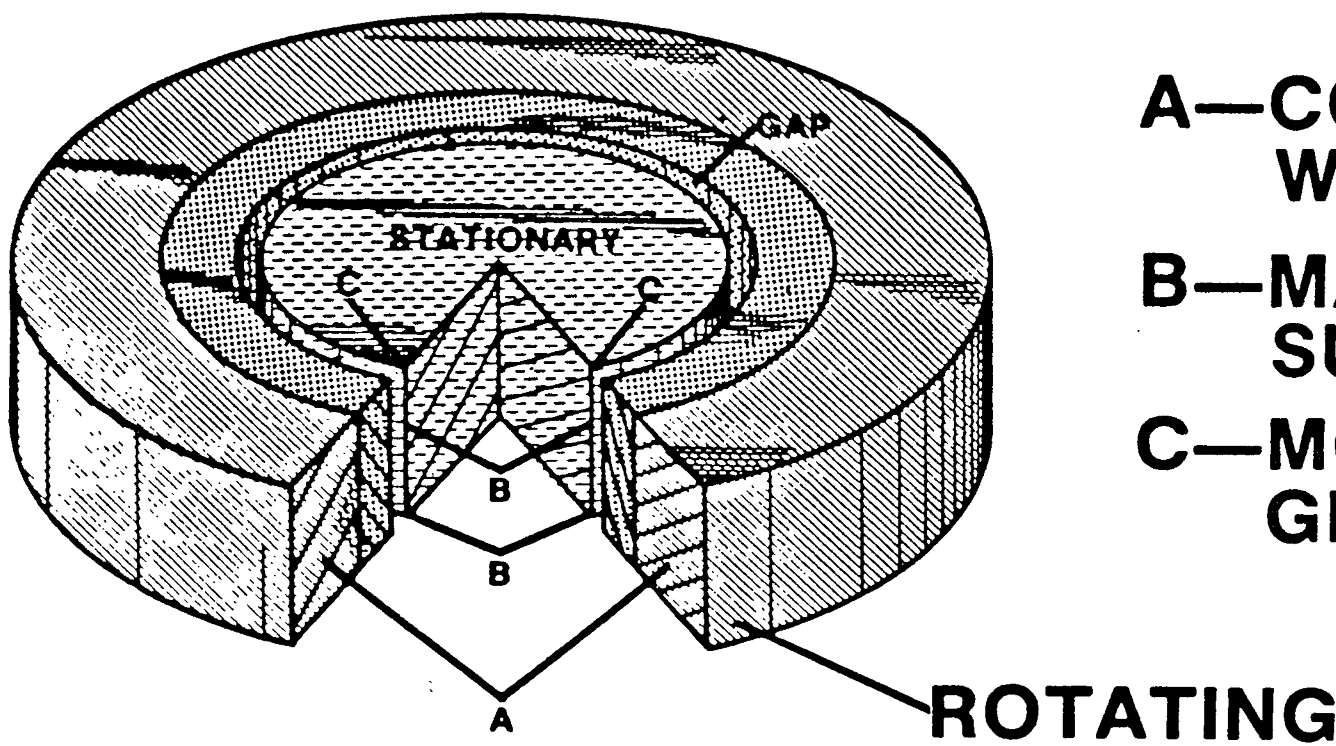
## Space Applications

The potential of magnetic bearings is enormous, and the advantages over conventional ball bearings numerous. Magnetic bearings require no lubricants, which completely eliminates outgassing problems for space applications. Magnetic suspension is particularly attractive in conjunction with the use of high-strength composites for the flywheel design. Composites allow the attainment of very high speeds and consequently high energy to weight ratios. A magnetically supported bearing could theoretically have a reliable lifetime on the order of 20 years due to the total elimination of bearing friction. The lifetime, in fact, should be governed only by the life of the control and motor electronics.

The work accomplished at the University of Maryland to this date can be separated into two parts. The first part is to simulate the operation of a flywheel magnetic bearing. Three computer programs are written to design the flywheel, magnetic bearing, and control system. The second part is to build a flywheel magnetic bearing and experimentally test this flywheel magnetic bearing to correlate with the simulation results of the first part.

An active pancake magnetic bearing successfully developed at the University of Maryland is shown in Fig. 3. "Pancake" refers to the sandwiching of permanent magnets between ferromagnetic plates. A cross section of the bearing is shown in Fig. 4 and 5. The flux distribution from the permanent magnets, which support the bulk of the rotor weight is shown in path A. Four electromagnetic coils are located near the permanent magnets to control the rotor about its unstable equilibrium point, i.e., the point at which the air

# GSFC + UMME = ACES

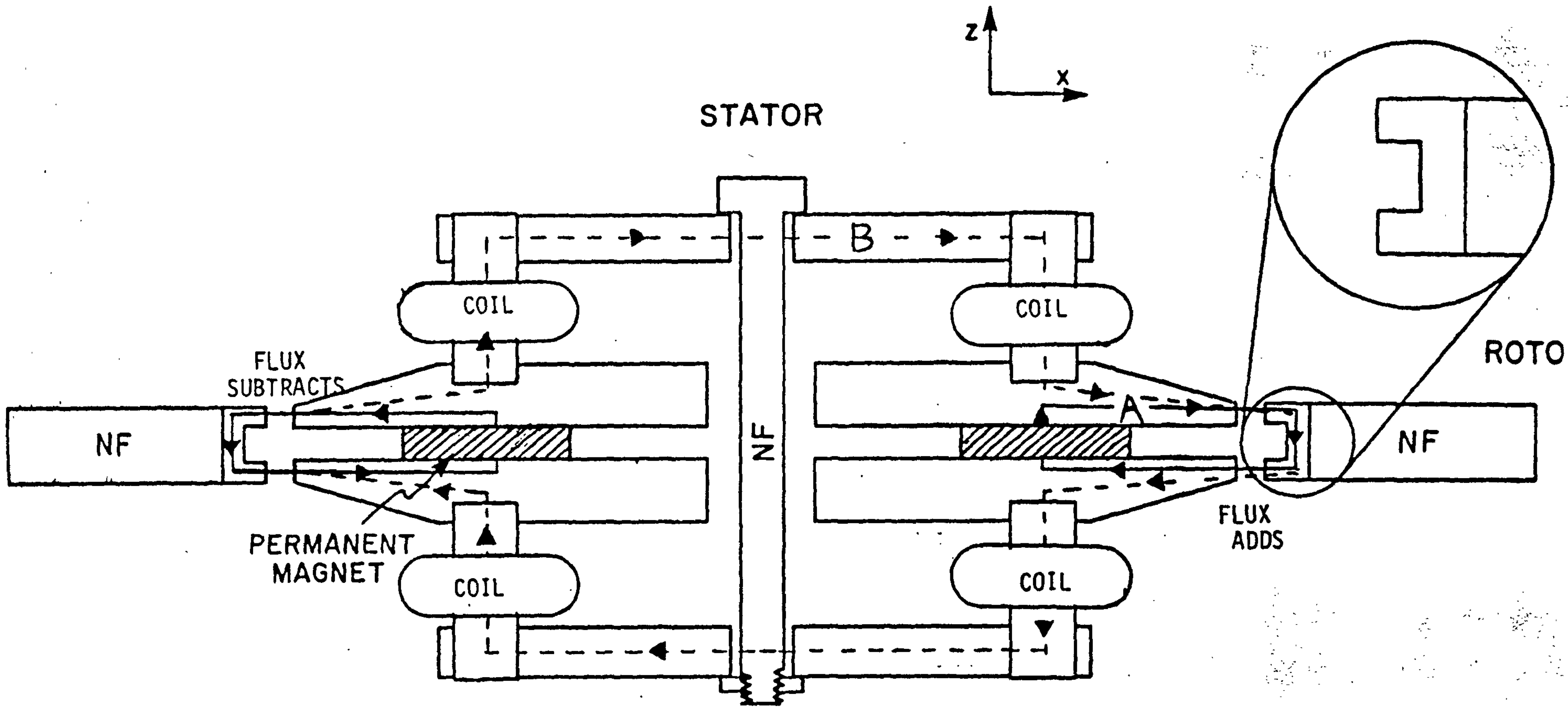



A—COMPOSITE WHEEL

B—MAGNETIC SUSPENSION

C—MOTOR/ GENERATOR

FIG. 3

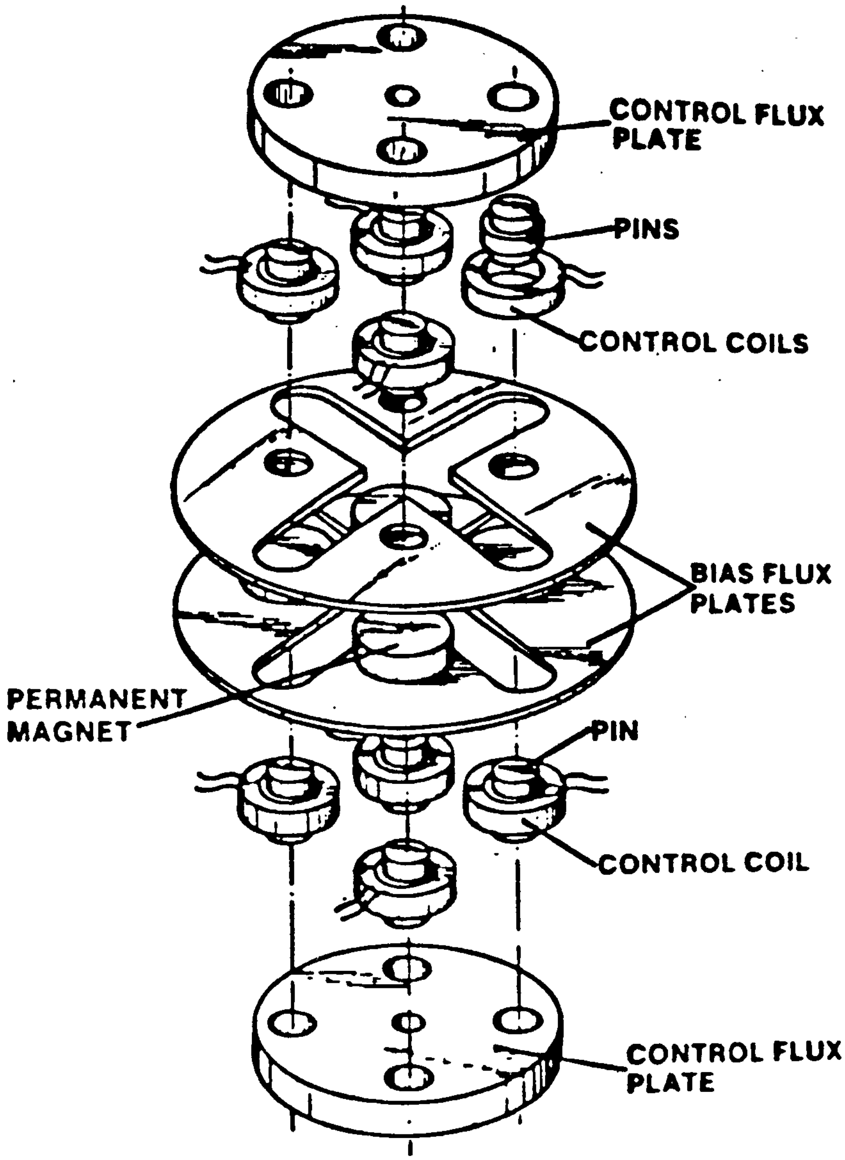



* All materials are Ni-Fe unless marked NF (non-ferromagnetic)

FIG. 4 **Cross Section of Pancake Bearing**

FIG. 5

## MAGNETIC SUSPENSION ASSEMBLY



gap is constant around the stator. When the rotor displaces radially, the motion is sensed by a position transducer at the periphery of the rotor. The control system responds by sending a control current through the coils which adds to the permanent magnet flux on the large gap and subtracts from the small gap side. The net result is a corrective force which moves the rotor back to the center position. An identical radial control system exists for the other orthogonal direction. The control in the axial direction is passive.

Results from the system parametric design and the control system analysis show that a 300 Watt-Hour magnetically suspended energy storage flywheel systems to 1 kwhr can be built incorporating characteristics of the magnetic bearing into a stack arrangement shown in Fig. 6. The major conclusions in this study are: 1) The system consisting of a stack arrangement is a viable approach in designing energy storage systems, 2) A method of reducing permanent magnet unbalance must be incorporated, and finally 3) Mechanical back up bearings are required to maintain flywheel excursions in the linear operating range of the control system.

Both a single magnetic bearing and a stack system have been built at the University of Maryland. The single magnetic bearing has been tested at rotational speed close to 10,000 rpm which is above the natural frequency of the system. The stack has been tested at approximately 4,000 rpm which is just below the natural frequency of the system. Rotational speeds on the order of 60,000 to 70,000 rpm can be achievable with the use of epoxy-graphite composite flywheels. This and other innovations are under research for incorporation into future designs.

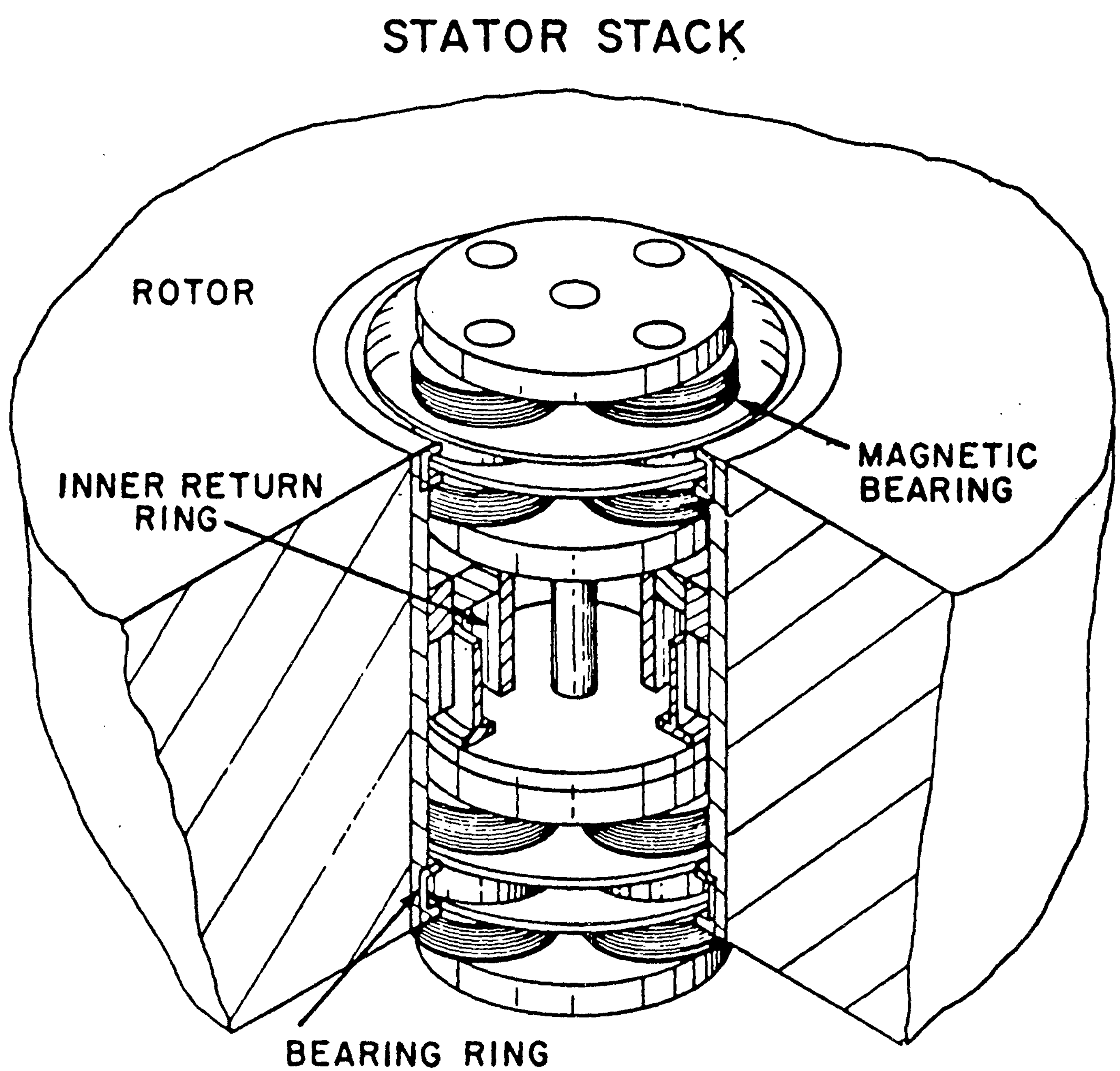


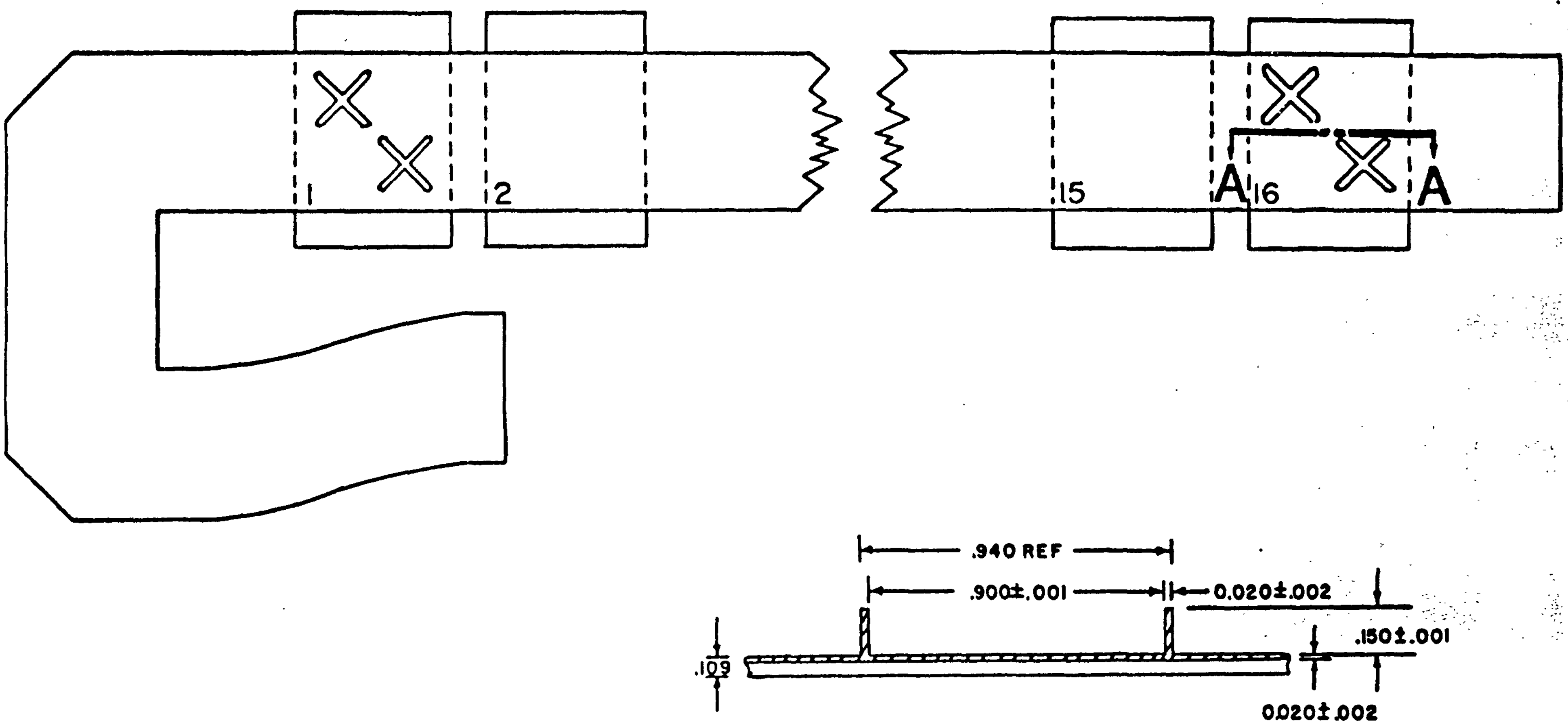

**FIG.6** Sectioned view of a two bearing stack arrangement for a magnetically suspended flywheel.

## MAGNETIC BEARING SPINDLE CONTROL IN MACHINING

To improve production efficienty of thin rib components, (Fig. 7), and to eliminate the secondary deburring operation, it is desirable to increase spindle speeds and table feeds (i.e., to move toward high speed machining) while maintaining part tolerances and surface finish within acceptable limits. In discussions with Westinghouse, Cincinnati Milacron, Magnetic Bearings Incorporated, and The National Bureau of Standards we have concluded that a magnetic bearing spindle can be retrofitted to existing machine tools and, with modification in feed rate, provide a solution to the accuracy, deburring and Material Removal Rate (MRR) problems in thin rib machining.

This research addresses the specific problem of identifying and controlling tool path error as it effects dimensional accuracy and surface finish in thin rib machining. Specifically, interest is centered around high speed end milling operations with particular interest on the use of a magnetically suspended spindle for controlling the tool path error.

TOOL PATH ERRORS. Tool path error in three dimensional cutting can be represented as shown in Figure 8. The tool path error in computer numerical control machine tools is defined as the distance-difference between the required and actual tool path.




SECTION AA
(ALL DIMENSIONS IN INCHES)

FIG. 7 MICROWAVE GUIDE (Courtesy of Westinghouse Corp.)

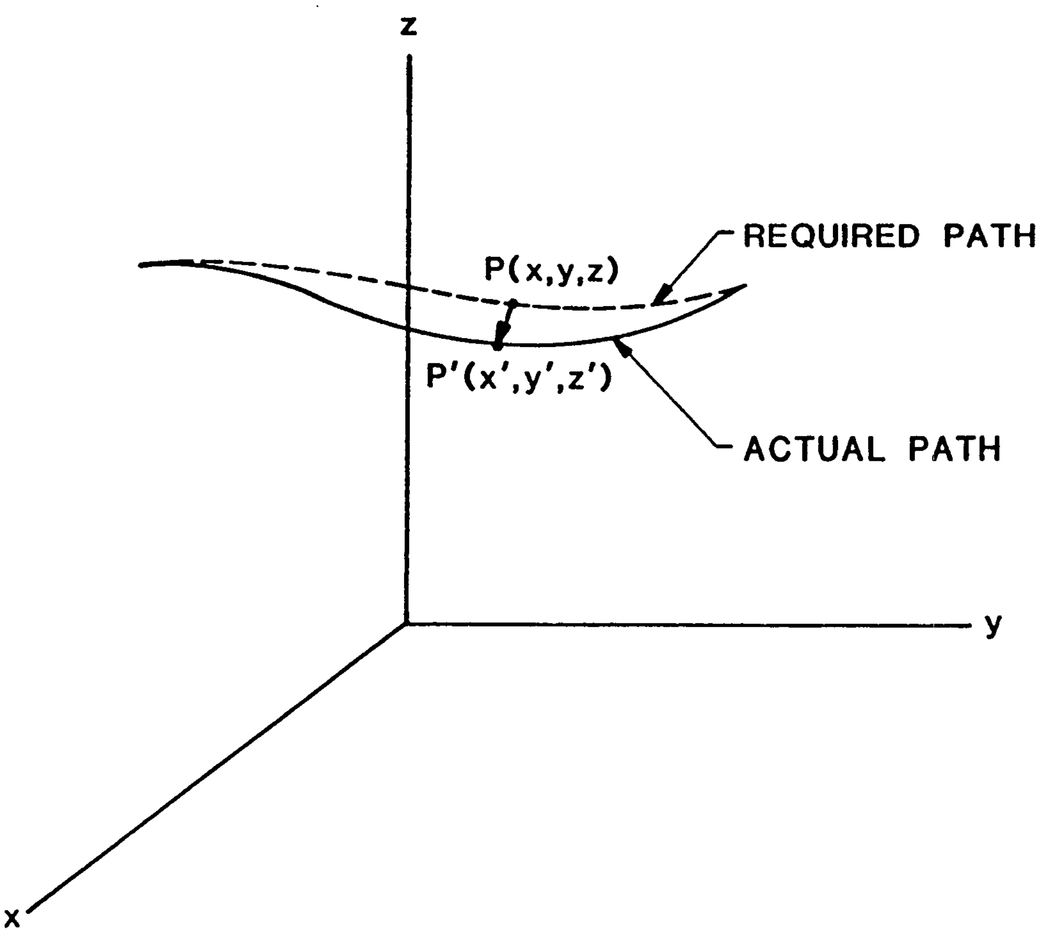



FIG. 8 TOOL PATH ERROR

Tool path error (in the absence of chatter) can be classified into the following four categories, based on the source of the error for each category;

- deterministic position errors
- deformation due to heat sources
- deformation due to weight forces
- deformation due to cutting forces.

These four error sources (Fig. 9) can cause three types of tool path errors, viz: static deterministic, dynamic deterministic and stochastic. Deterministic position and dynamic) errors (both static and dynamic) are defined as those repeatable errors which will reoccur when an identical set of input parameters exist on a given machine tool structure. Stochastic errors, on the other hand, are defined as those errors which occur when a random input is presented to the machine tool. The main sources of stochastic error are due to surface roughness of blank and in the cutting process itself.

MAGNETICALLY CONTROLLED SPINDLES. The magnetic spindles for use on machine tools are fairly experimental at this time. The only spindles currently available for use on machine tools are developed and built by Societe Mecanique Magnetique (S2M) of France. At present there are three models of magnetic spindles available for milling purposes. These 3 models cover the speed range between 30,000, and 60,000 rpm with a rated horsepower between 20 and 34. Magnetic spindles consist of a spindle shaft supported by contactless, active radial and thrust magnetic bearings, as is shown in Figure 10. In operation, the spindle shaft is magnetically suspended with no mechanical contact with the spindle housing. Position sensors placed around the shaft

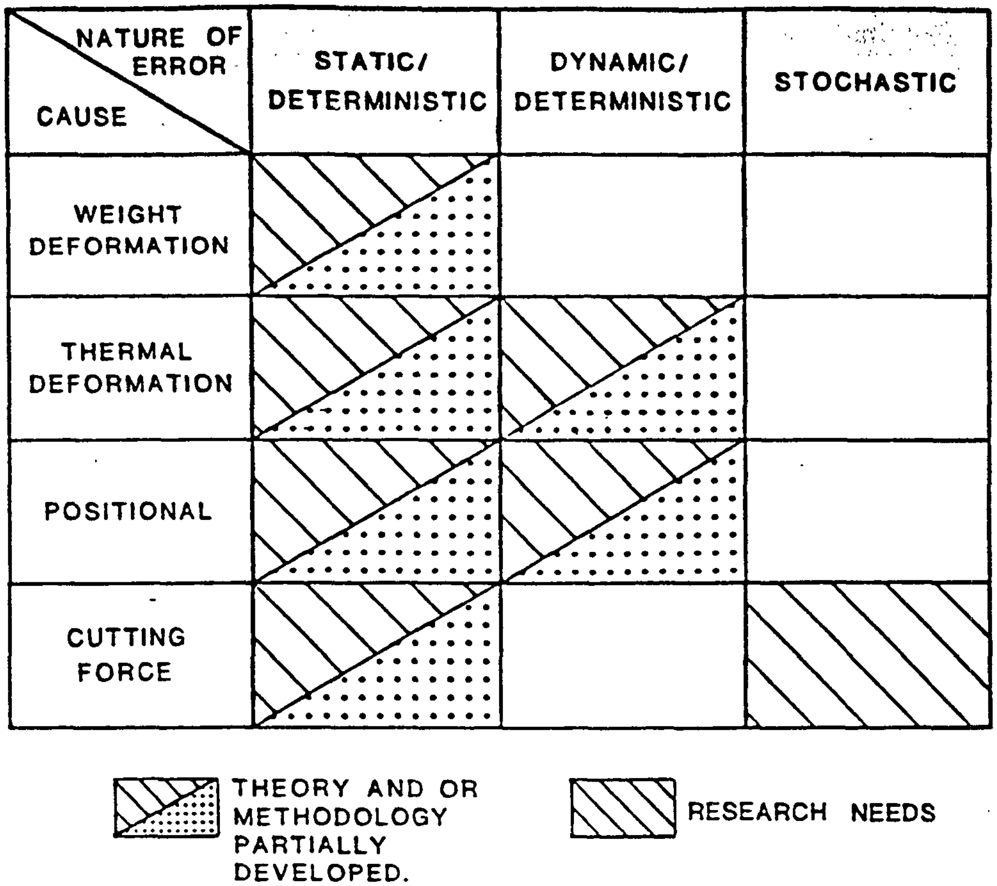



FIG. 9 END MILLING ERRORS

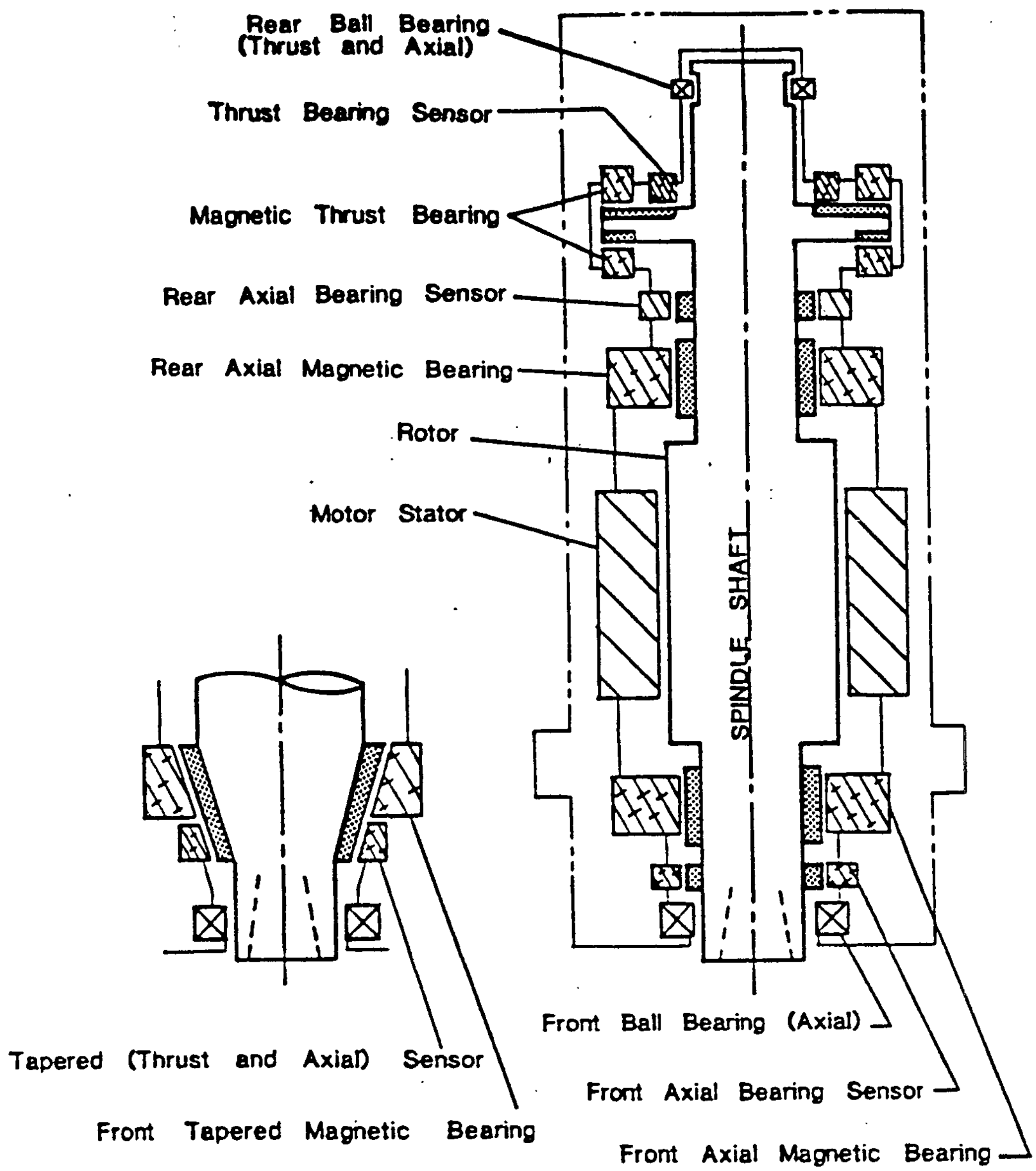



FIG. 10 MAGNETIC SPINDLE CONFIGURATION

continuously monitor the displacement of shaft in three orthogonal directions. The sensor information is processed by a control unit and any variation in the position of the shaft are corrected by varying the current level in electromagnetic coils, thereby forcing the spindle shaft to its original position. The magnetically floating spindle shaft can be rotated freely about its mass center even if the mass center deviates from the geometric axis.

It is particularly important to note that the spindle shaft can be translated up to ±.005 inches and tilled up to 0.5° with no effect on the performance of the spindle system. This unique feature of magnetically controlled spindles can have significant impact in correcting tool path errors.

The unique design of magnetic spindles provides significant advantages over conventional spindles with regard to tool path error correction. These advantages are:

1. Built-in 3-dimensional force sensors are available for adaptive control of the cutting process.
2. Built-in 3-dimensional position sensors are available for adaptive control of cutting process.
3. Ability to translate and tilt the spindle shaft (within air gap restrictions) for tool path error minimization. Applicable for minimizing both deterministic compliance error and stochastic errors due to variation in depth of cut and machine tool dynamics in thin rib machining.
4. High rotational speeds with reduction in cutting forces and improved surface finish (i.e., burr free cutting).

5. Ability to control the stiffness of the spindle which can be particularly beneficial for chatter control.
6. High material removal rate (MRR) available with increased table feed rates.

Several investigators have used magnetic spindles by retrofitting them on existing machine tools. Their primary focus was to use the magnetic bearing spindle to improve metal removal rate. In the approach suggested in this paper, the many other advantages of using magnetically controlled spindles to improve tool path errors can take precedence over the advantage of high metal removal rate. This approach exploits the full capabilities of the magnetic spindles and will be useful for retrofitting existing machine tools for tool path error minimization.

ERROR MINIMIZATION. In general, tool path error consists of machine tool errors and cutting force errors. These errors can be static and dynamic deterministic and/or stochastic. The machine tool static and dynamic deterministic errors can be quantified using a laser metrology system and put in the form of an error map for use in software correction. Cutting force errors are both static deterministic and stochastic and can be minimized by utilizing a magnetically controlled spindle and a control strategy which takes advantage of the spindles ability to tilt and translate, while continuing to rotate at high speeds.

ERROR MINIMIZATION METHODOLOGY. The University of Maryland in cooperation with Magnetic Bearings Incorporated, Cincinnati Milacron, Westinghouse, and the National Bureau of Standards has undertaken a program to implement an error correction methodology in a vertical machining center. The strategy is to utilize an experimentally determined error matrix of a test machine, along with models of cutting force errors, and to implement a corrective control scheme to significantly reduce overall part errors in thin rib machining.

A control scheme as shown in Figure 11, is the proposed block diagram for control of a magnetic bearing spindle. This scheme, although still being refined, will take the overall machine error matrix and cutting force model data and adjust the spindle location (both translation and tilt) in order to minimize the instantaneous overall tool path errors. The research currently involves the following activities:

- generate static and dynamic tool path error maps in end milling operations
- Expert system for deterministic tool path errors
- develop an expert system for stochastic error correction
- develop and implement control algorithms for controlling magnetically suspended spindles to minimize tool path errors
- experimentally test and validate models and algorithms using a CNC vertical machining center fitted with a magnetically suspended spindle.

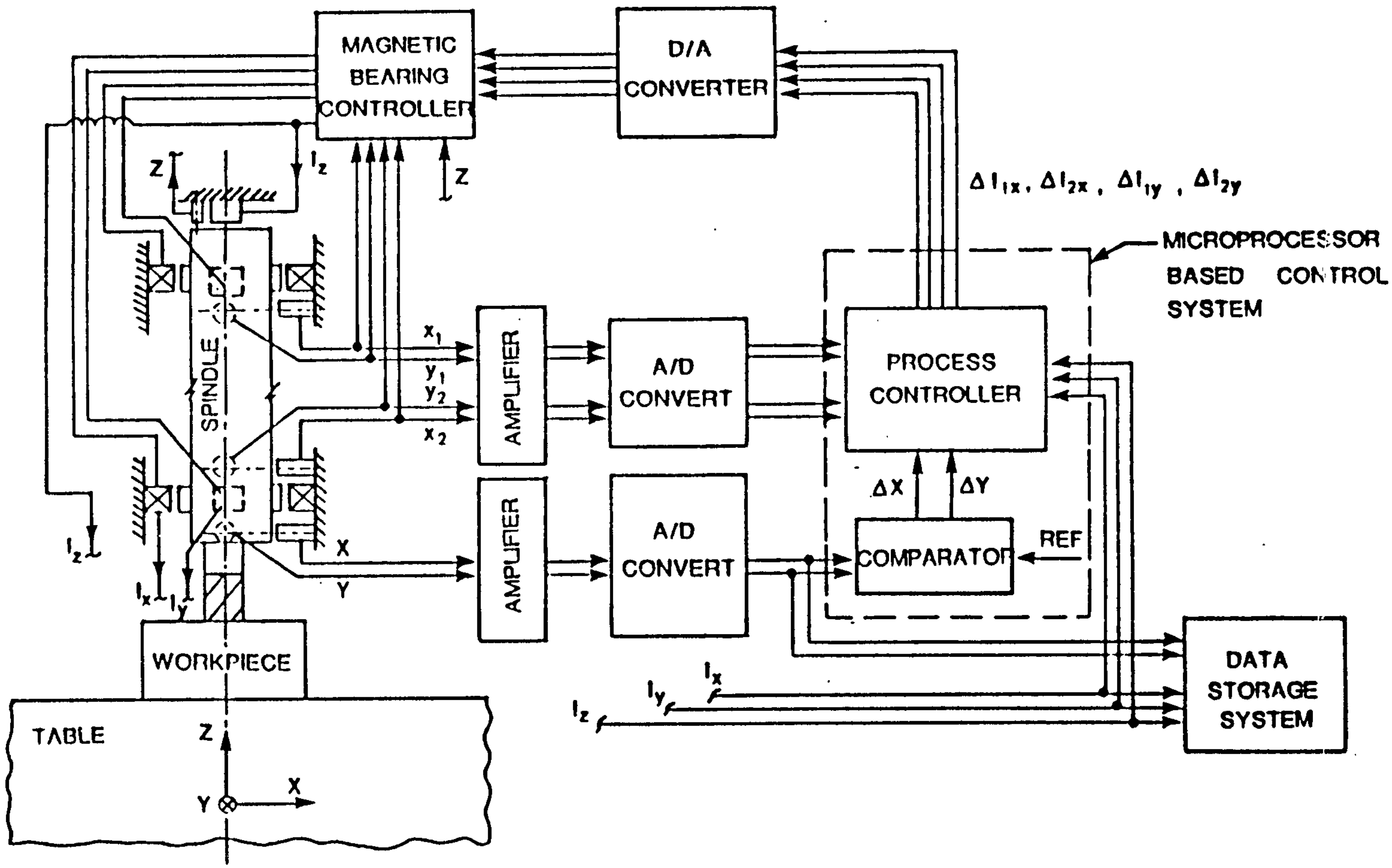



FIG.11 EXPERIMENTAL SETUP FOR TOOL PATH ERROR MINIMIZATION IN END MILLING

## THE FLEXIBLE MANUFACTURING CELL

**The present work is concerned with the development and implementation of a flexible manufacturing protocol for automated machining. Of specific interest is the machining of prismatic parts in a flexible manufacturing cell as shown in the flowchart of Fig. 12 and 13.**

The flexible manufacturing cell involves providing design input via a computer aided design (CAD) environment, an expert system for establishing manufacturability of the design, an intelligent process planning module for optimal component machining, standardization of the design data base in an IGES format, automatic generation of machining codes and, finally, the downloading of machining codes to the computer numerical control (CNC) machine, where the manufacture of the designed part occurs.

The DESIGN part of the software allows the user to sketch the part interactively with the aid of three basic entities - Point, Line, Arc, and four special entities - Rectangular frame, Rectangular pocket, Circualr pocket, & Drill hole. These entities are also supported by the Dynamyte 2200 CNC machine on which this work has been implemented. The EDITOR allows the designer to add, delete, or modify any entity to enable him to make any changes in his design.

Once he has the acceptable design in front of him the design data base is generated in IGES format. This feature is particularly useful and enhances the flexibility of this work by allowing the designer to sketch his part using some other commercial CAD software having an IGES translator, and not be limited to the inbuilt computer aided design software for designing his part.

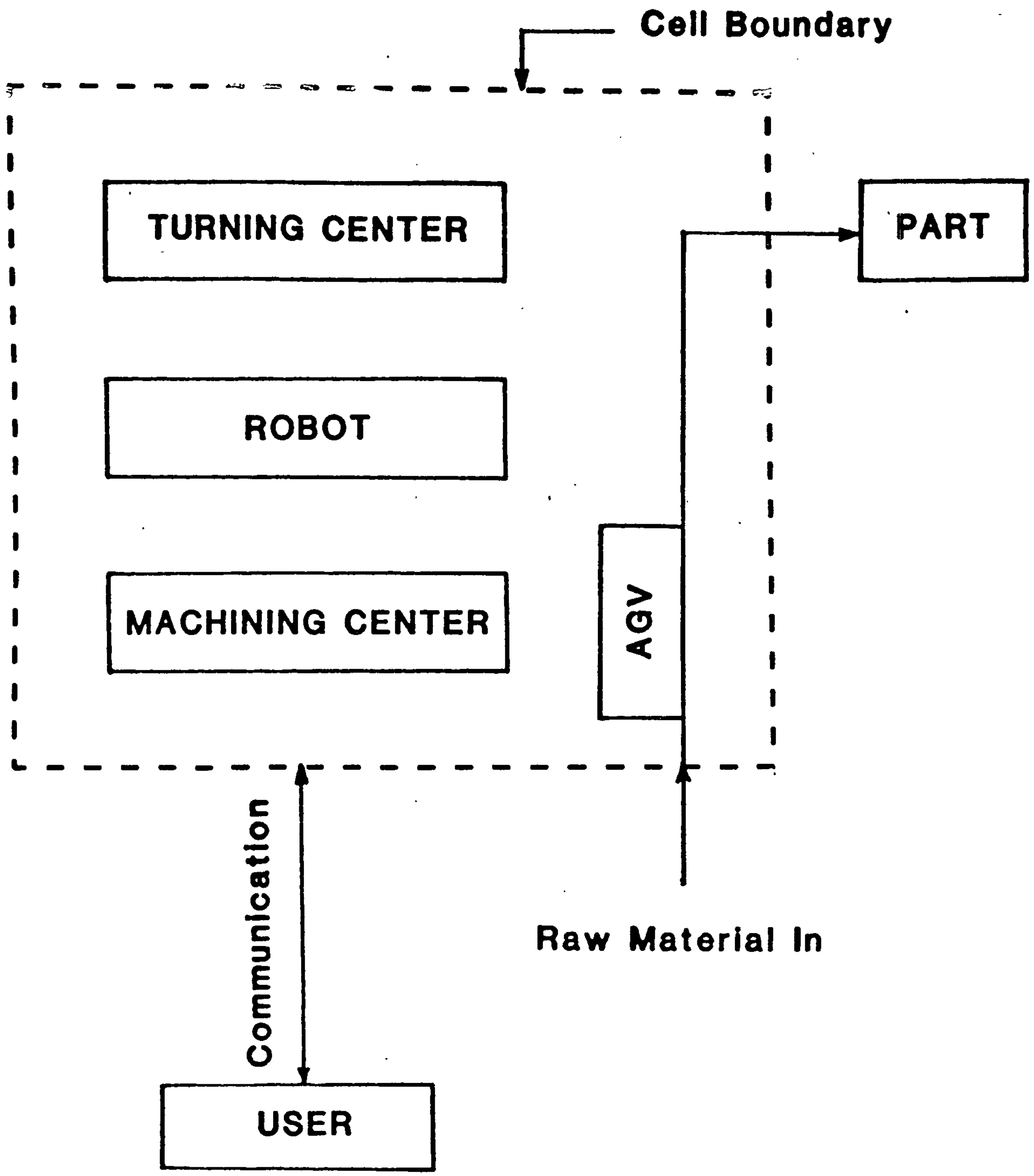
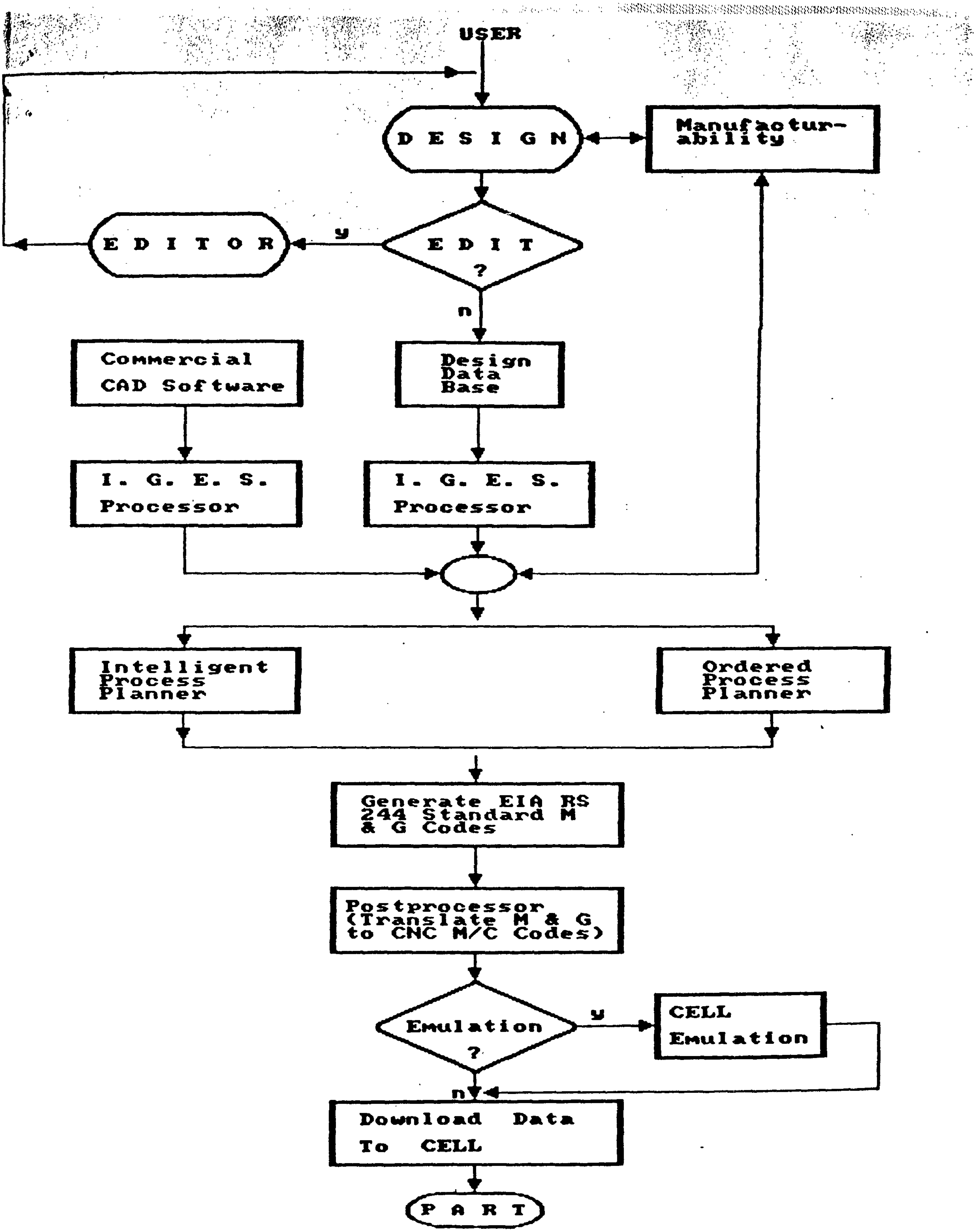



FIG. 12
**Flexible Manufacturing Cell**


USER
DESIGN
Manufacturability
EDIT ?
y
EDITOR
n
Commercial CAD Software
Design Data Base
I. G. E. S. Processor
I. G. E. S. Processor
Intelligent Process Planner
Ordered Process Planner
Generate EIA RS 244 Standard M & G Codes
Postprocessor (Translate M & G to CNC M/C Codes)
Emulation ?
y
CELL Emulation
n
Download Data To CELL
PART

# INTELLIGENT CELL

- **Manufacturability**
- **Accuracy Enhancement**
- **Interfacing**
- **Emulation**
- **Intelligent Process Planning**
- **Protocal Standardization**

After the PROCESS PLANNER has determined the most optimal sequence of processes for machining the part, the design data base is translated to standard M & G codes containing all information regarding the part topology, and machining parameters such as tool diameter, spindle speed, feed and the depth of cut. The generation of M & G codes also enhances the flexibility of this work as most of the large computer numerical controlled machine tools being made today are able to understand M & G codes besides having their own language. The M & G codes are generated in a user defined sequential file and can be saved for future use.

There is a second postprocessor which translates the M & G codes into DYNA language. The second stage of postprocessing is required since the Dynamyte 2200 on which this work is implemented only accepts Dyna language codes. The Dyna codes are also generated in a user defined sequential file and can be saved for future use.

The Dyna codes are downloaded from the computer on to the Dynamyte 2200 CNC machine through a RS232 standard serial interface port at 2400 band rate. The part is then cut by the CNC machine to the designer's specification.

## AN IGES TO N/C TOOL INTERFACE

The introduction of the Initial Graphic Exchange Specification (IGES) by the National Bureau of Standards and the use of existing standard numerical control machine codes (M & G codes) has paved the way for a standardized interface between computer aided design (CAD) and numerically controlled (N/C) manufacturing. At present we are working to develop such an interface for the special case of 3-axis (2-1/2 D) milling using IGES files for geometric input and producing M & G code output. An example of the input is shown in Fig. 14 and 15. When the interface is completed, the part to be machined can be designed on any CAD system that can produce IGES files and produced on any N/C milling machine that can accept standard M & G codes.

The emergence of the micro-computer along with the development of excellent CAD software for these systems has brought sophisticated design capabilities to even the smallest companies. Likewise, low cost numerically controlled machines are becoming common. In accordance with these developments our interface is being programmed on the IBM PC in the BASIC language. This approach brings advanced CAD/CAM to the cottage industry level. In the near future an effective CAD/CAM system may be available for the price of a premium micro-computer.

While there are many systems available to interactively develop tool paths for machining, very few are automatic. This is particularly true of micro-computer systems. Because of this, our system is going to be designed to be as automatic as possible. At present only certain machining parameters such as tool diameters and feeds and speeds are expected to be user supplied.

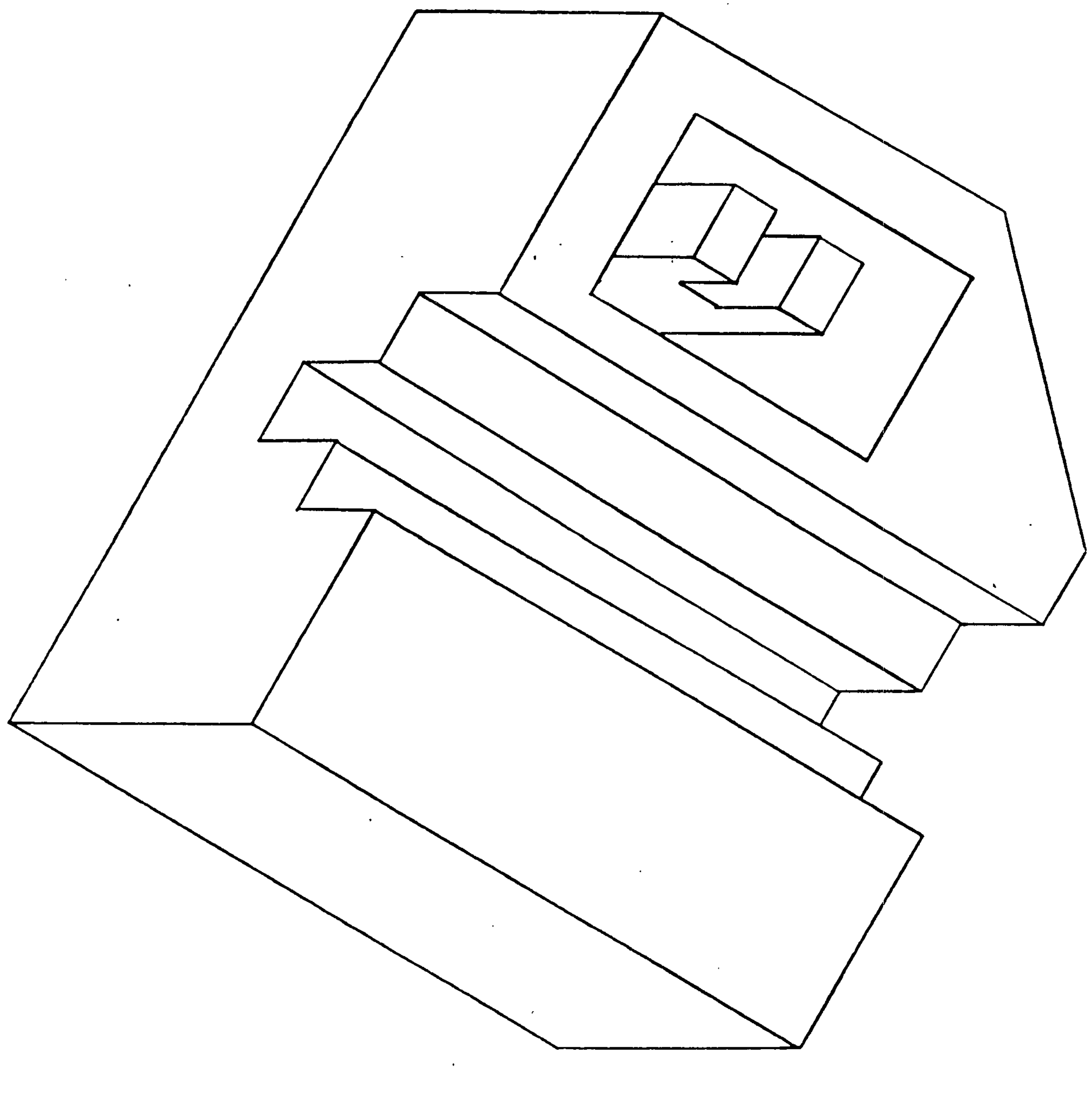


FIG. 15

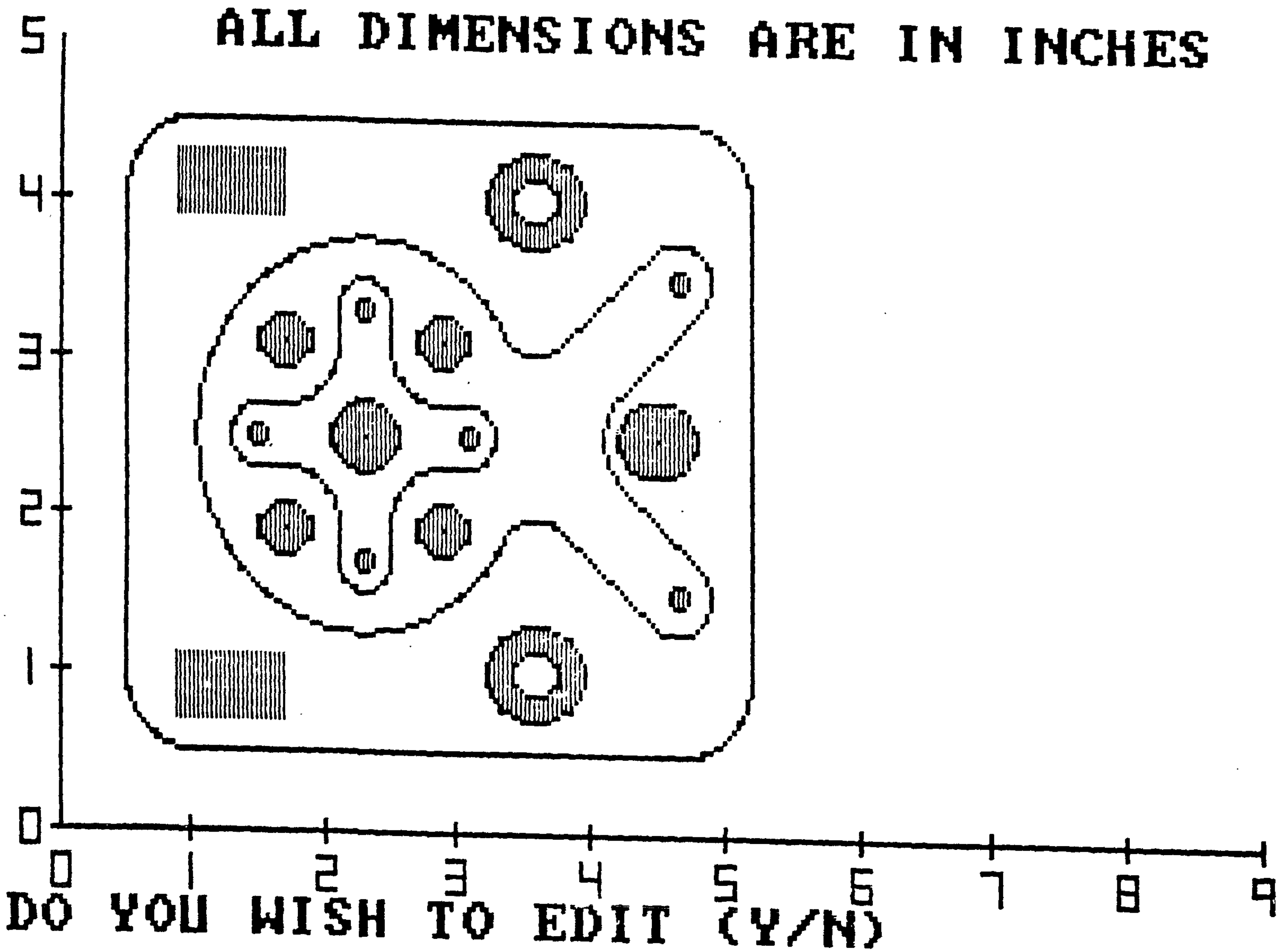

ALL DIMENSIONS ARE IN INCHES
0
1
2
3
4
5
6
7
8
9
DO YOU WISH TO EDIT (Y/N)

FIG. 14

Eventually, these user inputs may also be eliminated with the application of expert systems technology. The interface will automatically pick out the features to be milled from the geometric input and develop a plan to mill these features. Therefore, the core of the interface will be a feature extractor and feature planner. These modules will be bounded by an IGES converter at the top end and an M & G code generator at the bottom end. This is the general structure of the interface.

At present the feature extractor is almost completed. The next step will be the feature planner. A report has been prepared on IGES concentrating on those aspects relevent to this project. Work on the IGES converter will begin when a method of transfering the files from the VAX, our CAD system, to PC disk files is found. The M & G code generator will be developed after the feature planner is completed.

## AI PROCESS PLANNING

Currently, the process planner is a link between the design and manufacturing of any product. The information about the part to be manufactured is traditionally given in the form of a set of engineering drawings. The manufacturing features are then manually interpreted and the corresponding processes outlined. In a computerized CAD/CAM system, the equivalent function can be carried out by an expert system which has been taught with the heuristic rules that are involved.

This research consists of establishing a 3-D feature extractor which uses the given data on part geometry to decompose the workpiece into a set of primitive geometric features. The various problem areas investigated appear in Table 1. The output from the feature extractor will become an input to an expert system which will outline the required machining processes. The knowledge base for this expert system will include manufacturability information regarding each machinable primitive geometric feature and it will be able to generate a set of processes for machining these primitive features on an automated machining center in accordance with Fig. 16.

To carry out the above steps, one would start with a part drawing file (prepared by the designer by using a CAD package) represented in the standard IGES format. The feature extractor would read this file and create a linked list of faces, edges and vertices which will represent the complete topology of the part. The 3-D features will then be recognized by applying rules that test for predefined patterns which may exist within this linked list. The faces corresponding to the recognized feature will then be removed from the

TABLE -1

| | Geometric Modeler/ CAD Package | Feature Extractor | Automatic Process Planner | N/C Code Generator |
|---|---|---|---|---|
| Armstrong | X | | | X |
| Kyprianou | | X | | |
| Henderson | | X | | |
| Woo | | X | | |
| Grayer | X | | | X |
| PADL | X | | | |
| CDC Model | X | | | |
| SIPP | | | X | |
| **Proposed Work** | **X** | **X** | **X** | **X** |

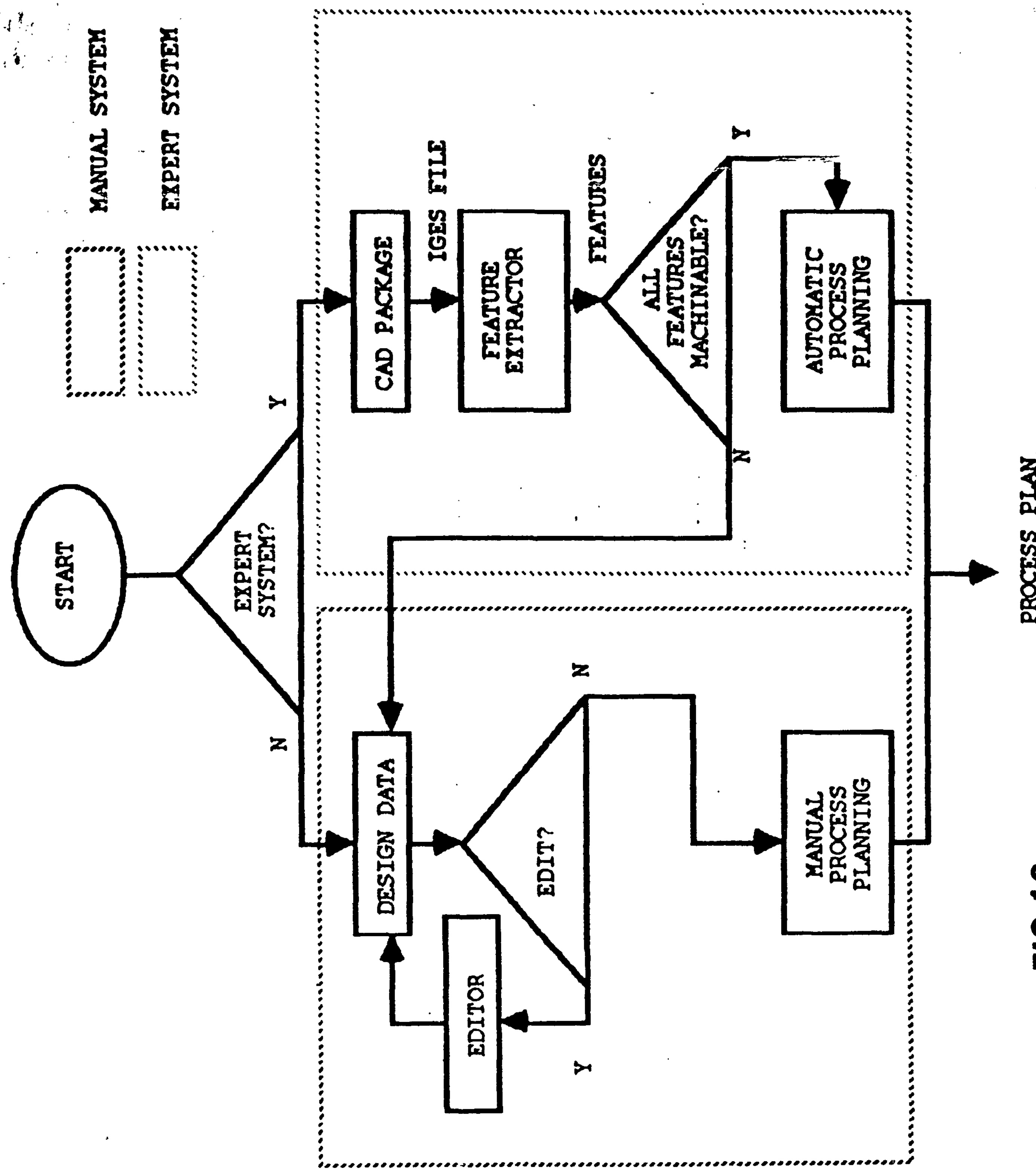

MANUAL SYSTEM
EXPERT SYSTEM
START
EXPERT SYSTEM?
Y
N
CAD PACKAGE
IGES FILE
FEATURE EXTRACTOR
FEATURES
ALL FEATURES MACHINABLE?
Y
N
AUTOMATIC PROCESS PLANNING
DESIGN DATA
EDIT?
N
Y
EDITOR
MANUAL PROCESS PLANNING
PROCESS PLAN

FIG.16

data base and set aside. Proceeding on a surface by surface basis, the above steps will be recursively applied until there are no more surfaces left. This is illustrated in Fig. 17. We note that before finalizing the feature extractor, an iterative procedure will be carried out to ensure that the selected primitive features are the optimum ones.

Once all the features have been identified, the expert system for process planning will proceed on a feature by feature basis and test given constraints (e.g., tolerances) for the machinability of each feature. It will then outline a sequence of processes that need to be carried out to manufacture the part. A translator can then be used to generate the necessary NC tool path which can be downloaded to the automated machining center.

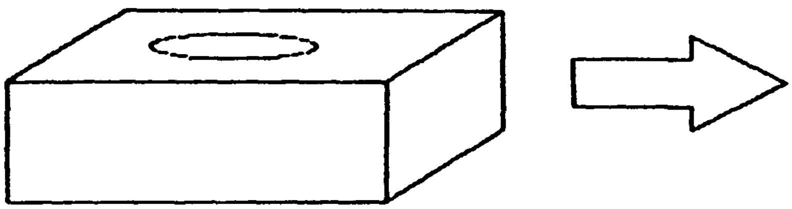
The current thinking is briefly summarized as follows:

- Previously, the emphasis has been on isolated aspects of the problem (e.g., CAD, feature extraction or process planning). Here, an attempt is being made to obtain an integrated system.
- Previously, the emphasis has been on developing algorithmic approaches to solving the problem. Many existing automatic process planners are hand-crafted tools that are very difficult to modify by the user because of poor transparency inherent in such an approach. Here, an attempt will be made to use heuristic rules that offer better performance and transparency.
- A 'Mark-1' version will be created first. It will then be refined continuously in order to improve the knowledge base.

FIG. 17

# STEPS FOR AUTOMATIC PROCESS PLANNING

(1) START WITH THE LIST OF FEATURES OUTPUT BY THE FEATURE EXTRACTOR



THE ONLY FEATURE IS HOLE S7

(2) APPLY RULES TO DETERMINE IF THE INDIVIDUAL FEATURES SHOULD BE MACHINED IN A PARTICULAR ORDER OF PRECEDENCE.

(3) SEARCH THE MANUFACTURING KNOWLEDGE BASE TO PICK OUT THE RELEVANT MACHINING PROCESSES FOR AN INDIVIDUAL FEATURE.

(4) TEST THE CONSTRAINTS (E.G., TOLERANCES) TO DETERMINE THE MACHINABILITY OF THE INDIVIDUAL FEATURE.
(EXAMPLE: A CENTER DRILLING OPERATION, FOLLOWED BY FINISH DRILLING MAY BE INDICATED FOR THE ABOVE HOLE FEATURE.)
OUTLINE THE SEQUENCE OF THE INDIVIDUAL PROCESSES IN A PROCESS PLAN.

(5) RECURSIVELY APPLY THE PREVIOUS TWO STEPS TILL NO MORE FEATURES ARE LEFT.