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THE CDF FIELD MAPPING DEVICE - "ROTOTRACK"

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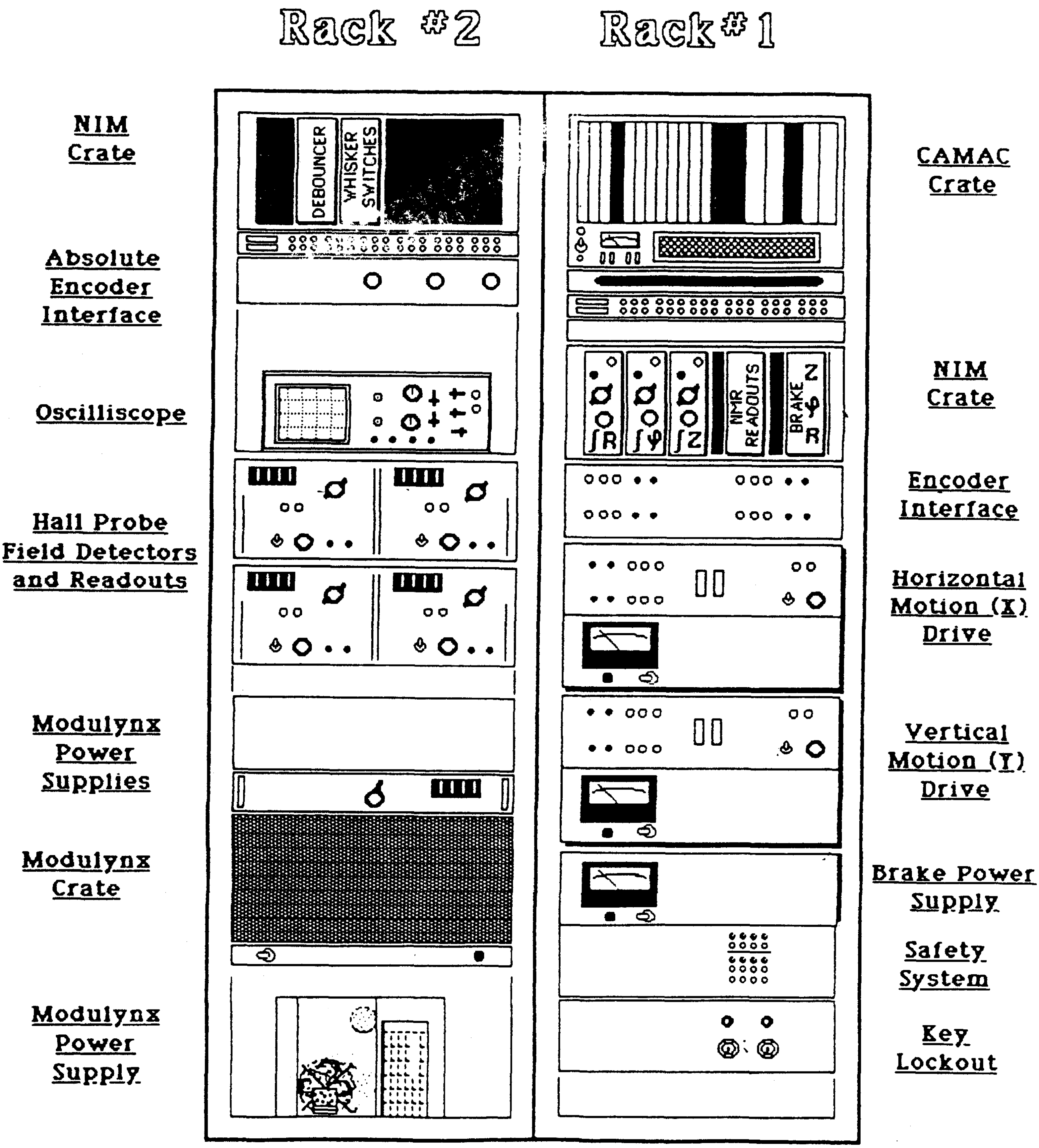

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August 1, 1985

Abstract

A field mapping device for the magnet of the Collider Detector at Fermilab (CDF) was constructed. The device was used for extensive study of the CDF magnetic field distribution. The mechanical and electrical features of the device, as well as the data acquisition system and software, are described. The mechanical system was designed so that the errors on the position and angle of the probe were ± 0.75 mm and ± 1 mrad, respectively.

I. Introduction

The central part of the CDF detector is structured by a 2000 ton magnet[1] which is excited by a superconducting solenoid[2]. The magnet is composed of the outside return yoke, an end plug at each end and the superconducting solenoid. The central magnetic volume is about 3 meters in diameter and 4.5 meters long. This volume has a fairly uniform magnetic field except near the openings to the end plugs. The fringing field volumes inside the end plugs are conical in shape, and the magnetic field is drastically changing, as shown by a computer calculation[3].

In order to do accurate field mapping, the magnetic field probe should be moved steadily and accurately inside the magnetic field volumes. Therefore, a mechanically stable manipulator is required. To achieve this mechanical stability, many new, light, and strong materials, some made commercially and some made at Fermilab, were developed and used. Carbon fiber material and aluminum honeycomb were used to reduce weight while keeping strength.

In April, 1985, the magnet was turned on for field measurement. The magnetic field measurement data for the CDF magnet are presented elsewhere[4].

II. The "ROTOTRACK" Manipulator

The general mechanical features of the mapping device are shown in Figure 1. The major components are the base, the upper and lower carriages, the long cantilevered beam, the rotor, the shuttle and the sensing elements. The whole system is designed with the philosopy that the sensing elements (search coils) can be placed with positional accuracy of 0.75 mm in space coordinates and angular accuracy of ± 1 mrad.

The sensing elements are moved three-dimensionally in cylindrical coordinates. The coordinate system is shown in Figure 2. On a long fixed base, a carriage composed of lower and upper parts moves in the z direction parallel to the axis of the solenoid. A 20 ft. long beam made of carbon fiber is attached to the carriage and a rotor is at the end of the beam. The rotor is rotated azimuthally around the axis of the magnet.

A shuttle which carries the probe is moved radially along the rotor. These three-dimensional movements, radial, azimuthal and longitudinal are carried out with stepping motors and a MODULYNX controller, manufactured by Superior Electric Co.

The upper carriage may be moved vertically relative to the lower carriage using front and back jacking mechanisms. It may also be moved horizontally using front and back sliding mechanisms. Using these, the z axis of the measuring device is made to be coincident with that of the magnet and the plane of rotation of the rotor is made orthogonal to the z axis.

The base is made of two long I-beams and a top plate, welded together with bulkhead plates. It was annealed and stress-relieved. Two parallel 2 in. x 2 in. steel bars were welded on the top plate and their surfaces were machined. Attached to the machined surfaces were rails to carry precision linear bearings NSK20TBC2UU by THK in Japan. With this setup, a positioning accuracy of ± 5 mils (±0.13 mm) was achieved over the whole length.

The cantilevered 20 ft. long beam is made of top and bottom carbon fiber U-channels and two carbon fiber honeycomb side plates glued together with six bulkheads made of the same U-channel. The U-channels are 3/8 in. thick and 6 in. wide, made with prepregnated unidirectional Fortafil 5 manufactured by Great Lakes Carbon. They were pressed and cured by the 3000 ton press which had been used for curing coils for the Fermilab Tevatron. The side plates are constructed from 0.4 in. thick honeycomb structure "Floor 7 Type 3" by General Veneer Mfg. Co. in California. It is made with Nomex honeycomb and two sheets of carbon fiber plate, each with skin thickness of 14 mils.

Inside the beam there are two concentric aluminum tubes. One is used to rotate the rotor and the other to power the shuttle drive along the rotor. They are supported by five sets of three glass bearings inside the beam. At the end of the beam there is an aluminum casing which has 6 in. outer diameter copper-beryllium bearings, specially made by Bearing Mfg. Co. in Chicago.

To reduce the weight and still keep the rigidity of the rotor structure, 1 in. thick aluminum honeycomb board was used ("Blue Seal Sandwich Board" made by Hexcel). It has 20 mil thick aluminum skins over an aluminum honeycomb and its surface is quite flat.

The sensing elements were moved along each coordinate (r, z, ϕ) individually. The carriage is moved in the z direction at the speed of 2.5 in./sec. The rotor is rotated 360 degrees in 106 sec, corresponding to 3.3 in./sec at the end of the 110 in. long rotor. The shuttle is moved at the speed of 0.9 in./sec.

To reduce the effects of eddy currents in the materials, the use of thick aluminum plates near the sensing elements was avoided. Nonmetallic materials were also used as much as possible. The movement of the shuttle does not cause any eddy current effects because there are no big metallic moving parts. When the rotor is rotated in the fairly uniform central field region, the eddy current effects in the structure of the rotor, if any, are small. But when the carriage is moved in and out of the magnet, there will be small eddy currents flowing inside the rotor structure and the aluminum shafts. These could have some effect on the sensing elements at faster moving speeds than those normally used.

With the manipulator properly aligned, there is about one half inch clearance between the edge of the rotor and the cryostat wall. To protect the rotor from hitting the magnet, two types of safety interlocks are installed on the ends of the rotor. One is a microswitch with an extended arm. The "Type V3 Miniature Basic Switch V3-129" by MicroSwitch, made of all nonferromagnetic material was used. The other is a home-made proximity switch with a whisker.

III. Sensing Elements

A search coil system with three components was used to measure the magnetic field in three dimensions. The search coil assembly is identical to that used for the Fermilab ZIPTRACK field mapping device[5]. The output voltages of the search coils are integrated by individual integrators and the resultant voltages, which are proportional to the field changes, are sent to an ADC in a CAMAC system.

The sensitivity of the field measurement could be varied by changing the integrator time constants. In the central region, the axial field (B_z) was measured to a precision of a few Gauss (less than 0.1% of the operating field of 15 kG). In the end plug regions, B_z was measured with errors on the order of 25 Gauss. The radial and azimuthal components were measured to within a few Gauss.

Ideally the axes of the three component coils should be orthogonal to each other, and the z axis should be parallel to the z axis of the solenoidal magnet. But in reality, there are some errors in their orthogonality and in the alignment of the axes. There is also some imperfection in the radial motion of the rotor and some wobbling in the transit of the shuttle. These imperfections introduce fictitious radial and azimuthal field components from the huge axial component. If the z axis of the search coil is tilted by α, then the apparent radial or azimuthal components are on the order of αB_z. If B_z is 15,000 Gauss and α is 1 mrad, then the error is 15 Gauss.

In the central uniform field region, an NMR probe was used to get more precise field values. The NMR probe gave the magnitude of the absolute field values to less than 1 Gauss. This is essentially the same as the z component of the field as B_r and B_ϕ are typically less than or on the order of $10^{-3} \times B_z$. During the measurement a second NMR probe was mounted on the inside surface of the west end plug and used to monitor the field at a fixed point for normalization purposes.

IV. Data Acquisition and Control System

Data acquisition and manipulator motion control were handled by an IBM-PC interfaced to CAMAC via a TRANSIAC Model 6002 crate controller and a matching expansion board in the IBM chassis. In addition the MODULYNX stepping motor controller was commanded by the PC through a CAMAC GPIB interface module. The IBM-PC was used only for primary data acquisition and system control. Raw data were transferred to a VAX-780 for further analysis. Figures 3, 4, and 5 show block diagrams of the system.

The IBM-PC was configured with two 360 kbyte floppy disk drives, 640 kbyte of memory (much of which was used as a fast "RAM" disk), a color graphics board, the CAMAC interface board, a parallel printer port, and an RS-232 serial communications port to link the PC to the Fermilab Port Selector for access to other computers. The only peripherals were an AMDEK 300A video monitor and an EPSON FX-80 printer.

Motions of the shuttle, rotor, and carriage were accomplished by individual SLO-SYN stepping motors through the MODULYNX controller. One high power MODULYNX motor driver was needed for the large carriage stepping motor while two smaller MODULYNX drivers were used for the shuttle and rotor.

The alignment axes (front and back jacks and front and rear slides) used to align the upper carriage were powered by four separate SLO-SYN stepping motors. These motors were controlled by the combination of JOERGER SMC-24P CAMAC stepping motor controllers and drivers originally designed and built by Fermilab for the TEV-1 magnet measurement project.

Except during movement, the axes drives were locked in placed by electrically actuated brakes. The individual brake interfaces were controlled through bits in a CAMAC output register. The system contained a number of motion limit switches interlocked to the brakes and motor driver power supplies. The status of these bits could be queried through the PC via a CAMAC input register.

Positions of the various axes were read by a variety of different (and sometimes redundant) encoders. The carriage and rotor were monitored with BEI Electronics, Inc. absolute rotary encoders. The outputs of the absoulte encoders were directly read into input registers as binary values. The radial position of the shuttle was marked at a series of fixed points by an arrangement of a microswitch on the shuttle and a precision notched rail. The output of the microswitch was monitored through both a CAMAC up/down counter and an input register. All axes including the alignment axes were also monitored by incremental encoders pulsing into CAMAC up/down counters (Kinetic Systems model 3640).

The output of the search coil integrators, a magnet current transductor, and analog Hall probe voltages were fed into a multi-channel "simultaneous sample and hold" ADC, Lecroy CAMAC Model 8212A/32. The BCD outputs from the two NMR probes were put into Joerger quad input register CAMAC modules.

V. Software

The IBM-PC was operated under DOS 2.1 and the main controlling program was written in IBM/MS BASIC. To obtain sufficient operating speed, the program was compiled and linked to an assembly language CAMAC driver supplied by TRANSIAC. The driver was modified to more conveniently support compiled BASIC and 24 bit CAMAC data transfers (the supplied driver only handled 16 bit data transfers). A single call to CAMAC took about 0.3 msec. The software and IBM-PC operated very reliably with virtually no down time for either system crashes or hardware failure during the first mapping of the CDF solenoid (a run time of about a month).

The software was designed to be easy to use and quick to learn and to prevent (or allow correction of) as many operator mistakes as possible. Data were taken under operator command with one command necessary for each sweep of one of the three principal axes of the manipulator. A map of 2000 points on the surface of a 2.4 m diameter by 3.8 m long cylinder took about 8 hours and generated about 160 kbytes of character information on the PC. That amount of data took 7 minutes to transfer to a VAX-780 over the RS-232 serial port using KERMIT[6] software running at 9600 baud.

Within the limitations of BASIC, the software was structured as shown in Figure 6 with the corresponding logical program flow shown in Figure 7. Much of the software was devoted to setup and system checkout. Constants and calibrations were read from a data file to eliminate the need for program recompilation for minor system changes. Run dependent parameters were stored and recalled for the operator so that only changed parameters needed to be entered. All CAMAC modules were checked for response in the initialization phase of the software. The Camac up/down counters needed to be reset each time the hardware system had been powered off. For these, the software recalled from a "last state" file suggested values that could be overwritten by the operator.

After initialization and setup, the software was "command" driven, either by operator keyboard commands or by commands stored in a file. In practice, the majority of runs were done using operator entered commands only. Figure 8 shows possible system commands. The main data command allowed the operator to specify for one of the principal axes a start point, stop point, and sampling interval. Most data were taken by sweeping the rotor through 360 degrees, taking data every 10 degrees. The carriage would then be moved to a new z position and another sweep of the rotor taken. Since the primary probes (search coils) measured only relative field changes, data sweeps with the carriage (z) and the shuttle (r) were also needed to tie all the data points together along with normalization values from either the NMR probes or the Hall probes.

VI. Conclusion

A new magnetic field mapping device designed to map large volumes has been built. The probe manipulator for this device moves naturally in cylindrical coordinates ing rise to the nickname "ROTOTRACK". One advantage of this manipulator is its long cantilevered support beam that eliminates the need for supporting structures at both ends of the volume to be mapped. The ROTOTRACK magnetic field mapping device has been successfully used for the CDF solenoid magnet and is continuing to undergo refinement.

Acknowledgements

We appreciate the helpfulness we received from the Fermilab Magnet Test Facility group during the construction and testing of this equipment. We especially acknowledge E. Schmidt for the NMR system.

References

1. Design Report for the Fermilab Collider Facility, August, 1981; J. Grimson et al., "Magnetic Structure of CDF Central Detector", Proceedings of the 1983 International Accelerator Conference at Fermilab.

2. Design Report for an Indirectly Cooled 3-m Diameter Superconducting Solenoid for the Fermilab Collider Detector Facility, Fermilab TM1135, October, 1982; R.W. Fast, et al. "Testing of the Superconducting Solenoid for the Fermilab Collider Detector", Fermilab TM-1334, July, 1985.

3. R. Yamada, "Magnetic Field Calculation on CDF Detector (I)", Fermilab TM-1162 and CDF Note No. 150, January 20, 1983.

4. R. Yamada, C. Newman-Holmes, and E. E. Schmidt, "Magnetic Field Measurement of CDF Magnet", Fermilab TM-???? and CDF Note No. 346, August, 1985.

5. R. Yamada, et al., Nucl. Inst. and Meth. 138, 567 (1979).

6. KERMIT is a file transfer protocol program developed at the Columbia University Center for Computing Activities.

List of Figures

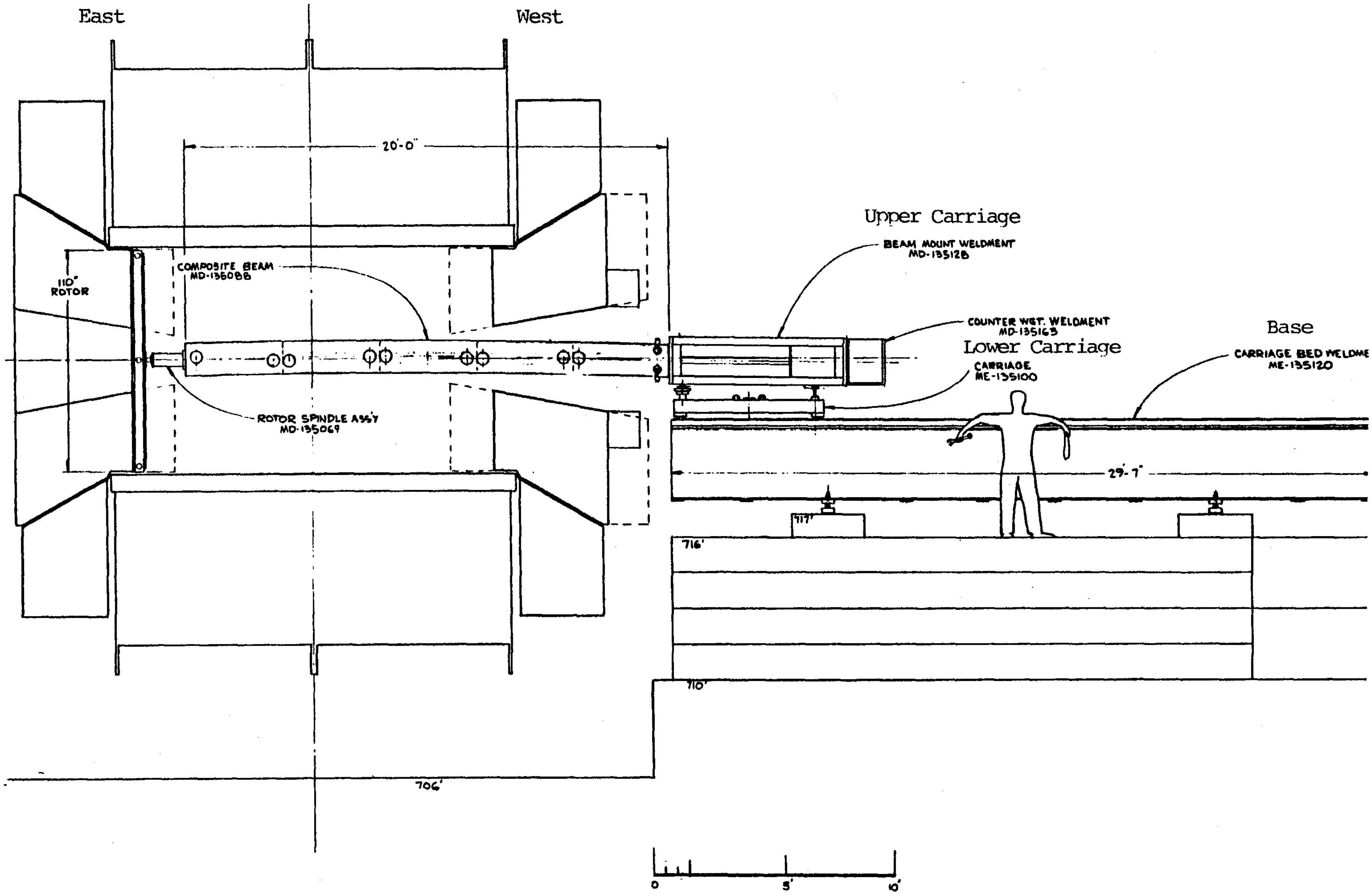
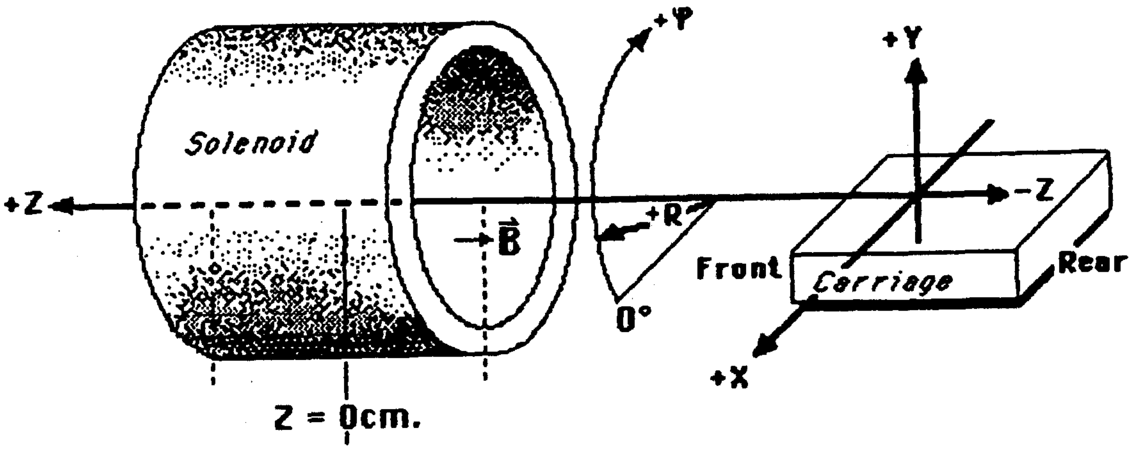


Fig. 1
CDF Field Mapping Device "Rototrack"



C. D. F. Coordinate System

Fig. 2

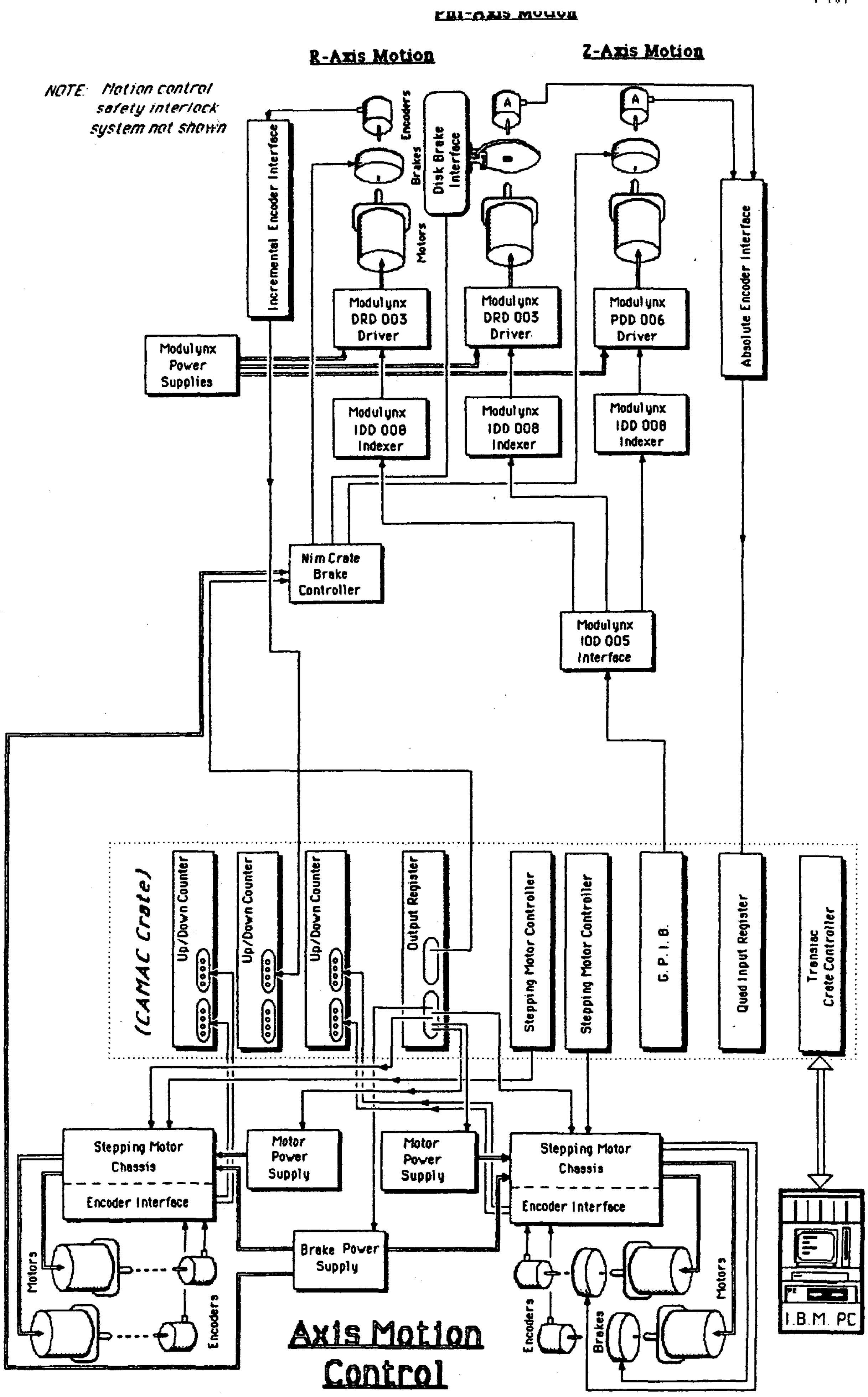

Phi-Axis Motion
R-Axis Motion
Z-Axis Motion
NOTE: Motion control safety interlock system not shown
Incremental Encoder Interface
Encoders
Brakes
Motors
Disk Brake Interface
A
A
Absolute Encoder Interface
Modulynx DRD 003 Driver
Modulynx DRD 003 Driver
Modulynx PDD 006 Driver
Modulynx Power Supplies
Modulynx IDD 008 Indexer
Modulynx IDD 008 Indexer
Modulynx IDD 008 Indexer
Nim Crate Brake Controller
Modulynx IOD 005 Interface
(CAMAC Crate)
Up/Down Counter
Up/Down Counter
Up/Down Counter
Output Register
Stepping Motor Controller
Stepping Motor Controller
G. P. I. B.
Quad Input Register
Transiac Crate Controller
Stepping Motor Chassis
Encoder Interface
Motor Power Supply
Motor Power Supply
Stepping Motor Chassis
Encoder Interface
Brake Power Supply
Motors
Encoders
Encoders
Brakes
Motors
I.B.M. PC
Axis Motion Control
Horizontal Motion
Vertical Motion

FIG. 4

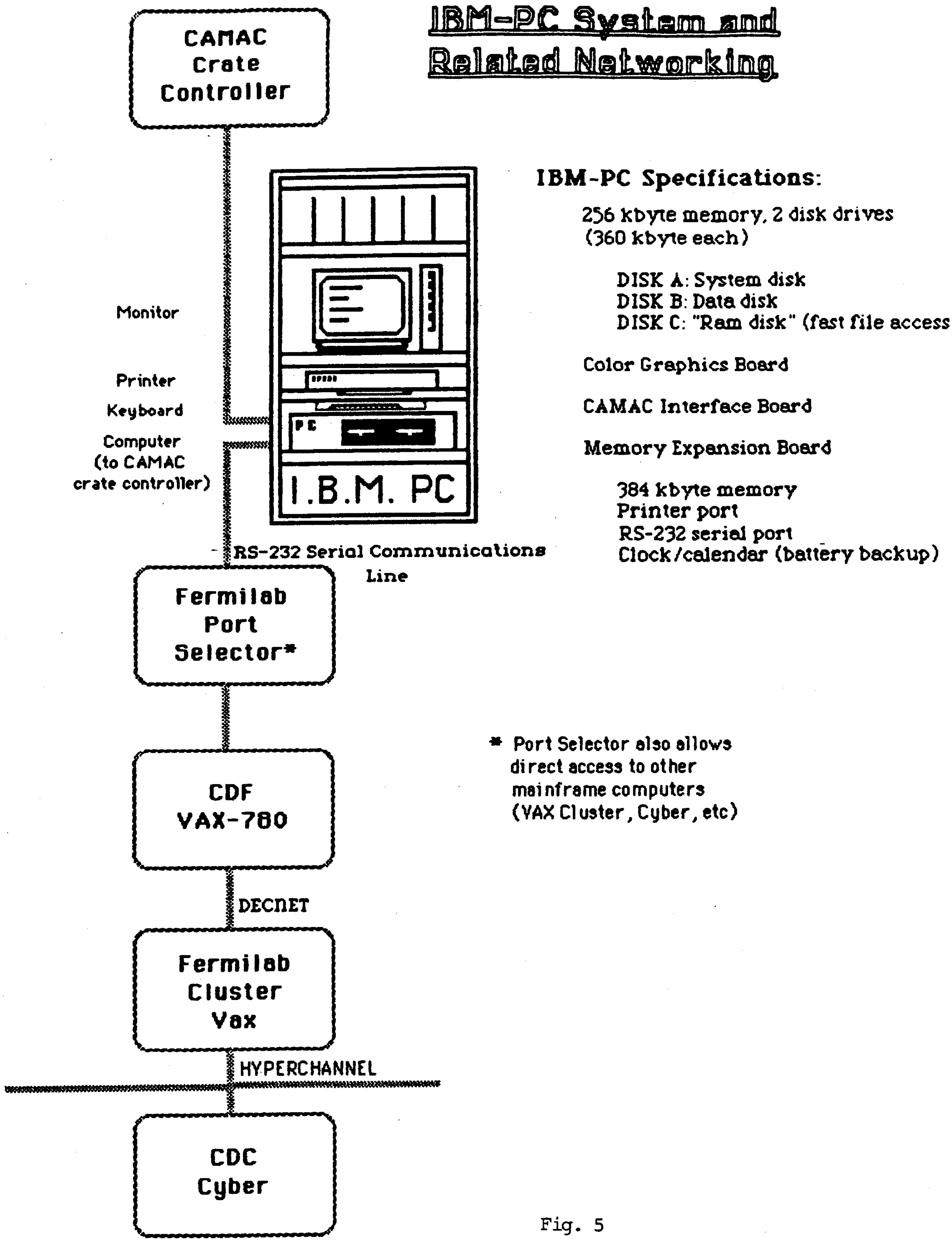

IBM-PC System and Related Networking
CAMAC Crate Controller
Monitor
Printer
Keyboard
Computer (to CAMAC crate controller)
I.B.M. PC
RS-232 Serial Communications Line
IBM-PC Specifications:
256 kbyte memory, 2 disk drives (360 kbyte each)
DISK A: System disk
DISK B: Data disk
DISK C: "Ram disk" (fast file access
Color Graphics Board
CAMAC Interface Board
Memory Expension Board
384 kbyte memory
Printer port
RS-232 serial port
Clock/calendar (battery backup)
Fermilab Port Selector*
* Port Selector also allows direct access to other mainframe computers (VAX Cluster, Cyber, etc)
CDF VAX-780
DECNET
Fermilab Cluster Vax
HYPERCHANNEL
CDC Cyber

Fig. 5

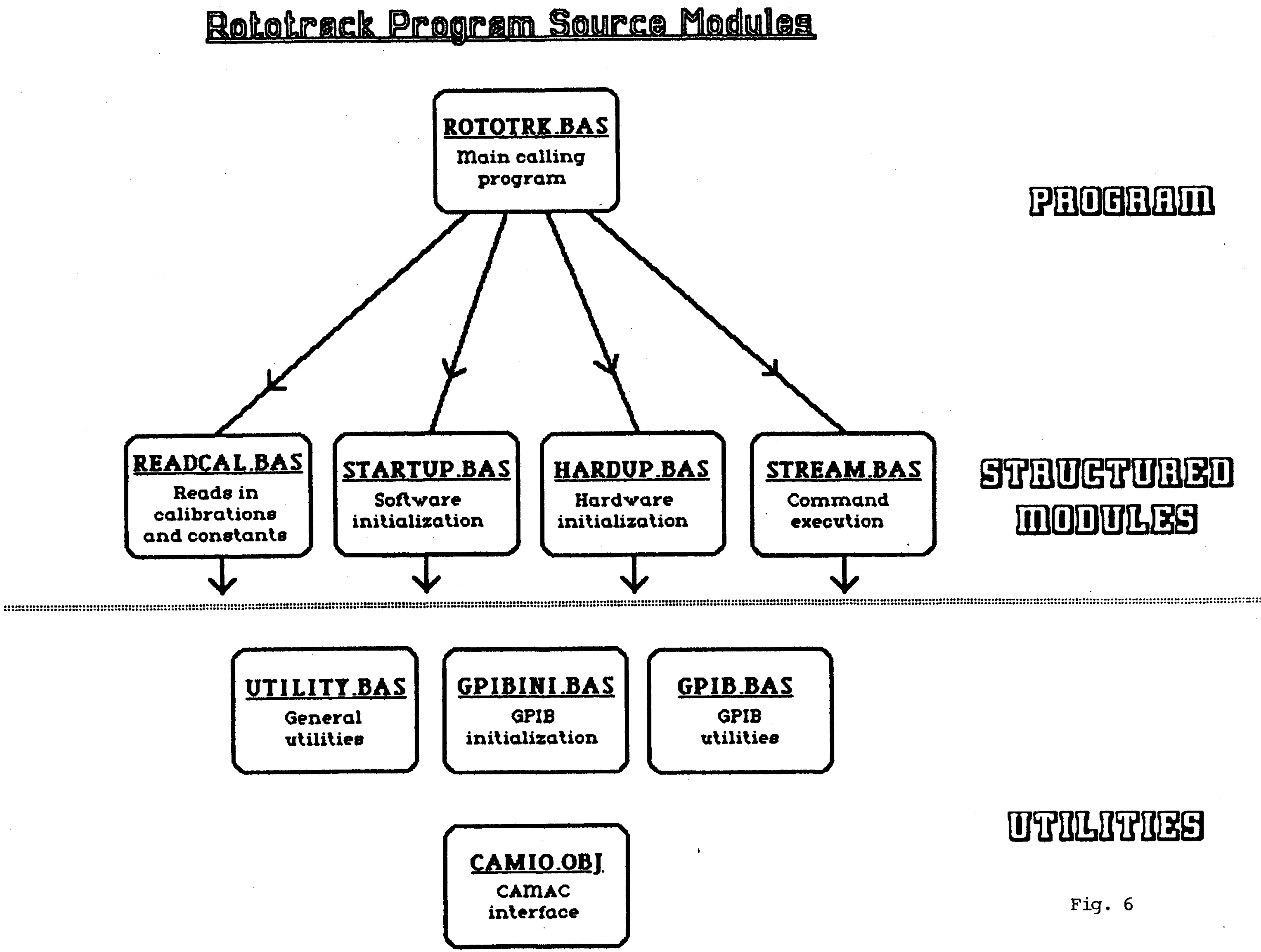
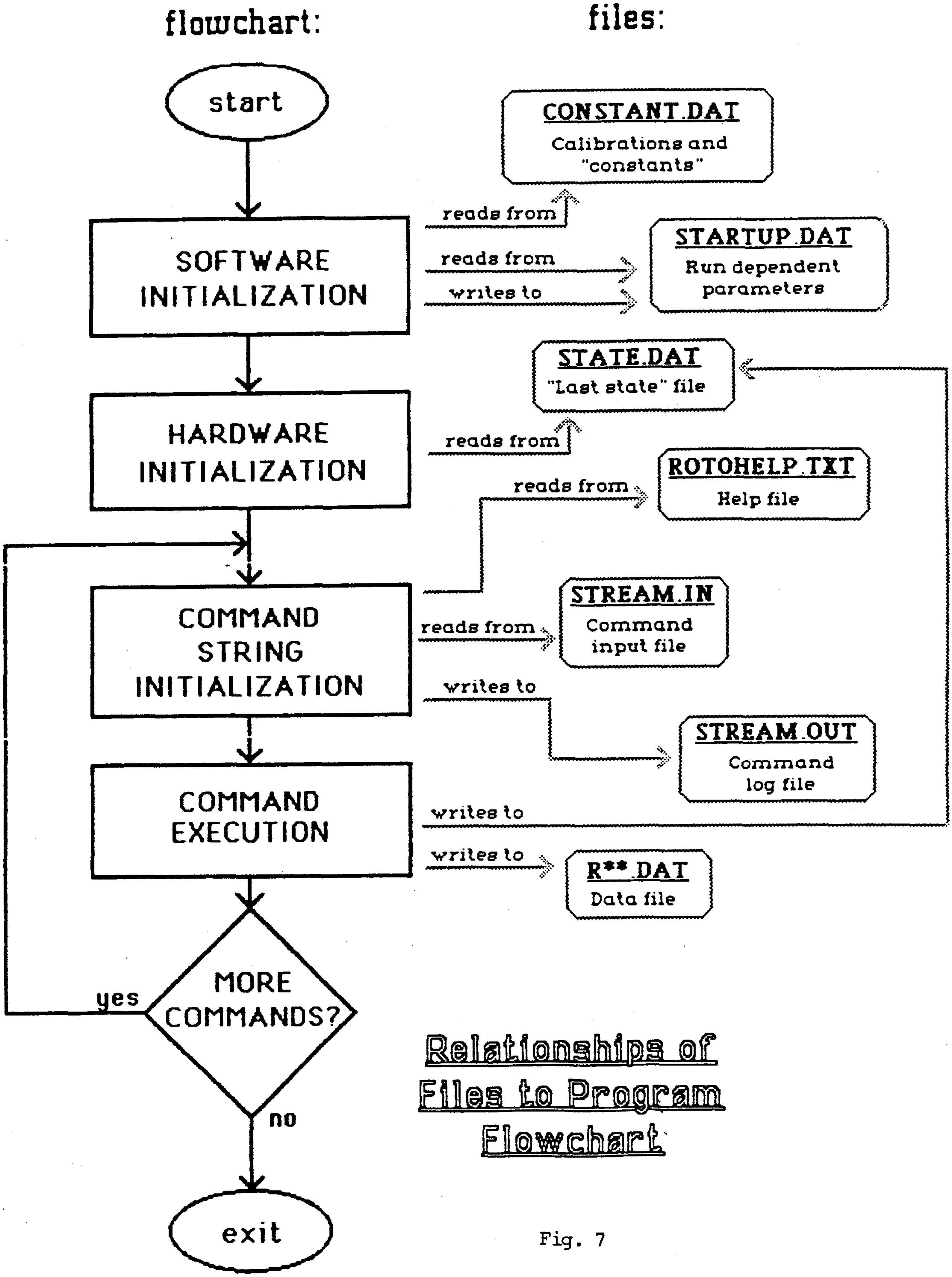

Rototrack Program Source Modules
ROTOTRK.BAS
Main calling program
PROGRAM
READCAL.BAS
Reads in calibrations and constants
STARTUP.BAS
Software initialization
HARDUP.BAS
Hardware initialization
STREAM.BAS
Command execution
STRUCTURED MODULES
UTILITY.BAS
General utilities
GPIBINI.BAS
GPIB initialization
GPIB.BAS
GPIB utilities
CAMIO.OBJ
CAMAC interface
UTILITIES

Fig. 6



Relationships of Files to Program Flowchart

Fig. 7

```
>>>>>>>>>>>>> LIST OF ROTOTRK COMMANDS <<<<<<<<<<<<<<<     April, 1985

     HELP => list HELP file
     Q  => Quit (only way out)
     KI => switch to Keyboard Input
     FI => switch to File Input
     S,STRING => Send string to MODULYNX
     P,AXIS,B,H,A => set motion Parameters for axis
     MI,AXIS,DISTANCE => Move Incremental for axis (cm or degrees)
     MA,AXIS,LOCATION => Move Absolute for axis (cm or degrees)
     R  => clear MODULYNX registers and Reload current parameters
     D  => Display system status (including interlocks and limits)
     DJ => Display Joerger status (also set brakes on, power off)
     SU => SetUp encoders, enter integrator gains, test read NMR and ADC
     PD => Print last Data run on line printer
     OD => Open Data file (and close any existing file)
     CM => add CoMment to data file
     LS,AXIS,DIRECTION => repeat Last Scan for axis in direction (+ or -)
     CD,AXIS,ENC TYPE,START LOCATION,LOCATION OF 1ST DATA POINT,INCREMENT,
        # OF POINTS,END LOCATION  => scan with Continuous Data

Allowed AXIS names: SHUTTLE, ROTOR, CARRIAGE, FS, RS, FL, RL, BS, BL.
FS = Front Slide, RS = Rear Slide, BS = Both Slides
FL = Front Lift,  RL = Rear Lift,  BL = Both Lifts
Allowed ENC TYPE: INC, MSW, or ABS (incremental, micro-switch, or absolute).

For CD command, only the following combinations should be used:
    CD,CARRIAGE,ABS,... (preferred)
    CD,CARRIAGE,INC,... (not preferred)
    CD,ROTOR,INC,...
    CD,ROTOR,MSW,...
    CD,SHUTTLE,INC,...
    CD,SHUTTLE,MSW,...
    **** CD,ROTOR,ABS,... should NOT be used! ****
If ENC TYPE is MSW, then location of 1st point and increment are in "notches".

In P command, B = Base speed, H = High (final) speed, A = Acceleration

>>>>>>>>>>>>> SAMPLE ROTOTRK COMMANDS <<<<<<<<<<<<<<<

     HELP   (list help file)
     Q    (Quit)
     P,ROTOR,400,400,500 (set ROTOR motion parameters to 400,400,500)
     MI,SHUTTLE,10  (move SHUTTLE +10 cm)
     MA,SHUTTLE,10 (move SHUTTLE until the encoder reads 10 cm)
     R   (clear MODULYNX registers and reload current parameters)
     D   (display system status)
     SU  (setup encoders, enter integrator gains, test read NMR and ADC)
     PD   (print last data run on line printer)
     OD   (open data file and close any existing file)
     CM   (add comment to data file)
     LS,ROTOR,+  (repeat last scan (CD command) of ROTOR in + direction)
     CD,CARRIAGE,ABS,380,400,10,11,520  (take data while moving in the Z
     direction, start move at 380 cm, take the first data point at 400 cm,
     take data points every 10 cm with a total of 11 points, have the
     carriage end up at a position of 520 cm)
```

Figure 8. ROTOTRACK Commands