A COMPUTER-CONTROLLED, 3-D, MAGNETIC FIELD MAPPING SYSTEM[+]

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Abstract

From January 1963 until July 1970 the Magnetic Measurements Group at LBL surveyed the magnetic fields of 104 magnets with a measuring system controlled by a special-purpose digital computer.[1,2]

In July of 1970 the special-purpose computer was replaced by a Digital Equipment Corporation PDP-5. The modified system has demonstrated flexibility, convenience, and reliability during the execution of 13 varied magnet field measuring programs.

Since March 1972 the system has been measuring three orthogonal components of magnetic field at each grid intersection in each pass.

This paper discusses some of the advantages of the general-purpose computer and describes recent developments of the system.

Introduction

The immediate motivation for remodeling the magnet mapping apparatus that is referred to in the abstract and the associated references was the need for an effective system for making performance studies of developmental magnets for the Berkeley 200-GeV Accelerator. When the responsibility for that accelerator was transferred to the NAL, the magnet group at Berkeley reduced the priority of the remodeling project. The group agreed on a revised plan and I proceeded with it as a fill-in job.

Because I was inexperienced in electronic logic circuitry and machine language programming, I chose to build a hardware RIM* loader as a first-step didactic exercise. It turned out to be a very effective exercise and I heartily recommend it (or the equivalent) for inexperienced others who are faced with similar projects. And, as a part of the development of a computer-controlled mapper control system, a hardware RIM loader is very valuable when it replaces time-consuming switch-register programming for computer dead starts.

General

Physically, the mapper system separates into two parts: (1) the triple rack and teletype illustrated in the photograph, Fig. 1, and (2) the probe-positioning apparatus illustrated in the photographs, Figs. 4, 5, 6, and 7.

The block diagram (Fig. 2) suggests a different binary division, i.e. (1) the computer with its satellites (teletype, hardware RIM loader, D/A converter, oscilloscope, and software) and (2) the interface with its many satellites, including the probe-positioning apparatus. I will list the blocks and discuss them more or less individually.

The Computer and Its Satellites

The Computer

Our computer is a Digital Equipment Corporation (DEC) PDP-5. Its core memory holds 4096 12-bit words. The cycle time is 6 microseconds. The "5" is the pioneer model of DEC's PDP-8 family and while its original cost and its size are both an order of magnitude more than that of a 1972 PDP-8, it has almost exactly the same architecture and instruction set. The significant software for 5's and 8's is completely compatible or is compatible with trivial modification with both 5's and 8's.

The 5 communicates with the outside world through a teletype (TT), the D/A converter, and through Input/Output cable connectors.

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* "Hardware RIM loader:" The push of a button transfers from a ROM (read-only memory) 15 12-bit instructions that will cause a TT (teletype) to read paper tape into the computer core. In RIM (read-in mode), each 12-bit equivalent from the tape is preceded by its 12-bit core destination address.

A weakness of the 5 is that its printed-circuit discrete-component structure includes a huge number of aging, heat-sensitive, germanium transistors. However, we feel we have successfully compensated for this weakness by an exacting maintenance policy which requires replacements, repairs and/or adjustments such that the machine not only operates over the full range of supply voltages specified for margin checking by DEC but does so in an ambient temperature above 80° F (26° C) with its cabinet ventilating fan stopped.

Our 5 has been reliable in spite of the jarring it frequently gets in moves of (say) a half of a mile on a fork-lift (it is designed to be moved by forklifts).

Teletype. The teletype (TT) is a standard Model ASR 33. It inputs to the computer through the keyboard and the paper tape reader. It generates punched paper tape output and types under control of the PDP-5.

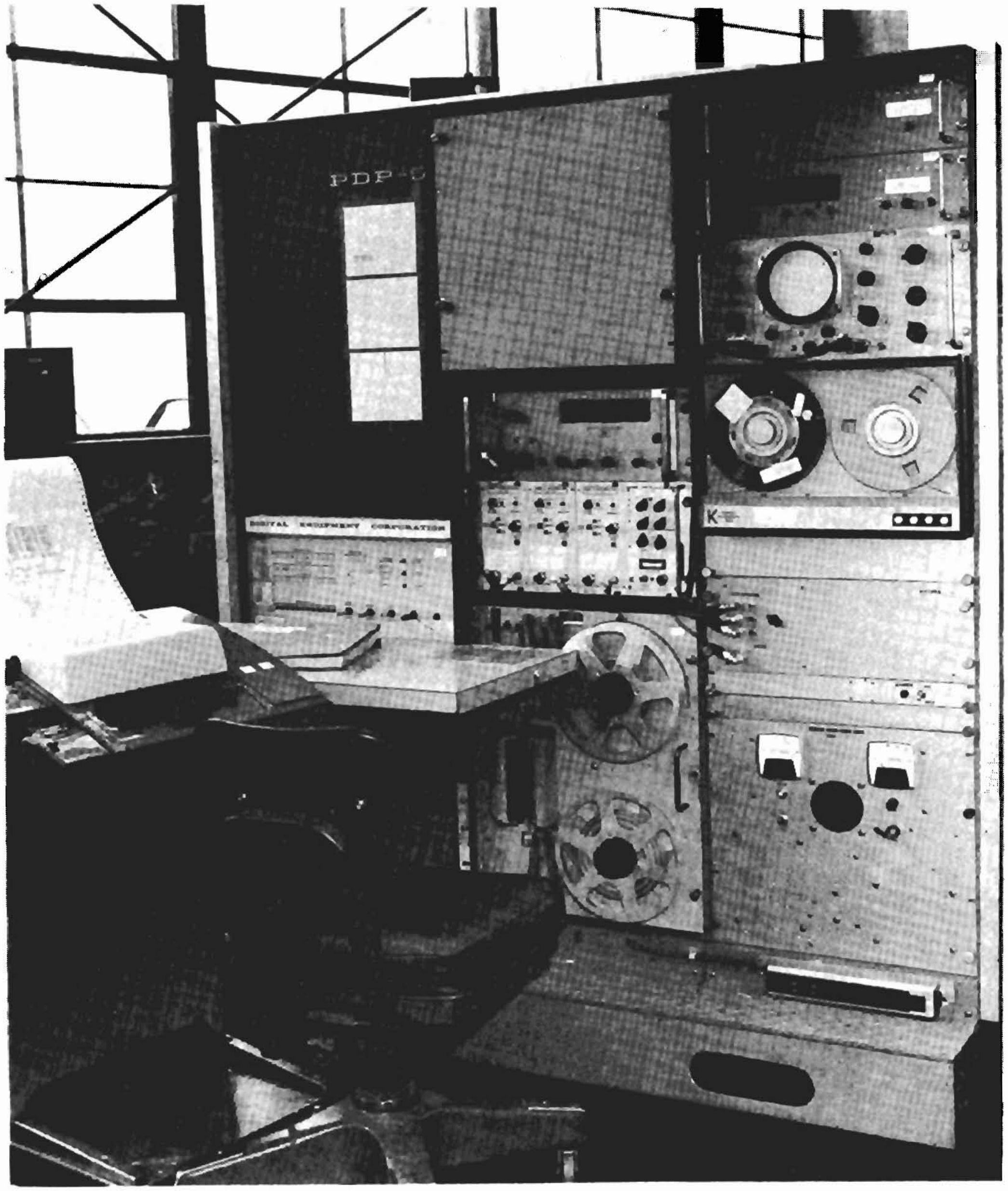

Fig. 1. The computer mapper triple-rack and teletype.

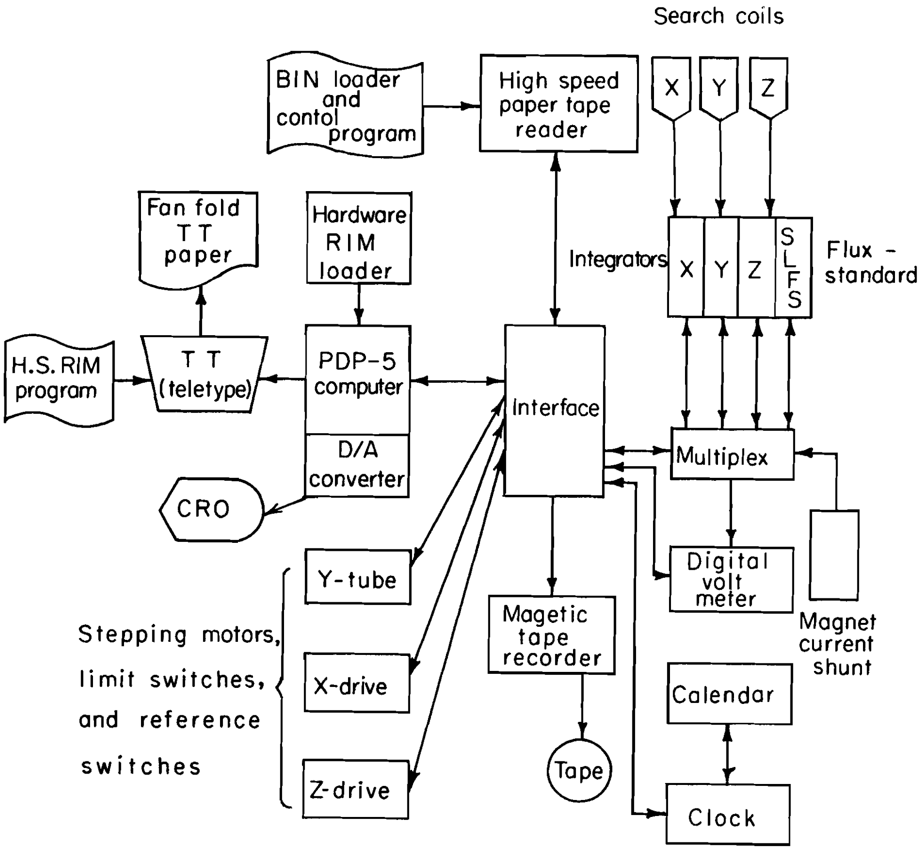

Fig. 2. Computer mapper block diagram.

Rim Loader. The hardware RIM loader is, mostly, TTL integrated circuits and consists of a 16-word ROM, (starting address and 15 instructions), gates, inverters, a clock, and the level-converters for converting TTL to PDP-5 logic voltage levels. The loader acts on the computer through the SR (switch register), the "Load Address" switch, and the "Deposit" switch in a sequence similar to that used by a human operator when, if ever, he enters the 15 instructions manually.

D/A Converter and CRO. The cathode ray tube oscilloscope is not at present used in our mapping procedures. However, when we load the versatile program "Focal-69" to do engineering computing, we sometimes use Focal's capacity to generate graphical displays on the CRO.

We have also displayed positions in "Space War" and "Tic Tac Toe" on the CRO.

Software. Standard software for mapping consists of a Rim Loader for the High Speed Tape Reader, a BIN* loader, and the main mapper program, which is now called "MAP72."

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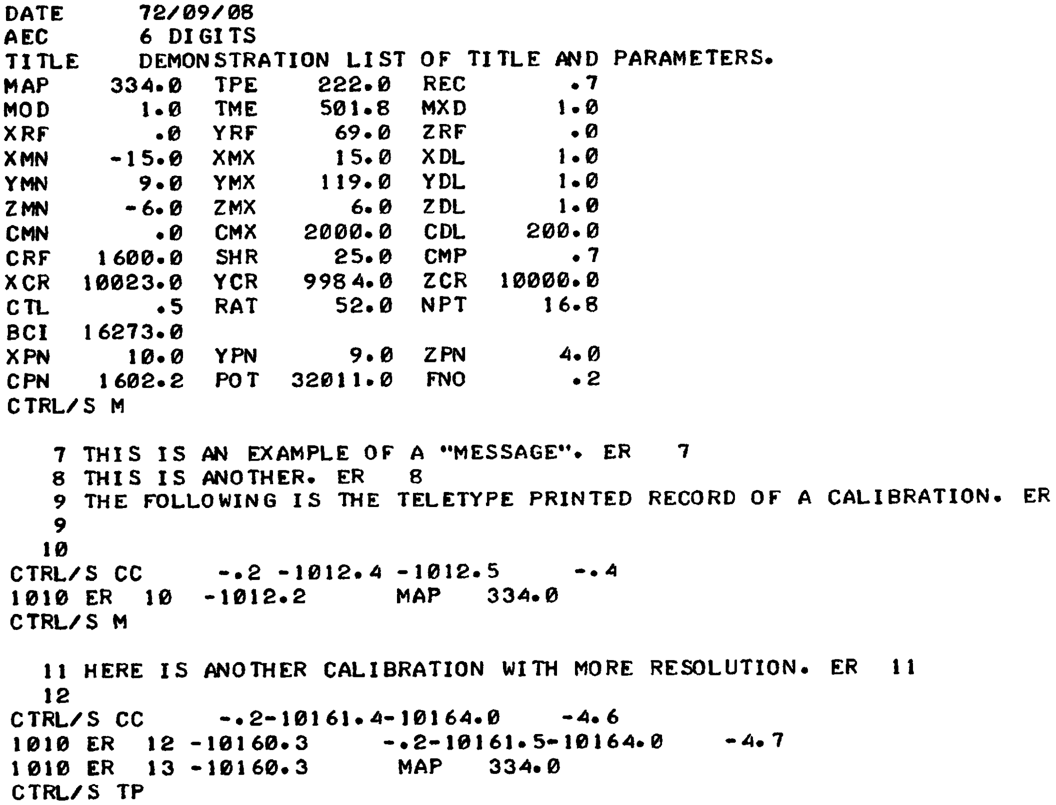
* A "BIN" loader reads a "binary format" paper tape. In general BIN loaders are much more versatile than RIM loaders. They read RIM format and also load successively ascending addresses in core when a first address is given. Ours reads either from the TT or the high speed reader, displays the address-being-loaded on the accumulator lights, and checks the program's longitudinal parity against that determined at the time of assembly.

Our dead-start procedure illustrates some of the functions of the software. With each of the 12 Switch-Register (SR) switches on the PDP-5 console at zero, the push button of the Hardware RIM loader is pushed. A teletype (TT) RIM loader goes into core. A RIM-format tape of the RIM-loader for the High Speed Tape Reader is positioned in the TT (switched to START); a tape with BIN and MAP72 (in series) is positioned in the H.S. Reader; the PDP-5 console START switch is depressed.

The TT RIM loader reads the H.S. RIM which is self-starting and which, in turn, reads the (RIM format) BIN program which is (again in turn) self-starting and which reads the binary-format MAP72 program. At this point, in less than two minutes, the (almost invariable) indication of zero parity errors gives one a comfortable feeling -- in some contrast to the all-too-frequent result of pre-HSTR (High Speed Tape Reader) loading attempts. It was frustrating to see the accumulator lights displaying a parity error, after 15 minutes of T T clacking.

MAP72 accepts TT Keyboard assignments of parameter values, automatically calibrates, positions the coil assembly, and records parameters and integrator output magnitudes on magnetic tape. The program responds to 30 different one- or two-character TT commands. Figure 3 is an example of TT output produced by three of them. TP-CR- (-CR- = carriage-return, the standard terminator) initiated typing of the "Title" and the Parameter list. M-CR- accepted and echoed messages; -CR- before the end of a message line puts that line on the magnetic tape. CC-CR- resets an integrator and (with 1-second delays at each step) reads the DVM, reverses the SLFS excitation, reads twice, restores the SLFS excitation,* and reads again. The four readings are written on tape, averaged, and reported on the TT.



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DATE       72/09/08
AEC        6 DIGITS
TITLE      DEMONSTRATION LIST OF TITLE AND PARAMETERS.
MAP     334.0  TPE     222.0  REC        .7
MOD       1.0  TME     501.8  MXD       1.0
XRF        .0  YRF      69.0  ZRF        .0
XMN     -15.0  XMX      15.0  XDL       1.0
YMN       9.0  YMX     119.0  YDL       1.0
ZMN      -6.0  ZMX       6.0  ZDL       1.0
CMN        .0  CMX    2000.0  CDL     200.0
CRF    1600.0  SHR      25.0  CMP        .7
XCR   10023.0  YCR    9984.0  ZCR   10000.0
CTL        .5  RAT      52.0  NPT      16.8
BCI   16273.0
XPN      10.0  YPN       9.0  ZPN       4.0
CPN    1602.2  POT   32011.0  FNO        .2
CTRL/S M

   7 THIS IS AN EXAMPLE OF A "MESSAGE". ER   7
   8 THIS IS ANOTHER. ER   8
   9 THE FOLLOWING IS THE TELETYPE PRINTED RECORD OF A CALIBRATION. ER
   9
  10
CTRL/S CC      -.2 -1012.4 -1012.5      -.4
1010 ER  10  -1012.2       MAP   334.0
CTRL/S M

  11 HERE IS ANOTHER CALIBRATION WITH MORE RESOLUTION. ER  11
  12
CTRL/S CC      -.2-10161.4-10164.0     -4.6
1010 ER  12 -10160.3      -.2-10161.5-10164.0     -4.7
1010 ER  13 -10160.3       MAP   334.0
CTRL/S TP
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Fig. 3. An example of TT printing.

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* See "Flux Standard" p. 7.

The major devices controlled by the program are very slow relative to the computer central processor: TT, 0.1 second per character; positioning motors, 0.005 second per step; magnetic tape recorder 0.005 second per character; and DVM, 0.1 second per reading. Although the motors are not, in general, allowed to move while the DVM is counting, the use of program-interrupt allows all of these devices to operate simultaneously. Thus, e.g., the teletype can type positions and integrator outputs and record data on tape without delaying the move, read; move, read; etc. sequence.

Mapper programs are written in the LBL version of PAL, DEC's program assembly language, and assembled by LBL's CDC 6600/7600 complex. This flexible assembly program was introduced into the computer center library by Robert Belshe, who is responsible for many of its valuable features.

The input to the assembly program consists of: the basic mapper program which is stored at the computer center on magnetic tape and/or LBL's PSS (Program Storage System); and program modifications punched into IBM cards. The output consists of: the modified program on Mylar-reinforced paper tape, in binary format and a "print-out." The print-out contains: a printed list of command, variable, and constant mnemonics with programming comments; an error listing; a complete index of internal programming references; an error summary; and a core map (a display of the memory allocations).

A basic measuring sequence called a "Y-run" consists of a series of measurements of the three field components -- Bx, By, and Bz, at even intervals ("YDL") along the Y-tube.

A Y-run begins and ends at Y = "YMN" (usually with the coils inside a mu-metal shield to establish a zero field reference). Measurements of the three components are made as the coil assembly stops momentarily at each Y position in steps of "YDL" to and including Y = "YMX." The direction of the Y motion is then reversed and each position is remeasured as the coil assembly returns to Y = YMN.

A typical magnet mapping project includes:

1) Regulating magnet current to a specified value.

2) Ordering the computer to generate and record Y-run data at each X,Z grid intersection in the specified range of X and Z.

3) Ordering the generation of X and Z "tie-in" runs.

4) Repeating 1, 2, 3 at other values of magnet current.

5) Generating tie-in magnetization runs by making Y-runs at fixed X and Z and varying magnet current.

Each tape record includes a list of parameter values. Calibrations are performed frequently and automatically.

The Interface and Its Satellites

Interface. The interface interconnects the computer with the:

1. High Speed Photoelectric Paper Tape Reader
2. Calendar and Clock
3. Multiplex
4. X, Y, and Z Integrators
5. Flux Standard
6. Digital Voltmeter
7. Tape Recorder
8. Probe-Positioning Apparatus.

The interface includes level converters to accommodate the PDP-5 logic levels (-3, 0 volts) to the TTL circuitry (0, +3.6 volts) of the interface. The TTL integrated circuits of the interface consist of a large number of Digital Equipment Corporation M-series Flip Chip modules. Control connections to external stepping-motors and switches are made through noise-insensitive K-series modules. Switch positions (for example) are interrogated through RC-integrator filters with a time constant of 16 ms.

M-series modules are used for gates, inverters, flip flops, "pseudo device selectors," bus drivers, buffer registers, etc. K-series boards include gates, flip flops, DC drivers, etc.

High Speed Tape Reader. Our high speed photoelectric paper tape reader (HSTR) is a rather ancient Ferranti, model 196. I got two, this one and another, for spare parts when they were "excessed" from their last job. This model was originally rated to read 200 characters per second in start-stop mode. The ones I got had been modified to read 400 characters per second. Not too unexpectedly, operation in start-stop mode at 400 characters per second was marginal.

I replaced the 3600-rpm synchronous capstan drive motor with a 1200-rpm motor, slowed the reel drives correspondingly, and we now have a reliable, 160 characters per second HSTR.

Calendar and Clock. The calendar and clock display date and time as month, day, hour (1-24), minutes, and 0.1 minutes. The computer interrogates them frequently, reports their positions, upon request, on the TT as e.g., DATE and TME in Figure 3, and (every record) on magnetic tape. Automatically recorded dates and times are valuable in tracing operator errors and equipment malfunctions.

Multiplex. The Multiplex permits computer or manual control of connections of the SLFS into the input circuits of the integrators and connects the DVM input to a choice of shunt or integrator. Connections are made through shielded, guarded relays. Single point references are maintained by switching all input connections (e.g., Dymec High, Low, and Guard are switched).

Integrators. The three electronic integrators in the mapper are LBL MOD-71. The MOD-71 design reflects many years of experience with and development of integrators at Berkeley. This design incorporates careful guarding, isolation, and simplification of the summing junction. We use Teflon dielectric capacitors to achieve low soakage and low temperature coefficient of capacitance.

An indication of the integrator drift is part of each measuring sequence. The first and last measurement of the integrator output voltage in a Y-run (see above) is usually made with the search coil inside a mu-metal shield where the magnetic field is negligible. The closure (the difference between the first and last readings) is used to adjust each point in the measuring sequence, using the assumption that the drift is linear with time.

Table 1 contains integrator drift data from a typical recent magnet measuring project with RC = 0.1 second $R \approx 51{,}000$ ohms, $C \approx 2$ μF, and NA, search coil area, ≈ 4500 cm^2. The closure of 9 measuring sequences is listed along with the average closure and the deviation from the average of three consecutive measuring sequences of 2.5 minutes duration each. These samples were chosen completely at random. No integrator adjustments were made in this period. When the closure error is averaged over a measuring sequence, integrator drift contributes less than 0.01% to measurement error. Note that these drift data were taken when the apparatus was in service in LBL's Building 6, the 184" synchrocyclotron building. The electrical, thermal, and vibration "noise" level was high.

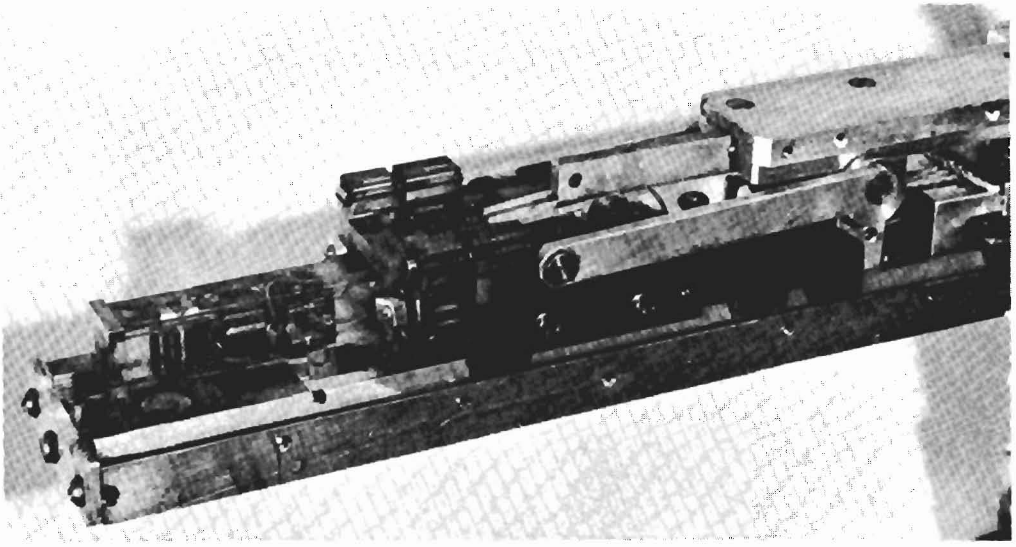

Fig. 4. The end of the Y-tube showing the 3-D coil assembly, the precision rack, and the positioning mechanism.

Table I

A Sample of Drift Data for Integrator Mod. 71 No. 7

Y-RUN MAXIMUM EXCURSION (VOLTS)	CLOSURE (μVOLTS)	AVERAGE CLOSURE (μVOLTS)	DEVIATION FROM AVERAGE CLOSURE (μVOLTS)
Time: 72 June 17, 1142			
1.45	370		50
1.65	330	320	10
1.85	250		-70
Time: 72 June 19, 1339			
7.60	2530		90
7.60	2500	2440	60
7.60	2290		-150
Time: 72 June 21, 1408			
1.45	730		10
1.65	650	720	-70
1.85	790		70

Flux Standard. The flux standard is a SLFS (square loop flux-standard -- pronounced: slewfuss). A temperature-controlled core of ribbon-wound Deltamax is normally saturated stably in some direction. When the excitation is reversed, an accurately reproducible flux change links the output winding. See Reference 3. The SLFS is in series with a search-coil and an integrator input.

Digital Voltmeter. We are using a Dymec Model 2401B integrating digital voltmeter (DVM). The nominal accuracy is 0.01% and the 0.1-volt range when used with a counting time of 1.0 second gives magnet-current shunt voltage readings with 1-microvolt resolution.

When the DVM is reading the output voltage of one of the electronic integrators, we have two integrators in series and the DVM output is conveniently insensitive to random spikes of electrical noise.

Tape Recorder. The tape recorder is a Kennedy Model 1400 with an Echo-check option. Writing is start-stop; speed is 200 6-bit words per second; density is 200 words per inch. It accommodates 8-1/2 in. IBM-standard reels of magnetic tape. It generates horizontal and vertical parity marks and reports the results of its own determination of horizontal parity. The echo check does not represent a full loop-closure; the "echoes" are generated at each writing head when it is pulsed. Thus, for example, magnetic defects in the tape could easily pass the echo check. However, we have encountered very few defective tapes.

Probe-Positioning Apparatus. A rigid assembly of three coils with orthogonal axes (photograph, Fig. 4) is positioned in a cartesian coordinate system by two "Z-stands," two "X-drives," and the "Y-tube" (Photographs, Figs. 5 and 6).

The stainless steel and aluminum Z-stands (Photograph, Fig. 5) move the X-drives simultaneously vertically in increments ("ZDL") that are multiples of 0.1 inch. The X-drives simultaneously move the Y-tube horizontally in increments of "XDL". The coil assembly is moved reproducibly along the Y-tube in precise increments.

Stepping motors drive all three axes, but only the X and Z positions are closely constrained by the motor positions. One 2-pitch screw is used for each X-drive and two 5-pitch screws for each Z-stand. The accuracy of X and Z positioning is determined by the precision of the screws and the straightness of the guides.

The accuracy of Y-positioning is determined by the precision of the rack and by the epicyclic mechanism described in Reference 2 and illustrated in the photograph, Fig. 4. The cable take-up reel illustrated in the photograph, Fig. 7, is equipped with a "negator" spring to maintain constant tension on the cable and a safety switch that interrupts the Y-motor operation if the cable fails to wind evenly.

Discussion

The computer mapper has brought to us major gains in flexibility and reliability. Its flexibility permits us to seriously consider plans for expansions of the system in many directions.

Flexibility. Ever since the first computer mapper job in July 1970 (with the old system standing by) every job has justified and/or required modifications, extensions, or improvements in the mapper program. We have found that "patching" through the CTRL/s mode, ED (Examine, Deposit, or Dump) often could be done in a few minutes. And we could generate an updated tape in one day.

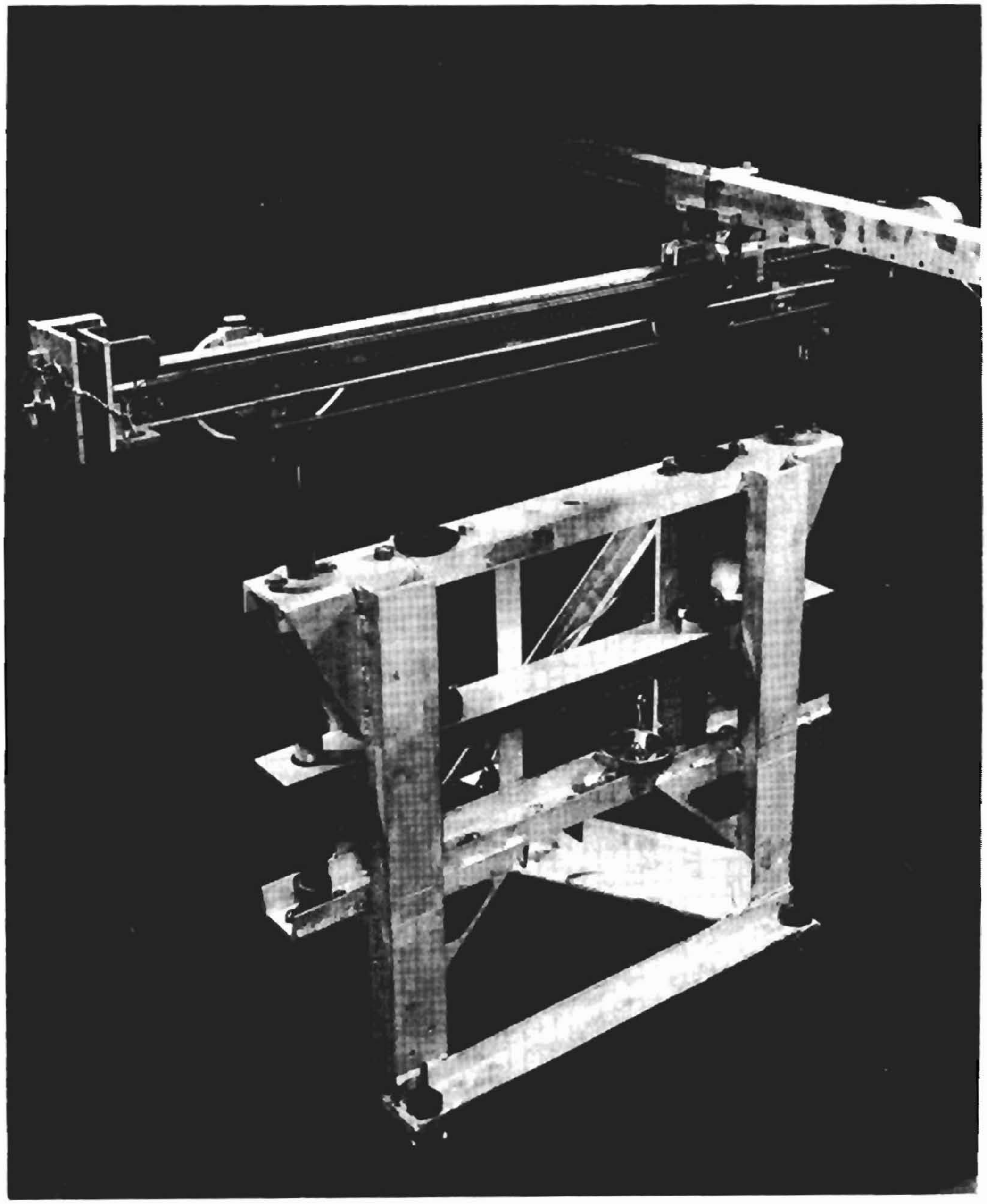

Fig. 5. The Z-stand supporting the X-drive and the Y-tube.

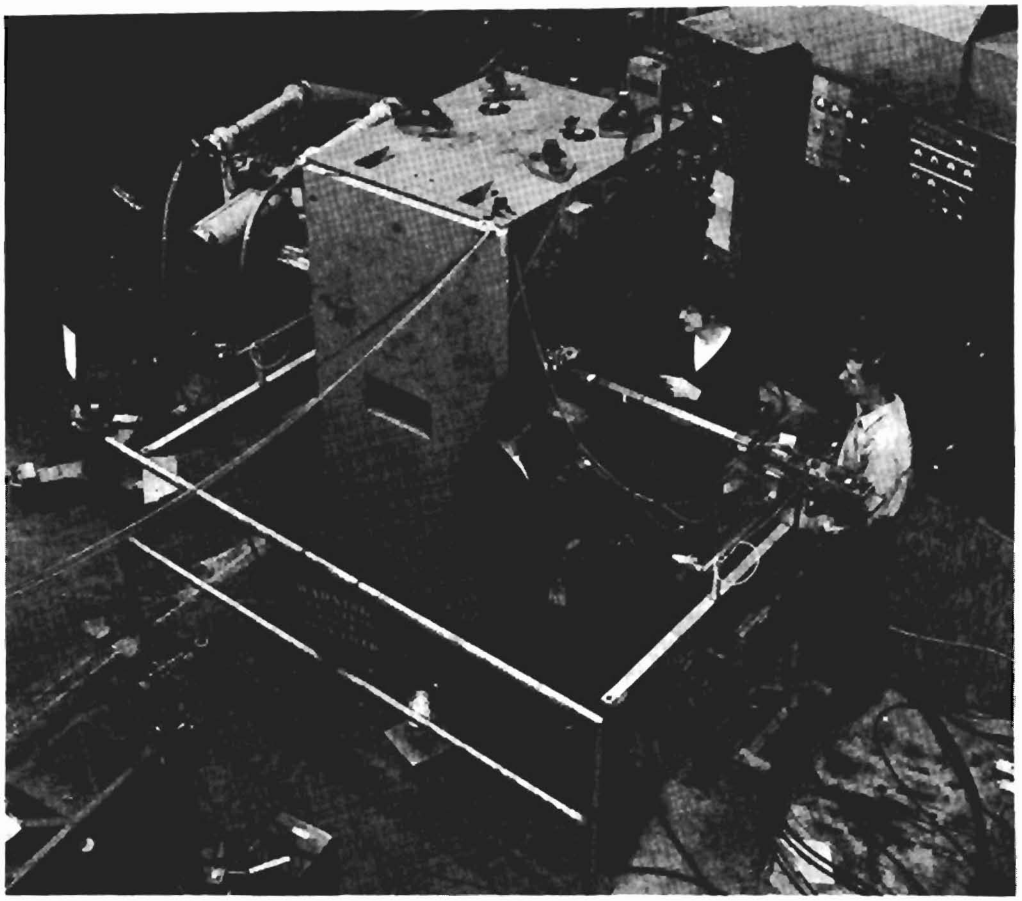

Fig. 6. The probe-positioning apparatus in place for a job.

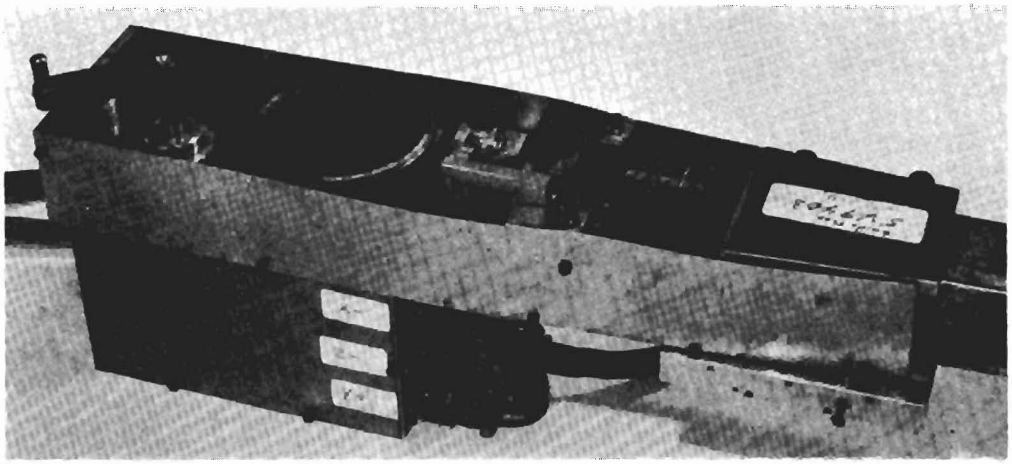

Fig. 7. The Y-tube motor-end assembly.

Reliability. The old mapper suffered from some of the same weaknesses that the PDP-5 has, e.g., aging, heat-sensitive, germanium transistors. However, the earlier mapper did not have the compensations provided by: (a) thorough documentation, (b) improvements developed during mass-production, (c) maintenance technicians working more-or-less continuously with the systems.

Plans. On a time scale of about a year, we plan to incorporate a faster DVM and Multiplex to permit detailed measurement of pulsed fields. We also plan to get a compatible 12-bit computer with 8K of memory. The larger memory will permit more on-line data processing and error checking.

Acknowledgments

F. W. Macondray made the basic design decisions that determined the character of the computer mapper system, e.g., the choice of K and M series modules. He sketched schematic wiring diagrams of most of the circuits of the interface and the basic peripherals. I do not believe that I would have assembled this system if I had not had Fred's major, basic contribution.

M. L. Clinnick programmed valuable general-purpose routines, e.g. data formatting, input/output, and the examine-deposit-dump routines.

T. D. Robinson has made important contributions. He suggested, designed, built, and installed the Y-tube cable take-up drum safety-switch described above. He has demonstrated craftsmanship of the first order in machining precision parts for the probe-positioning apparatus.

D. H. Nelson and P. G. Watson, who each had extensive experience with the earlier mapper systems, guided the development of the computer mapper with many significant observations and suggestions.

Paul Salz has been the key man in integrator development.

I especially wish to acknowledge the valuable assistance of Kaaren Dickman, J. G. Mathios, and D. H. Nelson in preparing this report.

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2. F. W. Macondray, The Rapid Mapper: A Data Acquisition System for Large-Scale Magnetic Field Measurements, Proceedings of the Second International Conference on Magnet Technology, Oxford, 1967, p. 646.

3. F. W. Macondray, The "Square Loop" Flux Standard: A Precision Pulse Generator, Proceedings of the Second International Conference on Magnet Technology, Oxford, 1967, p. 639.

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