COMPUTER AIDED COORDINATE MEASUREMENT FOR QUALITY ASSURANCE

by

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ABSTRACT

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Automated production methods have led to an increased need for faster inspection equipment in the metalworking industry. A coordinate measuring machine, especially when integrated with a manufacturing computer system, will increase inspection productivity while maintaining historical records of relevant inspection and quality assurance data.

A Bendix layout machine with a local measurement processor was interfaced to a Hewlett-Packard minicomputer through an asynchronous multiplexer. Since a compatible protocol was not available for interfacing the measurement processor to the minicomputer, a protocol was developed which utilized the echo feature of the measurement processor. This protocol was successfully implemented with few problems. The system permitted part inspection procedure files to be created, measurement instructions to be sent to both the layout machine operator and measurement processor, and measurement data to be collected.

Integrating the coordinate measuring machine into the computer network using the multiplexer provided a flexible, cost-effective solution to the problem. This could lead to improved productivity once the system is optimized.

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CHAPTER I

INTRODUCTION

1.1 Scope and Objectives

This thesis describes the operation, use and characteristics of coordinate measuring machines in manufacturing quality assurance programs and, by means of a case history, illustrates how a coordinate measuring machine was interfaced with a minicomputer to improve a quality assurance program.

The objective of this study was to develop a hardware/software interface between a Hewlett-Packard model HP 1000 minicomputer and a Bendix coordinate measuring machine to improve inspection efficiency and to permit automatic recording of measurement data.

Bendix coordinate measuring machines are controlled by a measurement processor. Upgraded performance can be attained by using a desktop computer to control the measurement processor. Bendix supplies a variety of desktop computers, varying from the Hewlett-Packard models HP 85 to the HP 9835 for upgrading performance. Bendix is presently developing a system using a Hewlett-Packard model HP 1000 minicomputer as an even more powerful level of computer support. This computer interfaces with another Hewlett-Packard desktop computer, which in turn interfaces with the Bendix measurement processor.

In the case study outlined in this thesis, a Hewlett-Packard minicomputer was interfaced directly with the Bendix measurement processor, eliminating the desktop computer. The availability of the minicomputer enhanced the project feasibility. Advantages of this approach are as follows:

i) Cost

A substantial cost reduction can be realized by eliminating the intermediate desktop computer and replacing it with a single eight-channel asynchronous multiplexer. However, a teletype or cathode-ray terminal is required for each machine operator work station.

ii) Flexibility

Company resources, such as programmers, software, and hardware, are not devoted to the additional desktop computer but can be solely used for the larger minicomputer.

Measurement data can also be stored in a data base for future analysis and historical purposes.

iii) Productivity

The coordinate measuring machine can be used primarily for the inspection of production parts, rather than the on-line development of inspection programs. Throughput is also higher since the inspection procedure is preprogrammed for the operator.

iv) Flexible Manufacturing

With the trend to flexible manufacturing systems, this approach permits future capability for direct computer control and total system integration. There will not be several localized systems to tie in, only one network.

v) Upgrading

With the rapid changes in technology, it will be possible to upgrade hardware without major disruptions. Also, changing hardware suppliers would not seriously affect the performance of the system.

1.1.1 Hardware Interface

The first specific objective was to develop a hardware interface between the Hewlett-Packard model HP 1000 minicomputer and the Bendix layout machine. In addition to being physically compatible, the interface must also be electronically correct.

1.1.2 Software Interface

The second specific objective was to ensure that data communication between the Hewlett-Packard model HP 1000 minicomputer and Bendix layout machine is established. Protocols (handshakes) between the Hewlett-Packard model HP 12792A multiplexer and Bendix model MP-2 measurement processor must be compatible.

1.1.3 Inspection Software

The third specific objective has three requirements:

i) the creation of a part inspection file,

ii) the transmission of inspection instructions to the Bendix layout machine and the reception of inspection data by the Hewlett-Packard model HP 1000 minicomputer, and

iii) the retrieval of the inspection data file.

1.2 Background

1.2.1 Why Coordinate Measuring Machines?

The introduction of numerically controlled machine tools resulted in great improvements in the manufacturing industry. Parts could be produced faster, more accurately and precisely, and with less error and thus better quality. This posed a problem due to the greater volume of more accurate and complex parts requiring inspection. This problem led to the development of the Coordinate Measuring Machine (CMM).

The statement by Buckley (1981), "As NC is to manufacturing, coordinate measurement is to inspection", summarizes the effect of the CMM on quality assurance. The CMM has evolved into two categories, horizontal-arm and vertical-arm machines to meet industry needs. Each has specific speed and cost advantages and disadvantages depending upon part geometry, part size and operator skill.

Major advances are occurring in the inspection process, especially for the first part in a batch from numerically controlled machines and for complex, high-tolerance parts.

The use of conventional surface plates and gages is generally too expensive, error prone, insufficiently accurate and slow. Specialized dedicated gages permit more productive and reliable use, but exhibit high maintenance and obsolescence costs.

The CMM with a microprocessor system is a flexible tool, especially for single items and short runs. It leads to increased inspection productivity due to faster throughput. Operator influence is minimized since the system can provide measurement instructions and process control in addition to data analysis. Program software virtually eliminates holding fixtures and setup time by permitting electronic part orientation and levelling. Accuracy is also improved since parts can be measured in a single setup.

With the introduction of microprocessors to control the CMM, data collection and analysis are enhanced. Data can be analyzed with preprogrammed functions, while permanent records, either on electronic media or paper, can be maintained.

Inspection time is shortened by on-line analysis, simplifying the inspection procedure. The operator's task, therefore, is to collect coordinate data in the correct sequence which the microprocessor can then analyze. This type of CMM is still basically a manual unit and subject to operator-induced error.

Computer assist capability can be added to a manual CMM to provide local data acquisition and analysis, with or without preprogrammed software, as well as data recording. A local measurement processor, for example, can provide a Bendix CMM with data processing capability between the position tranducers and display. The factory preprogrammed memory contains software which can be accessed by push buttons, while instructions and results can be displayed on the local digital readout. Results can be output to hard copy or manually recorded. In addition to the four-axis-position transducers, interfaces to an electronic touch probe and operator footswitch are provided.

The ultimate solution is direct computer control which is a means of probe positioning using a computer-driven servo-system, and the use of an electronic probe to obtain measurement data. As an intermediate step to direct computer control, measurement processors controlled by intermediate controllers such as local desktop computers, are available for a Bendix CMM. Bendix machines currently support Hewlett-Packard models HP 85, HP 9825 and HP 9835 desktop computers. While further integration to a minicomputer system is possible, this is not yet commercially available.

It would be desirable to integrate a CMM with a measurement processor into a minicomputer system without using an intermediate controller such as a desktop computer.

1.2.2 Why Integration?

There are four principal areas into which Computer Aided Quality Assurance can be divided:

i) Measurement and Testing

By the use of coordinate measuring machines a part can be inspected more rapidly, accurately, and efficiently. A CMM, whether automatic or manual, can be interfaced to a minicomputer through microprocessors or intermediate controllers. Instructions can be issued to the CMM or the operator, data can be collected and analyzed, and reports can be issued.

As product complexity increases, more advanced testing methods will be required. A minicomputer can be used to automate these tests and to collect and analyze test data.

ii) Process Control

Analysis of measurement data will enable prediction and control of changes in a process and will provide preventative maintenance data and other manufacturing information. When flexible manufacturing systems come into place, the computer will play an important role in control of the manufacturing process.

iii) Quality Systems

Tool and gage control, quality assurance and reliance techniques, laboratory procedures, calibrations, and inspection procedures can be handled on a central computer.

iv) Information Systems

Computerized systems will allow vast storage and retrieval capabilities. Sample inspection reports, defective part data, product release records, rework and scrap costs, part and supplier service and warranty records are just a few of the many applications which can be computerized. What is happening and what has happened in production will be a matter of record, not speculation since records will be available and easily accessible. The key to all of these applications is that the data be integrated into a common data base, which can be made available to and utilize information from manufacturing and engineering in particular, and other departments in general.

There are many reasons for developing a computer aided quality assurance system:

i) To modernize inspection methods.
ii) To improve reporting systems.
iii) To quicken response to warranty and service problems.
iv) To enable prediction of changes in process.
v) To establish historical records.
vi) To improve quality systems.
vii) To allow future integration with advanced manufacturing and engineering systems.
viii) To remain competitive.
ix) To increase productivity.
x) To improve quality.

1.3 Definitions

Several terms need to be defined before discussing computer applications to engineering and manufacturing. Computer Aided Design (CAD) means the use of computer aided graphics programs to model and draft machine components in two to three dimensions, using wire-frame, surface or solid modeling techniques, rather than the traditional methods of pencil and drafting board. CAD can also include analysis and component testing functions using computer methods.

Computer Aided Manufacturing (CAM) entails the use of computer technology to design tools and fixtures, determine cutter location paths, and produce instructions to operate machine tools. In addition robotics, process planning, and factory management are all integrated CAM functions.

Computer Aided Engineering (CAE) utilizes an integrated approach to CAD and CAM using a common engineering and manufacturing data base.

Numerical Control (NC) refers to the control of machine tools using an instruction set created by a computer and transferred to the machine tool by a paper or mylar tape, magnetic tape, or other electronic medium. The computer generating the instructions does not control the machine tool in real time.

Direct Numerical Control (DNC) or Direct Computer Control (DCC) means the control of a machine tool by a computer in real time.

A Flexible Manufacturing System (FMS) is an automated system utilizing a dedicated group of machine tools to produce a mix of parts in limited quantities with an automated materials handling system. System control is accomplished by a real-time computer system.

Computer Integrated Manufacturing (CIM) refers to an automated method of manufacturing which uses feedback from the machine tools to correct machining operations as parts are manufactured or in-process. A common engineering and manufacturing data base is required for successful CIM.

Computer Aided Quality Assurance (CAQA) means the automation of the inspection process using computers. Applications include on-line and off-line inspection, as well as statistical analysis of measurement data to determine trends.

A Coordinate Measuring Machine (CMM) is an inspection machine used to determine the dimensional representation of a part by coordinate measurement. Computers may or may not be used to help collect and analyze measurement data.

CHAPTER II

LITERATURE REVIEW

The review of literature will include the development of coordinate measuring machines, why integration is desirable, and a brief look at current equipment. As part of these areas of review, the CMM marketplace and their applications will be discussed.

Any references to Imperial, rather than SI units are made to reflect the context of the citation or to represent a nominal or specified dimension.

2.1 Development of Coordinate Measuring Machines

In 150 years measuring precision advanced two decimal places to ten-thousandths of an inch (Polk, 1960), while in the last 12 years capability has increased to millionths of an inch, a thousand-fold increase. In 1960, state-of-the-art included mechanical gaging (GO, NO-GO) and pneumatic gaging if speed and precision were desired. Pneumatic technology has been used since 1930, and proved to be quite rugged in a production environment.

In the 1950's, electronic gaging moved from the metrology laboratory to the production environment, providing high-speed response and faster cycle times, as well as tolerances in the order of 10^{-6} inch. Other techniques under development included optical devices such as autocollimators, projectors, and interferometers, in addition to ultrasonic, radar, and radiographic gaging.

Polk also predicted an evolutionary rather than a revolutionary development process which would result in better product reliability, reduced scrap, rework, direct labor, and manpower, while increasing productivity.

The advent of numerical control in 1955 (Birrell, 1968) was a major improvement in the metalworking and machining business. This led to the requirement for better measurement control. Prior to the 1960's coordinate measurement was typically a comparative two-dimensional operation, utilizing surface plate technology which required complex fixtures, care, operator skill and judgement, and manual recording. The first CMM in the early 1960's utilized built-in standards, eliminating the need for comparative measurement, while providing three-dimensional capability. This eliminated complex fixturing, while providing a digital readout and automatic data logging, error correction, alignment and true position calculations.

Hicks (1976) classified the CMM into five basic physical configurations - jig borer (column), cantilever, horizontal, overhead bridge (bridge), and travelling bridge (gantry) - each of which developed to meet a need. The need dictated the relative advantages and disadvantages of cost, speed, accuracy, part size, part complexity and operator skill.

The jig borer style (SIP Genevoise or Moore Special Tool Co.) was typically the most accurate, but extremely slow, limited in size, capable of inspecting only one face per setup and dependent upon operator skill (Figure 1).

Ferranti, in the late 1950's, introduced the cantilever style to provide a unit which was a faster, less accurate production inspection machine. A tapered, self-centering probe was used to obtain X - Y coordinates. The part could be indexed, and a low-inertia stiff Z-axis with short stroke design was used. Bendix, North American Boice, and European Olivetti utilized these concepts (Figure 2). Originally designed for X-axis and Y-axis measurement only, the Z-axis was later included, and led to extended Z-axis movements, decreasing accuracy. The support structure was stiffened, increasing inertia and reducing access, and ultimately imposing a practical limit of about 1 m for the cantilever (Y-axis).

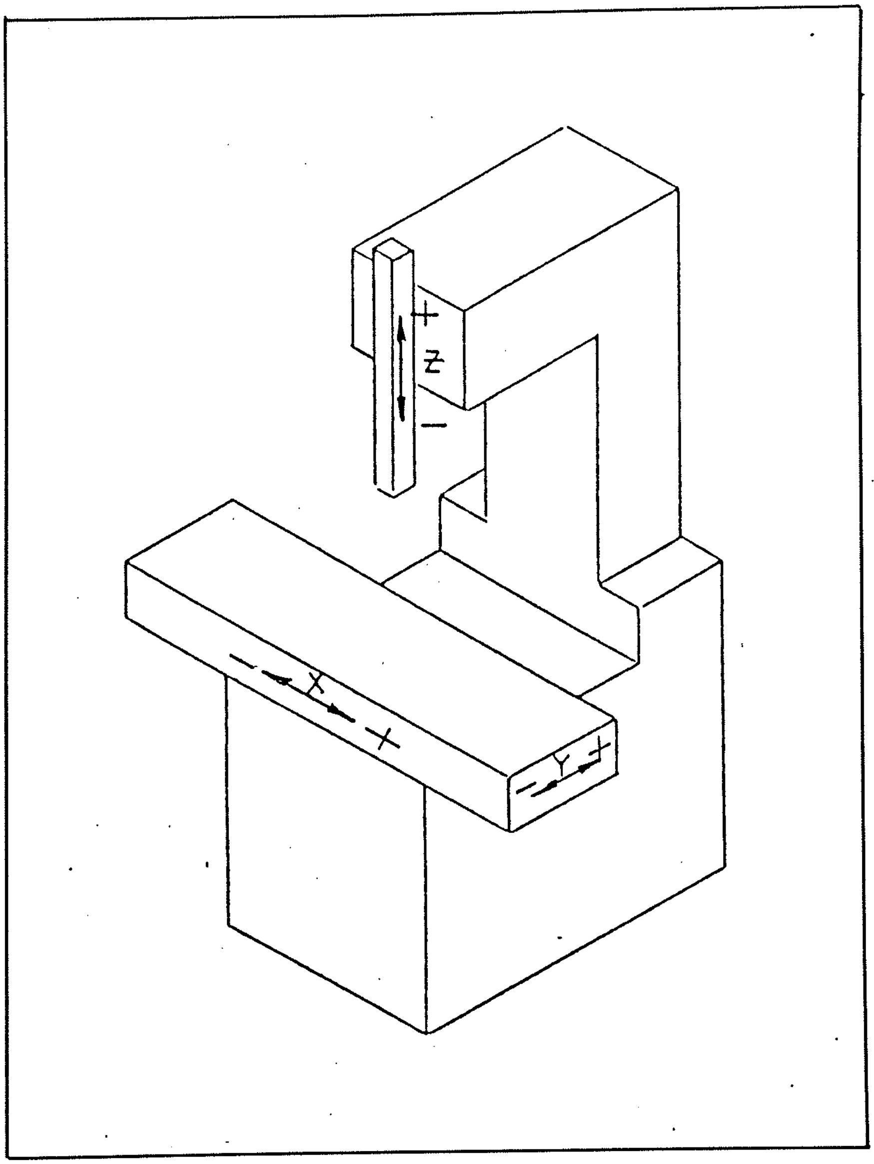

Figure 1. Jig borer or column CMM

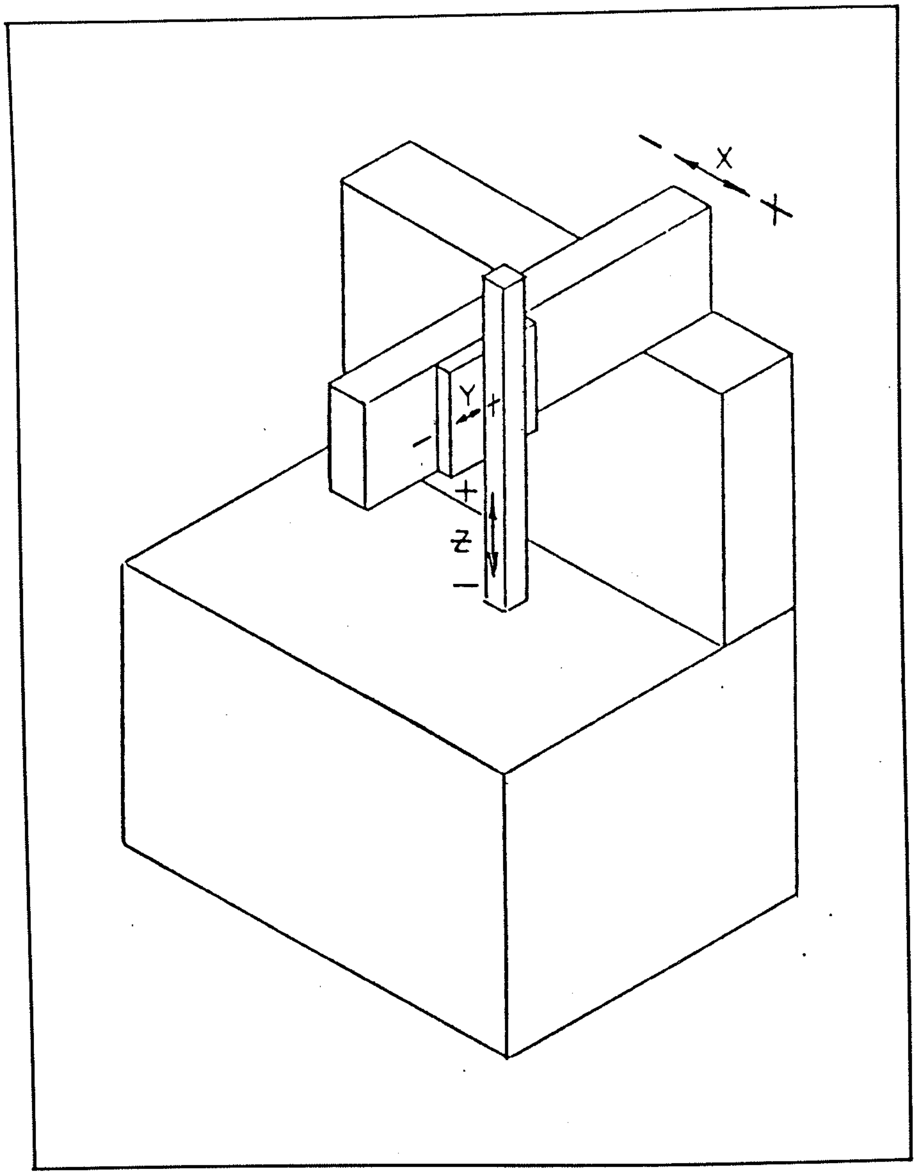

Figure 2. Cantilever CMM

Digital Electronic Automation developed the overhead bridge CMM in the early 1960's to handle large three-dimensional parts. Since it was impractical to move the part, the operator moved with the probe. The Ferranti tapered-probe concept was no longer feasible, so it was necessary to develop the electronic touch probe, enabling data to be quickly collected. By making the reading independent of the operator, the application of numerical control to the CMM was possible. Due to the size of the CMM, there was an economic limit to down-sizing for smaller parts (Figure 3).

The travelling bridge (gantry) CMM filled the size and economic gap between the cantilever and overhead bridge styles. A large Y-axis was possible for lower cost. Mass was increased relative to the cantilever style, while the extra support limited part size compared to the overhead bridge style (Figure 4).

The horizontal spindle machine was developed by the Portage Machine Company. A fixed ram with electronic indicator was used. A rotary table brought the part to the probe. Accuracy, compared to the bridge style, was greater but significant penetration was not possible. Speed was less than for the cantilever or bridge styles (Figure 5).

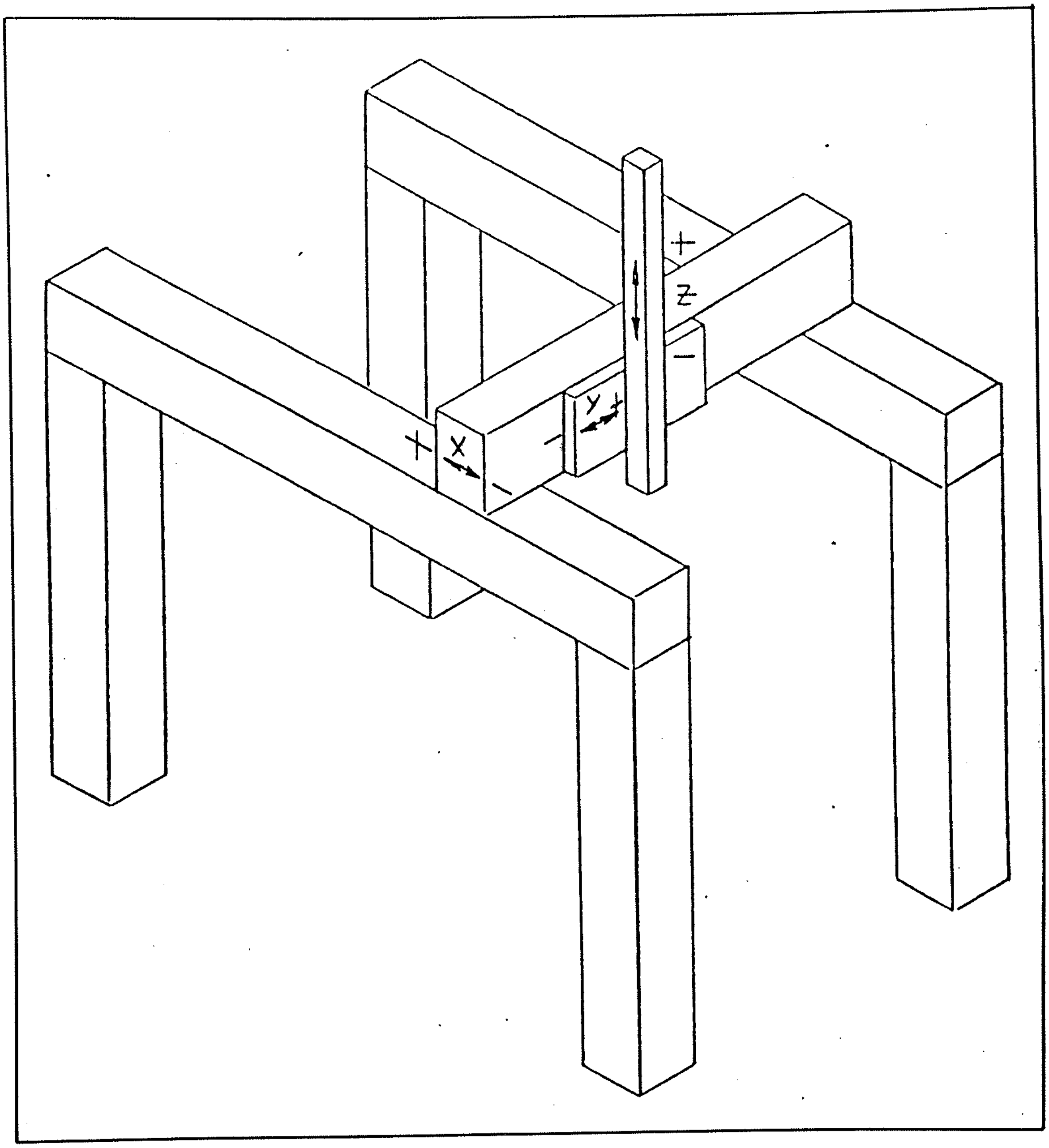

Figure 3. Overhead bridge or bridge CMM

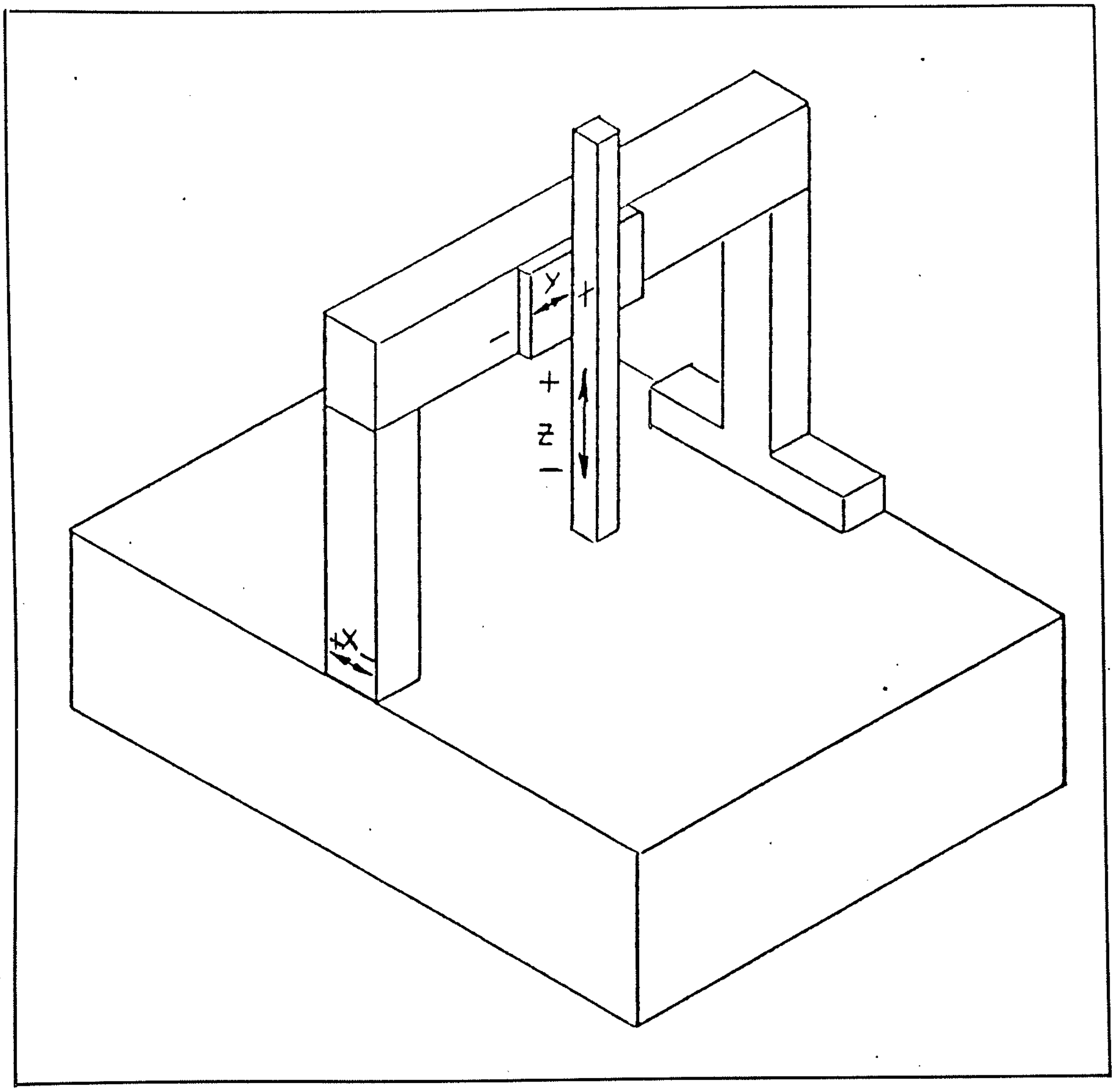

Figure 4. Travelling bridge or gantry CMM

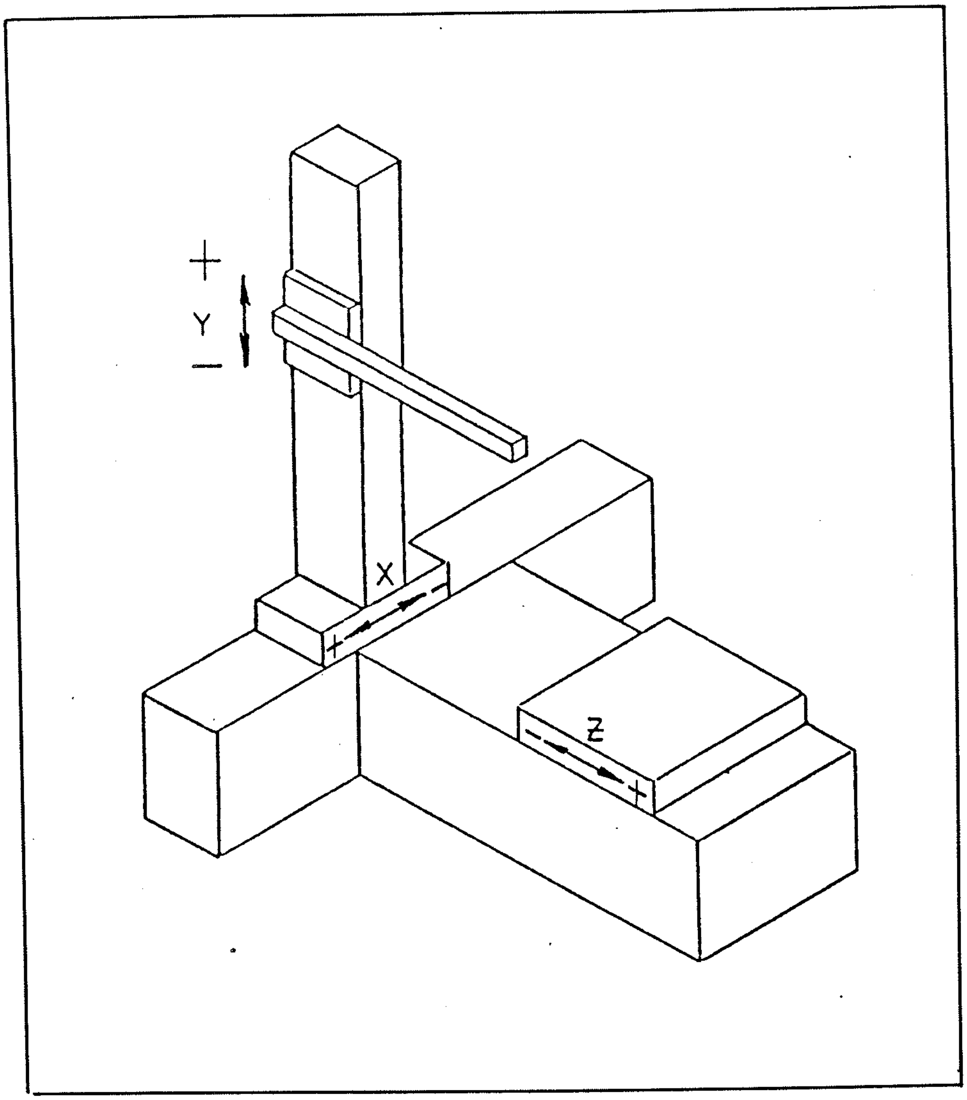

Figure 5. Horizontal arm CMM

Deis (1975) described the evolution of the Bendix layout machine (a horizontal-arm type of CMM). The primary purpose of a layout was, and still is, to verify the design. Fred Schiler of the Portage Machine Company first added wheels to a height gage. Later, a scale was added to the scriber arm, which was modified to make it moveable. Accuracy was improved by developing an independent inner arm to support the crossarm. Control and measurement in the longitudinal axis was achieved by utilizing a grid in the layout table, with guide rollers and a scale. Bendix later replaced the vernier and scales with a digital readout. In the twenty years the layout machine has been available, the design has been kept simple with few added refinements. The layout machine could improve the quality of the layout and reduce time by a factor of 40 to 50%. Digital readout enabled a further 40 to 50% time saving but computer assist for the CMM was still in the early stages of development.

Coggin et al. (1971) stated that the then state-of-the-art CMM improved data quality and reliability, while reducing inspection time by up to 80%. The advent, in the mid-1960's of high-speed, low-cost digital computers, like the Digital Equipment Corporation model PDP-8, led to economic, automatic on-line data processing. Until 1969, operator-induced error remained the main obstacle to realizing full CMM potential. Complete automation, enhanced by the ability of a 4K 12-bit computer coupled with proportional (first-order) servos and software control, provided the solution to operator boredom, distraction, and inconsistency.

Stroman (1970) stated that hardwired numerical controllers for inspection machines were not as successful as for machine tools due to the need for extensive data manipulation. Analog input devices required frequent calibration while digital devices such as the moire fringe grating system used on Bendix equipment did not (since environmental effects were minimized). Rapid point-to-point data measurement created a data reduction bottleneck if manual or off-line computer methods were used. Automation of the production inspection process, while not always economically justifiable when computer costs represented 55% of system cost, reduced the need for gages, inspection time, and real-time mathematical calculations. This provided the potential of feeding back inspection data to optimize fabrication on-line.

Electronics were used in the 1970's (Butts, 1982) to overcome the problems of finding skilled operators and reducing inspection time and data processing errors. Most electronic devices then available functioned primarily as smart calculators. In 1978, Bendix introduced a measurement processor which was the first low-cost microprocessor to be incorporated into a CMM. Placing the data processing unit between the measurement input and digital readout provided the capability of powerful user-friendly data collection and analysis utilizing function software resident in the memory. A serial interface was provided for connecting various input/output devices. In 1981, the capability of the measurement processor was extended to handle sophisticated three-dimensional geometry and general programming capabilities. A parallel interface (IEEE-488) replaced the serial interface (RS-232) and the Hewlett-Packard desktop computer was used as a host computer. Operator Friendly Interface, an interpretative BASIC language program, was used as a programming and operator aid for inspection and direct computer control. These electronic aids allowed faster inspection throughput by letting the microprocessor do most of the time-consuming tasks, such as data analysis and reporting. However, there was still a problem with manually operated machines due to the possiblity of operator-induced error and inconsistency due to boredom and distraction. By going to direct computer control of the CMM, the operator had no influence. Productivity was generally two to three times higher than previously possible, and accuracy and production were improved (Butts, 1982). Table 1 (Paolino and Lambie, 1980a), illustrates the

Table 1. Comparison of typical measurement times (minutes) - conventional versus CMM methodology (Paolino & Lamble, 1980b)

Operation	Surface Plate Method	CMM with D.R.O.	Cordax with M.P.P.	Computer Assisted Cordax	DCC Cordax
Sizing					
Hole	3	1.5	.5	.5	.3
Boss	2	1.5	.5	.5	.3
Length	6	.5	.3	.3	.15
Height	6	.5	.25	.25	.15
Thickness	6	.5	.25	.25	.15
Bolt Hole Diameter	12	.6	2.0	2.0	1.5
Center Distance	6	1.0	.5	.5	.3
Relationships:					
Angle Between Faces	15	8	5	2	.8
Angle Between Bores	24	12	6	2.5	1.5
Arc Length	N.A.	N.A.	2.0	2.0	1.5
Roundness	N.A.	N.A.	2.0	1.5	1.2
Squareness	15	10	6	2.5	1.5
Flatness	4	4	2	2	1
Concentricity	30	6	2	2	1
True Position	15	3	.5	.5	.3
Profile (30 pts.)	N.A.	12	12	4	1.5
N.A. (Not Applicable)					
Set-up	Included	Included	3.0	3.0	1.0
Computation	Included (Hand calculator)	Included (Hand calculator)	Included	Included	Included
Hard Copy Recording	Included	Included	Included	Included	Included

NOTE: The time for the Bolt Hole Diameter Operation for a CMM with D.R.O. should be "6" not ".6". This is an error in the original publication.

labor requirement (minutes) of various techniques for common inspection operations. Generally, the increase in the electronics (computer) capability of a CMM reduced inspection time, and thus cost.

Esken, as reported by Gettelman (1979), recognized the relationship between electronics capability and time, but that people are still part of the inspection system by saying "There is no absolute - not even in the finest gaging equipment". Precision requires an understanding of metrology concepts, discipline and good equipment.

2.2 Why Integration?

There has been demonstrated need by industry to automate and integrate the inspection process with computers. This is confirmed by the inspection equipment now on the market, and by predicted trends.

2.2.1 Industry Need

Numerical control has given the manufacturing industry cost reduction and increased quality more than any other advancement in fifty years (Walton, 1970). This has imposed a heavy burden on inspection and processing.

Increased productivity is needed to increase industrial competitiveness, while considering the consumer's perception of reduced product quality (Butts, 1982). The need for high-speed production of high-precision parts which are more complex and made by more versatile machining centres, with considerable added value, quickly highlighted the inadequacies of standard surface plate and height gage techniques. The cost and lack of speed of conventional techniques, coupled with the lack of skilled labor, point to the need for the CMM.

As Gay (1982) pointed out, the principal advantage of the CMM is the ability to obtain coordinate dimensions, convert them to true position and, if desired, print a report.

Dickinson (1981), examined the relationship between quality and productivity and reported an estimate by Feignebaom (of Quality Progress magazine) that quality problems require 15 to 40% of an American manufacturer's capacity. Rework, scrap, warranty and liability can amount to 20% of gross sales. Acton (Dickinson, 1981) of General Electric was quoted as stating "Because the most useful piece of manufacturing technology is the computer, it follows that a good structure for computerized manufacturing could have a significant impact on productivity. And that holds for any company, regardless of its size". He further added "Anyone who prescribes high-technology equipment for an ailing industry must keep in mind that a new organizational structure will be required to maximize the utilization of that equipment."

This prediction has been confirmed by the increased use of computers in the financial, production, engineering, and quality assurance fields. Since quality assurance departments are not generally looked upon as profit centres, they generally are the last to reap the benefits of computerization. The CMM is the response to this needed investment, but the management tools (gage history, vendor performance, past history and statistical analysis) are still being developed.

Buckley (1981) observed that the "Automated Factory", which has the key elements of productivity and flexibility, will not be attained until the loop between manufacturing and planning is closed. The ability to "close-the-loop" in the manufacturing process by detecting bad parts and taking corrective action is important (Faux, 1982). The advantages of the CMM, compared to conventional manual methods, namely faster inspection rates, the absence of need for jigs and thus reduced costs, built-in analysis capability, automatic feature determination, programming similarity to NC, and the ability to handle complex and sculpted shapes, make their use attractive. An added advantage is the use of the historical data obtained for geometric and statistical analysis. The elimination of manual information transfer enhances CMM incorporation into the concept of computer integrated manufacturing.

Computer aided quality assurance will become widespread once the inspection process does more than detect bad points (Schaffer, 1982). The major obstacle to this is the lack of facility within existing data bases to incorporate tolerance data. Ultimately, an electronic representation of a part within a graphical (CAD/CAM) data base will be used to close the loop through a CMM.

2.2.2 Market Share

Paolino and Lambie (1980a) observed that there was justification for the CMM in three specific areas: inspection cost savings, reduced manufacturing downtime and scrap, as well as increased manufacturing and inspection capacity. In the Machine and Tool Blue Book, Paolino and Lambie (1980b) stated that over 1000 firms annually invest in CMM technology identifying the need for fast, high-precision and productive inspection machines.

Bowe (1981) described Britain's market for the three-axes CMM as growing despite the recession. The aerospace and automotive industries were the prime users, encouraged by increased defense spending and government incentive programs. Western European manufacturers, such as Rank Taylor Hobson, Ferranti, LK Metrology, and Vickers Maxi-Check dominated the marketplace. Ian Craig of Vickers Maxi-Check estimated the size of the UK market to be at least 200 machines. It was generally believed that high technology could produce parts a hundred times faster than traditional methods could inspect them, and that firms with older CMM installations were discovering production bottlenecks.

Howell[1] of Computervision observed that this market, the metalworking portion of the mechanical component industry, was divided into three areas: manual with digital readout manual with computer assist, and motorized, with or without direct computer control. She estimated that the market was split at 55%, 40% and 5% respectively.

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1 Personal correspondence, January 18, 1983

Moyer of Rank Precision Industries, was reported by Schaffer (1982) to state that the CMM market was divided between (70%) manual and (30%) automatic or direct computer control. Moyer then stated "But 95% of all CMM's sold today have some sort of data processing capability". Schaffer also stated that since 1978, some form of computer was shipped with every Bendix CMM.

Since marketing information is generally very difficult to obtain, there are little available data on users and volumes to substantiate estimated market shares.

2.2.3 Market Trends

Schaffer (1982) observed that true computer integrated manufacturing will become a reality as a result of the use of computers with the modern CMM. Butts (1982) commented that distributed processing must be considered since the opportunities of faster setup, calculation, data acquisition, and increased availability and complexity of inspection are possible. Software must be developed to overcome language incompatibilities which hinder data file transmission among different machines. Another alternative is that low-capability microprocessors may be multiplexed to collect data and to use the host computer for creating data files. By networking the CMM to a computer, inspection procedures can be developed, statistical analysis undertaken, and reports generated. The risk of CMM downtime due to network host computer downtime can be minimized by utilizing backup hosts and a CMM with stand-alone capability.

Schaffer (1982) states that "according to most observers of the CMM market, software capabilities are going to be the principal feature differentiating CMM systems". This capability is said to include both user friendliness as well as functional capability.

Butts (1982) and Buckley (1981) of Bendix believe that the next five to ten years will see the development of CMM's with more sophisticated on-line analysis, better accuracy and microprocessors, off-line program generation and verification using a CAD/CAM data base, graphical reports, a common information data base, more advanced probes, and automated loading and unloading of parts.

2.3 Current Equipment

2.3.1 Hardware

The survey by Schaffer (1982) of CMM hardware, software, and services contained some interesting information. Of the 27 manufacturers studied, 17 (63%) offered direct computer control, while only four (15%) explicitly offered a link, usually a serial interface, to a host computer for further data processing. All offered some form of local computer. Twelve firms (44%) supported Hewlett-Packard programmable calculators, desktop computers, or minicomputers. The bridge style of CMM was dominant, with 15 (55%) firms. Six firms offered cantilever (22%), five horizontal-arm (19%), four gantry (15%) and three column (11%) styles, indicating a trend to more productive machines, sacrificing accuracy, to some degree for speed, yet still able to handle most component sizes commonly found in the manufacturing environment. Ten manufacturers (37%) offered a non-contact probing system, compared to 19 (70%) which utilized contact probes, indicating that most of CMM applications are still three-dimensional. Optical-electric devices are best suited for two-dimensional work, although some have limited three-dimensional capability. These devices permit rapid data acquisition.

2.3.2 Software

William Tandler of Multi Metrics, contends that there are four classes of CMM software - manual, automatic, programming and batch (Schaffer, 1982). Manual software uses a keyboard or menu approach to measure individual parts, unlike automatic software which uses preprogrammed routines. In a direct computer controlled CMM, the automatic software drives the servos to move the probe. Programming software, on-line or off-line, is used to prepare the inspection routine for automatic inspection. It would be desirable to tie this function into a CAD/CAM data base. The batch software is used to analyze data of similar parts to determine trends and problems.

The availability of pre-programmed functions greatly enhances the inspection process. The incorporation of simple programming languages, such as FOCAL (FOrmula CALculator) a Fortran-like interpretative language by Bendix (Coggin, 1972) led to easier part programming, improved accuracy and speed, while reducing operator error. Twenty-four (90%) of the firms surveyed by Schaffer (1982) offered some level of software ranging from programmable functions to statistical analysis and reporting functions.

Of these 24 firms, all offered at least pre-programmed functions. Ten (42%) indicated that on-line (self-teach) or off-line programming capability was available. This capability allows the user to assemble the vendor's function into a program for repetitive measuring applications. Finally, nine (38%) firms indicated that a high-level language, such as BASIC, was available. This allows the user to develop such software as reporting functions and statistical analysis, and to provide the opportunity to develop CMM functions.

2.3.3 Computer Aided Quality Assurance Systems

Schaffer (1982) indicated that the main obstacles to using the CAD/CAM data base for CMM programming are the lack of provision for tolerance data in the data bases and the abundance of incompatible languages. While General Electric is believed to be developing this capability, Computervision recently announced a product called CMM Interface (Anonymous, 1982) to meet this need. The Computervision CADDS (CAD/CAM) software package is interfaced to a Bendix Cordax CMM. The preprocessor generates an inspection path, while the post processor creates machine instructions to control the CMM.

In 1974 (Gehner, 1982), a Deere and Company study found that minicomputers could be used to improve inspection technology and productivity. It was noted that CMM vendors each used unique software and that a common language did not exist for providing computational assistance to a CMM. A system was developed and released in 1977. Input is possible with any type of CMM. A Digital Equipment Corporation model PDP series computer was the typical host, and used a serial interface to communicate to the CMM. The software utilized a program called CAL (Computer Aided Layout) to convert input into measurement data and to handle analysis. FORTRAN IV, or a FORTRAN-like language was used in the host and satellite stations. Virtually any major brand European or North American CMM could be used with the Computer Aided Inspection and Reporting (CAIR) system.

As observed previously, one stumbling block to integrating a CMM into a computer aided quality assurance system is the lack of a common language. Deere and Company's approach using CAIR, or Multi Metrics' solution of retrofitting with a common language could resolve this issue. Co-operation between CMM and CAD/CAM vendors such as Brown and Sharpe and

CADAM, or Bendix and Computervision will ultimately resolve the problem of the lack of a common data base.

2.3.4 Coordinate Measuring Machine Applications

Advances in manufacturing technology have historically developed from military applications. The CMM was no exception. Bendix introduced the Sheffield Universal five-axes numerical tape-controlled measuring machine (Model TC-101) in the United States for a military missile application (Wilt, 1961). The unit was capable of automatically completing nearly a thousand precise measurements in two hours, while previous methods would have required 125 hours.

The TC-101 had a one-piece cast gage base with a mass of 8 t, and used a horizontal arm to provide a nominal 500 mm high by 500 mm diameter inspection envelope (Anonymous, 1961). The hydraulic power supply, refrigeration unit, and electric panel were located outside the environmentally controlled measuring room. Numerically controlled scanning and increment gaging, in addition to operator-controlled gaging was possible.

Over the years, applications have diversified. McDonnell Aircraft Company first started to consider and study a numerically controlled measuring device in 1958 (Bruenger, 1982). However, after years of waiting due to research, specification development, corporate reorganization and preparation, a manually programmable CMM was installed in 1967. Anticipated productivity improvements of 17:1 were confirmed. There were limitations due to the manual programming and keypunching techniques used. However, the CADD graphics system was later used to develop inspection paths and verify tool designs. Permanent inspection records were also kept, and used to determine repetitious defects allowing corrective action to be undertaken.

Papke (1982) of Douglas Aircraft Company reported a specialized application by the Quality Assurance Department to inspect lofting surfaces. A CMM inspection of the first part in a production batch was used to confirm the ability to fabricate a conforming part, and thus proved the part for production. The CMM was then used for feature inspection and to create soft tools, such as overlays and optical comparator charts. Douglas Aircraft Company found that utilizing CAD/CAM with CMM technology resulted in a $5,000,000 (US) cost avoidance for hard tooling on one project alone, as well as a 90% reduction in shimming and total scrap elimination on a small research and development project. Since the Quality Assurance Department started to produce soft tools, lead times decreased to two days from six to eight weeks, and resulted in increased use as well as a 50% reduction in inspection costs.

General Electric's A & E Systems Department developed their own CMM system (Lestage, 1982) using a Digital Equipment Corporation model PDP 11/35 host computer and a Bendix CMM, at a substantial saving compared to retrofitting. Also, due to the central approach selected in the mid-1970's, commercial software was not available, so General Electric wrote their own. Inspection programs could be debugged without tying up the CMM, and changes were easy to make due to the use of a high-level language. In 1981 an upgrade was completed, and incorporated servo drives, joysticks and electronic touch probes to meet user needs. To increase CMM capability, local Motorola 68000 microprocessors were added to handle the upgraded hardware and old software resident in the host. General Electric found that in-house skills in metrology and with computers permitted productivity gains at less cost than turnkey equipment.

At General Electric's Large Steam Turbine-Generator Department, a custom designed microprocessor-based system was used to acquire data from a two-axes Boice CMM with a Ferrand position display (Harris, 1975). The data were collected and then outputted to a telewriter which produced the tape used by a large program to control machine parameters.

Schaffer (1982) reported several examples of smaller-scale operations which successfully used the CMM to their benefit. A Digital Electronics Automation bridge-type CMM, in a numerically controlled job shop, reduced inspection time to 10% of the time required for manual inspection. Ingersoll Milling Machine Company found that a Zeiss-Mauser system eliminated trial-and-error in setting work station adjustments in addition to a significant saving in inspection time and analysis. One application alone now required 15 to 30 minutes compared to the 32 hours needed previously.

Miller and Arbuckle (1980) stated that the Steel Products Corporation used a Bendix Cordax model 803 CMM, with a measurement preprocessor, and cut inspection of one part from eight hours to eight minutes. Numerically controlled machine waiting time was minimized, and shimming eliminated.

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Borg-Warner in Letchworth, UK justified the acquisition of an LK Metrology Micro-Four for marking off and measuring castings because of projected utilization (60%), the ability to access the underside of the casting, and the cost and time savings (Dunn, 1979).

Hope (1980) expected the main advantage of using a CMM to "mark-out" or scribe workpieces would be the time savings, estimated at 50 to 80%. He stated one area recovered the cost of a CMM dedicated to scribing within six months. As well, the CMM compensated for the lack of skilled labor, while its usage improved the flow of work.

Ploszajski (1980) found that a VIS Tool Industry Group (Warsaw, Poland) XYZ CMM cut inspection times as much as 90%. This CMM was typically used to inspect turbine blades, headstocks, engine components and plates.

Chuchro and Ostrowski (1980) reported upon the development of a family of coordinate measuring machines - the first version of the MP-700A - at the Institute of Machinery in Cracow, Poland. A gantry design, the system incorporated the measuring machine, tape reader and punch, printer, plotter, modem, floppy disc drive, and central processor. A Hewlett-Packard model HP 9825A desktop computer was used as the central processor. Peripherals from MERA, MERA-BLUNIE, or Hewlett-Packard were used. System software included the operating system, metrological and statistical packages, as well as user programming capability. Available operating modes included manual, semi-automatic, automatic, and supervisory computer-assist automatic. Anticipated applications for these modes were a random inspection of a variety of parts, the repetitious inspection of a sample part, or an automatic production-line environment. Inspection time savings (over conventional methods) ranged from 50 to 60% (manual mode) to between 85 and 90% (supervisory computer assist). Savings of 60 to 70% were found in semi-automatic and 70 to 85% for automatic applications.

At its plants in Greenock and Havent, U.K., IBM reported saving 70 to 80% on inspection time with Ferranti-Cordax model 3000 CMM's controlled by IBM Series/1 computers (Kellock, 1980). It was planned to ultimately include process analysis software in order to detect drift in part dimensions, so that supplier and machine performance could be determined.

Treywin (1978) observed that the CMM is quite similar to a numerically controlled machine - parts are inspected in a way similar to the way they are manufactured, and both the CMM and numerically controlled machines use coordinate data to operate. He estimated that 50% of CMM's support numerically controlled machine tools, indicating the CMM is compatible with these machine tools, and thus justifiable for small- to medium-batch production runs, and even high-production runs. Labor savings, compared to standard methods, of at least 80% were predicted. These savings were based on faster analysis and less recording time. It was estimated that the clerical segment of an inspection was usually a minimum of 25%.

Gaskell (1980) of Ferranti stated that a CMM with computer assist was suitable for small quantities of parts, the first-off part in a production run, or non-repetitive batch runs. The automatic CMM was seen to be more useful for larger quantities of parts, or in an automated manufacturing cell. The average time saving, compared to conventional methods, for first-off parts (of a batch) such as cams, gear cores, shafts, plates and blades ranged from 78.3% (computer assist) to 95.3% (automatic).

Donat et al. (1978) described the model DKM 1-300 DP Model VEB Carl Zeiss JENA CMM as a "high-performance instrument for engineering dimensional metrology". The CMM design incorporated an electronic touch probe, a microprocessor for control and processing, a printer, and programming capability using a display screen and magnetic tape storage. An increase, compared to conventional techniques, "of up to 1300 per cent, and 1700 percent in productivity is achieved in single and repeat measurements, respectively" was reported. They also stated that increased productivity was due to reduced measuring time (because of the electronic probe), reduced data reduction time, and the elimination of part orientation which reduced setup and idle times.

Kobrinskii et al. (1979) observed that the CMM was characterized by the automation level and design principles, while being able to meet different requirements in purpose, operation, accuracy, and working volume. They also noted that most leading CMM manufacturers modified their basic products to varying degrees of automation to suit the customer's needs.

Two measurement methods, independent of degree of automation, were also discussed by Kobrinskii et al. The comparative method featured the comparison of the actual form of the part to the inspection path, and several dimensional deviations. The ASEA Company in Sweden was reported to use this method to inspect car bodies, and utilized a feedback loop to correct the production process. The second method described was that of obtaining actual dimensions, and calculating the deviations with a computer, rather than sensing the deviation (comparative method). They also stated that the A.A. Blagonravor State Research Institute for Machinery (Gos MIImash) in the USSR developed an experimental dynamic error composition technique (for the comparative method of inspection) on a Model KA-50 (Soviet-made) CMM with an MN-7 analog computer. Automatic measurement accuracy was improved to equal the measuring head's manufacturing accuracy and static machine accuracy.

Lucas CAV Limited established a new plant in 1981, which used the technique of Stewhart Control Statistics to maintain quality (Gallagher, 1982). Machine operators were made responsible for product quality and a computer-linked electronic gaging system used to monitor production. A local computer (Hewlett-Packard model HP 85) approach was taken to overcome possible fears of the computer by plant personnel. In-process rejects and grinding wheel utilization (a good indicator of rework) were reduced, and high yields obtained. Lucas CAV Limited concluded that if real-time data were available, the machine operators could control product quality. Future benefits, such as lower failure costs and better tool utilization were anticipated.

Rockwell International found that a user-friendly, computer aided device improved the throughput of a hybrid microelectronics inspection operation by a factor of three to one (Hoover and Scott III, 1982). The computer electronically tested a circuit, and was used as an aid in visual identification of the problem area by supplying potential problem causes. Error information was available in real time, permitting rapid correction.

Deere and Company found that their Computer Aided Inspection and Reporting system reduced manual CMM inspection time to one-seventh of the original time required, and produced a 15:1 increase in capability studies (Gehner, 1982) while it also permitted better engineering and manufacturing design decisions. The inspection of first-off parts was more rapid. The elimination of special single-purpose relation gages allowed a US $500,000 cost avoidance. Return on investment was found to be in the order of three digits. Lockheed Missiles and Space Company Incorporated were reported by Nix (1982) to be currently utilizing a CADAM system, nine Bendix and one Boice CMM in their quality assurance system. A Ferranti manual CMM was first used in the late 1960's before the Bendix direct computer control Cordax units were acquired in 1979, and subsequently manual and automatic Brown & Sharpe models of CMM in 1981. Lockheed-Georgia justified the technology by forecasting reductions of 30 to 50% in inspection time and 50% in part programming time (if the part was in the CADAM system). Lockheed noted that the numerical control programming time for the space shuttle heat tiles took 160 man-years, while the parts inspection programming required 10 man-years.

Kirmeyer (1982) described the Lockheed system capable of inspecting all 26,000 unique heat tiles for the space shuttles. In 1975, the dimensional data for the tiles were received by Lockheed, without engineering drawings, only punched cards and magnetic tapes and were referenced to the space shuttle's global coordinate system. The lack of engineering drawings, coupled with the need to identify, orient and inspect the parts, as well as the handling and measurement problem due to the material composition of the tiles, presented a unique challenge. The successful resolution of the project presented several benefits. First, there was a step towards a paper-free operation which allowed the inspector to concentrate on inspection, not paperwork. Second, by having engineering and inspection data in the computer, historical data were available for analysis. Finally, it was possible to meet the challenge.

The previous examples illustrate the diversity of applications, complexity, equipment, and techniques used in modern coordinate measurement. The decision to use CMM technology, and the level of computer capability required to operate the CMM, is governed by the application, company resources, and economy of scale.

CHAPTER III

EQUIPMENT

A Hewlett-Packard model HP 1000 minicomputer and a Bendix layout machine (a type of CMM) are located in the Quality Assurance Department at Versatile Farm Equipment Company[1]. The layout machine has been in service since early 1982, and the minicomputer since April, 1982.

3.1 Coordinate Measuring Machine System

The CMM system described is a Bendix model LO-4 layout machine with a measurement processor (Model MP-2). Preprogrammed measurement software is also part of the system.

3.1.1 Layout Machine

The layout machine is one of the Bendix Cordax LO Series (model LO-4, Bendix #45000181) and uses a base-mounted vertical column (Y-axis), a horizontal crossarm (Z-axis), and the layout table (X-axis) to obtain coordinate

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measurements. By moving the entire machine, head assembly and/or crossarm it is possible to measure all sides, as well as the top, bottom and inside of the part in one setup. Figure 6 illustrates the components of the layout machine. The layout grid is made up of two 50 x 70-inch English tables (Bendix #45000253), with machined grid slots on ten-inch centres. This permits the machine to be indexed about the part. A rotary table option (Bendix #45000695) allows the part to be rotated, rather than moving the machine.

The layout machine has an X-axis range, without staging, of 679 mm, Y-axis range of 1219 mm, and a Z-axis range of 965 mm. This is an effective part envelope of 679 m x 1219 m x 965 mm without indexing the machine, and is illustrated in Figure 7 and Table 2.

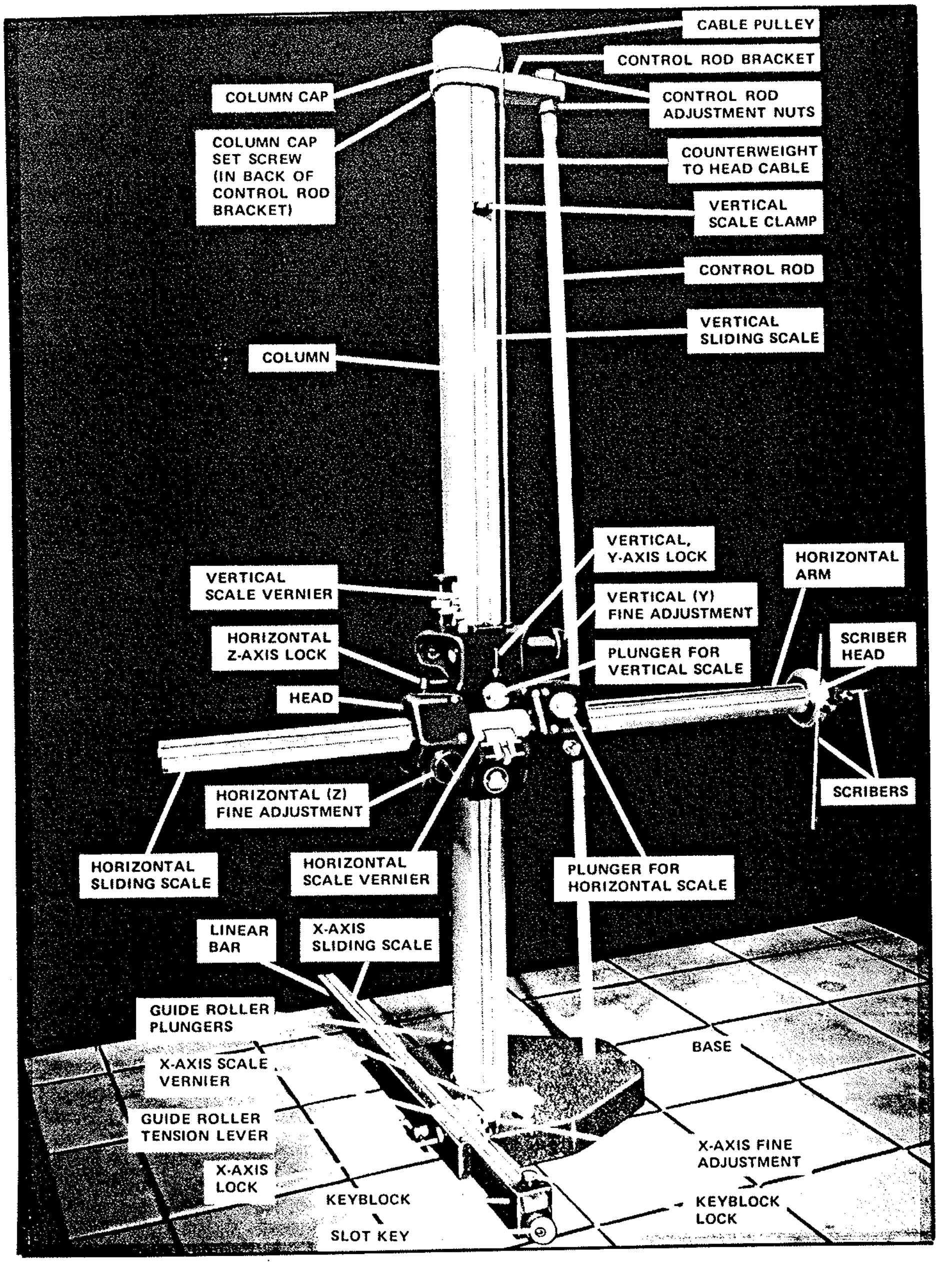

Figure 6. Bendix LO series layout machine (Courtesy of Bendix Corp.)

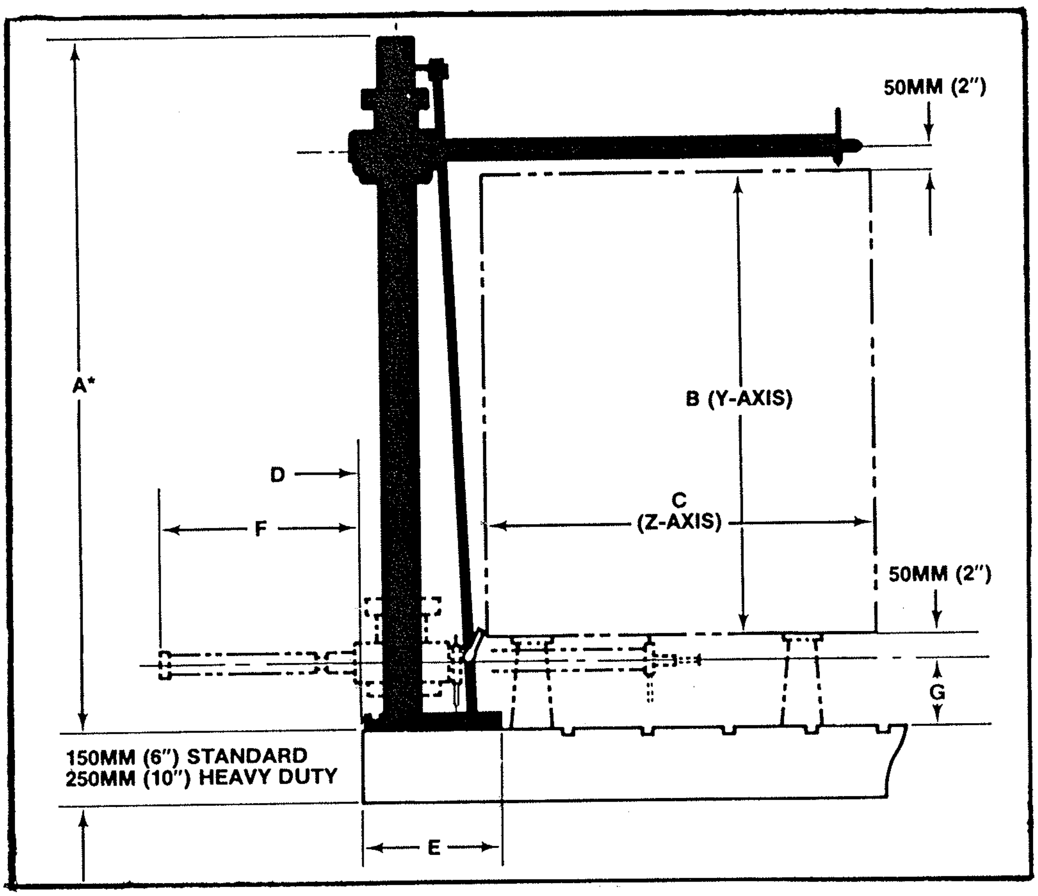

Figure 7. Layout machine dimensions (Courtesy of Bendix Corp.)

Table 2. Bendix layout machine dimensions (Bendix Corp.)

Model	A* Machine Height	B Y-Axis Range	C Z-Axis Range	D Back of Base To Back Of Z-Axis Travel	E Base Dimension	F Maximum Backward Extension of Arm	G Unuseable Space ℄ Arm To Table Top
LO-3	1613 (63.50)	914 (36)	686 (27)	330 (13)	375 (14.75)	762 (30)	178 (7)
LO-4	1911 (75.25)	1219 (48)	965 (38)	330 (13)	375 (14.75)	1041 (41)	178 (7)
LO-6	2165 (85.25)	1524 (60)	1168 (46)	356 (14)	432 (17)	1270 (50)	178 (7)
LO-7	2470 (97.25)	1829 (72)	1168 (46)	356 (14)	432 (17)	1270 (50)	178 (7)
LO-8	2959 (116.50)	2134 (84)	1270 (50)	572 (22.50)	622 (24.50)	1397 (55)	229 (9)
LO-9	3264 (128.50)	2438 (96)	1270 (50)	572 (22.50)	622 (24.50)	1397 (55)	229 (9)

All dimensions are shown in millimeters and (inches).

*Total system height should include machine height and table height.

3.1.2 Measurement Processor

The Bendix measurement processor (Model MP-2, Bendix #50081046) with a serial interface, is a Motorola 68000 microprocessor-based product capable of providing basic data processing and includes the microprocessor, counter, keypad, and a light-emitting-diode display (Figure 8). It is controlled by firmware which may be selected by a one- or two-digit command.

The data processing circuitry is located between the layout machine's position transducers and the measurement processor's display. Data are thus processed before they are displayed, and part dimensions rather than layout coordinates are displayed.

Two serial interfaces (RS-232 or 20-ma current loop) are available with the use of the Measurement Pre-Processor Control and Terminal Interface Board, Bendix #50023290. The general specifications are:

Baud Rate: 110, 300, 600, or 1200 baud

Data Word Size: 5, 6, 7, or 8 bits/word

Parity: even, odd, or none

Stop Bits: 1 or 2

Terminal Connector: DB25-S (25-pin female)

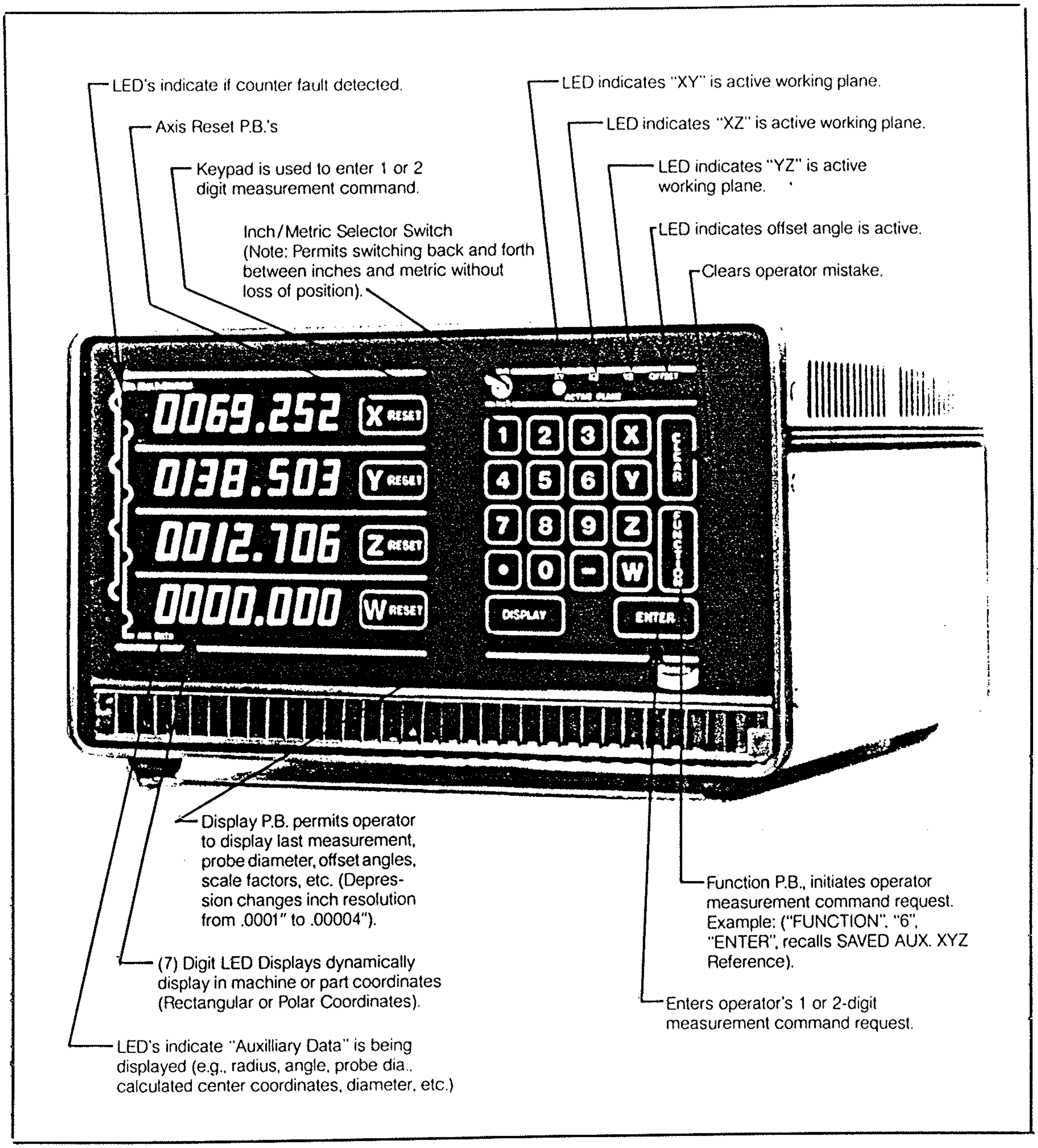

Figure 8. MP front panel functions (Courtesy of Bendix Corp.)

The connector on the rear of the Bendix model MP-2 measurement processor utilizes the pin assignments indicated in Table 3 and Figure 9. All other lines are not used. Two switches (identified as SWP1 and SW-2) are used to set the interface.

This interface may be used to optionally control a table-top printer (Bendix #50081074), a model ASR-43 teletype (Bendix #58000336) or a General Electric Terminet 30 dual cassette/printer (Bendix #300024221).

The table-top printer is part of the measurement processor at Versatile Farm Equipment Company, but is removed from the system to facilitate interfacing the minicomputer.

Table 3. MP-2 terminal pin assignments

Pin Number	Function
2	Receive Data
3	Send Data
5	Clear to Send*
6, 8	Data Set Ready
7	Signal Ground

* The input device must be under control of the Clear to Send Signal.

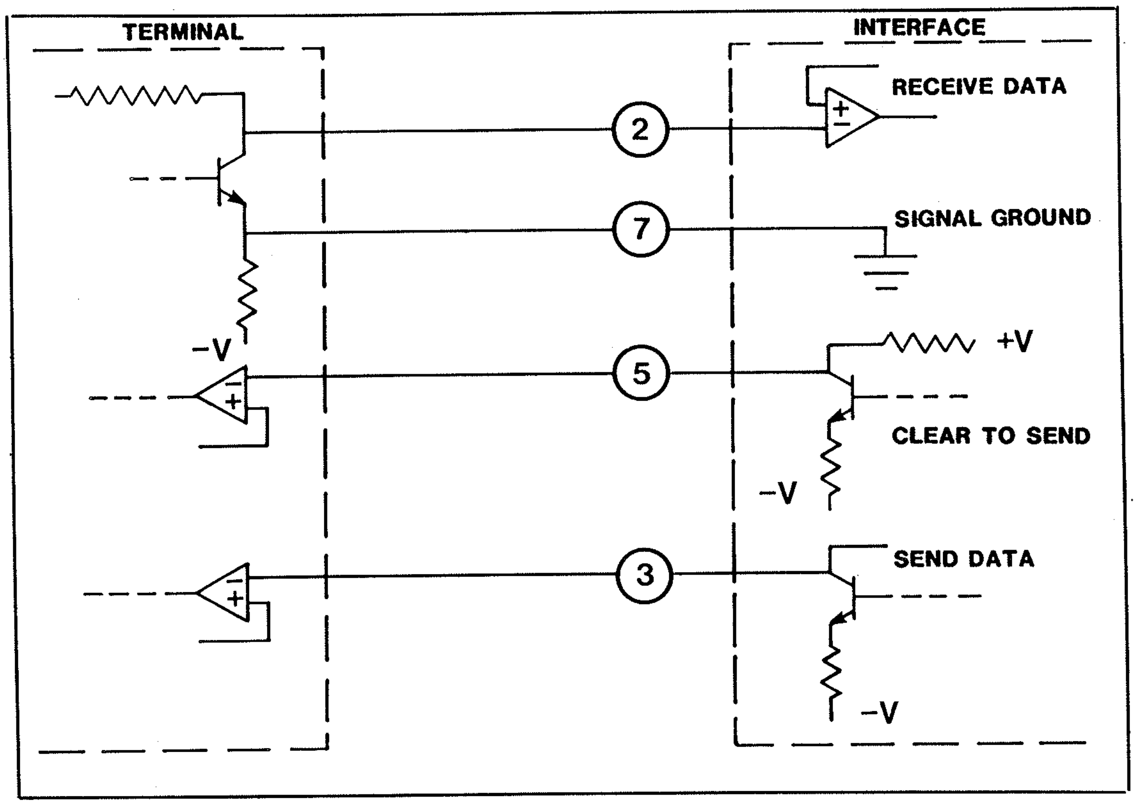

Figure 9. MP-2 interface (Courtesy of Bendix Corp.)

3.1.3 Firmware

All the measurement and control functions are preprogrammed in the memory of the measurement processor. These functions may be accessed using the front panel keypad, or by commands through the RS-232 interface.

A typical command will have three parts - data, function selection, and terminator. The data position is not always necessary, but when used it is either an alpha or alpha-numeric string. The function consists of the letter "F" and appropriate function number. The terminator is either an "E" (execute) or "D" (display). A maximum of forty characters may be used in a command.

There are various classifications of commands:

i) alignment
ii) reference establishment
iii) measurement
iv) data manipulation
v) programming
vi) data entry/display
vii) auxiliary

These commands can be used to control the inspection function, collect and analyze data, and display results and error message codes (Appendix A).

Version 4 was the level of firmware in the measurement processor at the time of this project.

3.2 Computer System

The computer system includes a Hewlett-Packard model HP 1000 minicomputer, a Winchester disc drive with integral cartridge tape drive, and an eight-channel asynchronous multiplexer. The system console uses its own interface card, while the terminals interface to the computer using the multiplexer remote panel.

3.2.1 Central Processor

The Hewlett-Packard model HP 1000 minicomputer is a Model 60 (E-Series) 2178A System Processor. This is a 16-bit computer with 256 Kbytes of memory. Input/output (I/O) to the computer is achieved by placing device interface cards in the I/O card cage. Up to 11 interface cards can be used before it is necessary to expand the I/O card cage. The system console is an Hewlett-Packard model HP 2645A display station with dual cartridge tape drives (for diagnosis and input/output).

3.2.2 Storage

A Hewlett-Packard model HP CS-80 Model 7912P Winchester disc drive is the system disc. Storage capacity is 64 Mbytes. An integral cartridge tape drive with a capacity of 64 Mbytes is used for backup purposes.

3.2.3 Communication

A Hewlett-Packard model HP 12792A high-speed asynchromous multiplexer interface is a Z-80 microprocessor-based product to provide serial communication between the computer and printers or terminals. The multiplexer can support up to eight asynchronous RS-232 compatible devices either hardwired or with full duplex asynchronous protocol. An eight-junction remote panel, the Hewlett-Packard model HP 12828A, is used to provide a convenient means of connection between the multiplexer and input/output devices. The multiplexer, with the remote panel, has these features:

Baud Rate: 50, 75, 110, 34.5, 150, 300, 1200, 1800, 2400, 3600, 4800, 9600, and 19200 baud

Data Word Size: 5, 6, 7 or 8 bits/word

Parity: Even, odd or none

Stop bits: 1 or 2

Echo: On or off

Terminal Connector: DB25-S (25-pin female)

The connector on the multiplexer remote panel, Hewlett-Packard model HP 12828A, utilizes the pin assignments indicated in Table 4 and Figure 10.

The remote panel is used to connect up to eight serial input/output devices through the junctions or ports to the multiplexer. The remote panel emulates a hardwired modem in its pin assignments (Table 4 and Figure 10).

Table 4. HP 12828A terminal pin assignments

Pin Number	Function
2	Receive Data
3	Send Data
7	Signal Ground

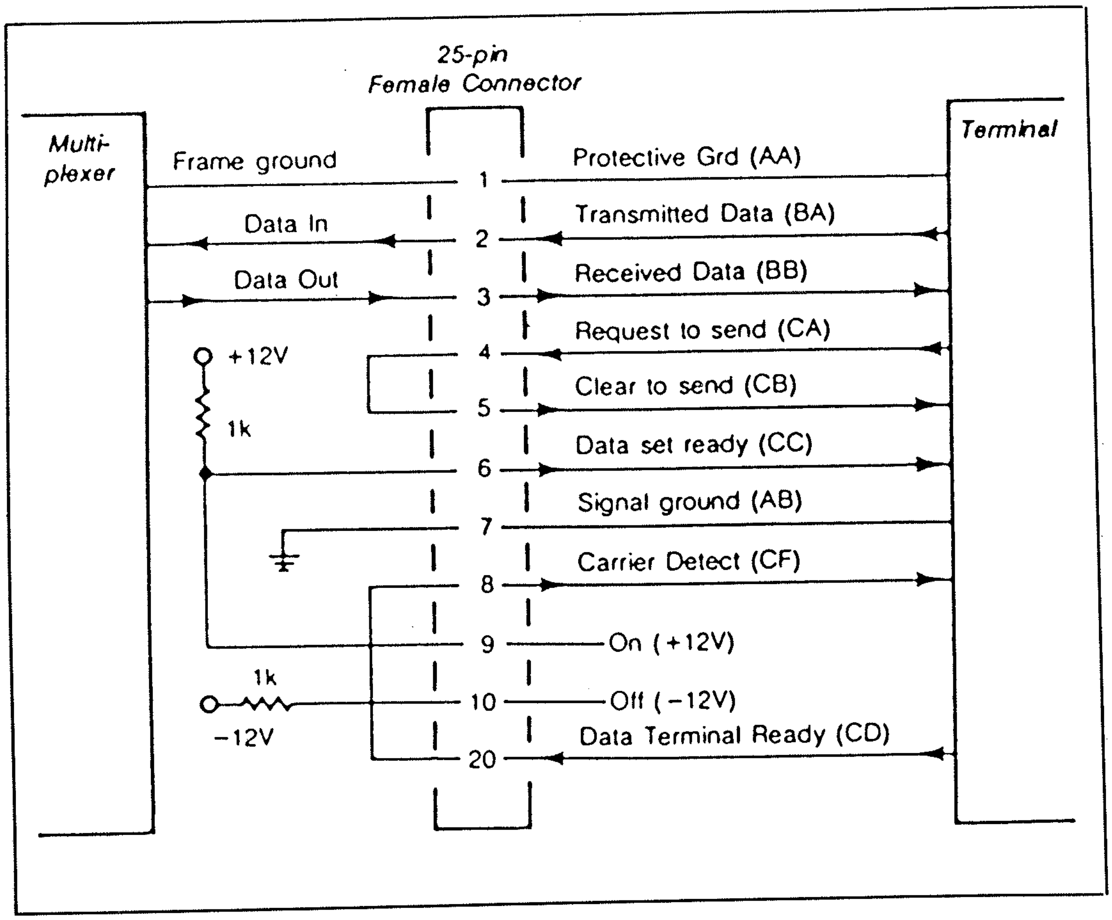

Figure 10. HP 12828A Interface (Courtesy of Hewlett-Packard)

The multiplexer interface also has 16 Kbytes of random access memory equally divided between the eight ports to buffer input/output.

Software drivers are provided to permit connection of different devices such as teletype or dumb devices (DVM00), Hewlett-Packard HP 26XX series terminals (DDV05), and Hewlett-Packard printers (DDV12). All communication is controlled by the multiplexer's software/firmware only. Modification of the software/firmware is required for devices utilizing hardware handshakes. The multiplexer supports only ENQ-ACK and DC1-DC2 (block mode with DDV05) protocols or handshakes.

These, and many other features, must be programmatically or interactively selected before successful data communication is possible. To interactively select these features the File Manager (FMGR) "CN" command may be used. Programmatically, there are two options to select features, the WELCOM file (batch file of FMGR commands which is run each time the system is booted-up or started) or EXEC calls in the application Fortran (FTN4X) program. The remote panel is used to interface the DECWRITER III terminals, the Hewlett-Packard model HP 2631B printer, and ultimately the measurement processor to the minicomputer.

3.2.4 Operating System

The newest operating system, RTE-6/VM, is a new product for the Hewlett-Packard model HP 1000 minicomputer. Real Time Executive (RTE) is a real-time multi-programming time-slicing operating system. Since RTE is interrupt-driven (every ten milliseconds), while one program is waiting for data transfer the central processing unit can execute another program. Time slicing will give time to a program on a priority basis - the lower the priority the longer the time slice at less frequent intervals. Thus, RTE manages programs, memory, and input/output. The services of RTE can be requested programmatically or interactively.

The file management system interfaces the user to RTE and allows the user to manipulate files interactively or programmatically. Files can contain ASCII or binary data in source or relocatable code.

Session Monitor restricts access to the system and its resources and protects users from each other, while providing a friendly multi-user environment. All users must have an account, and may be given restricted access to peripheral devices and limited use of commands. Users can share disc cartridges or have exclusive access, yet their programs are protected from the activities of other users. Every user does not need to know about the system configuration and has the impression (at a terminal) of being the only user on the system. The System Manager maintains each user's account which consists of a user and group name, password, capability , and device access record.

Program development in RTE begins with the EDIT program which creates, modifies or appends files. Editing is done in the source work area (track pool) and when terminated, the corrected file is put into the destination work area. Thus, a file cannot be accidentally destroyed during editing. After editing, the source file is compiled by the FORTRAN compiler and loaded by the loader. The program is then ready to run.

Programs can be in real-time or background and memory or disc resident. Using the dynamic mapping system, the computer can access all of physical memory (128 Kwords) for program use. However, the executable program (or segment) code must not exceed the limits of logical memory (32 Kwords less system requirements). Using Virtual Memory Area/Extended Memory Area programs, data can be extended beyond 32 Kwords of logical memory, to a maximum of 128 Mbytes. Segmentation and extended and visual memory access are transparent to the user. At system generation, each device is assigned an equipment table number which is in turn linked to the system logical unit number. This table contains the addresses and linkages between the peripheral devices. In every case the driver is the limitation of a device's capability. Programs can also communicate (in real time) with each other by transferring data blocks which are limited in size only by system available memory.

A program's state (or the relationship between the program and RTE) and information about disc usage is always available to the user via breakmode commands or utility programs. The user can also check the status of any piece of peripheral equipment in his session. Error messages are given and explanations are available (on-line) from utility routines.

Revision 2208 is the current level of the operating system.

CHAPTER IV

METHODS

To meet the objectives of this project, it is necessary to develop a hardware/softare interface and software for process control and data acquisition.

4.1 Hardware Interface

The first step in networking the measurment processor to the minicomputer, is developing the hardware interface, using the multiplexer system.

4.1.1 Technique

The measurement processor is interfaced to the multiplexer subsystem using the RS-232 interface. The multiplexer passively supports RS-232 devices which are hardwired or use a full duplex (short-haul) modem only. All handshaking is done by software or firmware.

Physical connection is made through the Hewlett-Packard model HP 12828A remote panel. The multiplexer panel and the measurement processor both have female terminators, thus a Hewlett-Packard model HP 13242G male-to-male cable and a Burroughs male-to-female terminal cable are used for the connection.

4.1.2 Problem

The measurement processor uses Pins 2, 3, and 7 as does the multiplexer. But the measurement processor also uses Pin 5 to signal when its eight-word input buffer is full, which the multiplexer does not recognize since it is hardwired (Figure 10). Thus, the measurement processor input buffer will overflow. The problem is further complicated since both devices do not use the same handshake or protocol for data communication.

4.1.3 Potential Solutions

There are several options available to solve this problem.

4.1.3.1 Hewlett-Packard Model HP 12966A Serial Interface

This Hewlett-Packard model HP 12966A interface is an asynchronous point-to-point terminal interface which recognizes all status control lines. It contains a 128-character buffer and will work with standard

Hewlett-Packard drivers. However, it is relatively expensive at approximately a $1000 per device and uses up one I/O slot in the card cage. This is not an optimum solution if many measurement processors or similar devices are to be interfaced.

4.1.3.2 Buffered Black Box

A buffered black box, such as a Western Telematic model PPD-4 could be used to meter output from the multiplexer to the measurement processor. While somewhat less expensive than the Hewlett-Packard model HP 12966A interface at $500, an ultimate solution such as handshaking would make the black box redundant.

4.1.3.3 Smart Controller

A smart or intermediate controller such as an Hewlett-Packard model HP 85, would be located between the measurement processor and multiplexer and could incorporate several data acquisition and analysis features and pass files back and forth, but it is not an optimum solution. This type of controller is expensive ($5,000 to $10,000), and depending on the brand used compatibility problems could result and further complicate the problem.

4.1.3.4 Read Only Memory with Handshaking

A read only memory with handshaking for the measurement processor would be an ideal firmware solution. A handshake suitable for use with the multiplexer such as ENQ/ACK or DC1/DC2 would be appropriate. Resources were not available to develop this alternative. Bendix was planning to develop a compatible handshake, but it was not yet available.

4.1.4 Solution

None of the four options outlined was suitable for the reasons mentioned. Thus, a software solution was required.

4.2 Software Interface

4.2.1 Technique

The multiplexer uses a Z-80 microprocessor to handle all data communication. The multiplexer features programmable start, stop and data bits, echo, handshake, baud rates, etc. The measurement processor port is programmatically configured for:

1200 baud

1 start bit

8 data bits/character

1 stop bit

Handshake disabled

Echo disabled

DVM00 (dumb) driver attached

Scheduling disabled

Select port #2

Carriage Return (CR) terminator (default).

To permit normal communication (EXEC READ's and WRITE's) commands in the the WELCOM file may also be used:

CT,32,30B,142072B

CT,32,33B,1B

CT,32,37B,200B

The measurement processor data communication port is set to the appropriate configuration by selecting the appropriate switch positions of the switches located on the Measurement Pre-Processor Control and Terminal Interface Board. The selected configuration is:

1200 baud

1 start bit

8 data bits/character

1 stop bit

RS-232 interface.

This is done by setting the switch identified as SWP1 to "00010100" (0 is open) and the rotary switch SW-2 to position number 4. No standard handshakes or protocols are recognized, but the measurement processor has several unique characteristics:

i) Characters are read until an executable command is assembled. Once complete, the command is echoed (back to the multiplexer) as it is processed.

ii) Any unacceptable characters received as a command are ignored and not echoed.

iii) Any characters after an asterisk "*" are ignored and echoed.

iv) When sending data the measurement processor is programmed to address a teletype, and appends a Carriage Return - Line Feed (CR-LF) to each line.

These features can be used to establish an echo protocol to overcome the hardware problem between the multiplexer and measurement processor (the multiplexer does not recognize Pin 5) by sending instructions only after the previous command has been echoed.

4.2.2 Problem

As an interim solution, the echo protocol is acceptable until measurement data are expected. All the data are not received by the minicomputer. The measurment processor normally communicates to a teletype device, and therefore appends a Carriage Return-Line Feed (CR-LF) to every line. The multiplexer interprets the CR as a terminator, and ignores any data not on the first line sent.

4.2.3 Potential Solutions

Three potential solutions exist to handle the loss-of-data and hardware problems.

4.2.3.1 Protocol

The multiplexer recognizes ENQ/ACK and DC1/DC2 handshakes, the measurement processor none. Resources were not available to develop these protocols. A commercially available solution from Bendix or Hewlett-Packard was not available.

4.2.3.2 Software Driver

A custom software driver for the multiplexer could be written to handle the measurment processor. However, I had no experience writing code at the assembler (or MACRO) level and future revisions to the operating system could require changes to the new driver.

4.2.3.3 Echo Protocol

The last solution is to develop a protocol based on the echo characteristics of the measurement processor explained in Section 4.2.1. This solution is the simplest since it required only modification of the FORTRAN application code, and could work on an interim basis until Hewlett-Packard and Bendix released compatible protocols.

4.2.4 Solution

The simplest solution is the echo protocol, and therefore was the chosen method to be developed.

4.3 Software

An integrated software package is required to handle data communication and acquisition.

4.3.1 Purpose

A package of software application programs is needed in order to integrate the Bendix layout machine into the Hewlett-Packard minicomputer network. Part measurement files need to be created, instructions sent to the measurement processor and operator, and data recorded. To ensure transportability between Hewlett-Packard systems the programming language is FORTRAN. However, it is also necessary before using the layout machine with the computer system to initialize the multiplexer port (to which the layout machine is connected). This is required only for the initial operation after this computer is started, and should be transparent to the user. This requires that port initialization take place in the WELCOM file (Section 4.3.2.1).

4.3.1.1 Part Inspection

A program is required to create a part inspection procedure file. This ASCII file is to contain measurement commands for the measurement processor. As well this program shall provide operating instructions for the layout machine operator. This file will replace instructions which would normally be keyed into the front panel. It is also necessary for the program to determine whether the requested part and revision already exist.

4.3.1.2 Process Control

This program is used to retrieve the requested part inspection procedure file, send commands to the measurement processor and operating instructions to the layout machine operator's terminal, collect inspection data, and store it in an ASCII file for future analysis.

4.3.1.3 Data Retrieval

This program is needed to retrieve inspection data from an ASCII data file for verification. The results are to be written to the user's terminal. No analysis is required.

4.3.2 Description

A description of the operation of each software program is required.

4.3.2.1 The WELCOM File

The WELCOM file is a batch-type file which is automatically run when the computer system is started. This process will initialize the system software and all peripheral devices.

The port for the layout machine (Port #2) is initialized to meet the data communication requirements specified in Section 4.2.1. Appendix B contains the WELCOM and related files such as *UPMUX, the multiplexer initialization file.

4.3.2.2 The PFILE Program

PFILE is the program which creates the measurement processor part inspection procedure or part input file ultimately used by the process control program (MP2IO). These instructions would normally be keyed into the front panel, thus a working knowledge of the measurement processor instruction language (Appendix A) is required.

The programmer is asked for a part number and revision level which is used to create the file. The programmer is then prompted for comments and layout machine operator instructions. The only restrictions when using PFILE are:

i) Comment lines (operator instructions) must start with an "*".

ii) If results are to be displayed:

a) "**" is required to start the comment line immediately preceeding the "F61E" (Display Results) call to indicate measurement results are expected.

b) "**" is required at the end of the same line as the "F61E" command to terminate reading data (see Section 5.3.2).

iii) The last command sent must be "F40E". This command is necessary in order to return control to the front panel. If this is not done the measurement processor cannot be cleared for front panel control until it is powered off, then powered on.

There is an opportunity to correct each line as it is entered. See Figure 11 for program flow.

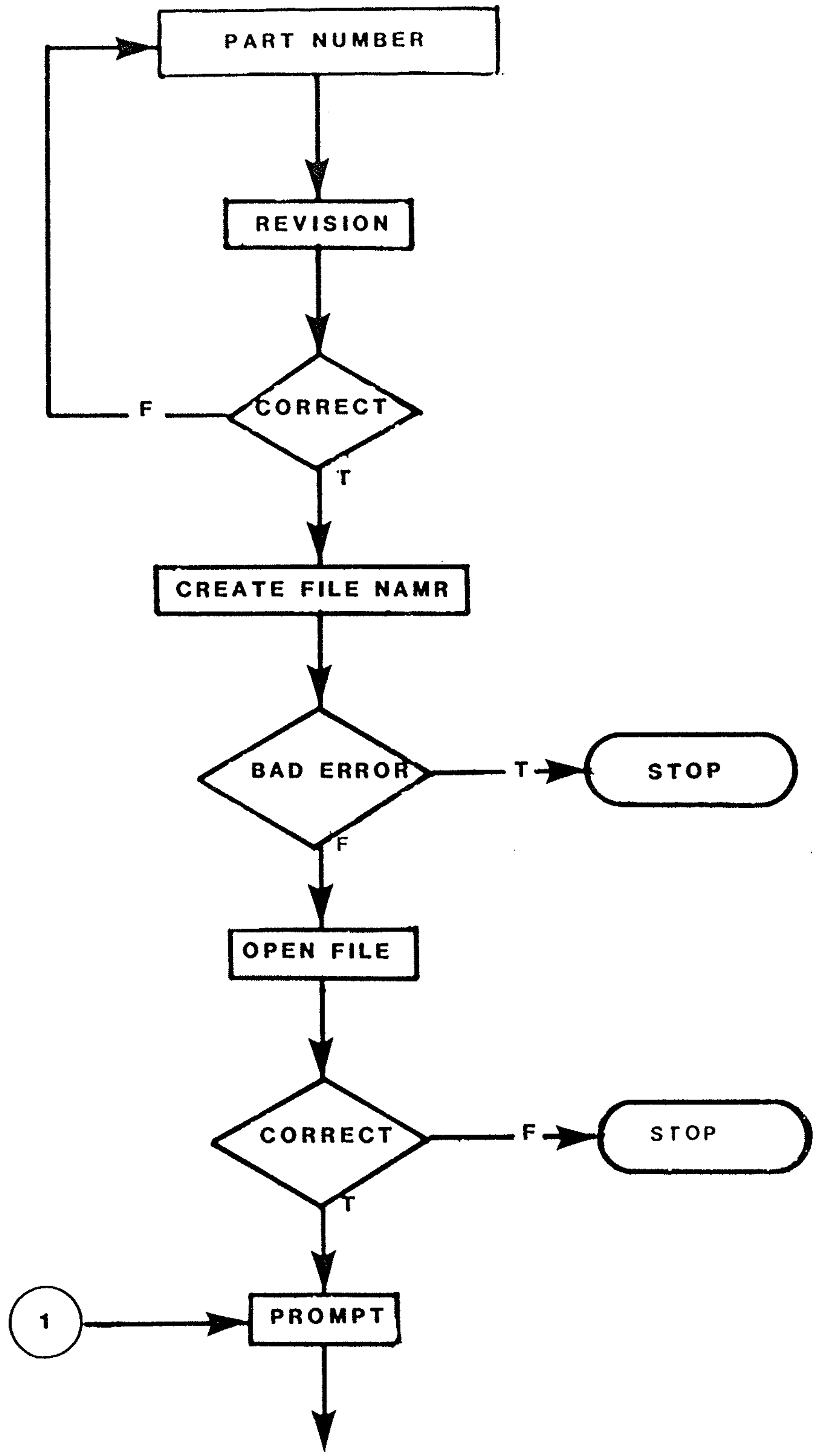

Figure 11. PFILE flowchart

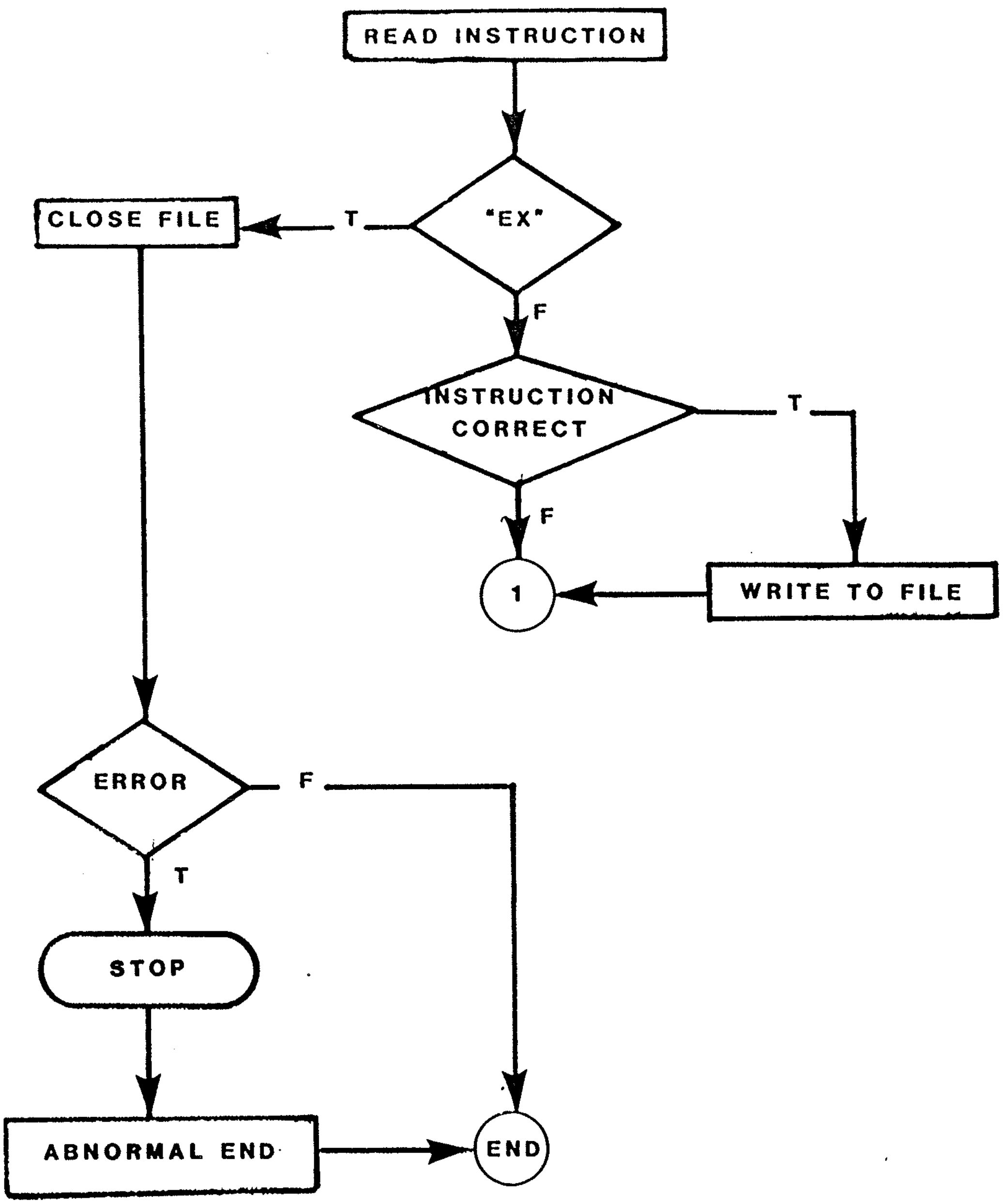

Figure 11. PFILE flowchart (cont'd)

4.3.2.3 The MP2IO Program

The program MP2IO is used to send instructions to the layout machine's operator teletype terminal and the measurement processor. The program will request the part number and revision level of the part to be inspected. These data are used to locate the part input file and open it. The program reads the instructions from the part input file created by the PFILE program, and sends them to the operator's terminal and/or the measurement processor, and will wait (when required) for a response, before issuing another command. It will then store the inspection results in a file.

It should be noted that before sending instructions to the measurement processor control must be turned over to the minicomputer. This is done by entering "F41D" on the front panel of the measurement processor before running the program. See Figure 12 for program flow.

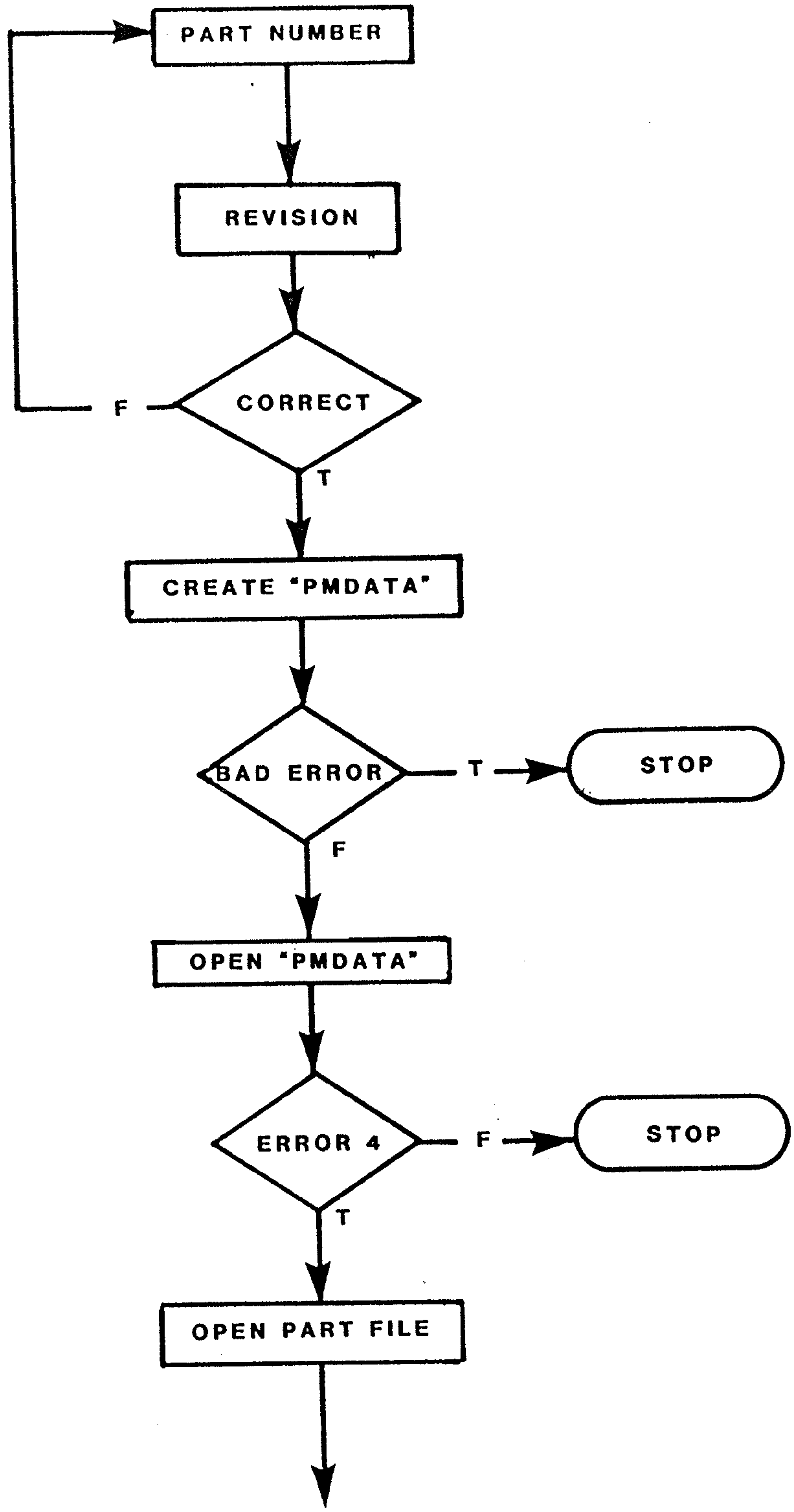

Figure 12. MP210 flowchart

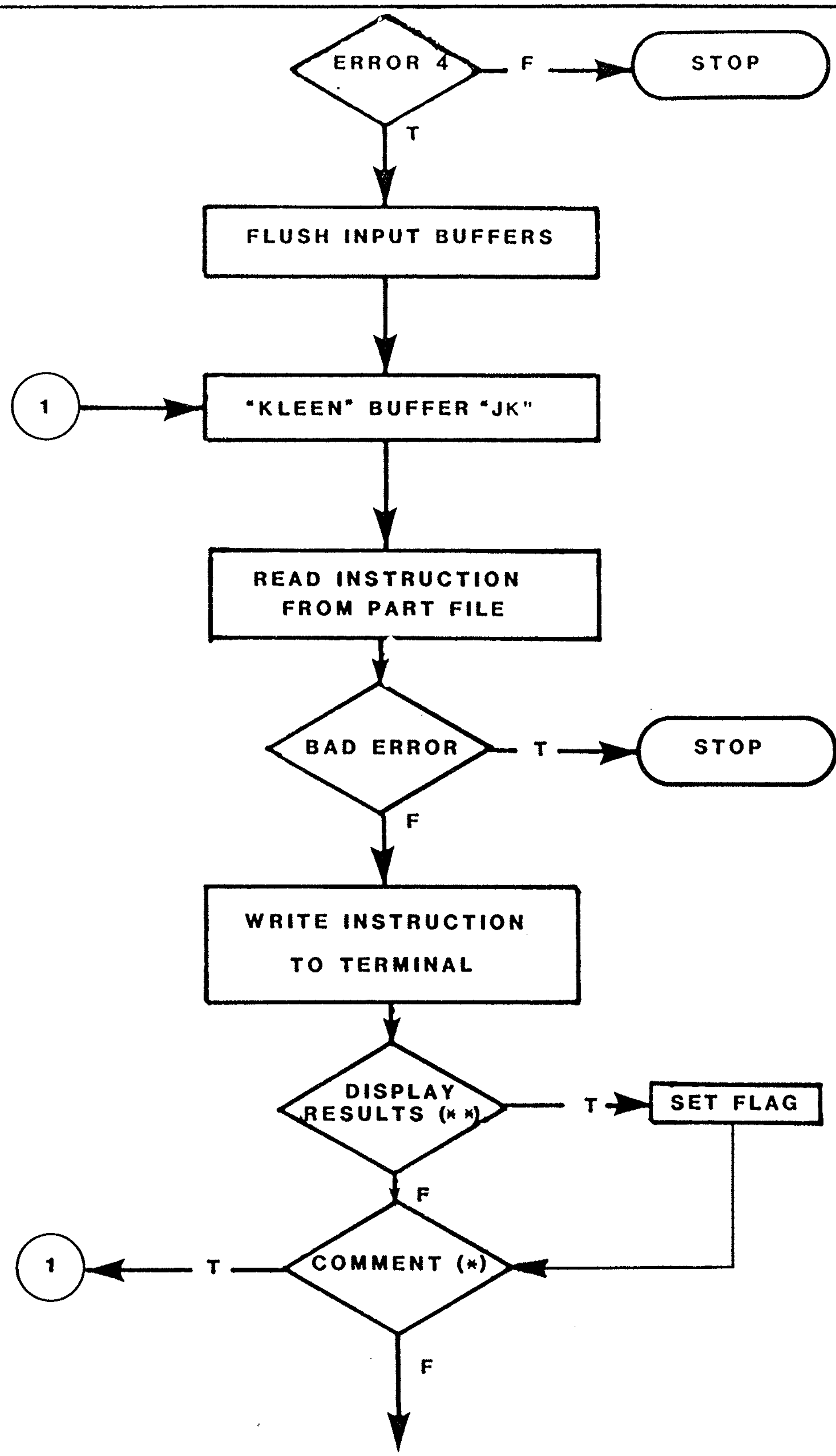

Figure 12. MP210 flowchart (cont'd)

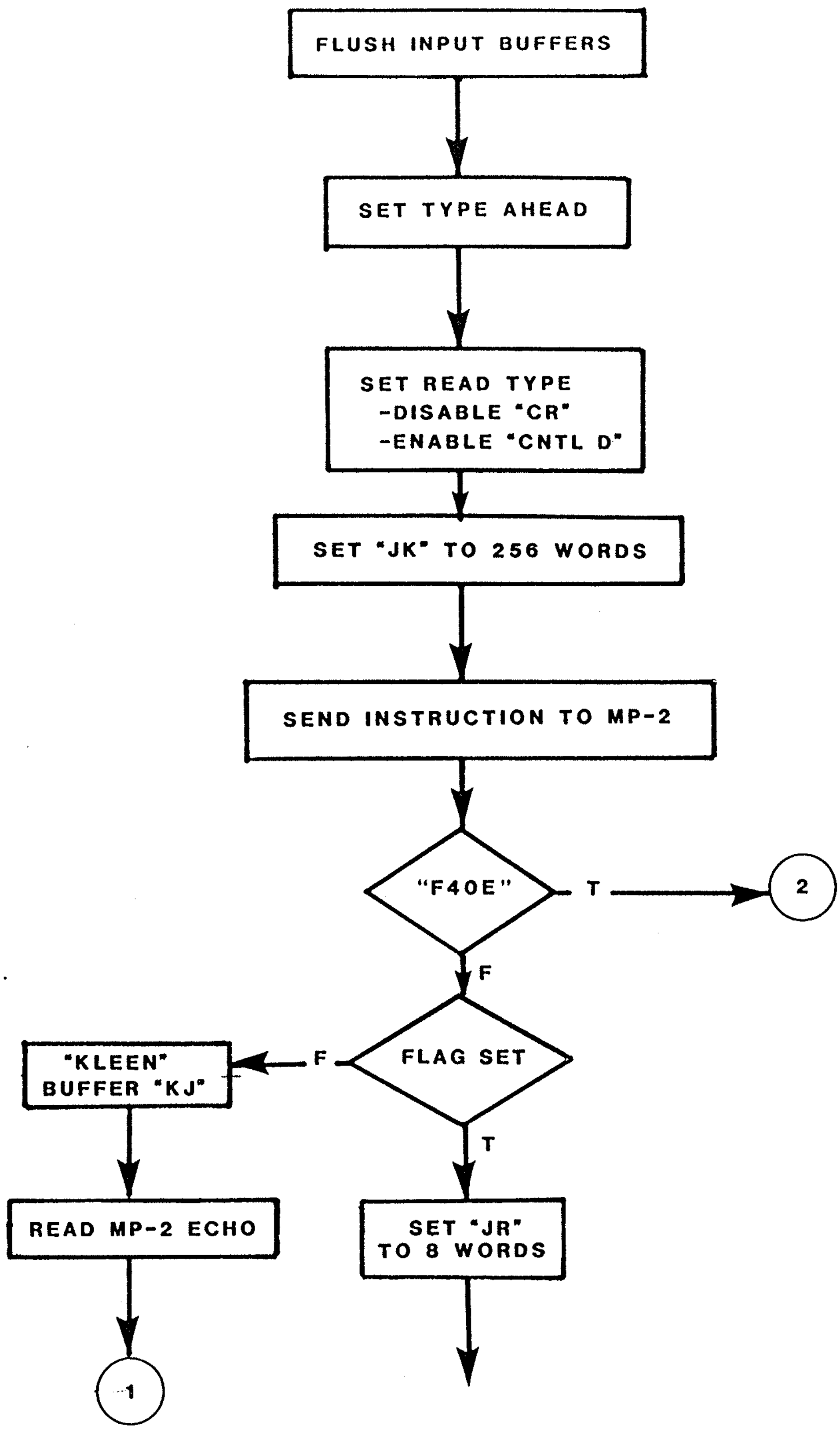

Figure 12. MP210 flowchart (cont'd)

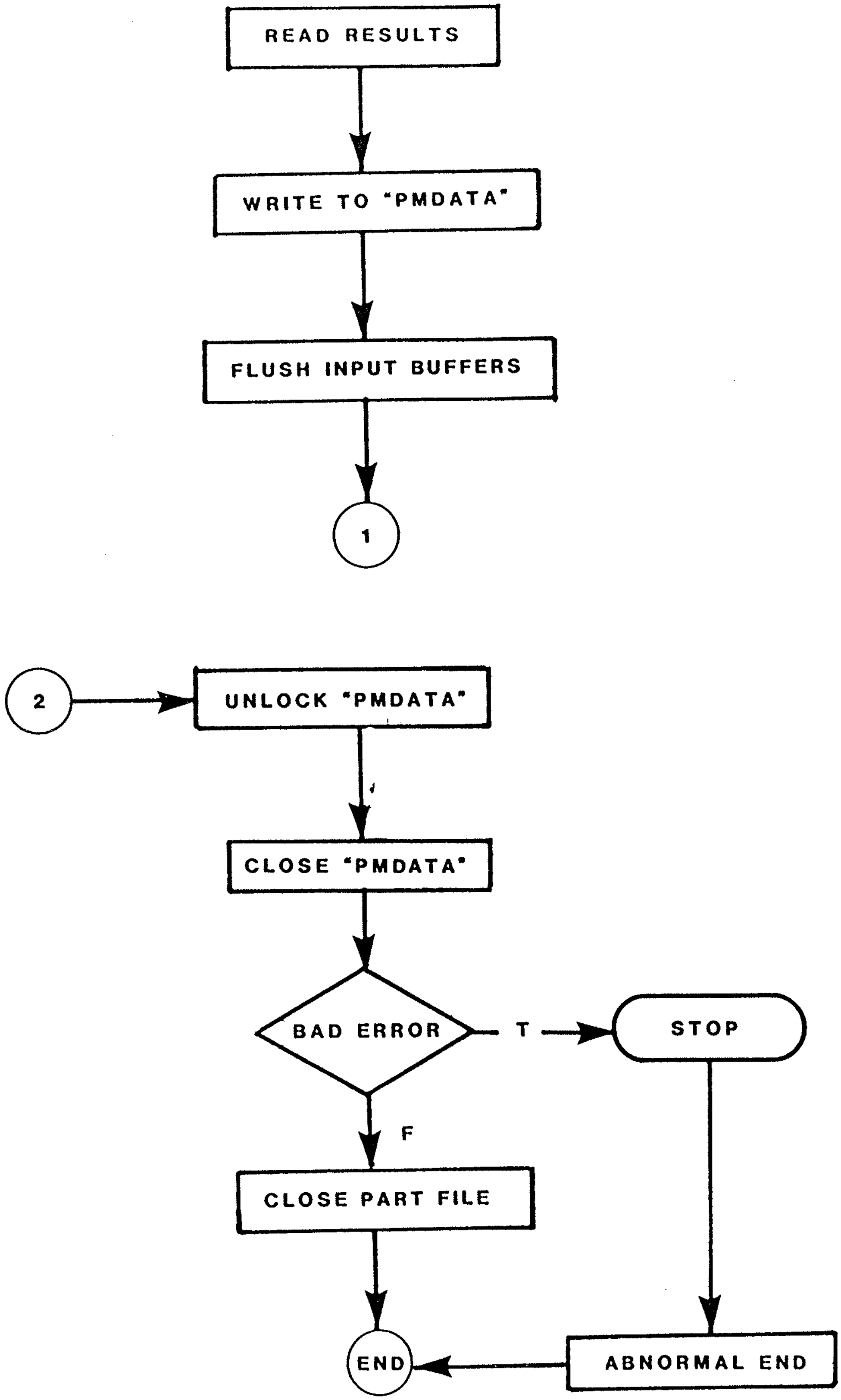

Figure 12. MP210 flowchart (cont'd)

4.3.2.4 The PREAD Program

The program PREAD is used to read the inspection results placed by the program MP2IO into the file PMDATA, and write them to the user's terminal. No analysis is done. However, note that six ASCII null characters are appended to each output lines by the measurement processor. See Figure 13 for program flow.

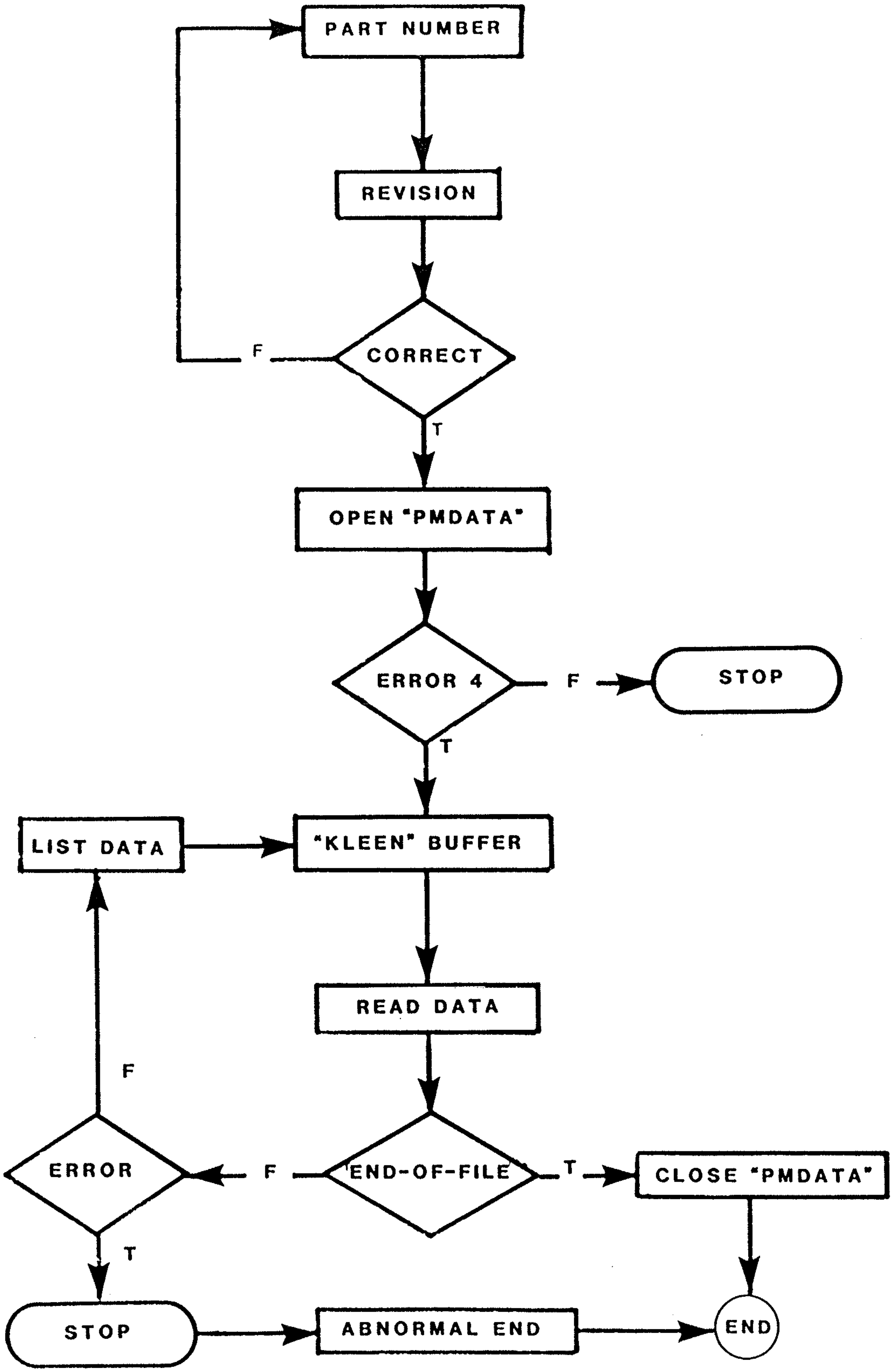

FIGURE 13. PREAD flowchart

CHAPTER V

RESULTS AND DISCUSSION

5.1 Hardware Interface

The Bendix model MP-2 measurement processor is interfaced to the Hewlett-Packard model HP 1000 minicomputer through the Hewlett-Packard model HP 12792A multiplexer subsystem (Section 4.1.1). The multiplexer port is programmatically initialized by the WELCOM file (Section 4.2.1). Physical connection between the measurement processor and multiplexer is made through the multiplexer remote panel using a cable (Hewlett-Packard model HP 13242G) in which Pins 2 (Receive Data) and 3 (Send Data) are reversed in order to establish data communication. By reversing these pins one device will appear to emulate a terminal to the other, enabling data to be exchanged. The hardware interface (Figure 14) is complete and ready for data communication once control of the measurement processor is changed from the keypad to the serial interface (i.e. the minicomputer) by entering "F41D" on the measurement processor keyboard.

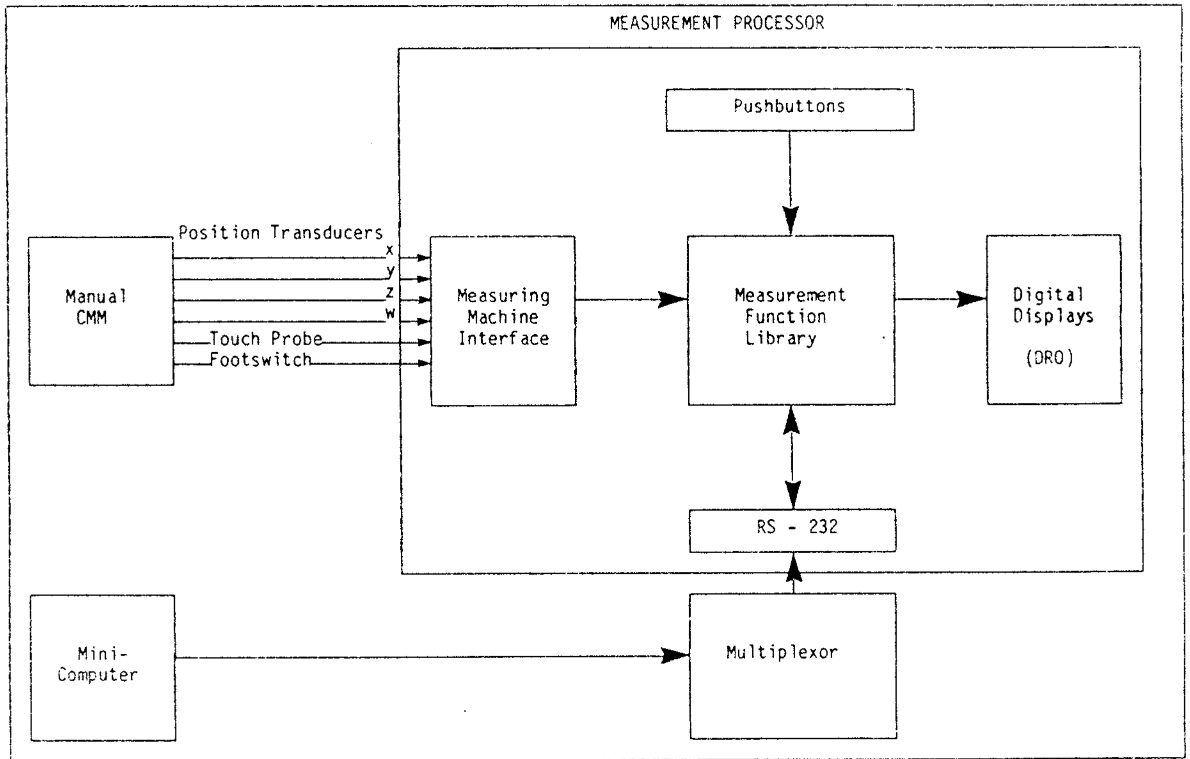

Figure 14. HP 1000/CMM system schematic

Thus, the hardware interface is very straightforward as is generally the case in developing interfaces. While most devices can be made plug equivalent, they are not always electronically compatible as is the case here.

The measurement processor uses Pins 2, 3, and 7 as does the multiplexer. But the measurement processor also uses Pin 5 to signal when its eight-word input buffer is full which the multiplexer does not recognize. For this reason, to prevent overflowing of the measurement processor input buffer a software handshake is required. This handshake is described in the next section.

5.2 Software Interface

The multiplexer is capable of supporting three device drivers:

i) DVM00 - teletype or dumb devices
ii) DDV05 - Hewlett-Packard HP 26XX terminals
iii) DDV12 - Hewlett-Packard line printers

The multiplexer is also capable of supporting three levels of handshaking:

i) ENQ/ACK - controls data sent to the device in 80 character blocks

ii) ENQ/ACK disabled - serial transmission (character by character) to devices

iii) DC1/DC2 - controls block mode data transfer from the device and is in turn controlled by the DDV05 driver.

The measurement processor does not use any handshake recognized by the minicomputer. Therefore handshaking for the multiplexer must be disabled. The DVM00 driver has to be attached to the multiplexer port since it is necessary to treat the measurement processor as a dumb device.

As indicated in Section 4.2.1 it is apparent that the measurement processor will ultimately echo (back to the multiplexer) acceptable characters. This command echo feature can therefore be exploited, and used to control data communication. However, an obvious problem of the command echo feature is that the multiplexer is normally configured to echo data back to a device. If the echo in the multiplexer is not disabled, then a data communication loop will occur. Therefore, it is necessary to disable echo in the multiplexer. Thus, due to the programmable features of the multiplexer and measurement processor, it is also necessary to ensure that the data string is properly described and compatible, in addition to handling the previously mentioned problems. The WELCOM file (Appendix B) is used to intialize the multiplexer port (Section 4.2.1).

It is not possible to institute any more of the protocol at this point. The handshake has to be incorporated into the process control application software program MP2IO (Section 5.3.1).

5.3 Software

A package of application software programs is used to create part inspection files, control the measurement process, and read measurement results (for verification). All programs are written in FORTRAN 4X.

5.3.1 The PFILE Program

The PFILE program (Appendix C) is the program which creates the part input file used to supply instructions to the layout machine operator and commands to the measurement processor. This part input file is used by the program

MP2IO. These commands would normally be keyed into the front panel, thus, a working knowledge of the measurement processor's instruction language is required. The programmer, normally an experienced inspector, is asked for a part number and revision level, which is used to create the file. The file name cannot start with a number or the characters plus (+), minus (-), colon (:), or comma (,), cannot use an embedded blank, and must be six or less characters long. The default revision level which is also the file security word is "99". The security word minimizes the possiblity of accidental file purging. The (Type 4 or ASCII extendable) file is automatically located in Cartridge Reference Number 13, which is a logical sub-division of the physical disc used by the CMM group for storage. Once the file has been successfully created the programmer is prompted for commands and instructions. After each line has been entered, there is an opportunity for editing (correction). The programmer must observe the restrictions described in Section 4.3.2.2. To stop file input and close the file, the programmer enters "EX". The file is now closed and the program terminates. After the program has been terminated, corrections can still be made using one of the system editors. Appendix D contains a typical part input file created by the PFILE program.

5.3.2 The MP2IO Program

The program MP2IO (Appendix E) is the process control application software program controlling the software handshake. It retrieves the part input file created by the PFILE program and sends the commands and instructions to the measurement processor and operator. It also receives and stores measurement results. The MP2IO program will request the part number and revision level of the part to be inspected, which is used to locate the part input file and open it. A measurement data file, PMDATA, is now created. The MP2IO program reads the instructions and commands from the part input file a line at a time, and sends them to measurement processor and/or operator's terminal. It will wait (when required) for a response before issuing another command.

The command echo feature (described in Section 4.2.1) is used to control the multiplexer. The control sequence is as follows:

i) The lines read from the part input file are echoed by the program, to the operator's terminal.

ii) If the first word is "**", a flag is set, indicating a result is expected.

iii) If the first word is "*" the line is a comment, and the program returns to Step i after the measurement processor command buffer (JK).

iv) By default, the line is now a measurement processor command. Therefore, the command buffer is sent to the measurement processor if a result is not expected.

v) Then, if control is not being returned to the measurement processor (i.e. the command is not "F40E", thus terminating the program) the "expect results" flag set in Step ii is checked.

vi) If the flag is not set the echo buffer (KJ) is cleaned (set equal to ASCII blanks), the echo from the measurement processor read and then written to disc, and the MP2IO program returns to Step i.

vii) If the flag in Step iv had been set the multiplexer's input buffers are flushed and set into "Type Ahead" mode, allowing input data to buffered without a pending read.

viii) Now, Carriage Return is disabled as a terminator and Control D (CNTL D) enabled. This is done since the measurement processor is programmed to communicate to a teletype and appends a "CR-LF" to each line. The multiplexer normally interprets the "CR" as a terminator and stops looking for data. Thus, if six lines of data are sent, only one would be received if this change is not made. This change is only effective for one read since Bit 7 in the driver response control function (33) is not set.

ix) Next, the size of the command buffer (JK) is increased from eight words to 256. If this is not done, the response will not be placed in the results buffer (JR) and the system will suspend operation. This problem is discussed in Section 5.4.2.

x) The command is sent to the measurement processor and the program returns to Step v.

xi) Now, when the flag in Step vi is checked it is set. Thus, the length of the command buffer is shortened to eight words.

xii) The measurement data are read from the measurement processor and written to disc.

xiii) After again flushing the multiplexer's input buffer the program returns to Step i.

xiv) If Step v had indicated command was being returned to the measurement processor the measurement result file (PMDATA) is closed and the program terminates.

All measurement results are always written to the file PMDATA. Thus, when a job is complete it is necessary to rename the file using the File Manager "RN" command.

The MP2IO program is able to control the process although bugs or problems do exist. These are explained in more detail in Section 5.4.

All READ's and WRITE's to the measurement processor as well as the multiplexer reconfiguration commands are made using File Manager EXEC calls. Disc access is made using FMGR FMP calls.

Appendix F is a sample of the MP2IO program dialogue.

5.3.3 The PREAD Program

The PREAD program (Appendix G) is a simple program which can read the results obtained from the measurement processor by the MP2IO program. The part number and revision level are requested. Again, the default security level is "99" and is set equal to the revision level. Once the file, originally PMDATA (Appendix H) but now renamed, is located it is opened. The contents are read then listed one line at a time until an End-of-File is found. The file is then closed.

The PREAD program does not do any analysis, only file listings. If a binary listing of the file created by the MP2IO program is made, there will be six ASCII null characters appended to each line. This is done by the measurement processor.

A typical PREAD program dialog is in Appendix I.

5.3.4 Documentation

Documentation for use of the measurement processor and the minicomputer system is in Appendix J.

5.4 Problems

There were two types of problems, those encountered in establishing data communication and the bugs or unexplained problems with no known solution (or cause).

5.4.1 Data Communication

The problems encountered establishing and maintaining data communication are summarized in Table 5. Data communication problems were a result of a lack of compatible handshake. In order to develop this handshake the following development process occurred.

The measurement processor's (printer) port is set to the multiplexer configuration by setting the appropriate switch positions on the processor board (per Bendix Specification 5002390). Version 4 of the software is installed. The measurement processor reads characters until an executable command is assembled. Once complete, the command is echoed back to the multiplexer and executed. Comments are echoed while unacceptable characters are ignored. This echo feature can be used for control.

Table 5. Data communication problem and solution summary

Problem	Solution
Establishing communication	- Reverse Pins 2 and 3 - Attach DVM00 - Enter F41D on Keyboard
Overflowing measurement processor eight-word input buffer since multiplexer does not recognize Pin 5	- Use measurement processor command echo feature as a control
Multiplexer terminating on CR-LF from measurement processor during EXEC READ's	- Set TYPE AHEAD - Set READ TYPE - change terminator from CR to CNTL D
Measurement processor unable to send terminator	- Comment terminator after F61E command, and echo back to multiplexer

As an interim solution, an echo-based protocol was selected. Instructions will be sent to the measurement processor only after the previous command has been echoed.

This approach works until a response is expected. Responses follow an nnn.cccF71E command. The measurement processor is programmed to append a CR-LF to every line. The multiplexer interprets these as terminators and all the data are not received by the minicomputer. To work around, the multiplexer is programmatically reconfigured using EXEC 3 calls. TYPE AHEAD is set to allow incoming data (without a pending read) to be buffered on one of the multiplexer's two 254-byte buffers. Then, the READ TYPE is set to disable CR as a terminator and to look for a CNTL D instead. This configuration is only valid for one READ.

However, the measurement processor is not able to send CNTL D's. To get around this a terminator is commented into the F61E command. This is echoed back after the results are sent. Normal execution then continues.

5.4.2 Bugs

Bugs are unexplained problems which can be a result of irregularities in the computer system, device, or application program. The source of a problem is difficult to pinpoint and while a problem is apparent, the solution is not always obvious. In this project bugs from all sources were discovered.

This was the first known attempt to network the Bendix layout machine to a Hewlett-Packard model HP 1000 minicomputer. Another mitigating factor was that the Hewlett-Packard operating system (RTE-6VM) was a brand new release with known bugs. Finally, the Hewlett-Packard model HP 7912P disc drive was a new product. All the bugs encountered are in Table 6.

The control sequence of the program MP2IO (Section 5.3.2, Step ix) alluded to the most perplexing bug encountered. If data were expected from the measurement processor, the size

Table 6. Summary of bugs and subsequent action

Bug	Action
DVM33 (disc driver) destroys information when doing EXEC READ's and WRITE's to the disc drive	- Reported in HP SR #1322 - no known fix - The recommended work around is to break requests into 128 word or 1/2 sector requests
The stand-alone measurement processor will sometimes lose input characters	- Known bug in Version 4 of MP-2 software - Will be fixed in Version 5
The system would hang or suspend operation intermittently	- No known cause - Likely due to a combination of the bugs in DVM33 and Version 4 software previously described
EXEC READ terminates on any ASCII character, rather than a CNTL D	- Not a problem, but why not is not known - A possible answer is that once the multiplexer's input buffer is full, the multiplexer won't accept any more data and terminates the READ
If results are expected (after an F61E call), the command buffer JK in MP2IO must be 256 words, or else results are lost and the system will suspend operation	- No known reason - neither Hewlett-Packard nor I could understand why this happened - May be related to DVM33 bug - Perhaps a timing problem since the measurement processor uses the faster Motorola 68000 chip, versus the slower Z-80 chip in the multiplexer. It may start processing the command and responding before the slower multiplexer is ready to receive data

of the buffer (JK) containing the command had to be increased from eight words to 256 words or else the results would be lost and the system would suspend operation. No known solution was found, only the work around (changing buffer size) described. It was theorized that perhaps there was a timing problem between the multiplexer and measurement processor since it used a faster (Motorola 68000) microprocessor than the multiplexer (Z-80). While a workaround is an acceptable solution in the short term, future changes in the operating system may jeopardize the workaround.

The other bug which created concern was the intermittent suspension of operation by the system. The MP2IO program could stop running and it would be necessary to stop the program and restart it. The second time the program would work. This problem was likely due to bugs in the operating system and the measurement processor Version 4 software. Another possible source of the problem could have been the power supply. The computer was drawing electrical power from the same transformer as the NC machine shop. Up to 2400 power surges per day outside of acceptable limits were recorded. The surges in power may have affected the operation of the computer.

5.5 System Performance

The system performed reasonably well. Data communication was established and maintained. Most problems or bugs could be overcome or worked around. The only serious problem was the intermittent hanging of the system. An application could hang the system, and after the system was restarted the very same application would work. This problem would likely be resolved with Version 5 of the measurement processor software and resolution of the DVM33 bug. The command echo protocol was able to establish and maintain data communication.

Part inspection files could be created, and then retrieved and used to control the measurement process. Data obtained from the measurement process were stored on the disc drive for future analysis. Incorporation of the Bendix layout machine alone cut inspection time on layouts and first-offs by 60 to 75% compared to conventional methods. Typical parts inspected on the Bendix layout machine were raw castings and weldments. It is estimated that the system developed in this project could reduce inspection time by a further 20 to 30%. Assuming an average wage of $12.50 per hour, single-shift operation, 75% initial time savings and a further time savings of 25% by the system developed, annual savings would be approximately $1600 for networking the Bendix layout machine to the minicomputer. Three-shift operation would increase savings to nearly $5,000. These savings reflect direct labor costs only. Developing the integrated system did not require any additional hardware, only time. Thus, development costs could be recovered in 15 months.

Since the prime application for the Bendix layout machine is first-off parts there is a financial benefit to approve the part quickly (since the numerically controlled machine is not working during this time period). Assuming a typical part turn around of two hours, average numerically controlled machine operating cost of $100 per hour (per machine), three-shift operation, a new part every day, and a 25% time saving using the networked system, annual cost savings would be a further $13,000. Considering that there are approximately 40 numerically controlled machines at Versatile Farm Equipment Company, annual cost savings could be several thousands of dollars. Not considered are the benefits of better quality, reduced scrap and warranty costs and better historical records.

CHAPTER VI

CONCLUSIONS

There are definite conclusions which can be drawn concerning the function of the integrated network and the echo protocol. It is not possible to draw firm conclusions on the economic viability of the networked system.

6.1 Coordinate Measuring Machine/Computer Network

i) The coordinate measurement machine system was integrated into a minicomputer network using a multiplexer. This met the major objective of the project.

ii) Hardware cost was minimized since the cost of the additional multiplexer port and teletype terminal to service the CMM was only 25% of the cost of an intermediate controller (or desktop computer) and a minicomputer was available.

iii) The system was flexible since resources such as hardware, software, and personnel were not tied up servicing a desktop computer, in addition to the central minicomputer. The multiplexer also provided the capability to integrate more CMM systems.

iv) Productivity could be improved when the system is optimized. Layout machine operators can work using preprogrammed procedures. Inspection procedure development time on the CMM will also be minimized. It will also be possible to analyze the collected data statistically, to determine trends in machine tools producing the part, and develop vendor and part histories.

6.2 Command Echo Protocol

It was possible to use the measurement processor's command echo feature to establish and maintain communication with the minicomputer.

CHAPTER VII

RECOMMENDATIONS

There are several ways to improve the CMM/computer network at Versatile Farm Equipment Company.

7.1 Protocol

Bendix and Hewlett-Packard should establish compatible protocols. Two options are available:

i) Bendix develops the ENQ/ACK protocol which would be compatible with the existing Hewlett-Packard model 12792A multiplexer.

ii) Bendix and Hewlett-Packard should both make XON/XOF protocol available.

NOTE: Project development took place during May, June, and July of 1982. In early 1983, Hewlett-Packard released the Hewlett-Packard model HP 12792B multiplexer which incorporated XON/XOF. Bendix has recently (February, 1983) released a measurement processor (the model MP-3) with XON/XOF.

7.2 Data Analysis

Several steps are required to integrate good data analysis capabilities.

i) Establish a common data base using the Hewlett-Packard IMAGE data base product, rather than storing part input and measurement data in ASCII files.

ii) Develop or purchase suitable statistical packages to analyze results. Potential applications would include sample inspection reports, part, supplier, service and warranty histories, defect data, and manufacturing process data to name a few. Commercial products are also available from companies such as Hansford Data Systems.

7.3 Network Expansion

The network should be expanded to include direct computer controlled coordinate measuring machines such as the Bendix Cordax model 1820 already in place. Thus, the Bendix line should be considered first, then other manufacturers. Ultimately, the network should be able to handle any brand of CMM.

7.4 Automation of Part Inspection File Preparation

When a CAD/CAM system is available the CMM network should be integrated. Ultimately the numerically controlled machine cutter location file should be used to generate an inspection path.

7.5 In-Process Manufacturing Control

Once direct computer controlled coordinate measuring machines are integrated and a CAD/CAM system is available in-process manufacturing control of numerically controlled machines should be undertaken by using in-process measurement results to control the next operation.

Once this is accomplished the loop between Computer Aided Design and Computer Aided Manufacturing is closed.

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APPENDIX A

Cordax Measurement Pre-Processor Model MPP-2 Quick Reference Card

Bendix

Automation & Measurement Division

CORDAX™
MEASUREMENT
PRE-PROCESSOR
DATA CARD

MPP, MPP–1, & MPP–2

OPERATING MODES

MODE	REQUIREMENT	DESCRIPTION
Manual	Touch probe must be disconnected	Selects hard probe point recording
Automatic	Touch Probe must be connected	Selects touch probe point recording
Point Recording	Press footswitch	Records current probe position (hard probe) or last touched point (touch probe)
Inch	Set INCH/MM switch to INCH	All displayed linear quantities in inches
Metric	Set INCH/MM switch to MM	All displayed linear quantities in millimeters

BASIC OPERATIONS

CONTROL KEYPADS

Command	Description
Clear (C)	Cancels partial command (keypad entries since last E or D entry)
	Cancels temporary display
	Cancels error display
Display (D)	Moves decimal point to extended position if in normal or to normal if in extended Setting / Normal / Extended MM / XXXX.XXX / NA INCH / XXX.XXXX / XX.XXXXX
	Command terminator
Enter (E)	Command terminator
Function (F)	Used with numeric or implied zero to select command operation

RESET REFERENCE DATUMS

X RESET (XR) Y RESET (YR) Z RESET (ZR) W RESET (WR)	Resets designated display to zero Clears all FAULT-CAUTION LED's

PRESET REFERENCE DATUMS

XnE YnE ZnE WnE XnYnZnWnE	Presets selected axes to entered value and stores value in associated register. If MM/INCH switch is changed, value is converted to new measurement unit.
XE YE ZE WE XYZWE	Presets selected axes to value previously stored in corresponding register.

NOTE: n = variable number

Part No 56020068

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PART ALIGNMENT

Command	Condition	Description
FE .	Measure two points before entering command	Establishes offset angle in active plane. The angle computed ranges from -90° to +90° in the MPP and from 0° to 360° in the MPP-1 and MPP-2, increasing ccw. (Causes display to show part rather than machine coordinates.)
n°FE*		Sets offset angle to n°
FD*		Displays offset angle
ØFE		Cancels offset angle

MPP–1 & MPP–2 FUNCTION COMMAND OPERATIONS

MODIFY OFFSET ANGLE

±n° F1E	Must have established offset angle; enter in degrees	Modifies offset angle by n°, ccw if plus, cw if minus
XnYnF1E XnZnF1E YnZnF1E	Point must be described by using two axes of the active plane	Computes angle using coordinates (n) given and modifies offset angle by that amount.

SCALE FACTOR

XnF2E YnF2E ZnF2E WnF2E XnYnZnF2E	Enter before taking part measurements	Changes normal 1:1 scale factor to n:1, e.g., for a half size model, n=2, for a 10x model, n=.1
F2E		Resets all axes scale factors to 1:1
F2D		Displays scale factors for all axes
nF2D		Scales X, Y and Z by n factor.

ACTIVE PLANE SELECTION

F3E		Selects XY plane as active plane
XYF3E		Selects XY plane as active plane
XZF3E		Selects XZ plane as active plane
YZF3E		Selects YZ plane as active plane

REFERENCE DATUMS**

XF4E YF4E ZF4E XYZF4E	Must have recorded point	Sets reference for selected axis to last recorded point. Enter individual axis or combination of axes.
X ±nF4E Y ±nF4E Z ±nF4E	Reference datums must have been established	Moves reference for selected axis by entered amount. Enter individual axis or combination of axes.
XF5E YF5E ZF5E XYZF5E	Reference datums must have been established	Saves reference for the selected axis. Enter individual axis or combination of axes.
F6E XF6E YF6E ZF6E XYZF6E	Reference datums must have been saved (F5E)	Recalls reference for the selected axis or all axes. Enter individual axis, combination of axes, or function only for all axes.

*MPP–1 and MPP–2 only

**Also see Reset Reference Datums and Preset Reference Datums

CIRCULAR FEATURES, THREE POINT CENTERFIND*

Command	Condition	Description
F7E	ID; before entering command enter probe diameter (see F9E); measure three points before entering command	Computes and displays center coordinates and diameter of circle in working plane. Probe diameter is added to obtain ID. Last three recorded points are replaced by single point defined by the circle center and the average third axis.
F8E	OD; before entering command enter probe diameter (see F9E); measure three points before entering command	Same as F7E, except probe diameter is subtracted to obtain OD center coordinates and diameter.
F7D	ID	Displays active plane coordinates of last recorded point and last computed diameter.
F8D	OD	

PROBE DIAMETER

nF9E	Set MM/INCH switch to appropriate position before entering command	Sets probe diameter to value of n.

POLAR COORDINATES

F10E	AUX. DATA LED's lit after function is entered	Sets display mode in active plane to polar coordinates; radius in upper display, angle in lower.
F11E	AUX. DATA LED's extinguished after function is entered	Cancels polar coordinate display and returns display mode to rectangular coordinates.

SEQUENCE NUMBER

±nF12E		Sets the sequence number for the next measurement display to the value of n ($-9999 \leq n \leq +9999$).
F12E		Increments current value of sequence number by one.
F12D		Displays sequence number.

TEMPORARY DISPLAY INTERVAL

nF13E		Sets temporary display interval (normally 5 seconds) to value of n ($0 \leq n \leq 4095$).
F13D		Displays the number of seconds in the temporary display interval.

BUILD COMMAND LOOP

nF14E	Sequence of commands must follow this entry	Prepares Measurement Preprocessor to accept a sequence of commands, which will be executed n times. Omit n for indefinite looping.
E	Must be entered after loop command series is completed	Ends command input for loop and initializes execution. Must be EE if last command in loop ends with D.

*Also see Circular Features (F24, F25, F26)

BUILD COMMAND LOOP (cont.)

Command	Condition	Description
X		Stops execution of a loop.
nF14D		Restarts loop execution at the beginning of the sequence anytime after initial execution regardless of why it stopped. Omit n for indefinite looping.

WAIT FOR POINT RECORDING

Command	Condition	Description
nF15E		Causes the Measurement Pre-Processor to wait for n points to be recorded before continuing command execution. If n is omitted, the wait is for one point; n may equal 1, 2, or 3.

POLAR/RECTANGULAR DATA NOMINAL CONVERSION

Command	Condition	Description
F16E	Associated with F50E; nominal values must be entered before this command	Converts nominal polar coordinates to equivalent rectangular coordinates relative to the active plane.
F17E	Associated with F50E; nominal values must be entered before this command	Converts nominal rectangular coordinates to equivalent polar coordinates relative to the active plane.

RECORDED POINTS

Command	Condition	Description
n18E		Displays the designated recorded point. The value of n designates which point of the last six is to be displayed. Therefore, n equals 1 (most recent point), 2, 3, 4, 5, or 6 (least recent point). Omitting n causes the most recently recorded point to be displayed.
F19E		Deletes the most recently recorded point.

HARD PROBE CHANGE OR REORIENTATION

Command	Condition	Description
F20E	Use with rigid probes only Place probe in fixture and enter this command before any other compensations; place probe in fixture and enter after each probe change.	Records probe tip coordinates to allow probe change or reorientation without having to reestablish datums or measurement compensations, e.g., offset angle.

FOOTSWITCH

Command	Condition	Description
F21E	Footswitch is normally active	Disables footswitch except when F15E command is being executed to prevent accidental point recording.
F22E	Necessary only after F21E has been used	Reactivates footswitch to normal after it has been disabled.

AUTOLEVELING †

Command	Condition	Description
±nF23E	Measure three points before entering command	The variable, n, identifies the machine axis which points toward the positive side of the measured plane; thereby describing from which direction the plane is being measured. Values for n are: +1 = +X −2 = −Y −1 = −X +3 = +Z +2 = +Y −3 = −Z
FE	Measure two points before entering command	Used in conjunction with F23E to establish three-axis alignment.
F23D		Displays autolevel angles
0F23E		Cancels autoleveling or three-axis alignment

CIRCULAR FEATURES †

Command	Condition	Description
nF24E	ID; measure points after entering command	Computes and displays the center coordinates and diameter of a circular feature using n points.
nF25E	OD; measure points after entering command	
F24E	ID; scan feature after entering command	Computes and displays the center coordinates and diameter of a circular feature by scanning. Operate footswitch to start scan and again to stop scan. Hard probe only.
F25E	OD; scan feature after entering command	
nF26E	Measure 3 points of each feature after entering command	Computes and displays the center coordinates and diameter of a circular pattern from n circular features.

TOUCH PROBE REORIENTATION †

Command	Condition	Description
F27E	Measure four points on a reference sphere after entering this command; enter this command and measure four points on the reference sphere after each probe change or reorientation.	Records probe tip coordinates to allow probe change or reorientation without having to re-establish datums or measurement compensations, e.g. offset angle. Note: May also be used with hard probes.

† MPP–2 only

DATA ENTRY/DISPLAY COMMAND FORMAT
(ccc.rrrFnE)*

Row \ Column	1 Actual	2 Nominal	3 Plus Tol	4 Minus Tol	5 Dev	6 Out of Tol
1 X-axis Coordinate	1.1	2.1 (XN)	3.1 (XP)	4.1 (XM)	5.1	6.1
2 Y-axis Coordinate	1.2	2.2 (YN)	3.2 (YP)	4.2 (YM)	5.2	6.2
3 Z-axis Coordinate	1.3	2.3 (ZN)	3.3 (ZP)	4.3 (ZM)	5.3	6.3
4 W-axis Coordinate	1.4	2.4 (WN)	3.4 (WP)	4.4 (WM)	5.4	6.4
5 Diameter	1.5	2.5 (DN)	3.5 (DP)	4.5 (DM)	5.5	6.5
6 Radius	1.6	2.6 (RN)	3.6 (RP)	4.6 (RM)	5.6	6.6
7 Angle	1.7	2.7 (AN)	3.7 (AP)	4.7 (AM)	5.7	6.7
8 True Position			3.8 (TP)		5.8	6.8

*The data entry/display command format is
ccc.rrrFnE, where
c = the column number
r = the row number
n = the number of the desired command
As shown in the table, a maximum of six digits may be specified
for the column entry and eight digits for the row, e.g., 123456.12345678F71E.

NOTE: Only columns 2, 3, and 4 may be used for data entry.

DATA ENTRY/DISPLAY OPERATIONS

Operation	Command	Description
Data Entry	ccc.rrrF50E	Enters nominal and tolerance values specified by format ccc.rrr. The Pre-Processor will display the single element format for each item until the value is entered.
	F50E	Enters nominal and tolerance values specified by previously defined data entry format.
Data Display	ccc.rrrF60E	Displays data items specified by format ccc.rrr. At most, four values are displayed.
	F60E	Displays data items specified by previously defined display format.

NOTE: See commands F16 and F17 for nominal data conversion.

TELEPRINTER OPERATIONS

The following operations are available only when a Teleprinter is connected to the Pre Processor. They may be initiated from the Pre-Processor keypad or from the Teleprinter keyboard.

Operation	Command	Description
Enter Commands from Teleprinter	F41D	All keypad operations except for reset originate from Teleprinter. Entered characters are echoed. (note 3)
(notes 1 & 2)	F41E	Same, except that entered characters are not echoed. (note 3)
Enter Commands from Keypads	F40E	Return to Pre-Processor keypads as only source for further commands.
Comment	*	All characters following an "*" in Teleprinter data entry are ignored by the Pre-Processor until a carriage return is encountered. Used for annotating program.
Enter Data from Teleprinter	ccc.rrrF51D	Enter data items specified by format ccc.rrr from Teleprinter. The Pre-Processor will type a prompt for each value to be entered (indicated in parentheses in data format table) and will echo accepted entered characters.
	F51D	Same, except that previously specified entry format is to be used.
	ccc.rrrF51E	Enter data items specified by format from Teleprinter. Prompts and entered characters are not printed. Recommended only for paper tape input.
	F51E	Same, except that previously specified format is to be used.
Print Column Headings	ccc.rrrF71E	Print headings for specified columns on Teleprinter and save new output format.
	F71E	Print column headings for current output format.
Print Data	ccc.rrrF61E	Print data elements specified. Data is preceded by the sequence number which is incremented after printing.
	-ccc.rrrF61E	Same, except that sequence number will not be printed or incremented.
	F61E	Print data specified by current output format.

Note:

1. This command is entered at the Pre-Processor keypad to activate the Teleprinter keyboard. Once the keyboard is activated, this command may be used to add or delete echo in the Teleprinter.
2. When the Teleprinter is designated as an input device, the following characters are used for command and data entry:

CHARACTER	DESCRIPTION
C	Clear
D	Display
E	Enter
F	Function
Carriage Return	Enter

Numbers, decimal point, and minus sign are conventional.

3. The Teleprinter keyboard operations repertoire is the same as that for keypad operations.

ERROR HANDLING

When an error is detected by the Pre-Processor, an error message is displayed: Error NN, where NN equals the type of error detected. Most error conditions are eliminated by pressing the CLEAR key. However, when an overflow error (indicating that the display limit has been exceeded) is detected, the condition must be corrected before the error is cleared. Possible corrective actions include the following:

a. Move the probe back into range
b. Preset axis to new value.
c. Reset axis to zero.
d. Change INCH/MM switch setting.

ERROR MESSAGES

Error	Condition	Affected Operation
01	Quantity too large for display	–
02	X-axis display overflow	–
03	Y-axis display overflow	–
04	Z-axis display overflow	–
05	W-axis display overflow	–
10	Illegal function number	–
11	Data incompatible with operation	FE
14	Two points needed to compute offset angle	FE
15	Points defining offset angle too close together	F1
17	Point entered to modify offset angle is not in offset plane	F15
18	Too many points specified for wait operation	F3
19	Illegal active plane selection	F7, F8
20	No point data for three-point center find or display	F7, F8
21	Less than three points available for three-point center find	F7, F8
22	Three points for three-point center find are co-linear or coincident in the active plane	F4
23	No point to set reference	F18
24	Attempt to display nonexistent point	F14
25	Attempt to build nested loop	F14
26	Negative repeat loop count	F14
27	Repeat loop buffer exceeded	F14
28	Attempt to select new command device within loop	F50, F51
30	Nonexistent axis row selected	F60, F61
31	Illegal attempt to enter actual, deviation, or out-of-tolerance value	F50, F51 F60, F61
32	No actual, deviation, or out-of-tolerance data available	–
33	Illegal device number	F41, F51
34	No Teleprinter interface in Pre-Processor	F61, F71
35	Illegal data entry/display command format	F50, F51 F60, F61 F70, F71
36	Display selected for column heading printout	F70
40	Three points for plane alignment too close together or colinear	F23
41	Less than three points available for plane alignment	F23
42	Illegal change of offset plane	FE
50	No solution possible in the active plane with given points	F24, F25 F26
51	Scanning attempted with touch probe	F24
60	Points too close together	F27

APPENDIX B

WELCOM and *UPMUX Code

```
WELCOM T=00004 IS ON CR00002 USING 00002 BLKS R=0000

:SV,4,,IH
:*
:* *WELCOM 92084-13301 REV 2208 820506
:*
:DU,'START,1
::*STIME            SET SYSTEM TIME
:DP,
:DP,PACKING LU'S 2 & 3
:DP,
::*PACK             PACK LU'S 2 & 3
:DP,
:DP,BRINGING UP MULTIPLEXER
:DP,
::*UPMUX            UP MULTIPLEXER
::*SYTO             SET MULTIPLEXER TIMEOUTS
:DP,
:DP,RP'ING ID SEGMENTS
:DP,
::*RPS
:DU,'DONE,1
:SYCU,ON            TURN ON CPU BUSY CLOCK
:SV,0,,IH
:EX                 EXIT TO RTE
```

```
*UPMUX T=00004 IS ON CR00002 USING 00005 BLKS R=0000

:*
:*
:*********************************************************
:**  MUX INITIALIZATION FOR FIRST GENERATION (#ANRH1)    *
:*                                                       *
:**  CREATED BY RAY HOEMSEN 820406 <830222.1752>         *
:*********************************************************
:*
:*
:*
:*
:**  MUX INITIALIZATION
:*
:*
:**  PORT #0 SET UP FOR 2631 PRINTER
:**  AT 1200 BAUD (BRG #0)
:**  HANDSHAKE ENABLED
:*
:**  NOTE THAT 'CN' CMD USED - LU IS NOT INTERACTIVE
:*
:CN,6,30B,142270B
:CN,6,33B,2
:CN,6,21B
:CN,6
:*
:*
:**  PORTS #1&3 SET UP FOR TTY DEVICES
:**  AT 1200 BAUD (BRG #0)
:**  HANDSHAKE DISABLED
:*
:*
:CT,31,30B,142071B
:CT,33,30B,142073B
:CT,31,33B,3
:CT,33,33B,3
:CT,31,20B
:CT,33,20B
:*
:*
:**  PORT 2 SET UP FOR MP-2
:**  1200 BAUD (BRG #0)
:**  HANDSHAKE DISABLED
:*
:**  ATTACH DRIVER DDM00 (#1)
:*
:**  ECHO DISABLED
:*
:*
:CT,32,30B,142072B
```

```
:CT,32,33B,1
:CT,32,37B,200B
:*
:*
:**  PORTS 4-7 SET UP FOR DDV05 TERMINALS
:**  9600 BAUD  (BRG#1)
:**  HANDSHAKE ENABLED
:*
:*
:CN,34,30B,152334B
:CN,35,30B,152335B
:CN,36,30B,152336B
:CN,37,30B,152337B
:CN,34,33B,3
:CN,35,33B,3
:CN,36,33B,3
:CN,37,33B,3
:CN,34,20B
:CN,35,20B
:CN,36,20B
:CN,37,20B
:*
:*
:**  FINISHED !!
:*
:*
::
```

```
*SYTO  T=00004 IS ON CR00002 USING 00001 BLKS R=0000

:SYTO,4,0
:SYTO,5,0
:SYTO,6,30000
:SYTO,7,30000
:SYTO,8,30000
:SYTO,9,30000
:SYTO,10,30000
::
```

APPENDIX C

PFILE Code

```
&PFILE T=00004 IS ON CR00002 USING 00002 BLKS R=0000

FTN4X,Q
C
C     PROGRAM: PFILE
C
C     AUTHOR: RAY HOEMSEN
C     DATE: 82 05 27 <820810.0816>
C     RELEASED TO SYSTEM: 82 08 09
C     COMPUTER: HP 1000
C     OPERATING SYSTEM: RTE-6/VM * REV 2208
C     LANGUAGE: FORTRAN 4X
C
C     PFILE CREATES THE PART INPUT FILE
C     USED TO SUPPLY OPERATOR INSTRUCTIONS
C     TO THE BENDIX LAYOUT MACHINE MP-2
C
      PROGRAM PFILE
      DIMENSION JK(40),KJ(100),NAME(3)
      INTEGER DCB(144),ERROR,OPTION,SECURE,CRN
      INTEGER SIZE,TYPE
      DATA CRN/13/,SECURE/0/,SIZE/-1/,TYPE/4/,OPTION/0/,IL/40/
      WRITE(1,100)
100   FORMAT(/'WELCOME TO PFILE'
     */'PFILE CREATES THE PART INPUT FILE'
     */'TO OPERATE THE BENDIX LAYOUT MACHINE')
11    WRITE(1,101)
101   FORMAT(/'WHAT IS THE PART NUMBER ?_')
      READ(1,102) (NAME(I),I=1,3)
102   FORMAT(3A2)
      WRITE(1,103)
103   FORMAT(/'WHAT IS THE CURRENT REVISION LEVEL ?_')
      READ(1,*) SECURE
      WRITE(1,104) (NAME(I),I=1,3),SECURE
104   FORMAT(/'ARE THE PART NUMBER: ',3A2,
     */'AND THE REVISION LEVEL: ',I2,
     */'CORRECT (Y or N) ?_')
      READ (1,105) NY
105   FORMAT(A2)
      IF(NY.EQ.1HY)GOTO 10
      GOTO 11
10    IF(SECURE.EQ.0)SECURE=99
      CALL CREAT(DCB,ERROR,NAME,SIZE,TYPE,SECURE,CRN)
      IF(ERROR.GE.0.OR.ERROR.EQ.-2)GOTO 12
      WRITE(1,106) ERROR
106   FORMAT(/'ERROR # ',I5,' IN CREATION')
      GOTO 13
12    CALL OPEN(DCB,ERROR,NAME,OPTION,SECURE,CRN)
      IF(ERROR.EQ.4)GOTO 14
      WRITE(1,107) ERROR
107   FORMAT(/'ERROR # ',I5,' IN OPEN')
```

```
      GOTO 13
14    WRITE(1,108)
108   FORMAT(/'ENTER INSTRUCTION or EX TO EXIT',/)
19    CALL LGBUF(KJ,100)
      READ(1,109) JK
      IF(JK.EQ.2HEX)GOTO 16
109   FORMAT(40A2)
      WRITE(1,110) JK
110   FORMAT(/40A2,/'CORRECT (Y or N) ?_')
      READ(1,105) NY
      IF(NY.EQ.1HN)GOTO 15
      CALL WRITF(DCB,ERROR,JK,IL)
      GOTO 14
15    WRITE(1,116)
116   FORMAT(/'RE-ENTER INSTRUCTION')
      GOTO 19
16    ILEOF=-1
      CALL WRITF(DCB,ERROR,JK,ILEOF)
      CALL LOCF(DCB,ERROR,IREC,IRB,IOFF,JSEC)
      ITRUN=(JSEC/2)-(IRB+1)
      CALL CLOSE(DCB,ERROR,ITRUN)
      IF(ERROR.GE.0)GOTO 17
      WRITE(1,112) ERROR
112   FORMAT(/'ERROR # ',I5,' IN CLOSE')
      GOTO 13
17    WRITE(1,113) (NAME(I),I=1,3),SECURE,CRN
113   FORMAT(/'PART FILE ',3A2,':',I2,':',I2,' SUCCESSFULLY CREATE
      WRITE(1,115)
115   FORMAT(/'NORMAL TERMINATION OF PFILE')
      GOTO 18
13    WRITE(1,114)
114   FORMAT(/'ABNORMAL TERMINATION OF PFILE')
18    END
```

APPENDIX D

Typical PFILE Dialogue and Part Input Files

```
PFILE

WELCOME TO PFILE
PFILE CREATES THE PART INPUT FILE
TO OPERATE THE BENDIX LAYOUT MACHINE

WHAT IS THE PART NUMBER ?P55555

WHAT IS THE CURRENT REVISION LEVEL ?5

ARE THE PART NUMBER: P55555
AND THE REVISION LEVEL:  5
CORRECT (Y or N) ?Y

ENTER INSTRUCTION or EX TO EXIT

*     CIRCULAR MEASUREMENT

*     CIRCULAR MEASUREMENT
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

XYF3E

XYF3E
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

>1523F9E

>1523F9E
CORRECT (Y or N) ?N

RE-ENTER INSTRUCTION
.1572F9E

.1572F9E
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

*     MEASURE 4 POINTS OF THE ID OF FEATURE A

*     MEASURE 4 POINTS OF THE ID OF FEATURE A
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

4F24E
```

```
4F24E
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

**    WRITE RESULTS (NOTE **)

**    WRITE RESULTS (NOTE **)
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

1.125F61E **

1.125F61E **
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

*     RETURN CONTROL TO MP-2

*     RETURN CONTROL TO MP-2
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

F40E

F40E
CORRECT (Y or N) ?

ENTER INSTRUCTION or EX TO EXIT

EX

PART FILE P55555: 5:13 SUCCESSFULLY CREATED !

NORMAL TERMINATION OF PFILE
:
```

```
P55555 T=00004 IS ON CR00013 USING 00003 BLKS R=0000

*     CIRCULAR MEASUREMENT
XYF3E
.1572F9E
*     MEASURE 4 POINTS OF THE ID OF FEATURE A
4F24E
**    WRITE RESULTS (NOTE **)
1.125F61E **
*     RETURN CONTROL TO MP-2
F40E
```

```
P77777 T=00004 IS ON CR00013 USING 00010 BLKS R=0000

*
*     CIRCULAR FEATURE MEASUREMENT - <830316.1742>     *
*
*     ENTER ACTIVE PLANE - XY
XYF3E
*     ENTER PROBE DIAMETER
.1572F9E
*     MEASURE FOUR POINTS IN THE XY PLANE TO DEFINE CIRCULAR I.D.
4F24E
*     AFTER CALCULATING THE CENTREPOINT AND I.D. DISPLAY RESULTS O
F7D
**     WRITE RESULTS TO FILE (NOTE **)
1.125F61E **
*     RETURN CONTROL TO MP-2
F40E
*     CIRCULAR FEATURE MEASUREMENT COMPLETE     *
```

APPENDIX E

MP2IO Code

```
&MP2IO T=00004 IS ON CR00002 USING 00044 BLKS R=0000

FTN4X,Q
C
C     PROGRAM: MP2IO
C
C     AUTHOR: RAY HOEMSEN
C     DATE: 82 05 31 <820714.1141>
C     RELEASED TO SYSTEM: 82 06 28
C     COMPUTER: HP 1000 MODEL 60 E-SERIES (2178A)
C     OPERATING SYSTEM: RTE-6/VM * REV 2208
C     LANGUAGE: FORTRAN 4X
C
C     HARDWARE - HP 1000 MODEL 60 E-SERIES (2178A)
C              - HP 12792A 8-CHANNEL A/S MUX
C              - BENDIX MP-2 MICROPROCESSOR (MOTOROLA 68000 SERIES
C              - DUMB TERMINAL (TTY OR CRT)
C
C     SOFTWARE - FORTRAN 4X
C              - RTE-6/VM * REV 2208
C              - BENDIX MP-2 S/W - VERSION 4
C
C     MP2IO WILL SEND OPERATING INSTRUCTIONS TO
C     THE BENDIX LAYOUT MACHINE MP-2 AND OPERATOR
C     FROM THE PART INSTRUCTION FILE CREATED BY 'PFILE'
C
      PROGRAM MP2IO
C    ****************************************
C     INITIALIZATION                        *
C                                           *
C     JK - MP-2 COMMAND BUFFER              *
C     KJ - MP-2 ECHO BUFFER                 *
C     JR - MP-2 RESULTS BUFFER              *
C                                           *
C    ****************************************
      DIMENSION JK(256),KJ(8),JR(64),KK(500),NAME(3)
      INTEGER DCB1(144),DCB2(144),ERROR,OPTION,SECURE,CRN
      INTEGER SIZE,TYPE,FILE(3)
      DATA FILE /'PMDATA'/,SIZE/-1/,TYPE/4/,OPTION/2/
      DATA LUMP2/32/,CRN/13/,SECURE/0/,IPRINT/0/
      DATA IJK/256/,IL/8/,IJR/64/
C    ****************************************
C     INTRODUCTION AND PROMPT FOR PART FILE*
C     CREATED BY 'PNAME'                    *
C                                           *
C    ****************************************
      WRITE(1,100)
100   FORMAT(/'WELCOME TO MP2IO'
     */'MP2IO WILL GENERATE INSTRUCTIONS TO HELP YOU'
     */'TO OPERATE THE BENDIX LAYOUT MACHINE')
11    WRITE(1,101)
```

```
101   FORMAT(/'WHAT IS THE PART NUMBER ?_')
      READ(1,102) (NAME(I),I=1,3)
102   FORMAT(3A2)
      WRITE(1,103)
103   FORMAT(/'WHAT IS THE CURRENT REVISION LEVEL ?_')
      READ(1,*) SECURE
      WRITE(1,104) (NAME(I),I=1,3),SECURE
104   FORMAT(/'ARE THE PART NUMBER: ',3A2,
     */'AND THE REVISION LEVEL: ',I2,
     */'CORRECT (Y or N) ?_')
      READ (1,105) NY
105   FORMAT(A2)
      IF(NY.EQ.1HY)GOTO 10
      GOTO 11
C    ****************************************
C     USING 'FMP' CALLS:                     *
C        1.CREATE DATA FILE (DATA)           *
C        2.EXCLUSIVELY OPEN DATA FILE        *
C              NOTE: DCB2 ----> FILE         *
C                                            *
C    ****************************************
10    IF(SECURE.EQ.0)SECURE=99
      CALL CREAT(DCB2,ERROR,FILE,SIZE,TYPE,SECURE,CRN)
      IF(ERROR.GE.0)GOTO 12
      WRITE(1,106) ERROR
106   FORMAT(/'ERROR # ',I5,' IN CREATION')
      GOTO 13
12    CALL OPEN(DCB2,ERROR,FILE,OPTION,SECURE,CRN)
      IF(ERROR.EQ.4)GOTO 21
      WRITE(1,107) ERROR
107   FORMAT(/'ERROR # ',I5,' IN OPEN')
      GOTO 13
C    ****************************************
C     USING AN 'FMP' CALL                    *
C      -EXCLUSIVELY OPEN PART FILE           *
C              NOTE: DCB1 ----> FILE         *
C                                            *
C    ****************************************
21    CALL OPEN(DCB1,ERROR,NAME,OPTION,SECURE,CRN)
      IF(ERROR.EQ.4)GOTO 23
      WRITE(1,107) ERROR
      GOTO 13
C    ****************************************
C     USING AN 'EXEC' CALL FLUSH BOTH        *
C     254 BYTE INPUT BUFFERS FOR 'LUMP2'     *
C                                            *
C    ****************************************
23    ICODE=3
*     CONTROL FUNCTION 26
      ICNWD=LUMP2+2600B
*     CLEAR BOTH BUFFERS
```

```
      IPARM=1B
      CALL EXEC(ICODE,ICNWD,IPARM)
20    CALL KLEEN(JK,IJK)
C   ****************************************
C     USING 'FMP' CALLS:                   *
C       1.READ AN INSTRUCTION FROM         *
C         PART FILE (NAME)                 *
C                                          *
C   ****************************************
      CALL READF(DCB1,ERROR,JK,IJR,LEN)
      IF(LEN.EQ.-1)GOTO 25
      IF(ERROR.GE.0)GOTO 14
      WRITE(1,116) ERROR
116   FORMAT(/'ERROR # ',I5,' IN READ')
      GOTO 13
*     TO PREVENT RUNTIME ERROR 0496
14    CALL LGBUF(KK,500)
C   ****************************************
C     1. ECHO INSTRUCTION TO TERMINAL      *
C     2. CHECK FOR PRINT PROMPT '**'       *
C     3. CHECK FOR MP-2 COMMENT '*'        *
C                                          *
C   ****************************************
      WRITE(1,108) (JK(NN),NN=1,40)
108   FORMAT(/'INSTRUCTION - ',40A2)
      IF(JK(1).EQ.2H**)IPRINT=1
      IF(JK(1).EQ.1H*.OR.JK(1).EQ.2H**)GOTO 20
C   ****************************************
C     USING AN 'EXEC' CALL FLUSH BOTH      *
C     254 BYTE INPUT BUFFERS FOR 'LUMP2'   *
C                                          *
C   ****************************************
      IF(IPRINT.EQ.0)GOTO 26
      ICODE=3
      ICNWD=LUMP2+2600B
      IPARM=1B
      CALL EXEC(ICODE,ICNWD,IPARM)
C   ****************************************
C     USING AN 'EXEC' CALL SET TYPE AHEAD  *
C     MODE AND ATTACH 'DVM00' FOR 'LUMP2'  *
C     TYPE AHEAD WILL ALLOW INPUT DATA     *
C     TO BE BUFFERED WITHOUT A PENDING READ*
C                                          *
C   ****************************************
      ICODE=3
*     CONTROL FUNCTION
      ICNWD=LUMP2+3300B
*     NORMAL TYPE AHEAD AND DVM00
      IPARM=20001B
      CALL EXEC(ICODE,ICNWD,IPARM)
C   ****************************************
```

```
C     USING AN 'EXEC' CALL SET READ TYPE   *
C          -DISABLE 'CR' AS A TERMINATOR   *
C          -ENABLE 'CNTL D' (4B) AS A      *
C           TERMINATOR                     *
C     THIS IS NECESSARY SINCE THE MP-2     *
C     THINKS IT IS TALKING TO A TTY AND    *
C     APPENDS 'CR-LF' TO EACH LINE.        *
C     THE MUX INTERPRETS THE 'CR' AS A     *
C     TERMINATOR AND STOPS LOOKING FOR DATA*
C          NOTE: THIS IS ONLY EFFECTIVE    *
C                FOR ONE READ SINCE BIT 7  *
C                IN CONTROL FUNCTION 33 IS *
C                NOT SET.                  *
C                                          *
C    ***************************************
      ICODE=3
*     CONTROL FUNCTION 37
      ICNWD=LUMP2+3700B
*     SET 'CNTL D' AS TERMINATOR
      IPARM=20000B
      CALL EXEC(ICODE,ICNWD,IPARM)
C    ***************************************
C     USING AN EXEC CALL                   *
C      - WRITE INSTRUCTION TO THE MP-2     *
C                                          *
C    ***************************************
C
C    ***************************************
C                                          *
C          !!!!!    NOTE    !!!!!          *
C                                          *
C     THE SIZE OF THE COMMAND BUFFER (JK)  *
C     HAS BEEN INCREASED TO 256 WORDS      *
C     (FROM 8). IF THIS IS NOT DONE,       *
C     THE RESPONSE FROM THE MP-2 WILL NOT  *
C     BE PLACED IN THE RESULTS BUFFER (JR).*
C                                          *
C     THIS IS ONLY REQUIRED WHEN 'IPRINT'  *
C     EQUALS 1.  i.e. RESULTS ARE EXPECTED *
C     FROM THE MP-2.                       *
C    ***************************************
      IL=256
26    CALL EXEC(2,LUMP2,JK,IL)
*     CHECK IF CONTROL IS BEING RETURNED TO THE MP-2 (F40E)
      IF(JK(1).EQ.2HF4.AND.JK(2).EQ.2H0E)GOTO 25
*     CHECK IF RESULTS EXPECTED
      IF(IPRINT.EQ.1)GOTO 22
C    ***************************************
C     USING AN EXEC CALL                   *
C      - READ ECHO FROM MP-2               *
C                                          *
```

```
C   ****************************************
      CALL KLEEN(KJ,IL)
      CALL EXEC(1,LUMP2,KJ,IL)
      IF(IPRINT.EQ.0)GOTO 20
C   ****************************************
C     USING AN EXEC CALL                   *
C      - READ RESPONSE FROM MP-2           *
C                                          *
C   ****************************************
22    IL=8
      CALL KLEEN(JR,IJR)
      CALL EXEC(1,LUMP2,JR,IJR)
      WRITE(1,119) JR
119   FORMAT(/'MP-2 RESPONSE - ',/64A2)
C   ****************************************
C     USING AN 'FMP' CALL                  *
C      -WRITE MP-2 RESULTS TO DISC (FILE)  *
C                                          *
C   ****************************************
      CALL WRITF(DCB2,ERROR,JR,IJR)
C   ****************************************
C     USING AN 'EXEC' CALL FLUSH BOTH      *
C     254 BYTE INPUT BUFFERS FOR 'LUMP2'   *
C                                          *
C   ****************************************
      ICODE=3
*     CONTROL FUNCTION 26
      ICNWD=LUMP2+2600B
*     CLEAR BOTH BUFFERS
      IPARM=1B
      CALL EXEC(ICODE,ICNWD,IPARM)
      IPRINT=0
      GOTO 20
C   ****************************************
C     USING 'FMP' CALLS:                   *
C        1.TRUNCATE 'FILE'                 *
C        2.CLOSE 'FILE'                    *
C        3.CLOSE 'NAME'                    *
C                                          *
C   ****************************************
25    ILEOF=-1
      CALL WRITF(DCB2,ERROR,JK,ILEOF)
      CALL LOCF(DCB2,ERROR,IREC,IRB,IOFF,JSEC)
      ITRUN=(JSEC/2)-(IRB+1)
      CALL CLOSE(DCB2,ERROR,ITRUN)
      IF(ERROR.GE.0)GOTO 17
      WRITE(1,112) ERROR
112   FORMAT(/'ERROR # ',I5,' IN CLOSE')
      GOTO 13
17    CALL CLOSE(DCB1,ERROR)
      WRITE(1,113) (FILE(I),I=1,3),SECURE,CRN
```

```
113   FORMAT(/'DATA FILE ',3A2,':',I2,':',I2,' SUCCESSFULLY CREATE
*     TERMINATE MP2IO
      WRITE(1,115)
115   FORMAT(/'NORMAL TERMINATION OF MP2IO')
      GOTO 18
13    WRITE(1,114)
114   FORMAT(/'ABNORMAL TERMINATION OF MP2IO')
18    END
C
C  ************************************************************
C     THIS SUBROUTINE INITIALIZES A BUFFER TO ASCII BLANKS    *
C                                                             *
C  ************************************************************
      SUBROUTINE KLEEN(JK,LENGTH)
      DIMENSION JK(256)
      INTEGER BLANK
      BLANK=2H
      DO 10 I=1,LENGTH
10    JK(I)=BLANK
      RETURN
      END
```

APPENDIX F

Typical MP2IO Dialogue

```
:MP2IO

WELCOME TO MP2IO
MP2IO WILL GENERATE INSTRUCTIONS TO HELP YOU
TO OPERATE THE BENDIX LAYOUT MACHINE

WHAT IS THE PART NUMBER  ?P66666

WHAT IS THE CURRENT REVISION LEVEL  ?6

ARE THE PART NUMBER:  P66666
AND THE REVISION LEVEL:  6
CORRECT (Y OR N)  ?Y

INSTRUCTION - *

INSTRUCTION - *     CIRCULAR MEASUREMENT FEATURE - (820624.1133)

INSTRUCTION - *

INSTRUCTION - *      ENTER ACTIVE PLANE - XY

INSTRUCTION - XYF3E

INSTRUCTION - *     ENTER PROBE DIAMETER

INSTRUCTION - .1572F9E

INSTRUCTION - *     MEASURE FOUR POINTS IN THE XY PLANE TO DEFINE CIRCULAR I.D.

INSTRUCTION - 4F24E

INSTRUCTION - *     AFTER CALCULATING THE CENTREPOINT AND I.D. DISPLAY RESULTS

INSTRUCTION - F7D

INSTRUCTION - **    WRITE RESULTS TO FILE (NOTE **)

INSTRUCTION - 1.125F61E **

MP-2 RESPONSE -
1.125F61E
#0001
X  -1.9935
Y   2.9375
D   1.6845
**

INSTRUCTION - *     RETURN CONTROL TO MP-2

INSTRUCTION - F40E

DATA FILE PMDATA:   6:13 SUCCESSFULLY CREATED !

NORMAL TERMINATION OF MP2IO

:
```

APPENDIX G

PREAD Code

```
&PREAD T=00004 IS ON CR00002 USING 00024 BLKS R=0000

FTN4X,Q
C
C     PROGRAM: PREAD
C
C     AUTHOR: RAY HOEMSEN
C     DATE: 82 05 31 <820810.0817>
C     RELEASED TO SYSTEM: 82 08 09
C     COMPUTER: HP 1000
C     OPERATING SYSTEM: RTE-6/VM * REV 2208
C     LANGUAGE: FORTRAN 4X
C
C     PREAD WILL READ RESULTS WRITTEN TO 'PMDATA'
C     BY MP2IO.  THESE RESULTS ARE FROM MEASUREMENTS
C     MADE ON THE BENDIX LAYOUT MACHINE.
C
      PROGRAM PREAD
      DIMENSION JK(256),KK(1000)
      INTEGER FILE(3),DCB2(144),ERROR,OPTION,SECURE,CRN,TYPE
      DATA CRN/13/,SECURE/0/,IL/256/,TYPE/4/,OPTION/2/
      WRITE(1,100)
100   FORMAT(/'WELCOME TO PREAD'
     */'PREAD WILL LIST THE CONTENTS OF THE DATA '
     */'FILE 'PMDATA' CREATED BY MP2IO')
11    WRITE(1,101)
101   FORMAT(/'WHAT IS THE PART NUMBER ?_')
      READ(1,102) (FILE(I),I=1,3)
102   FORMAT(3A2)
      WRITE(1,103)
103   FORMAT(/'WHAT IS THE CURRENT REVISION LEVEL ?_')
      READ(1,*) SECURE
      WRITE(1,104) (FILE(I),I=1,3),SECURE
104   FORMAT(/'ARE THE PART NUMBER: ',3A2,
     */'AND THE REVISION LEVEL: ',I2,
     */'CORRECT (Y or N) ?_')
      READ (1,105) NY
105   FORMAT(A2)
      IF(NY.EQ.1HY)GOTO 21
      GOTO 11
C    *****************************************
C
C     DCB2=FILE
C
C    *****************************************
21    CALL OPEN(DCB2,ERROR,FILE,OPTION,SECURE,CRN)
      IF(ERROR.EQ.4)GOTO 23
      WRITE(1,107) ERROR
107   FORMAT(/'ERROR # ',I5,' IN OPEN')
      GOTO 13
23    CALL KLEEN(JK,IL)
```

```
      CALL READF(DCB2,ERROR,JK,IL,LEN)
*****************************************************************
      IF(LEN.EQ.-1)GOTO 25
      IF(ERROR.GE.0)GOTO 14
      WRITE(1,116) ERROR
116   FORMAT(/'ERROR # ',I5,' IN READ')
      GOTO 13
C     ****************************************
14    CALL LGBUF(KK,500)
      WRITE(1,108) JK
108   FORMAT(/'RESULTS - ',/256A2)
      GOTO 23
C     ****************************************
25    CALL CLOSE(DCB2)
      WRITE(1,113) (FILE(I),I=1,3),SECURE,CRN
113   FORMAT(/'RESULTS IN ',3A2,':',I2,':',I2,' SUCCESSFULLY READ
C     ****************************************
      WRITE(1,115)
115   FORMAT(/'NORMAL TERMINATION OF MP2IO')
      GOTO 18
13    WRITE(1,114)
114   FORMAT(/'ABNORMAL TERMINATION OF MP2IO')
18    END
C
C    ************************************************************
C    ************************************************************
C     THIS SUBROUTINE INITIALIZES A BUFFER TO ASCII BLANKS
C
      SUBROUTINE KLEEN(JK,LENGTH)
      DIMENSION JK(256)
      INTEGER BLANK
      BLANK=2H
      DO 10 I=1,LENGTH
10    JK(I)=BLANK
      RETURN
      END
```

APPENDIX H

Typical MP2IO Result File

```
PMDAT6 T=00004 IS ON CR00013 USING 00001 BLKS R=0000

0001  1.125F61E
# 0000
X   3.8845
Y  -9.0850


PMDAT6 T=00004 IS ON CR00013 USING 00001 BLKS R=0000


REC# 00001

030456 030462 032506 033061 042440 006412 000000 000000*1.125F61E
000000 021440 030060 030060 006412 000000 000000 000000*  # 0000
054040 020040 031456 034070 032065 020015 005000 000000*X   3.8845
000000 000131 020040 026471 027060 034065 030040 006412*   Y  -9.0850
000000 000000 000000 042040 020061 030056 030070 032465*      D  10.0855
020015 005000 000000 000000 000052 025040 020040 020040*         **
020040 020040 020040 020040 020040 020040 020040 020040*
020040 020040 020040 020040 020040 020040 020040 020040*
```

APPENDIX I

Typical PREAD Dialogue

```
PREAD

WELCOME TO PREAD
PREAD WILL LIST THE CONTENTS OF THE DATA
FILE 'PMDATA' CREATED BY MP2IO

WHAT IS THE PART NUMBER ?PMDAT6

WHAT IS THE CURRENT REVISION LEVEL ?6

ARE THE PART NUMBER: PMDAT6
AND THE REVISION LEVEL:  6
CORRECT (Y or N) ?Y

RESULTS -
1.125F61E
# 0000
X   3.8845
Y  -9.0850
D  10.0855
**

RESULTS IN PMDAT6: 6:13 SUCCESSFULLY READ !

NORMAL TERMINATION OF MP2IO
:
```

APPENDIX J

Documentation

```
**************************************************
*                 DOCUMENTATION                  *
**************************************************
```

PROGRAM: RS232C DATACOMM - HP1000 & BENDIX MP2

REVISION: 0

RELEASE DATE: 82 07 05 <820715.1249>

AUTHOR: RAY HOEMSEN

INTRODUCTION

This package of programs is used to help operate the Bendix layout machine using RS-232 data communication. The HP 1000 (12792A mux) is interfaced to the Bendix MP-2 microprocessor. Part measurement files can be created, instructions sent to the operator and MP-2, and data recorded (for future analysis). All programs are written in FORTRAN 4X.

PROGRAMS

PROGRAM	PURPOSE
&PFILE	Creates the part input file used to supply commands and instructions to the Bendix layout machine MP-2 and operator.
&MP2IO	Sends operating instructions to the Bendix layout machine MP-2 and operator from the part instruction file created by 'PFILE'. Results are placed into the disc file 'PMDATA'.
&PREAD	Reads results written to 'PMDATA' by MP2IO. These results are from the measurements made on the Bendix layout machine.

DISCUSSION

PFILE creates the MP-2 part input file used by MP2IO. These instructions would normally be keyed into the front panel of the MP-2. Thus, a working knowledge of the MP-2 instruction language is required. The programmer is asked for a part number and revision level, which is used to create the file NAMR. All part input files are created on CRN #13. The operator is then prompted for MP-2 instructions. To stop file input and close the file, enter 'EX'. The opportunity is given for error correction in PFILE. However, after the program has been terminated, corrections can still be made using EDIT 1000 or FMGR commands.

There are only two restrictions when using PFILE:

1. If results are to be displayed:
   a) a '**' is required in the comment immediately preceeding the 'F61E' call, and
   b) a '** 4B' is required on the same line as the 'F61E' command.

2. The last command sent to the MP-2 must be 'F40E'. This is necessary in order to return control to the MP-2 front panel. If this is not done, the MP-2 cannot be cleared for front panel control until the MP-2 is powered off, then on.

The following is an example of a typical part input file created by PFILE:

***** Sample Part Input File *****

```
*
*     CIRCULAR FEATURE MEASUREMENT - <820715.1249>     *
*
*     ENTER ACTIVE PLANE - XY
XYF3E
*     ENTER PROBE DIAMETER
.1572F9E
*     MEASURE FOUR POINTS IN THE XY PLANE TO DEFINE CIRCULAR I.D.
4F24E
*     AFTER CALCULATING THE CENTREPOINT AND I.D. DISPLAY RESULTS ON MP-2
F7D
**     WRITE RESULTS TO FILE (NOTE **)
1.125F61E **
*     RETURN CONTROL TO MP-2
F40E
*     CIRCULAR FEATURE MEASUREMENT COMPLETE     *
```

MP2IO is used to send instructions to the layout machine's operator and the MP-2. MP2IO will request the part number and revision level of the part to be inspected. This data is used to locate the part input file and open it. MP2IO reads the instructions from the part input file created by PFILE, and sends them to the operator's terminal and/or the MP-2. MP2IO will wait, when required, for operator and/or MP-2 response, before issuing another command. MP2IO uses the MP-2 command echo feature for control. MP2IO stores the results in a file called PMDATA on CRN #13.

It should be noted, that before sending instructions to the MP-2, control of the MP-2 must be turned over to the HP-1000. This is done by entering "F41D" on the MP-2 front panel before running MP2IO.

PREAD is used to read the results of MP2IO from PMDATA, and write them to the user's terminal. NO analysis is done. However, note that 6 ASCII null characters are appended to each output line.

OPERATION
----

1. LOG-ON to HP 1000 system.

2. IF a part input file has to be created:

   a) RUN 'PFILE'
   b) Follow PFILE instructions

3. IF a part is to be measured:

   a) ENTER 'F41D' on the MP-2 key panel
   b) RUN 'MP2IO'
   c) Follow MP2IO instructions

4. IF measurements results are to be read:

   a) RUN 'PREAD'
   b) Follow PREAD instructions.

   NOTE - all HP 1000 disc file accesses can ONLY be made on CRN 'AA'.

5. LOG-OFF the HP 1000.