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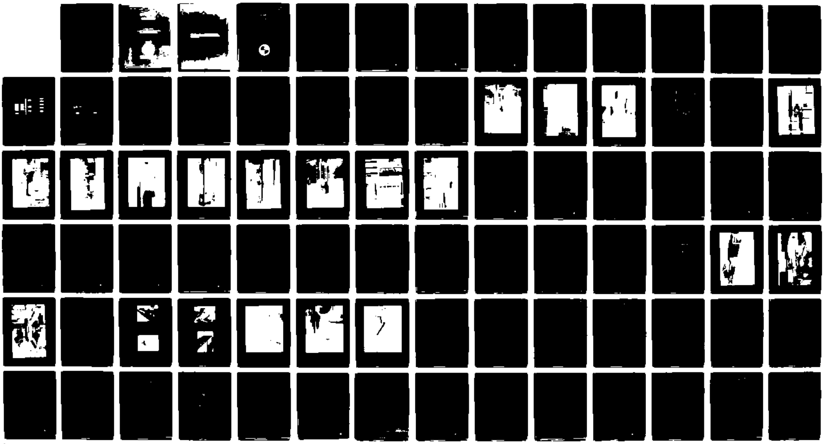

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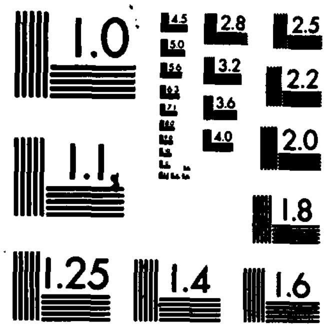

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AUGUST 1982

LASER MEASURING SYSTEM FOR LARGE MACHINE TOOLS

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

FINAL REPORT

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

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ABSTRACT

The demand on machine tools today for higher productivity and accuracy requires the latest in technology for tool positioning and calibration. To meet this demand, modern day machine tools are built to more exact standards and are numerically controlled for accurate tool positioning. To remain competitive today in industrial machining requires large expenditures for new machine tools or the up-grading of existing tools.

A large percentage of the Navy's machine tools were manufactured in the 1940's. The positioning system on these machines consist of lead screw graduated dials which are adequate when liberal tolerances are involved. To obtain a higher degree of accuracy, the time consuming use of pin gages, gage blocks, and dial indicators must be used or the machines have to be retrofitted with some type of modern measuring system.

With development of the Laser Interferometer, it was envisioned that older existing machine tools could be up-graded by retrofitting them with Laser Interferometer Measuring Systems. The Laser Interferometer provides the machine tool industry with a high accuracy length standard. The accuracy of the Interferometer is determined by the laser wave length which is known within 0.5 parts per million. This degree of accuracy is more than adequate for most machine tool measuring, calibration and inspection requirements.

In conclusion, the Laser Measuring System presently available is not recommended for general implementation at this time. Results of this work indicate that the equipment and installation cost are very high and pay back would be very slow. Also, the reliability of the electronic components is in need of improvement. The system requires frequent realignment and maintenance due to it's lack of toleration to "Shop Floor" conditions.

This conclusion is made in view of the availability of electrical inductance measuring systems. These systems are more economical and with .001 inch accuracy would be satisfactory for a large percentage of machining requirements. However, where extreme accuracy (.000005 inch) is required, the Laser Interferometer System should be considered.

FOREWORD

This is the final report of work completed under NAVSEA Project Order Number DNS-00658 "Laser Measuring System for Large Machine Tools". This Project Order was issued to investigate the practicability and cost savings in retrofitting large worn machine tools with Laser Interferometer Measuring Systems.

The work was performed by the Manufacturing Technology Branch, Naval Ordnance Station, Louisville, Kentucky, and the FMC Corporation, Northern Ordnance division, Minneapolis, Minnesota under contract N00197-79-C-0095. A parallel effort was made at each facility by installing a Laser Interferometer Measuring System on a large production machine tool. This is a combined final report on work performed at each facility including evaluation and recommendations for future efforts.

This Manufacturing Technology Report has been reviewed and is approved.

THAD A. PEAKE, JR.
Manufacturing Technology Branch
Production Support Division
Naval Ordnance Station
Louisville, Kentucky

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SECTION 1

INTRODUCTION

The subject machine tools in this report were manufactured prior to the N/C (Numerical Control) era. They have a very basic and elementary tool positioning system. Tool positioning relative to the work piece is accomplished by moving the machine component (table and/or tooling head) depending on the type machine. This is accomplished by means of a lead screw mounted in thrust bearings and connected by matching internal threads in the moveable machine component. A typical lead screw consists of a 0.100 inch lead (10 threads per inch) and a dial graduated in one thousandth increments. Tool position is determined by counting the number and fractional turns of the lead screw. This system is inherently inaccurate for precision positioning. This is due to the indicated tool position being dependent on the quality of the actuating linkage (lead screw threads, and thrust bearings). It is also dependent on thermal expansion and contraction of the lead screw and on human error in reading the graduated dial.

1.1 Precision Tool Positioning

For precision tool positioning, the linear movement of the machine (table or head) must be measured relative to its slide. The measurement must be read at this point or displayed directly to the operator, normally electrically. Any form of progressive mechanical linkage (lead screw) for indicating the measurement is subject to wear, backlash and thermal conditions. In summary, a graduated lead screw dial indicates the rotary position of the lead screw but not necessarily the exact tool position. To obtain precision tool positioning on machines equipped only with lead screw dials, the use of gage blocks or pin gages is required. These are length standards used to measure the linear movement of the table or tooling head relative to its slide. This often requires two people when large measurements are involved.

1.2 Vernier Scale Tool Positioning

The first improvement in tool positioning was the installation of a Vernier Scale on the machine slide for direct measurement. The Vernier is a precision scale but subject to human error in reading the fine graduated lines. When installed on large machine tools, it is particularly difficult to read because the scales are distant to the operator's controls. This often requires two people for tool positioning, one for operating the machine and the other for reading the scale and signaling the operator.

1.3 Electrical Inductance Tool Positioning

During the last decade a number of electrical tool positioning systems have been developed. The various operating principals include a magnetic scale with a flux responsive head, and etched glass scale with photo-optical reader, and a rack and pinion encoder system. These systems essentially consist of a length standard scale (magnetic or optical) mounted on the machine slide and a sensing unit mounted on the moving machine component. Most are unit constructed, designed for oil and chip protection of the sensing unit and installation is relatively easy. The measurement is displayed to the operator by an electronic digital readout console. Some systems are capable of performing arithmetic and logic functions that minimize operator error, such as keyboard entry of dimensions, programmable memory, absolute zero recall, instant inch/metric conversion, and variable resolution to .001 inch.

1.4 Laser Interferometer (LI) Tool Positioning

Development of the Laser Interferometer (LI) has provided industry with a high accuracy length standard. The frequency of a laser beam, in a vacuum, is an exact known standard. The frequency is affected by atmospheric conditions, temperature, humidity, and barometric pressure. These factors are compensated for by calculation or automatic compensation to a degree that the LI measuring system is accurate within .000005 inch. This degree of accuracy compares favorably with the best physical standards available and is certainly acceptable for machine tool evaluation and measuring systems. In addition, the LI system is easy to use, allowing measurements to be made in minutes instead of hours or even days previously required.

The principle of operation is that monochromatic light is directed at a beam splitter (half mirror), which passes half the beam to a movable mirror (the target) while the remainder is reflected to a fixed mirror. The reflections from the fixed and movable mirrors are recombined and directed to a photo cell within the receiver. Each time the movable mirror moves a distance equal to half the wave length of the beam source, the total optical path of the reflected beam changes by a full wave length. The comparative change in wave length is electronically processed to give a linear measurement in millionths of an inch.

There are two different models of LI measuring systems available today. One is a calibration system that is portable for plant wide use in calibrating various machines, surface plates and gaging equipment. The other system is engineered to be permantly mounted in retro fitting machine tools for accurate linear measuremnet. Both systems have the same basic components of laser head, interferometer, reflector, computer, automatic compensator, receiver, and readout.

In addition to linear measurement, the calibration system, with an array of optical components,is capable of complete machine tool calibration and surface plate flatness. This would include the 21 degrees of freedom of movement (21 possible sources of error on a machine tool). They are linear movement, pitch, roll, yaw, vertical and horizontal straightness in all three axes and squareness of the axes, one to the other, Calibration results are given in a printout and graphic plot.

Equipment calibrated and efficiency demonstrated:

Item	Conventional Method	Laser Calibration
4' X 6' Surface Plate	8 m/hrs	3 m/hrs
120" P&W Measuring Machine	48 m/hrs	6 m/hrs
80" P&W Measuring Machine	32 m/hrs	4 m/hrs
48" P&W Measuring Machine	20 m/hrs	2 m/hrs
Moore Jig Grinder	12 m/hrs (Detected mechanical defect in industry's most precise machine)	2 m/hrs
Cordex Measuring Machine	No comparable method available	2 m/hrs
Large Gray Boring Mill Large Sellers Boring Mill	No comparable method available. Any attempt to calitrate these machines by conventional methods would have taken 40 m/hrs for each machine. (A progressive error of 023 inch was discovered in a newly installed conventional measuring system.)	4 m/hrs 4 m/hrs
Lucas Boring MIll	In addition to linear calibration, this machine was completely calibrated in all 21 degrees of freedom of movement. It was calibrated to this extent to determine its accuracy and state of wear prior to retro fitting the permanently mounted LI system. This degree of calibration is more difficult and time consuming but is the ultimate with no comparable (accuracy) method available.	50 m/hrs

The permanently mounted laser system is capable of linear measurement only. It has a single laser head, but with the use of beam splitters and beam benders, the laser beam is divided and directed to all axes of the machine tool. The optical components and receivers are miniature in size for minimum restriction of axis movement. The beam path must be protected against chips and coolant. Different type machines require custom designed mounting hardware and the system should only be installed on machines in good condition so as to maintain beam alignment.

SECTION 2

SYSTEM ELECTRONICS

The purpose of this section is to present a very brief and basic operational and programming description of the laser transducer system electronics. The input/output interface is available in a wide variety of configurations and can be utilized with virtually any digital processor or controller. In this case a programmable calculator was utilized as system controller.

The system described here is referred to as a "Counter-Based, Laser Transducer System." It's purpose is to measure the linear displacement of a moveable point in relation to a fixed point and to continuosly display this measurement to the operator.

2.1 Interface Electronics

The interface electronics for the system is an electronic link between the laser transducer system components and the controller.

A typical two axes, counter-based system is composed of the following components (Figure 1);

A. Programmable calculator with a universal binary interface.

B. Laser transducer. (Laser head)

C. Coupler.

D. Bus interface module. (Coupler bus to laser head)

E. Receiver. (One per axis)

F. Counter interface module. (One per axis)

G. Automatic compensator.

H. Compensator interface module.

I. Material temp. sensor. (As required)

J. Digital display units. (One per axis)

K. Power supplies and connective cabling.

2.2 Simplified Theory Of Operation

A low-power, helium-neon laser (Figure 2) emits a coherent light beam composed of two slightly different optical frequencies, f_1 and f_2, of opposite circular polarization. After conversion to orthogonal linear

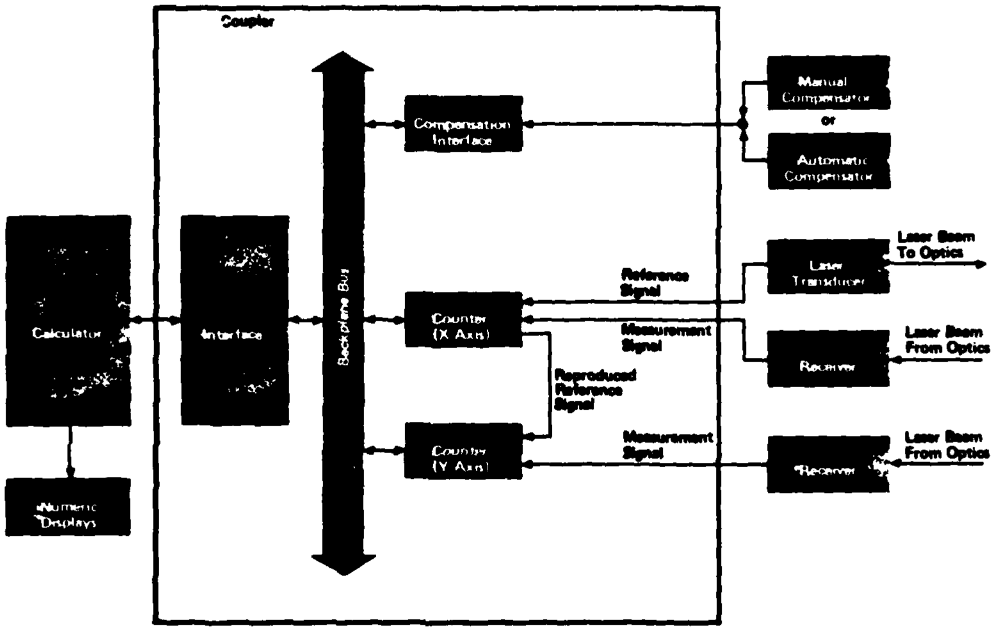

FIGURE 1 INTERFACE ELECTRONICS BLOCK DIAGRAM

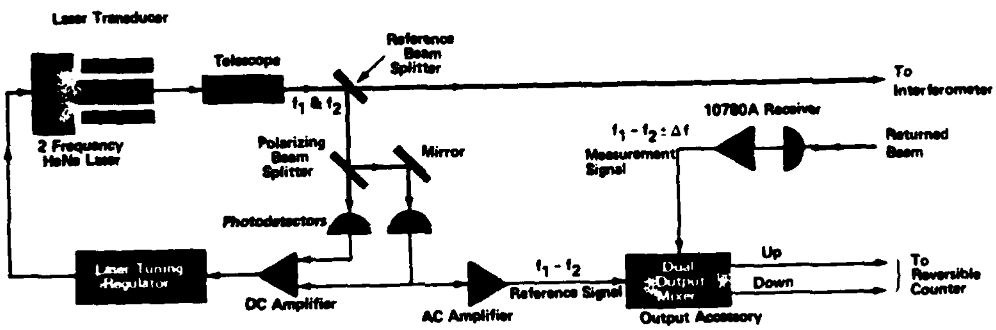

FIGURE 2 SIMPLIFIED BLOCK DIAGRAM

polarization the beam is expanded and collimated then directed to a reference beam-splitter. There, a small fraction of both frequencies is split off. The split off portion of the beam is used both to generate a reference frequency and to provide an error signal to the laser cavity tuning system. The difference in amplitude of f_1 and f_2 is used for tuning while the difference in frequency is used for the reference signal.

The major portion of the beam passes out of the laser head and is directed to an interferometer. The interferometer measures displacement of two reflectors by splitting the beam into it's two frequency components (f_1 and f_2) and directing them to two seperate reflectors. Both reflectors return their portion of the beam (frequency) back to a common point where they interfere with each other. These recombined frequencies are directed upon a photodetector within a receiver.

Relative motion between one fixed reflector and one moveable reflector causes a doppler shift in the difference frequency, ($f_1 - f_2 \pm f$) which is detected by the receiver. This doppler shifted, difference frequency is the measurement signal that is acted upon by the system.

Each output accessory receives the reference and measurement signals and compares them cycle-by-cycle in a dual output mixer. The mixer produces an appropriate up or down pulse whenever one signal gets one half cycle ahead of or behind the other.

Each pulse corrosponds to a reflector movement of one-quarter wave length of laser light. These pulses are accumulated, converted, amplified and output (upon command of the controller) to a display accessory.

2.3 Coupler

The coupler serves as a housing for all input/output interface modules. It can accept up to ten plug-in modules and provides all interconnections by means of a printed circuit board located at the rear of the housing. This circuit board is referred to as the coupler backplane bus.

The backplane bus, (or simply, bus) allows data transfer between interface modules and also distributes electrical power throughout the system. System electrical power is furnished by external power supplies connected to a terminal strip at the rear of the coupler. Connection points are provided on the bus to accept the plug-in interface module.

The bus consists of 86 lines. Each of these lines has a specific function. Any module that requires that function is electrically attached to and uses that line.

The 86 bus lines are divided into three functional groups, data related lines, instruction related lines and power related lines.

A. Data lines are used to transfer data between modules and other system components. Also, decimal point, error and operating mode information is transferred on these lines.

B. Instruction lines are used to transfer program instruction and address information to modules that require it.

C. Power lines distribute electrical power throughout the system and provides return lines for the external power supplies.

2.4 General System Operation

The laser transducer system is based on the coupler, it's assorted plug-in modules and a programmable calculator. The calculator is utilized to process data and to control system operations. The plug-in modules interface the various components to the coupler backplane bus. The bus carries all signals (data and control) between system components.

Basically a counter-based system operates as follows; displacement information, which is updated continuously, is transferred upon command, from the electronic counters on the counter modules to the bus. This displacement data is then transferred from the bus to the controller for later processing. Next, the automatic compensator (which compensates for variations in atmospheric conditions) transfers it's data to the controller via the bus. The controller then processes this raw data and out-puts meaningful displacement information to the display units. The controller commands and controls the laser system via an interface module so as to perform each function required to make and display a measurement. The controller accomplishes this by issueing instructions that contain eight bits of information. A bit is one binary digit, (0 or 1). These eight bits are divided into two parts and contain four bits of address and four bits of command information. Each module connected to the bus recognizes it's own unique address and responds to all commands associated with that address. Also, some modules automatically respond to commands sent to other modules. For example, when a counter module is instructed to output data onto the bus, another module may input these data and store them until instructed to output the stored data to the controller.

The movement of data, information and commands throughout the system is continuously taking place in an operating system. This results in a continuous updating and display of measurement information to the operator.

2.5 System Programming

As stated, the laser transducer system in this case is controlled by a programmable calculator. But of course, the calculator is controlled by the user's program that is loaded into it. Once a program that actually works, is loaded into the calculator there is a means of recording that program on magnetic tape. This allows the program to be reloaded from the tape each time the system is used.

The objective of programming is to obtain the desired results from the system that is under control of the program. In order to effectively program the laser transducer system to obtain the desired results, the operator must understand and be familiar with the system's controller. (It's capabilities, it's limits and it's program language.)

A program consists of a specific sequence of instructions that the system's electromics recognize and respond to, and which results in a measurement indication on the display units. These instructions are output from the controller via the interface module to the backplane bus.

An instruction consists of two parts, a numeric command and an alphabetic address. As an example, the instruction "2X". The "2" is the command that tells a counter module to load it's last sample onto the bus. The "X" specifies which counter module is to respond. In this case it would be the module that has it's address in the "X" position.

Instructions can be and normally are combined into one program statement. An example of this is the instruction sequence 10, 2X, 30. The "10" instruction generates a backplane sample command. The "2X" instruction causes the X-axis counter to output it's sampled data and the interface card to input those data, the "30" instruction causes this interface card to convert the data to B.C.D. (Binary Coded Decimal) and prepare to output it to the controller upon receipt of a command to do so.

Each instruction in a program statement must be sequenced in an order that will result in the desired operation. In the last example, you could not instruct the counter board to output it's data (2X) without first taking a backplane sample (10), if you desire to update from the last sample taken.

Because the displacement data contained in the counter cards are in units of ¼ wave lengths of laser light, the calculator must convert this raw data into a usable unit of measurement. The conversion can be made to inches or millimeters, also, the counters are preset to 160 counts so that the effects of vibration does not result in an underflow. The calculator must therefore subtract 160 counts from the displacement data prior to converting to inches or millimeters. The data must then be multiplied by the compensation data, (supplied by the auto compensator) prior to output as a measurement indication.

There are program statements that are not directly involved in the measurement operation. These statements cause the calculator to continuously monitor the system for errors or abnormal operating conditions. For example, if the laser beam became blocked by some object or beam power were to be reduced to a certain level (oil film on optics), the system would not continue normal operations. The calculator can be programmed to detect this condition and respond by discontinuing normal operation and causing an error message to be displayed along with the action required to correct the condition.

Personnel selected to install, program and operate a LI measuring system should have some background in electronics, and/or computers. Although not absolutely necessary, the venders technical publications requires that type background for understanding system installation and operation. Also, personnel proficient in programming can possibly expand on the basic program to a higher degree of system operation.

2.6 Sample Program

The general outline for programming a three axis counter based system:

Operation	Results
a. Backplane reset	Initializes all cards. Presets counter to 160 counts.
b. Output compensation	Puts compensation data on bus which is accepted by the interface.
c. Format data	Interface converts data to B.C.D. and stores same.
d. Read into calculator	Compensation data transferred to and stored in calculator.
e. Backplane sample	Samples all counters simultaneously, loads counter contents into output buffers.
f. Output X-axis data	Puts X-axis data on bus which is accepted by 10745A.
g. Format data	Interface converts data to B.C.D. and stores same.
h. Read into calculator	X-axis data transferred to and stored in calculator.
i. Subtract 160 counts from X-axis data; multiply by compensation data and constant (6.23023×10^{-6}) for inch conversion.	Converts data into inches.

j. Output to display	Display X-axis measurement.
k. Repeat steps b through j for y and z axes.	Display y and z measurement.

SECTION 3

LASER SYSTEM INSTALLATION

A Hewlett Packard (HP) 5501A Laser Interferometer Measuring System was selected for installation on a Lucas Horizontal Boring Mill, Model 542B-84 (Figure 3). The HP system was selected under sole source conditions and so far as known, these conditions exist today. Calibration of the Lucas Mill (Figure 4) indicated that it was the best machine available for installation. Also, the type of machining usually performed on this machine was ideal for evaluating the measuring system.

3.1 System Familiarization

After initial inspection of the laser system, it was decided that prior to hard mounting, it should first be used as a mock-up installation. The mock-up would facilitate the operational check and also allow personnel involved to become familiar with the equipment. A relatively quiet and dust free room was chosen to arrange and electrically connect the components (Figure 5). The mock-up installation proved to be very useful in that personnel became quite familiar with the equipment and system operation. Also, at this time, some electronic components were found to be faulty and had to be replaced or repaired.

During the mock-up phase it became apparent that laser beam alignment would be the critical factor for proper operation of the system. This is due to splitting the laser beam to accommodate three axes. Also, it was evident that a means for protecting the laser beam from metal chips and coolant must be provided.

3.2 Installation Diagram

When installing a laser system, there are a number of possible designs for arranging the various components. Each machine has to be studied carefully to determine which is the most suitable for a particular machine. This is due to machine configuration and the number of axes involved. The installation diagram for the Lucas Horizontal Boring Machine is shown in (Figure 6).

The laser head is mounted on top of the Y axis column with the beam directed downward to a 33% beam splitter. This splitter diverts 33% of the beam to the Y axis and is directed parallel to it by means of a beam bender. The beam passes through a fixed interferometer to a moving reflector, that in turn directs the signal back to the Y axis receiver.

The remaining 66% of the original beam passes through the 33% splitter to a 50% beam splitter that directs one half of this beam to a beam bender. The beam bender directs the beam parallel to the X axis.

FIGURE 3 LUCAS HORIZONTAL BORING MILL

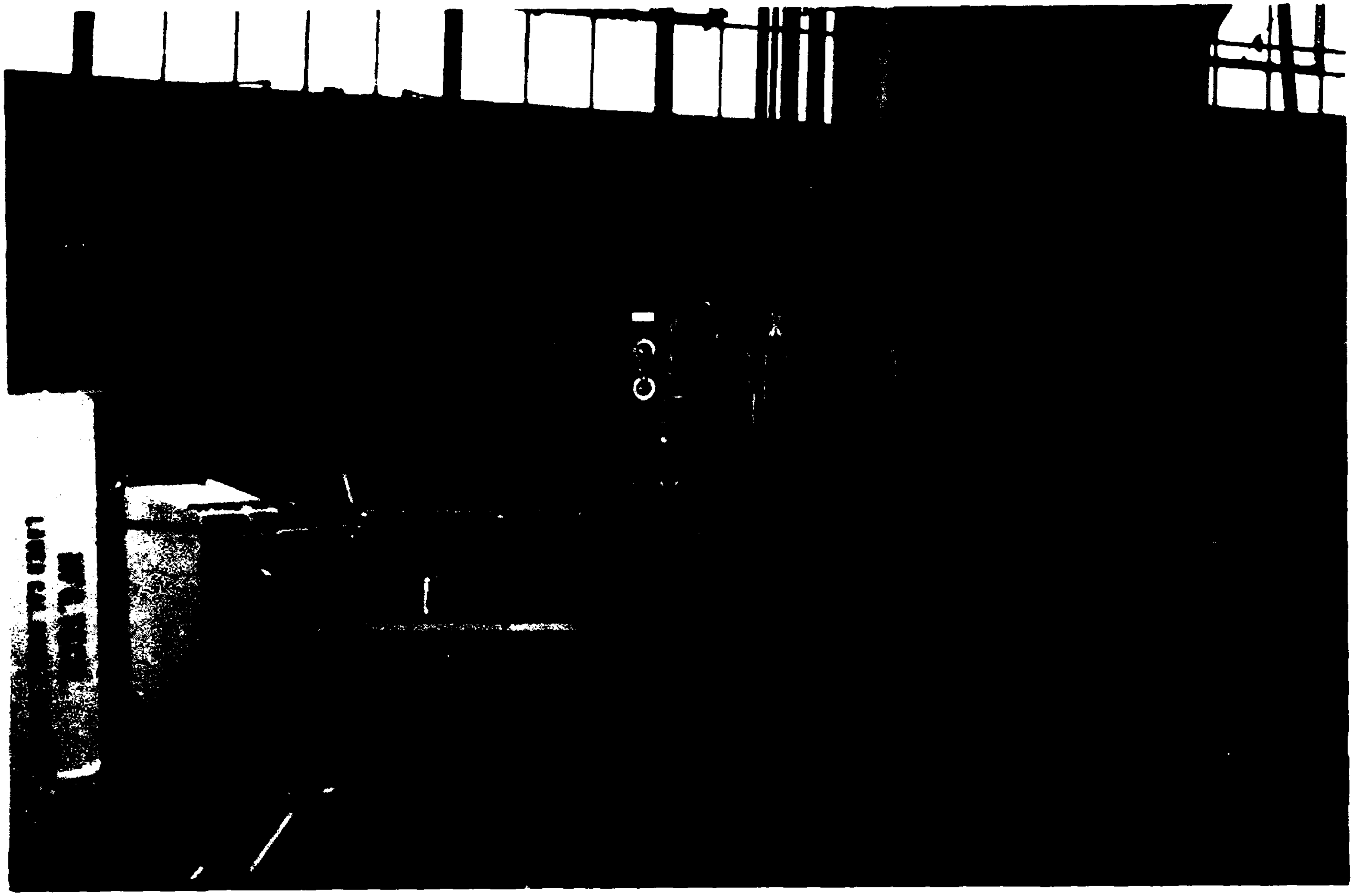

FIGURE 4 CALIBRATION SET UP

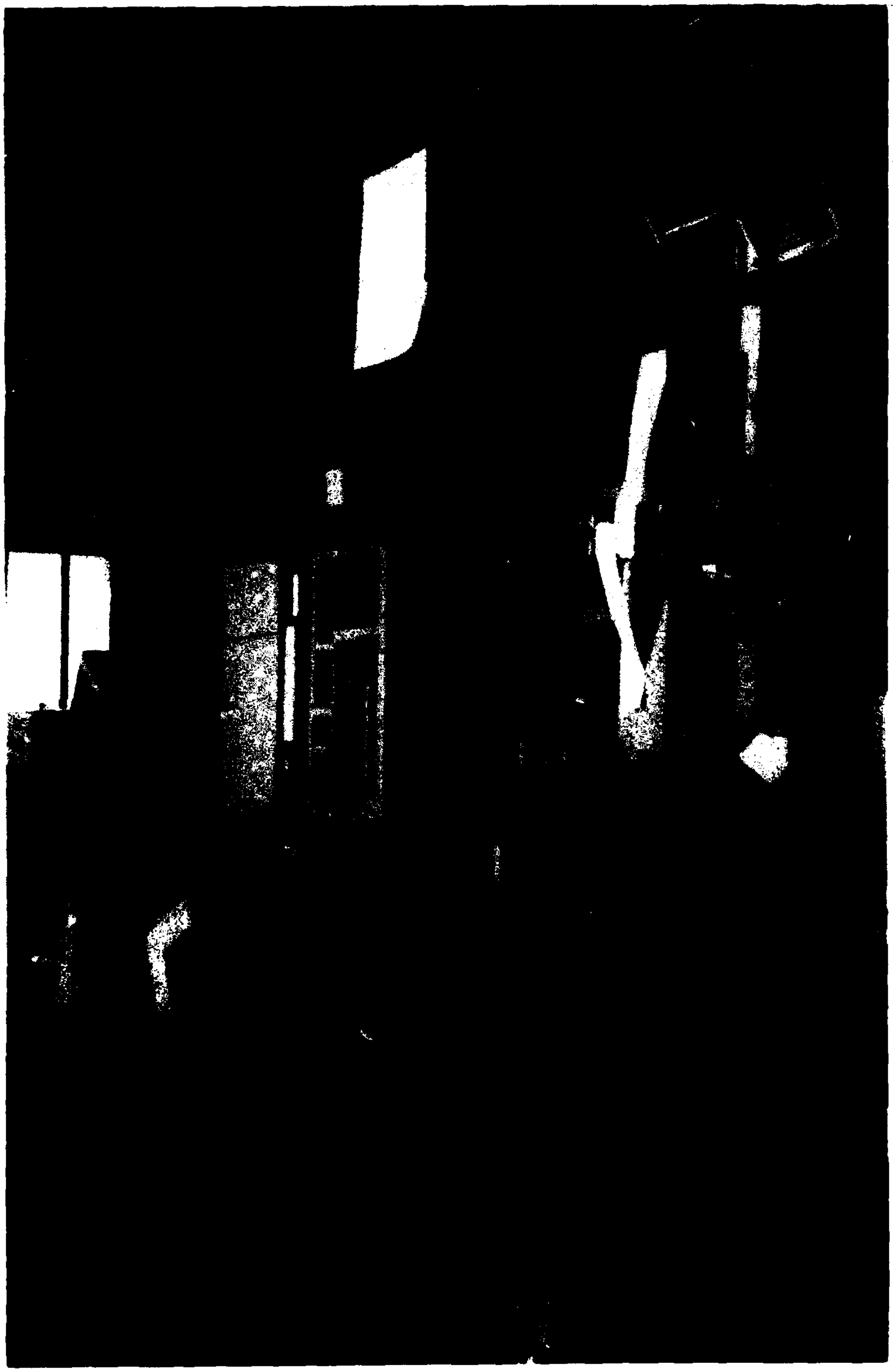

FIGURE 5 LASER SYSTEM MOCK-UP

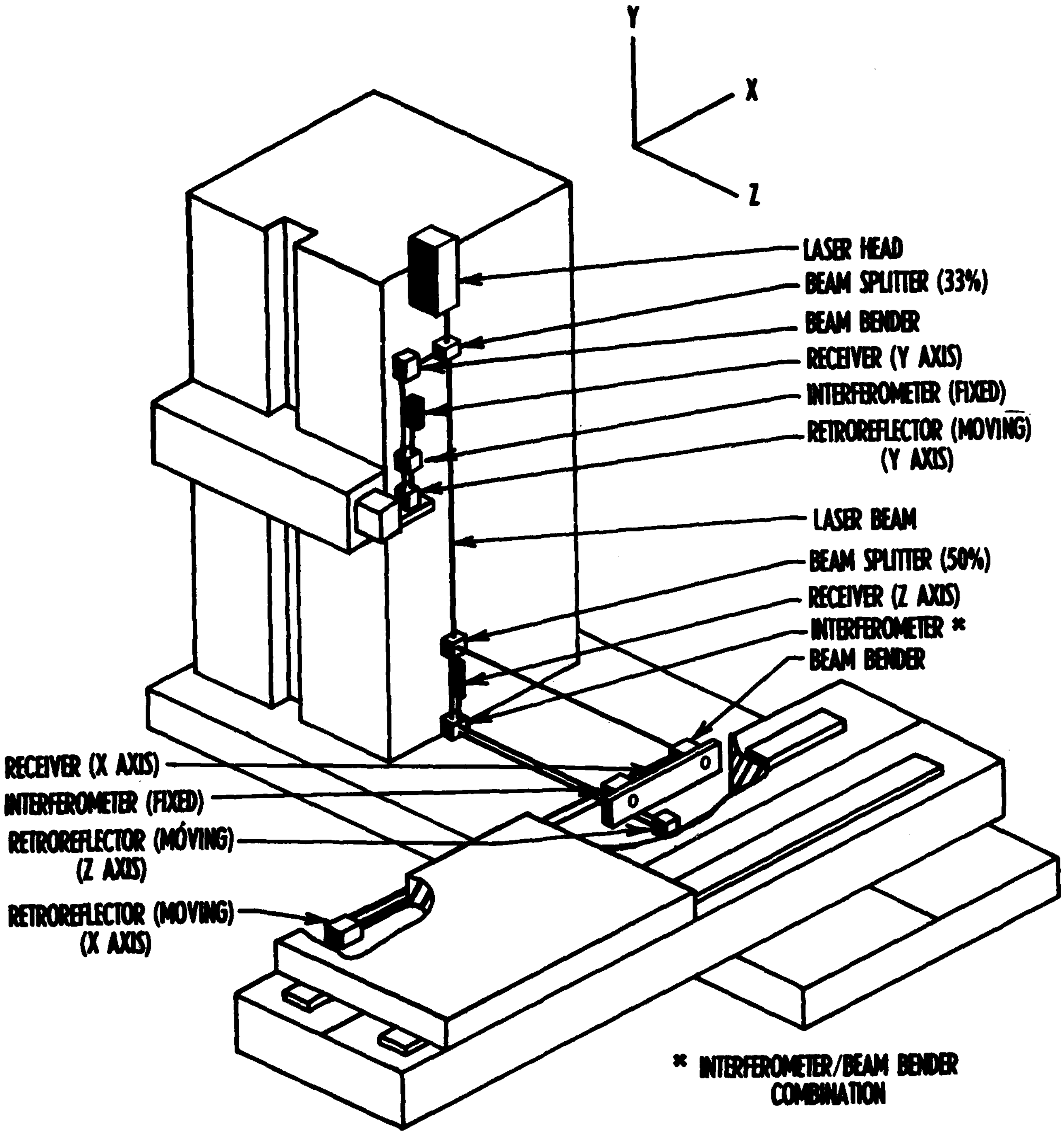

FIGURE 6 LASER INSTALLATION DIAGRAM (NOSL)

Once the beam is directed parallel to an axis, its path through the interferometer to the reflector and back to the receiver is typical for all axes.

The remaining 50% of the beam, or in essence 33% of the original beam source, is then directed to a combination interferometer and beam bender. The beam bender directs the beam parallel to the Z axis. The combination interferometer and beam bender permits mounting the receiver perpendicular to the axis. An interferometer will direct the beam straight through or perpendicular to the line of entry, depending on placement of the retroreflector on the interferometer.

3.3 Mounting Hardware

Where the design called for a cluster of components, mounting blocks were manufactured and the components were located on the blocks with tool maker precision. The mounting blocks were then installed relative to the machine axes with the same precision (Figures 7, 8, and 9). This resulted in minimum adjustment for aligning the laser beam to the machine axes.

(Figure 7) shows the laser head, and the Y axis 33% beam splitter, beam bender, interferometer and receiver.

(Figure 8) shows the X axis 50% beam splitter, and the Z axis interferometer and receiver.

(Figure 9) shows the X axis beam bender, interferometer and receiver.

Protection for the component clusters and laser beam was provided by aluminum covers and conduit (Figures 10, 11, 12, and 13). Beam protection for the Z-axis and the projected beam to the X axis proved to be the most difficult and is yet to be completely resolved. The problem is the need of an enclosure that will expand and retract the length of Z-axis monement and not restrict axis movement in the retracted position. A rubber enclosure (accordion shaped) is being considered but will have to be externally supported due to its use in a horizontal position.

3.4 Electronic Console

Electronic components (power supplies, coupler, and automatic compensator) are housed within a steel cabinet fitted with a cooling fan and air filter (Figure 14). Air vents were cut between compartments to aid circulation through and around components for maintaining cabinet temperature below 40°C. Electrical power is furnished to an on/off switch inside the cabinet. This allows single switch operation for the complete system. The system controller (calculator) and digital readout units are secured to the cabinet top (Figure 15) and covered with a transparent plastic (plexiglass) cover.

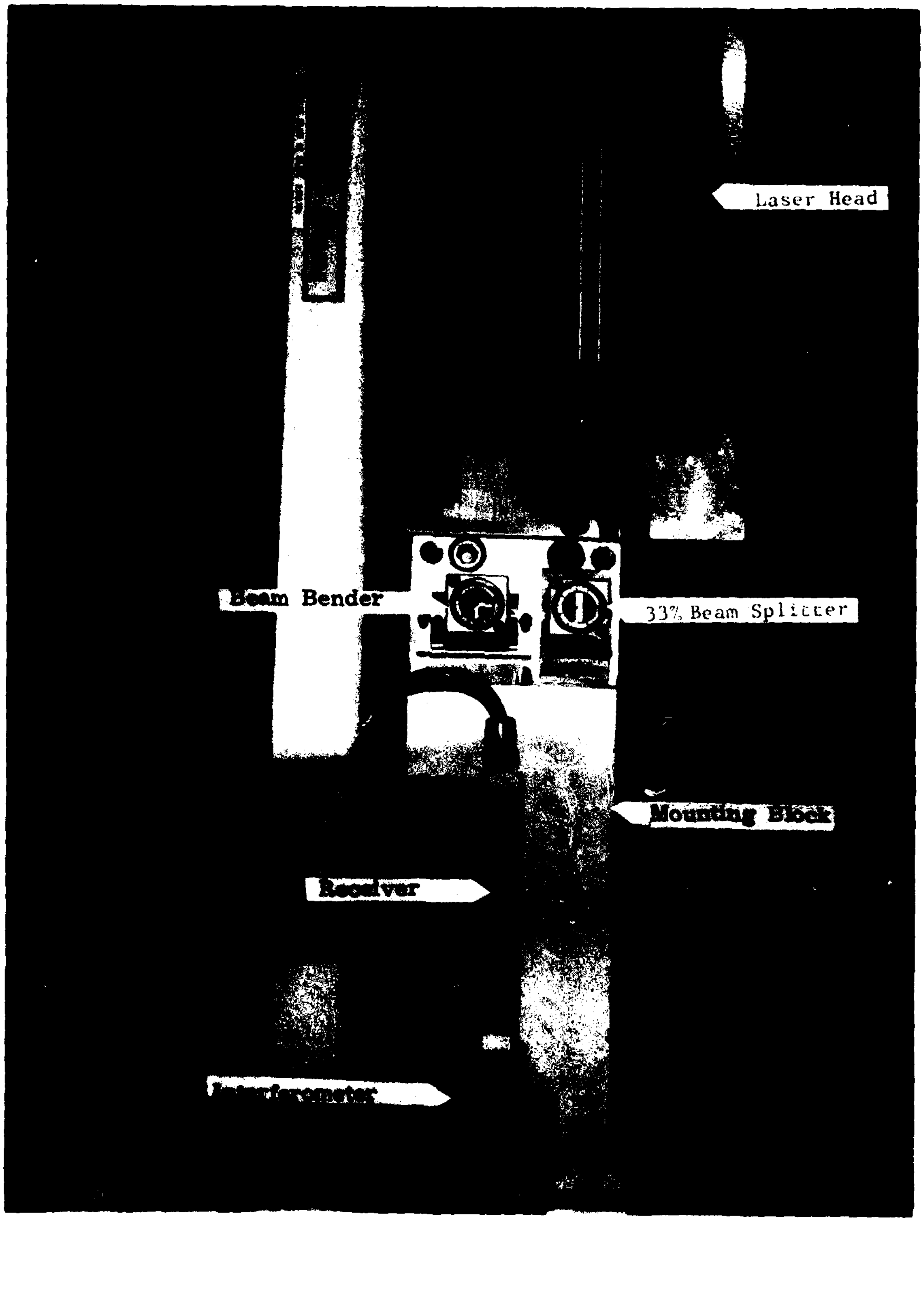

FIGURE 7 Y-AXIS COMPONENTS

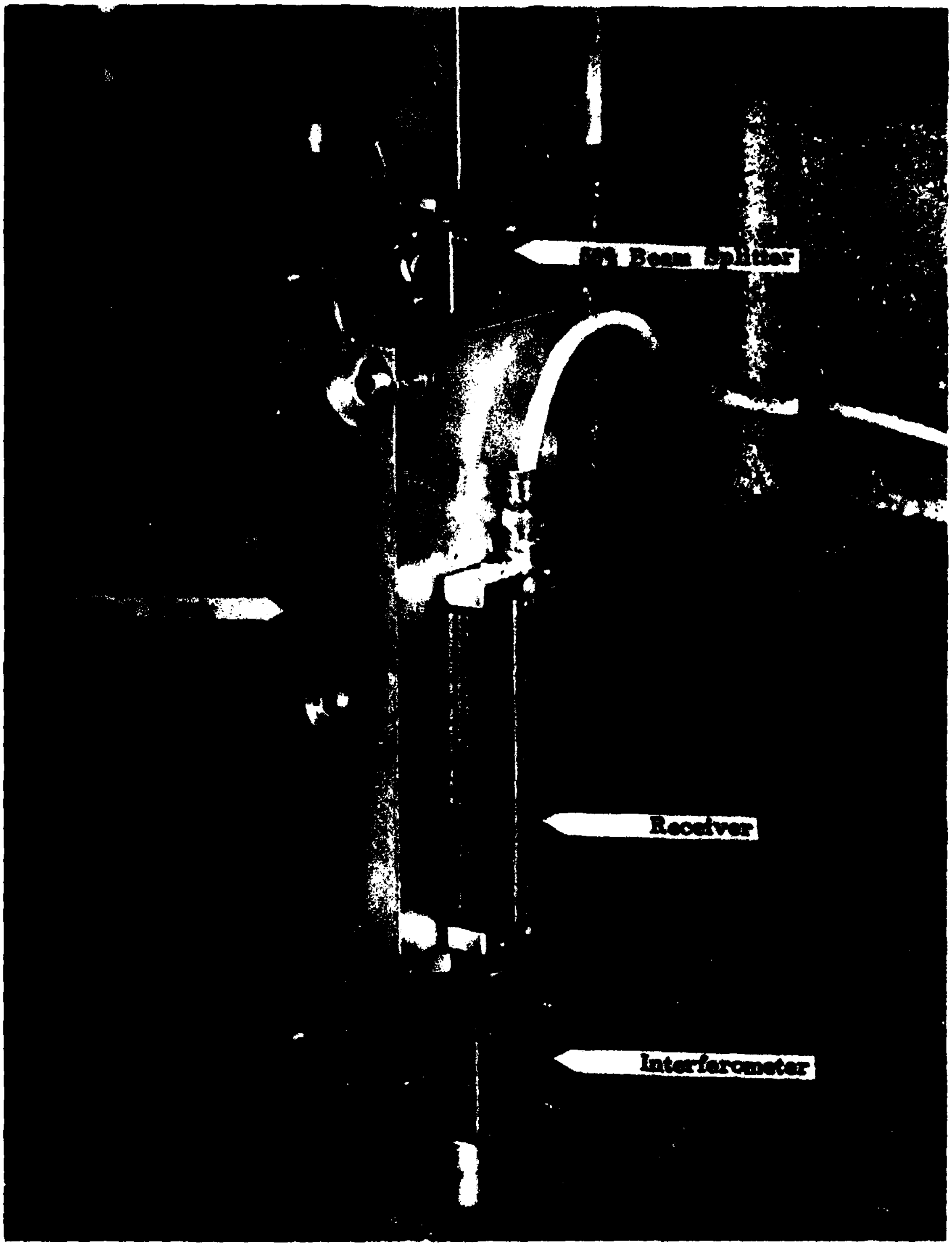

FIGURE 8 Z-AXIS COMPONENTS

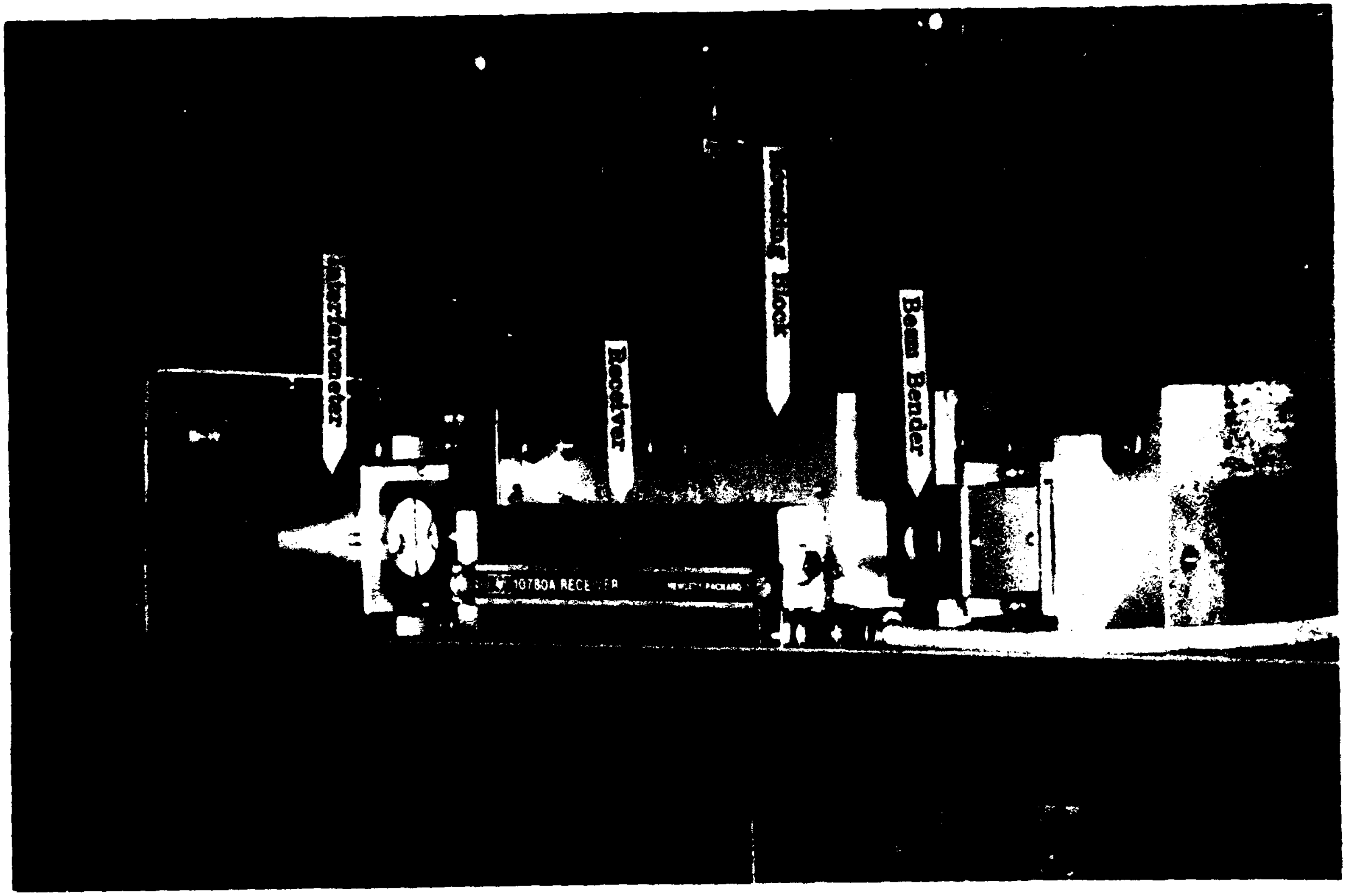

FIGURE 9 X-AXIS COMPONENTS

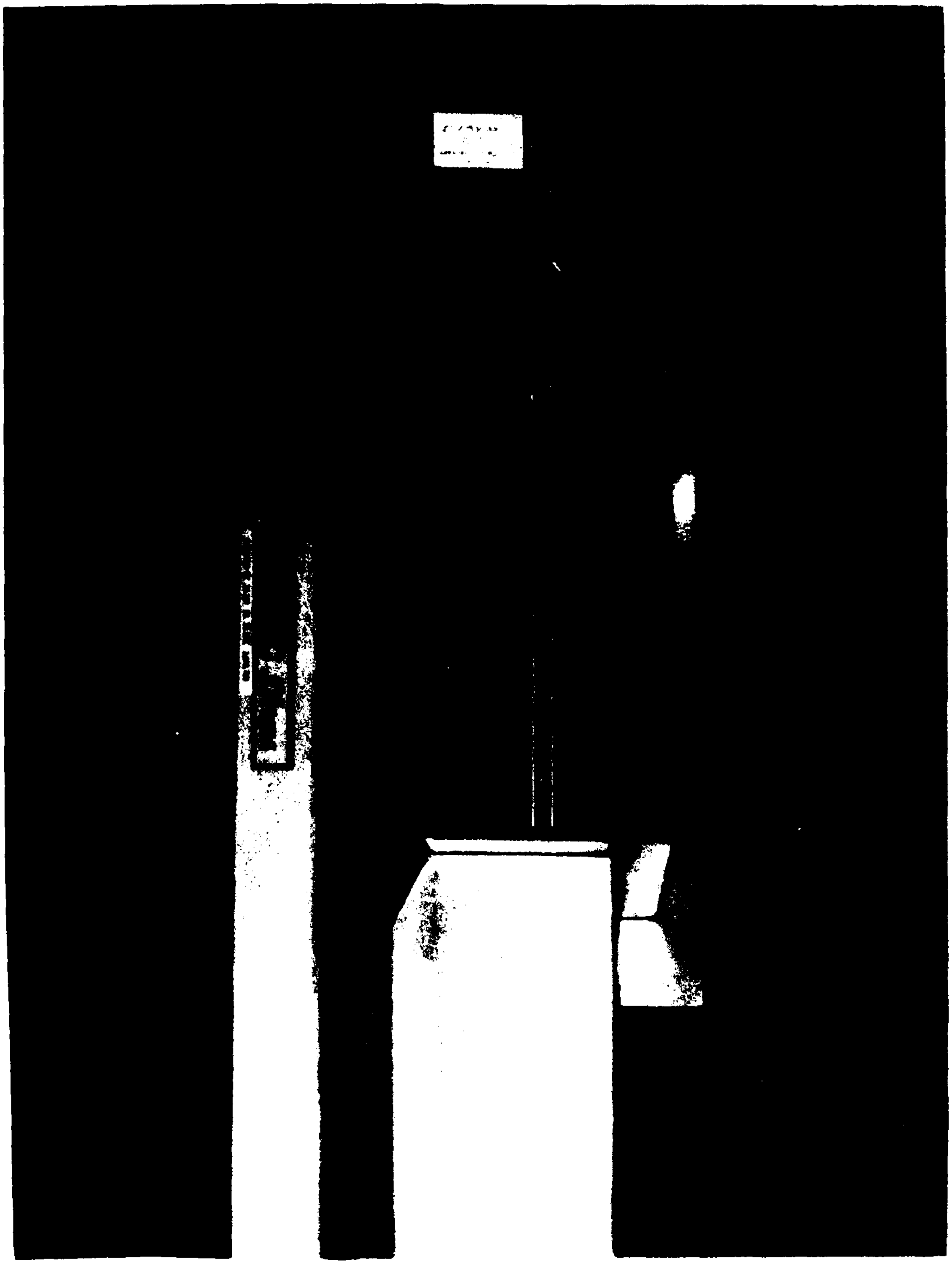

FIGURE 10 LASER HEAD AND Y-AXIS COMPONENTS

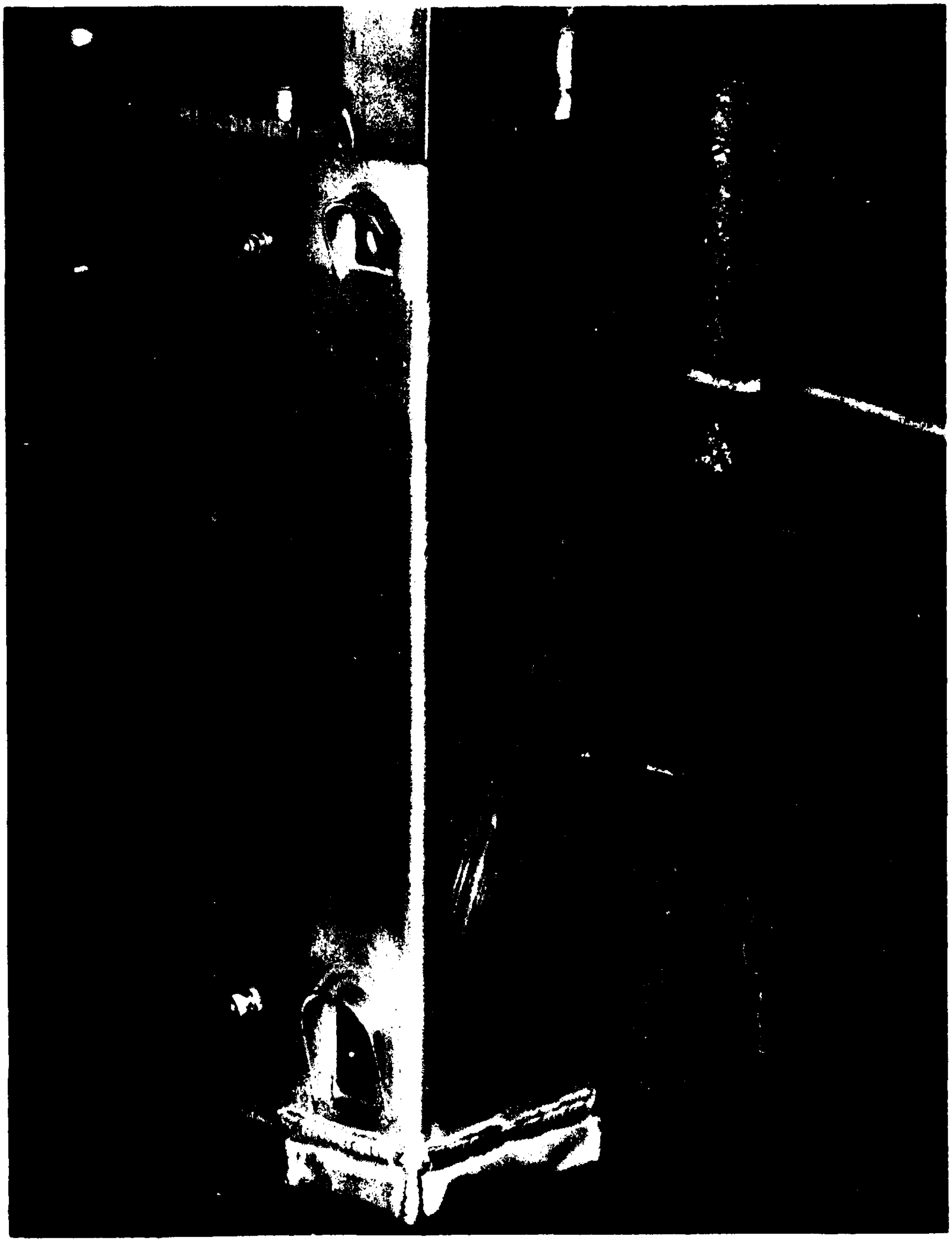

FIGURE 11 Z-AXIS COMPONENTS

FIGURE 12 X-AXIS COMPONENTS

FIGURE 13 BEAM PROTECTION (CONDUIT)

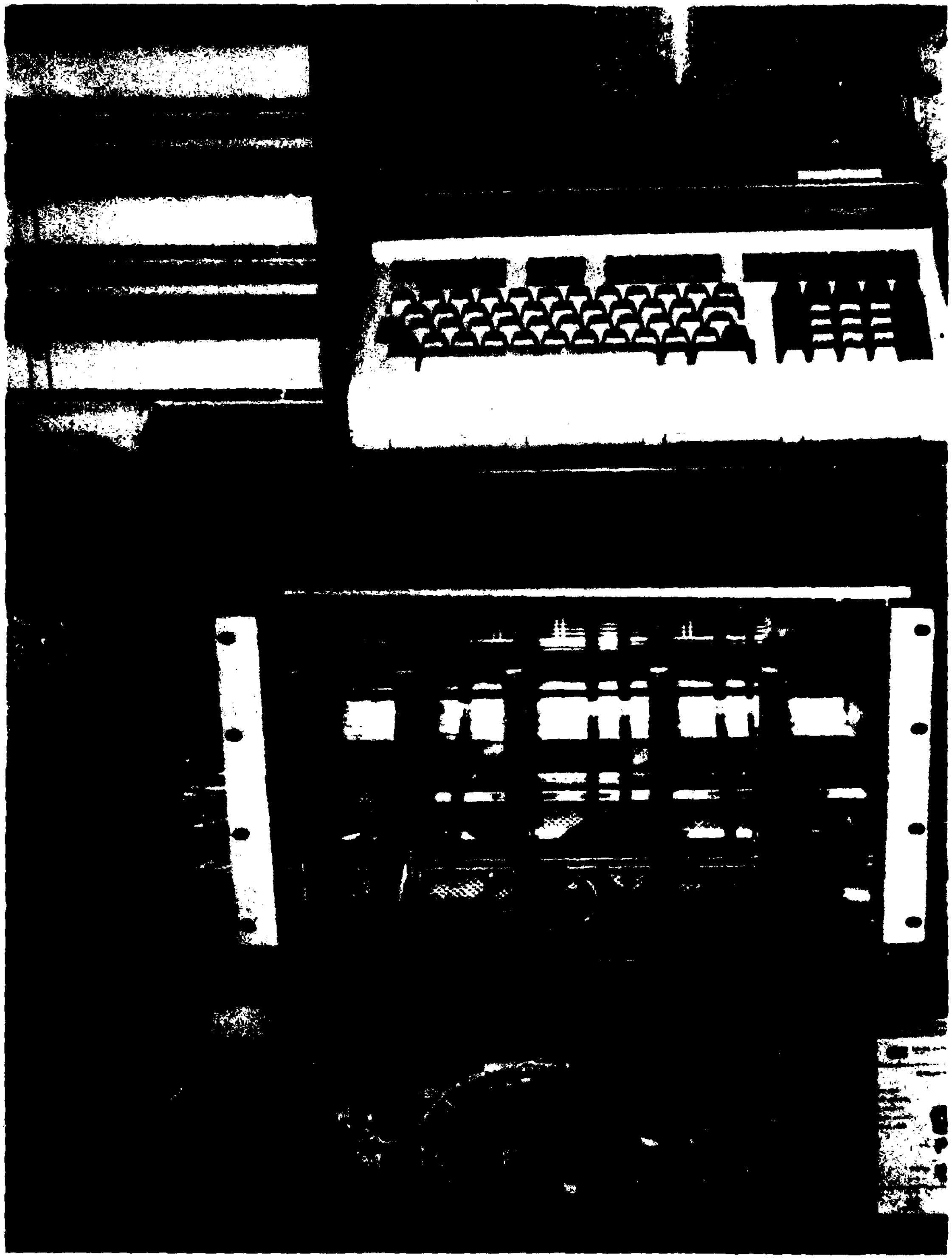

FIGURE 14 ELECTRONIC CONSOLE COMPONENTS

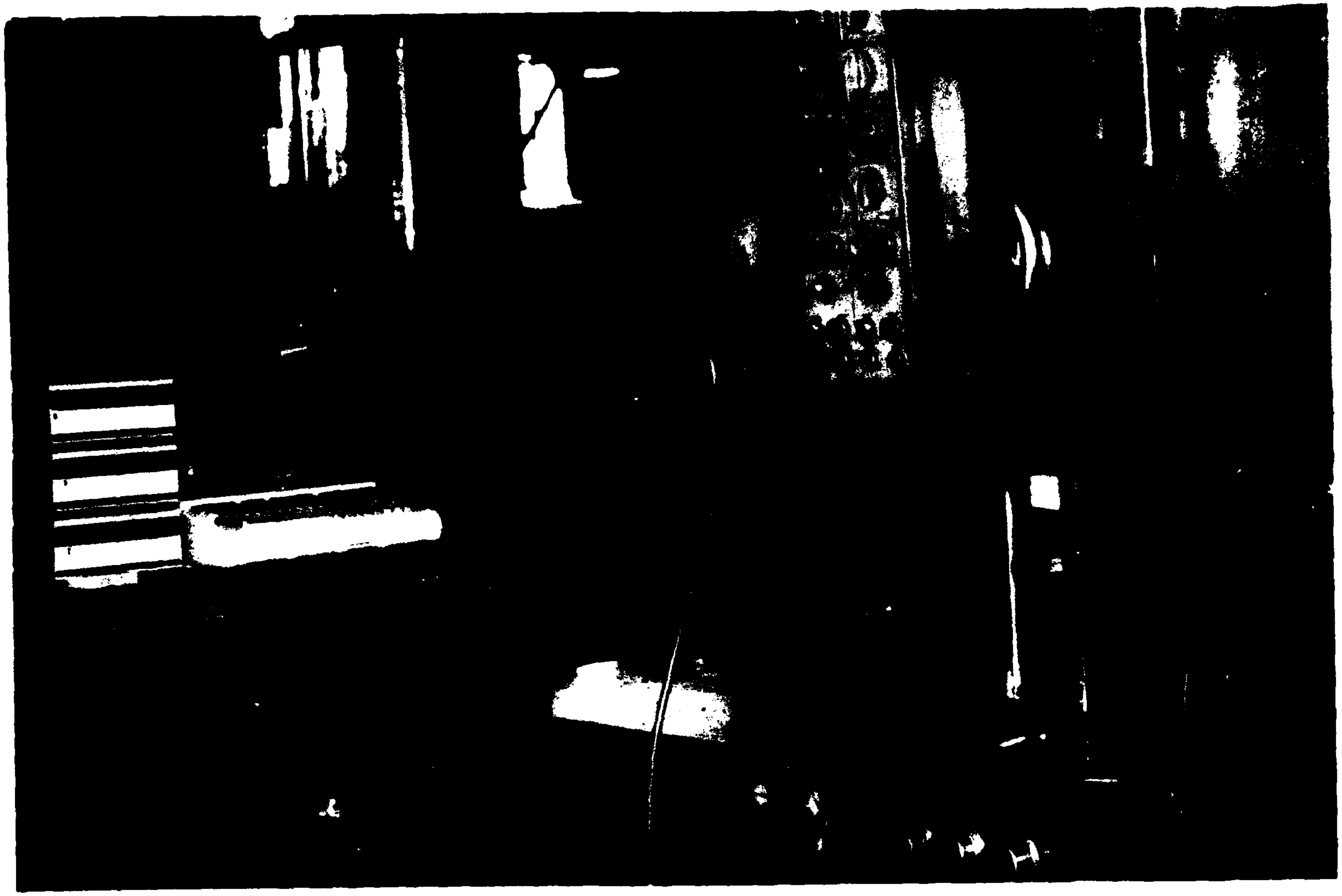

FIGURE 15 ELECTRONIC CONSOLE

Section 4

SYSTEM RELIABILITY

The following comments on the Laser Interferometer Measuring System and components pertain specifically to the difficulty encountered at NOSL. The system was never in operation over a six hour period. It was delivered with a manufactured mis-wired (shorted) connecting cable, a power supply out of adjustment, a defective R.O.M. (read only memory), and an open resistor in one of the receivers. A number of counter boards had to be replaced before the required three (for three axes operation) were found. After initial use of the system a defective circuit board was replaced in the automatic compensator and the laser head had to be returned to the factory for repair. Eventually, the entire system (at the manufactures' request) was dismantled and returned to the factory for inspection and repair. It was returned in a faulty condition (no laser beam). The laser head was again returned for inspection and repair. Inspection revealed no malfunction in the laser head and additional inspection of the system was necessary to correct the current problem. Further inspection showed another defective cable connector, (an intermittent short to ground). This defect was repaired in house. The system is now operative but requires frequent realignment and daily maintenance during heavy use.

It is reasonable to expect that the components of a complex electronic system be individually inspected to insure some degree of quality control. This would include counter boards of which it is understood that there is no method of inspection and testing other than field installation. By all means, the more elementary components such as cable connectors should be inspected. Although their function is obvious, an improperly wired connector can cause havoc in trouble shooting and may even initially damage an entire electronic system.

The degree of quality control required should be sufficient to instill confidence in the basic operation of a system. This would also permit devoting more of the alloted project time for installation and evaluation.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The project's current title "Laser Measuring System for Large Machine Tools" was changed from the initial title of "Laser Guided Machine Tools." This was to dispel any misinterpretations of the project's capabilities to compensate for older machine tool wear (straightness, flatness, parallelism and perpendicularity). The project's current capability is confined to axis linear measurement only. It is accurate in this respect since the laser interferometer measuring system operates independent of the machine tool axis lead screws. A general implementation plan for using the laser interferometer to upgrade (linear measurement only) older machine tools is not recommended at this time.

Equipment cost for a three axis machine tool is approximately $40,000. Installation cost is high due to custom fitting required for installing the system on different brands and types of machines. There are no unitized optical components or off-the-shelf mounting hardware. Machine tool frames and columns are generally cast-contoured (draft angle) surfaces. These surfaces do not provide a common datum plane from which the laser system mounting components can be designed, dimensioned and manufactured in quantity. This requires designer and toolmaker services working in a step by step (install and measure) process. Perhaps this explains why there is no vendor supplied mounting or beam protection hardware other than adjustable mounts for the optical components. Even with the adjustability of these mounts, the laser measuring system has to be basically installed with toolmaker precision.

The reliability of the laser electronic components supplied to Naval Ordnance Station, Louisville, (NOSL) was poor. To a lesser degree FMC Northern Ordnance also received some defective electronic components. When operational, the accuracy and potential of the laser interferometer measuring system is not questioned. However, it is recommended that improvements be made before further implementation. There was poor quality control to the extent of miswired electronic connectors and a defective laser source. NOSL personnel were able to perform some of the troubleshooting by interchanging duplicate components of the three axis system such as receivers, receiver cables, counterboards and connecting cables.

The Laser Interferometer Measuring System is accurate within five millionths of an inch. To fully utilize this degree of accuracy, the system should be used in a controlled environment for permanent beam alignment. This is particularly true for large machine tools where overnight thermal changes affect a large machine structure to the extent that beam realignment may be required each morning. The system is most applicable to large machine tools if beam alignment can be maintained.

The Laser Interferometer Measuring System, as engineered, should only be implemented where extreme accuracy is required. This is due to the initial cost of equipment, installation and maintenance cost. However, it is felt that the laser interferometer principle should be pursued as a measuring system for large scale implementation.

Substantially reduce equipment cost by prejudicing the accuracy and decreasing beam alignment sensitivity. The accuracy now attainable with the current laser interferometer is several orders of magnitude higher than the accuracy normally required of most machine tools. A measuring system with less beam alignment sensitivity while maintaining a one ten thousandth inch accuracy would have greater acceptance. Decreasing the beam alignment sensitivity is most important for improving the system. To accomplish this, consideration should be given to larger optical components and a larger beam diameter.

Offer some standard mounting and beam enclosure hardware as a production off-the-shelf item. This is particularly true of the enclosure for protecting the moving retroreflector which is used on all axes in the same manner. As it is now, each customer has to custom design and manufacture this enclosure. This requires specifying the type of flexible opening to use (type, thickness and durometer of material) that has to be tested and proven as a suitable design.

The reliability of the electronic components should be improved. Most facilities will not have qualified personnel to keep the system operating.

It is recommended that a second phase of this project be initiated for solving the above mentioned deficiencies and for investigating the suggested improvements.

Program results and comments of a more positive nature involve the HP 5526-A calibration system when used for linear calibration and measuring. This versatile, less expensive and less sensitive, system was used with ease and confidence on all axes on various machines (mobile unit). In fact, it is not unrealistic to consider use of this system in lieu of the hard fit system for some applications. The percentage of machining requiring extreme accuracy is small, extreme accuracy in two axes is smaller and in three axes it is practically nil. The HP 5526-A system can be set-up in minutes as a temporary or semi-permanent substitute measuring scale for a particular machining operation.

APPENDIX I

FMC FINAL REPORT

LASER MEASURING SYSTEM FOR LARGE MACHINE TOOLS

by

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Contract N00197-79C-0095

ABSTRACT

This report outlines the requirements for surveying the accuracy of a large horizontal boring mill and retrofitting the machine with laser interferometer equipment supplied by Hewlett-Packard. The Northern Ordnance Division of FMC Corporation, Contractor, was tasked by Naval Ordnance Station (NOSL) to deliver a final report including charts, diagrams, or other suitable information for demonstrating the accomplishments of the Laser Interferometer System.

The conclusion reached in performing the contracted task is that the Laser Measuring System as supplied (HP 5501A LTS) is not considered feasible for use on large machine tools in an uncontrolled environment. Thermal changes acting on a large machine tool frame affect the sensitive beam alignment.

FOREWORD

This report is prepared under Contract N00197-79C-0095, Item A002 on DD Form 1423, and is delivered to NOSL by Northern Ordnance. The work was performed by the Manufacturing Engineering Department at Northern Ordnance.

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SECTION 1

INTRODUCTION

As the need for more precision machining of ordnance components increases, a need will also arise for more precise measuring systems. Current best measuring systems have resolutions up to .0001 inch (.0025mm). Although adequate for most applications, the need to control the environment and to periodically calibrate these measuring systems add cost factors and machining reliability constraints. Also, the inspection of very large parts, requiring high accuracy on certain features, dictates either long and tedious setups at the machine or moving the parts to a separate air conditioned inspection station. In the event that a rework condition is found, it is necessary to disrupt schedules and move the parts back to the work station.

Northern Ordnance has been using laser interferometers since 1970 to calibrate machine tools for linear positioning error. In fact, those same laser interferometers are used periodically as substitute scales on machines with malfunctioning readouts or when the need arises to hold close tolerances on large parts.

With this background, Northern Ordnance and NOSL initiated a Manufacturing Technology Project to investigate using laser interferometers on a more wide scale basis throughout each facility.

1.1 Objective

The primary objective of this project was to demonstrate the feasibility of using laser interferometry for surveying the accuracy and state of wear of a selected large machine and to use this baseline information to evaluate any improvements made by the addition of a Laser Measuring System to the machine.

1.2 Approach

As originally conceptualized, the project was intended for installation of the Laser Measuring System on a NC controlled machine in an uncontrolled environment, (i.e. non-airconditioned). The reason a NC machine was specified originally, was that the literature describing the Laser Measuring System mentioned the advantages of a closed loop feedback control system in which the laser interferometer readings could be input for the machine controller; i.e. thus achieving higher repeatibility, accuracy, and resolution on critical part dimensions by controlling the machine's tool point path through laser interferometer feedback control. The original title of the project was: "Using Laser Controls to Update Worn Machine Tools".

As quoted from the executive summary of the Manufacturing Technology Brief DNS 00658 dated 18 August 1978:

"This project would utilize laser interferometer to restore accurate machining capability to worn machine tools and enable the operator to compensate for machine wear as indicated".

After reviewing the literature on the Laser Interferometer a decision was made by both Northern Ordnance and NOSL that the machine selected should first be retrofitted with the laser interferometer system minus the closed loop feedback control. Therefore, Northern Ordnance selected a 1955 vintage, 6", Horizontal Boring Mill with motion axes as follows:

AXIS	DESCRIPTION	RANGE(STROKE)
X	Table	144"
Y	Head	72"
Z	Spindle	48"
W	Column	36"

It was decided that three axes would be retrofitted with the Laser Measuring System. The X-axis, or Table, the Y-axis, or Head, and the W-axis, or Column.

It was felt that retrofitting a machine of this size and configuration would give the most meaningful information in determining the advantages and disadvantages of laser interferometry when used as a measuring system in an uncontrolled environment. Additionally, if the laser measuring system worked, this would provide the most immediate payback. Then the machine could possibly be retrofitted with a NC Control and closed loop feedback system to further exploit the benefits of higher resolution repeatibility, and accuracy through feedback control of the laser interferometer's readings. The advantage of such an approach is that it gives an immediate indication of problems associated with machining in an uncontrolled environment while providing data that could be used in retrofitting other machines. The main disadvantage of such an approach is that production schedules had to be considered with both the survey and installation. The approach basically dealt with "real" world problems.

Ultimately, it was hoped that a system could be developed that compensated for errors in real time utilizing information gained in the project.

The areas of error compensation versus error avoidance are receiving a great deal of attention by both the National Bureau of Standards (NBS) and the Lawrence Livermore National Laboratory (LLNL) respectively. Their main objective: provide a means of machining large precision components to a few microinches. Although Northern Ordnance and NOSL do not currently have such a requirement, the work on laser interferometry directly impacts NBS'and LLCL's work.

Prior to explaining the specific requirements for using laser interferometry as both a calibration tool and measurement device, perhaps some background on the approaches used to detect and control errors during machining will aid the reader in understanding the scope of the problem.

Depicting error sources, during machining and under static conditions, by means of casual relationships can best be illustrated in the form of a diagram as shown in Figure 1.

Laser Interferometry is maninly used in conjunction with the machine geometry and control factors. Other techniques, possibly in conjunction with laser interferometry, must be used in analyzing the other catagories of error sources. Appendix A lists and gives some examples of the variables involved in analyzing machine accuracy. The following is a listing of the major categories of error sources associated with machining and/or measuring:

Major Categories of Error Sources

1. Machine Geometry - i.e. How well does the machine travel, track, and respond to control commands?

2. Thermal Effects - i.e. What are the effects of both ambient and internal temperature gradients on tool point positional accuracy?

3. Mechanical Deflections - i.e. What are the effects of machine and part vibration and loading on tool point accuracy?

4. Tool Wear - i.e. What are the effect of tool wear on tool point accuracy and part geometry and surface finish?

5. Human Factors - i.e. What are the effects of operator and/or maintenance errors during setup and/or calibration?

What is an error? For purposes of machining the following definition is given:

Actual response of a machine to a command issued according to the accepted protocol of that machine's operation and the response to that command anticipated by that protocol. This definition is intended to apply only to machine tools and measuring machines.

1.2.1 Error Avoidance

Error avoidance is the approach advocated by LLNL and defined as follows:

Error Avoidance - A means of error reduction in which the source of the error or its coupling mechanism is eliminated .

The input is the source of error or cause; the output is the error.

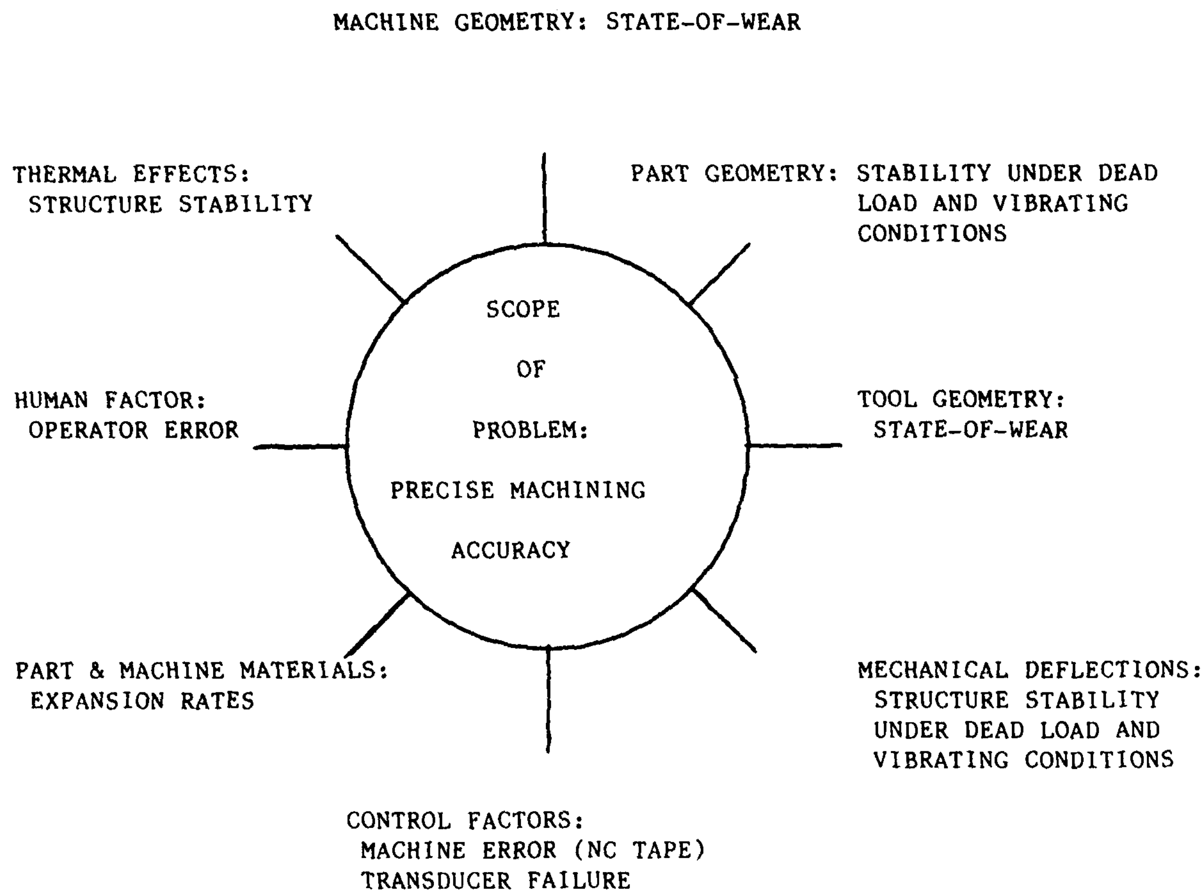


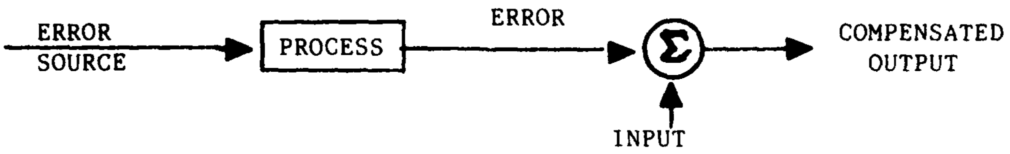
FIGURE 1 CATEGORIES OF ERROR SOURCES

Error avoidance attempts to eliminate the input or to alter the process to eliminate the error. For example, vibration is eliminated by isolating the foundation of a machine from its structure. LLNL used this technique in the design of their Large Optic Diamond Turning Machine.

1.2.2 Error Compensation

Error compensation is the approach advocated by NBS and defined as follows:

> Error Compensation - A means of error reduction whereby the effect of the error is cancelled .



Error compensation attempts to model the process and then measure or predict the input. From these two pieces of information, error compensation provides an additional input, possibly based on computer algorithms, that when summed with the uncompensated error provides a signal that controls the machine so as to eliminate the output error. For example, vibration is compensated for by sensing vibration through transducers and sending the signals back to the control unit of the machine so as to eliminate the output error by positioning the tool point at the correct coordinates.

NBS has initiated a project that utilizies error compensation techniques for many of the error sources shown in Figure 1. They have mapped out a mean work zone (MWZ), equal to a workpiece volume of 48in.x 24in.x10in. with cubic lattice spacing (test points) of 2 in., using laser interferometer calibration equipment and have loaded the data into a computer utilizing computer algorithms for compensations control of the machine's tool point. They have similarly added both thermal and strain transducers to model the machine's tool point path under machining conditions.

1.2.3 Error Reduction

The following definition outlines the strategies employed in the area of machine error reduction:

Error Reduction - The elimination or reduction of machine errors by any means .

Error Avoidance

- Eliminate the source of error
- Alter the process to minimize the effect of the source

Error Compensation

- Precalibrated error compensation

  Representation of the error map
  Hardware error compensation
  Software error compensation

  Type of master
  Preprocess gaging (external master)
  Post process gaging with feedback and intermittent-process gaging (workpiece master)

- Active error compensation

  Workpiece master
  External master ► In-process error compensation
  Sensors

Each of the error sources shown in Figure 1 contain several variables that must be defined, modeled, and controlled to achieve error reduction in measuring and/or machining in an uncontrolled environment. The degree of control is dependent on the economics and feasibility of using either error avoidance or error compensation techniques separately and/or together. The degree of accuracy required also plays a major role in determining error reduction requirements.

To achieve an understanding of error sources that occur during measuring or machining, a method or procedure must be devised that will analyze both static and dynamic error conditions. The laser interferometer provides a tool to use in this analysis.

1.3 Requirements

When first confronted with the task of surveying a machine for accuracy, the question that was raised concerned the degree of accuracy required for any particular machine. Northern Ordnance conducts periodic surveys and calibrations on several types of machines. On Navy owned equipment, DIPEC provides a "Test Pattern for Analytical Inspection of Metalworking Machinery", DD Form 1014, and "Interim Serviceable and Rebuilding Tolerances for Machine Tools, DSAM 4215.2, as specifications for aligning and calibrating machines.

1.3.1 Accuracy Survey

An accuracy survey, utilizing Hewlett-Packard's (H-P's) 5526A Laser Measurement System (LMS) was conducted on a Gray, 6", Horizontal Boring MIll, to determine the state of wear of the machine under static conditions. Figure 2 illustrates the geometric error sources on a 3-Axis machine. There are twenty-one individual error sources for each point to be calibrated on a machine. During the survey, only eighteen of these error sources were measured for only one point. (The mid-point of the MWZ). Roll error cannot be readily measured utilizing laser interferometry. Table 1 summarizes the results of the survey when compared to specifications outlined in PEC 3411-14. As evident from Table 1, PEC 3411-14 is somewhat limited in specifying the degree of performance of a complete calibration on a machine. (Normally, these specifications are supplied by the machine builder or customer, based on accuracy requirements.)

As mentioned earlier, several error sources contribute to inaccuracy of the Tool Point Path (TPP). During the survey of the 6" Gray, only machine geometry was considered when performing the calibration. The data from Table 1 was used to ascertain whether or not the machine geometry would prevent the installation of a "Hard-fit" laser measuring system. Based on the specifications supplied by Hewlett-Packard on their 5501A Laser Transducer System (LTS) the static machine tool geometry would have no effect on the alignment and performance of the "Hard-fit" system. In other words, the beam overlap at the receiver would maintain sufficient intensity over the full range of travel on all three axes. Sign convention (+ and -) was very important during calibration.

1.3.2 Pre-Installation Test

Prior to installation of the 5501A LTS, a mockup of a three axis system was constructed, using aluminum slides (for the retroreflectors) and wooden blocks (for mounting and aligning other optics), and a program was written for a 3-axis configuration. (This work was performed in an air conditioned room). Troubleshooting was accomplished on all electronic and computer components of the system (Figure 3).

1.3.3 Trial Installation

Upon completing pre-installation testing a trial installation was performed on one axis of the machine. (X-axis or Table). As shown in Figures 4 through 5. The installation was performed in a production environment. During loading and unloading of parts the laser readout changed in tens of microinches indicating that the table did slightly deflect under deadload. Also sharp blows with a leaded hammer to the table caused loss of signal. During machining of holes (boring and drilling) the reading on the display remained constant. Overhead cranes passing by caused the readings to grow and flicker. During rough milling operations the cutter produced vibrations severe enough to cause loss of signal. (Loosening of bolts on the mounting bracket caused misalignment). Adding dampening materials (rubber washers) has little effect on reducing misalignment.

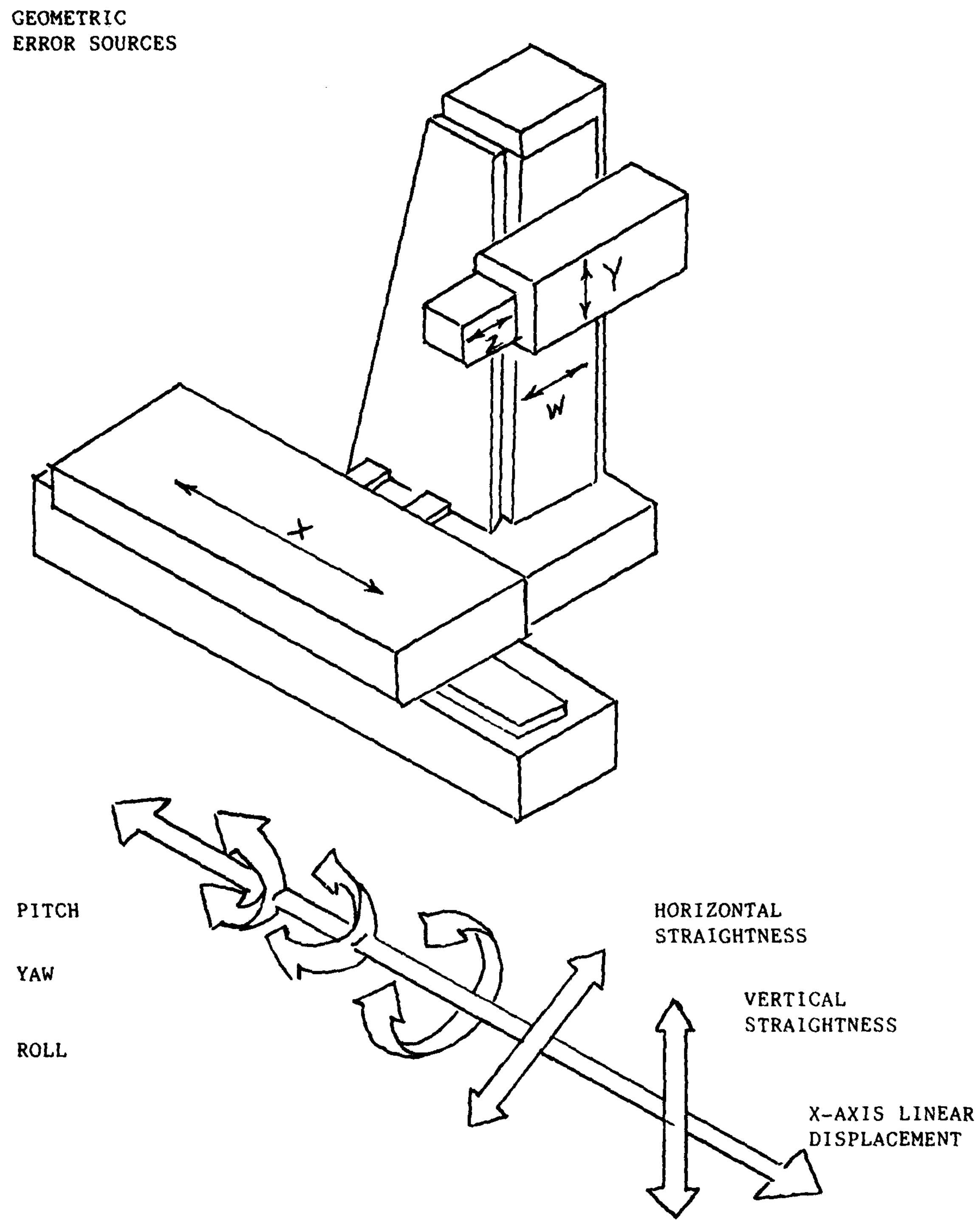


FIGURE 2 SIX DEGREES OF FREEDOM

TABLE 1. ACCURACY SURVEY RESULTS

ERROR NOTATION	DESCRIPTION	AXIS	[illegible] MAX. ERROR	PER. [illegible] SPECIFICATION SERVICEABLE	PER. [illegible] SPECIFICATION REBUILD	COMMENTS
X'	LINEAR POSITIONING ERROR - X	X	.0024"	N/A	N/A	DEPENDS ON IN-HOUSE QA REQMTS.
Y'	" " "	Y	.0032"	"	"	
W' OR Z'	" " "	W OR Z	−.0011" / .0009"	"	"	
X"	HORIZONTAL STRAIGHTNESS	W OR Z	±140MIC"	.0011"/FT.	.0006"/FT.	
Y"	VERTICAL "	X	+200MIC" / −445MIC"	N/A	N/A	
W" OR Z"	HORIZONTAL "	X	+100MIC" / −150MIC"	.0013"/FT.	.0007"/FT.	
X‴	VERTICAL "	Y	+335MIC" / −270MIC"	N/A	N/A	
Y‴	" "	W OR Z	+250MIC" / −130MIC"	"	"	
W‴ OR Z‴	HORIZONTAL "	Y	+335MIC" / −250MIC"	"	"	
ϵ_x	YAW ERROR	X	−4 ARCSEC	.0011"/FT.	.0006"/FT.	
ϵ_y	" "	Y	−7 ARCSEC	N/A	N/A	
ϵ_w OR ϵ_z	" "	W OR Z	−1 ARCSEC	"	"	
γ_x	PITCH ERROR	X	−3 ARCSEC	.0011"/FT.	.0006"/FT.	
γ_y	" "	Y	−6 ARCSEC	N/A	N/A	
γ_w OR γ_z	" "	W OR Z	−7 ARCSEC / −36 ARCSEC	"		
α_x	OUT-OF-SQUARENESS	X & Y	−.01 ARCSEC	"	"	
α_y	" " "	Y & Z	+2.7 ARCSEC	"	"	
α_w OR α_z	" " "	Z & X	+1.6 ARCSEC	"	"	
θ_x	ROLL ERROR	X	—	"	"	TEST MUST BE PERFORMED WITH OTHER EQUIPMENT
θ_y	" "	Y	—	"	"	
θ_w OR θ_z	" "	W OR Z	—	"	"	

TABLE 1 ACCURACY SURVEY RESULTS

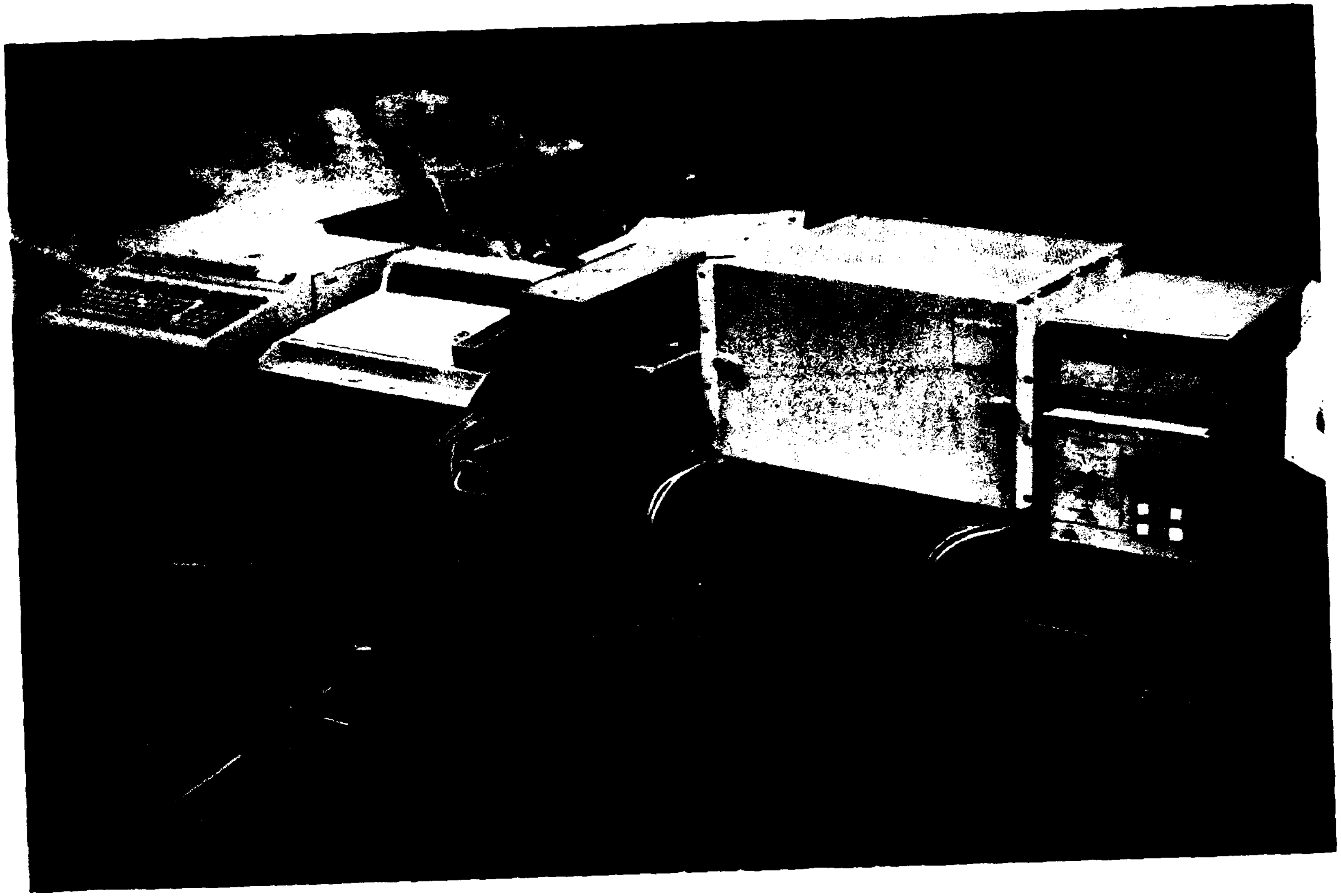


FIGURE 3 HP 5501A ELECTRONICS

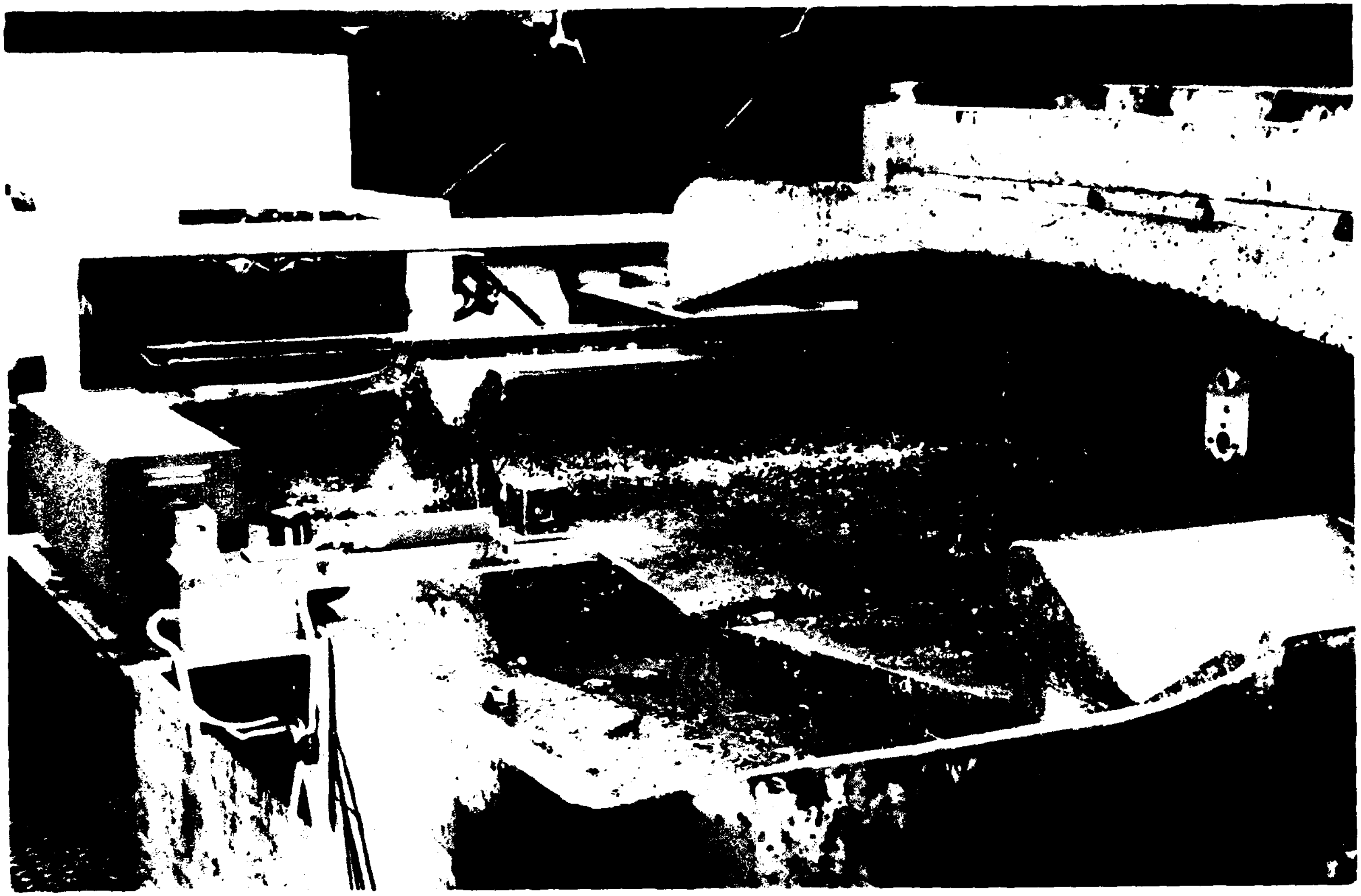


FIGURE 4 X-AXIS TRIAL INSTALLATION

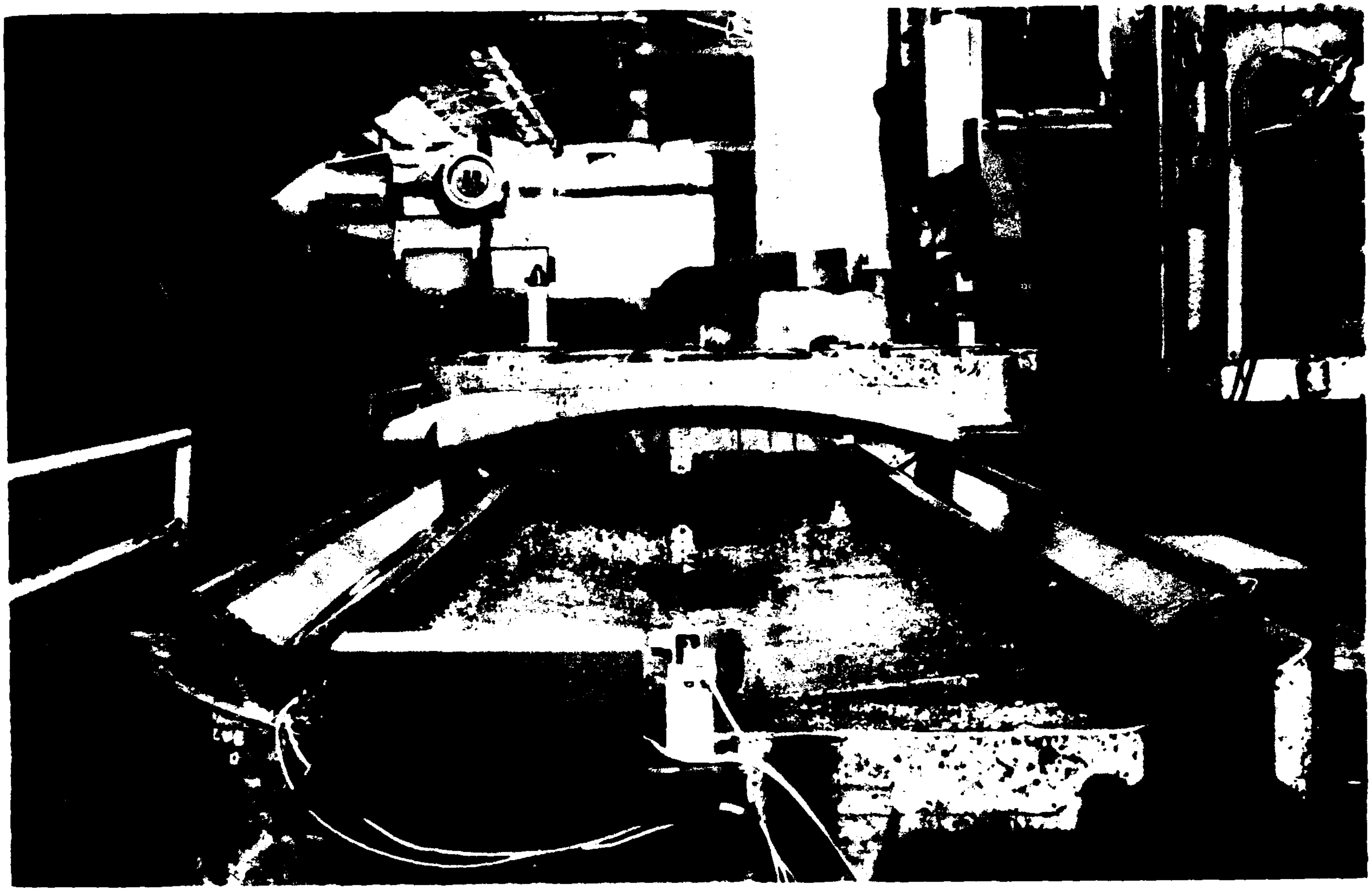


FIGURE 5 X-AXIS TRIAL INSTALLATION

When the laser transducer was mounted independent of the machine, signal was maintained consistently for a period of two weeks. During that time, A.017" positioning error was detected while trying to locate a $^{+.001"}_{-.000}$ bore. After investigating the problem, Maintenance personnel found that the Parametric transducer rack had loosened. During this same period of time, Machine Shop personnel used the laser readout to locate ±.001" holes on a large fixture successfully.

1.3.4 Mounting Design

The design of mounting brackets for the "Hardfit" LTS was performed by the tool engineering department at Northern Ordnance. Based on strong recommendations from Hewlett-Packard, they elected to mount the laser transducer and all optics directly onto the machine, although evidence from the trial installation indicated that vibration and thermal effects would cause misalignment problems. Figures 6 through 9 show some of the typical mounting and support brackets designed with beam protection in mind. A schematic is shown in Appendix B.

1.3.5 Beam & Optics Protection

Hewlett-Packard recommended optics protection but did not or could not specify the type of protection to use. Commercially available way covers were thought insufficient, and therefore the Tool Engineering Department designed custom beam and optics protection to fit the particular machine. Figure 9 shows the type of protection designed. Care had to be taken while machining the components to prevent collapse of the slot. Also, hole locations were critical since there were no reference datums (machined surfaces) to work off on the machine.

1.3.6 Installation

Upon completing trial assembly and rework of components for mounting the "Hardfit" laser transducer system (LTS), installation of the system began. Care was taken to plan the installation around production schedules to avoid delays. During installation, many of the components had to be reworked due to design errors caused by the lack of datum references. The finished installation is shown in Figures 10 through 12.

1.3.7 Alignment

Once all optics were in place, alignment of the system proceeded in a straightforward fashion. Each axis was aligned separately. The W-axis was aligned, the Y-axis was aligned by only slight movements of the final beam bender. The X-axis was aligned last by slight movement of the source and final beam bender.

Alignment was maintained on all three axes until thermal gradients caused misalignment of the source. To realign the system only the source was adjusted. This continues to be the problem. The system was checked out according to the HP5501A Operating Manual.

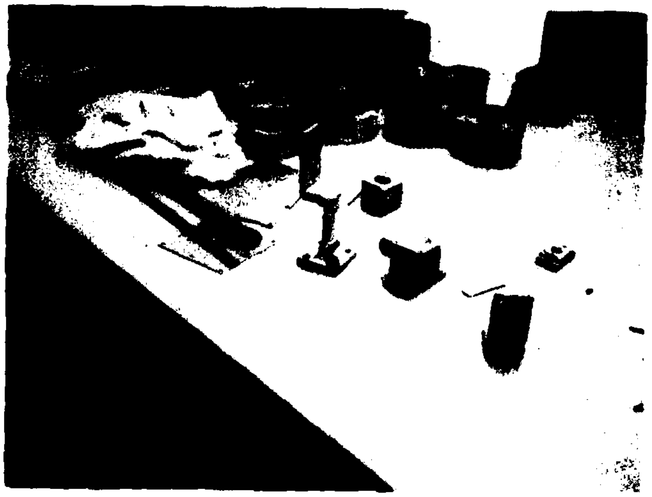


FIGURE 6 W & Y AXIS MOUNT

FIGURE 7 X AXIS RETROREFLECTOR MOUNT

FIGURE 8 LASER TRANSDUCER MOUNT

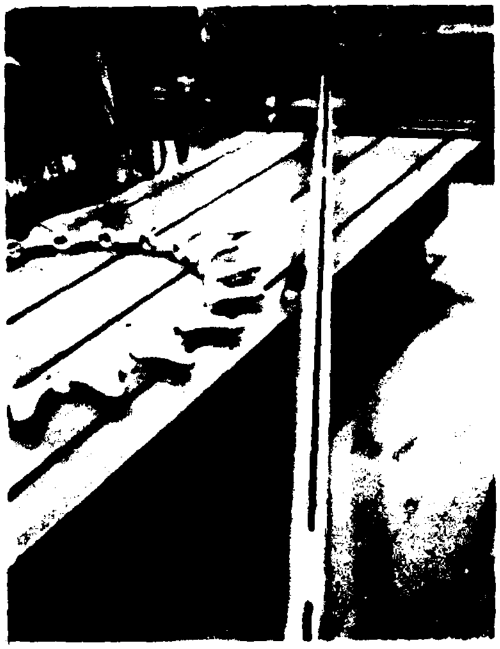


FIGURE 9 BEAM & OPTICS PROTECTION

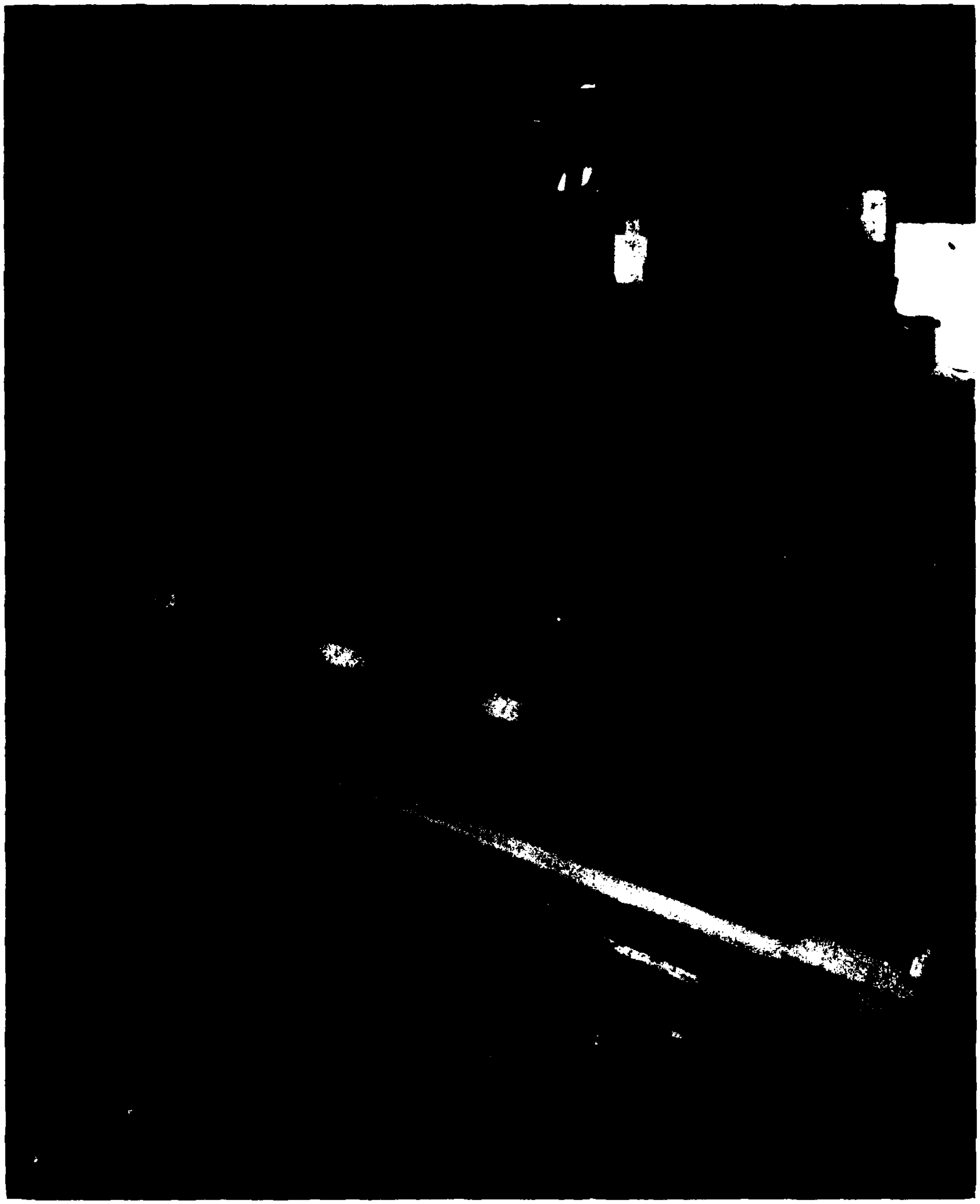


FIGURE 10 X-AXIS INSTALLATION

FIGURE 11 Y-AXIS INSTALLATION

FIGURE 12 W-AXIS INSTALLATION

1.3.8 Programming

Several programs were written for the operation of the LTS. Single axis programs were written for each axis and a three axis program, shown in Figure 13, was written so that the operator could start a machining operation at a given dimension and machine to some other dimension on the print. Also, the compensation data was made available on the minicomputer display so that Quality Assurance could verify that the automatic compensator was calibrated and giving the correct compensation values. Corrections for cosine error, deadpath error, and abbe' offset error could also be programmed into the computer.

Other programming features of the HP 9825A calculator include calibration and plotter routines for use with the laser interferometer calibration equipment HP 5526A. The operator can also use the keyboard, while the program is running, to do calculations. It is envisioned that the minicomputer could also be used as an aid during inspection of a part on the machine utilizing the "Hardfit" LTS and plotter to map out dimensions and bore locations in a 3-D plot. Measuring bore size is beyond the present capabilities of this laser measurement system, but technology does exist that could interface this data with the data from the LTS.

1.3.9 Calibration Check

A calibration check was performed on the machine comparing the reading from the "Hardfit" HP 5501A LTS and the readings from the HP 5526A LMS. Tables 2 through 4 show the results of the comparison check. Discrepancies between the two sets of readings can be attributed to the following factors:

1. Cosine error either in the setup of the 5526 LMS or in the alignment of the 5501 LTS.

2. Abbe' offset error.

3. Pitch error.

4. Yaw error.

5. Deadpath error.

Each of these error conditions could be compensated for in the software program of the 3-axis configuration by writing in equations that add or subtract the appropriate amount of error correction to the display reading. However, first a determination must be made on which system is exhibiting the error condition. If the HP 5501A is determined to contain the error correction, then a software change is necessary. If the HP 5526A contains the error condition, then no software change is necessary

1.3.10 Maintenance & Operation

Maintenance and Operation requirements for the HP 5501A LTS are outlined in the HP 5501A Operating Manual. The manual also includes

```
0: clr 7;rem 7
1: ent "WHAT IS
 X-REF?",Q;fmt
 1,f12.6
2: ent "WHAT IS
 Y-REF?",S;fmt
 1,f12.6
3: ent "WHAT IS
 Z-REF?",T;fmt
 1,f12.6
4: wrt 709,"006X
 "
5: wrt 709,"6Y"
6: wrt 709,"6Z"
7: wrt 709,"2Y30
 "
8: red 709,C
9: fxd 10;dsp C
10: 0→E
11: "loop":E+
 1→E;if E=10;
 gto -4
12: wrt 709,"102
 X30"
13: red 709,X
14: if rds(7)<12
 8;gto +2
15: 0→A;gsb "sta
 tus"
16: (X-16)*6.230
 23e-6*C+Q→X
17: fmt 1,f12.6
18: wrt 717.1,X
19: wrt 709,"2Y3
 0"
20: red 709,Y
21: if rds(7)<12
 8;gto +2
22: 1→A;gsb "sta
 tus"
23: (Y-16)*6.230
 23e-6*C+S→Y
24: wrt 718.1,Y
25: wrt 709,"2Z3
 0"
26: red 709,Z
27: if rds(7)<12
 8;gto +2
28: 2→A;gsb "sta
 tus"
29: (Z-16)*6.230
 23e-6*C+T→Z
30: wrt 719.1,Z
31: gto "loop"
32: "status":rds
 (709)→B
33: if B>=64;
 gsb "check"
34: wrt 709,"0P"
35: ret
36: "check":B-
 112→B
37: if B>=8;gsb
 "ovf"
38: if B>=4;prt
 "VOL OUT OF
 RANGE";B-4→B;
 0→D
39: if B>=2;prt
 "MEAS ERROR";B-
 2→B;0→D
40: if B=1;prt
 "REF ERROR";0→D
41: if D=1;ret
42: if A=0;prt
 "X-AXIS ERROR"
43: if A=1;prt
 "Y-AXIS ERROR"
44: if A=2;prt
 "Z-AXIS ERROR"
45: dsp "GO TO
 GAGE";stp
46: gto 0
47: "ovf":B-8→B;
 1→D
48: if A=0;X-
 2↑28/10→X
49: if A=1;Y-
 2↑28/10→Y
50: if A=2;Z-
 2↑28/10→Z
51: ret
52: end
*20313
```

FIGURE 13 3 AXIS LTS PROGRAM

FMC Northern Ordnance Division Minneapolis

MACHINE DIGITAL READOUT CALIBRATION CHART

Machine Type GRAY　　Number USN - 005151 #2

Readout Type HEWLETT - PACKARD　　Axis X - TABLE

Inspected By E. ANDERSON　　Date 10 / 08 / 81

Laser Comparative Readings

HP 5526A Calibration Laser		HP 5501A "Hardfit" Laser		Discrepancies in the two Laser Readouts	
W/E	E/W	W/E	E/W	W/E	E/W
10.0096	10.0220	10.0096	10.0220	.0000	.0000
20.1991	20.1206	20.1990	20.1205	-.0001	.0000
30.0142	30.0522	30.0140	30.0521	-.0002	-.0001
40.0449	40.0715	40.0446	40.0714	-.0003	-.0001
50.1202	50.1334	50.1198	50.1334	-.0004	.0000
60.0260	60.1108	60.0255	60.1108	-.0005	.0000
70.4162	70.0119	70.4156	70.0119	-.0006	.0000
80.0380	80.0185	80.0374	80.0184	-.0006	-.0001
90.0258	90.0464	90.0253	90.0462	-.0005	-.0002
100.1721	100.1356	100.1716	100.1355	-.0005	-.0003
110.1624	110.0454	110.1618	110.0449	-.0006	-.0005
120.1997	120.1439	120.1992	120.1433	-.0005	-.0006
130.0813	130.1931	130.0807	130.1924	-.0006	-.0007
140.1791	140.1666	140.1785	140.1658	-.0006	-.0008

NOTE: OUTSIDE LASER READOUT COMPARED WITH COMPUTOR ATTATCHED LASER HEWLETT - PACKARD # 91192 - 005151.

TABLE 2　　X AXIS CALIBRATION CHECK

FMC Northern Ordnance Division Minneapolis

MACHINE DIGITAL READOUT CALIBRATION CHART

Machine Type GRAY Number USN - 005151 #2

Readout Type HEWLETT - PACKARD Axis Y - HEAD

Inspected By J. NEVALA Date 10 / 09 / 81

Laser Comparative Readings

HP 5526A Calibration Laser		HP 5501A "Hardfit" Laser		Discrepancies in the two Laser Readouts	
UP	DOWN	UP	DOWN	UP	DOWN
5.1447	5.0387	5.1455	5.0386	+.0008	-.0001
10.0478	10.1041	10.0491	10.1037	+.0013	-.0004
15.2705	15.0427	15.2720	15.0421	+.0015	-.0006
20.0159	20.0276	20.0177	20.0268	+.0016	-.0008
25.1007	25.0773	25.1029	25.0763	+.0018	-.0010
30.2385	30.5601	30.2410	30.5591	+.0025	-.0010
35.1875	35.2753	35.1900	35.2742	+.0025	-.0011
40.0988	40.0243	40.1013	40.0233	+.0025	-.0010
45.2179	45.0296	45.2203	45.0290	+.0024	-.0006
50.0127	50.0207	50.0149	50.0203	+.0022	-.0004
55.1545	55.1166	55.1568	55.1166	+.0013	.0000
60.0397	60.0194	60.0419	60.0191	+.0022	-.0003
65.3549	65.0733	65.3570	65.0742	+.0021	+.0012
70.1869	70.1557	70.1888	70.1581	+.0019	+.0024

NOTE: OUTSIDE LASER READOUT COMPARED WITH COMPUTOR ATTATCHED LASER HEWLETT - PACKARD # 91192 - 005151.

TABLE 3 Y AXIS CALIBRATION CHECK

FMC Northern Ordnance Division Minneapolis

MACHINE DIGITAL READOUT CALIBRATION CHART

Machine Type GRAY Number USN - 005151 #2

Readout Type HEWLETT - PACKARD Axis Z - SPINDLE or W-Column

Inspected By E. ANDERSON Date 10 / 09 / 81

Laser Comparative Readings

HP 5526A Calibration Laser		HP 5501A "Hardfit" Laser		Discrepancies in the two Laser Readouts	
2.0215	2.0354	2.0216	2.0356	+.0001	+.0002
4.1359	4.0110	4.1363	4.0113	+.0004	+.0003
6.0884	6.0112	6.0890	6.0118	+.0006	+.0006
8.0884	8.0834	8.0892	8.0842	+.0008	+.0008
10.0304	10.0761	10.0314	10.0771	+.0010	+.0010
12.0007	12.0304	12.0020	12.0316	+.0013	+.0012
14.0276	14.0310	14.0291	14.0324	+.0015	+.0014
16.0863	16.3801	16.0880	16.3816	+.0017	+.0015
18.0113	18.1092	18.0132	18.1109	+.0019	+.0017
20.0077	20.0372	20.0097	20.0392	+.0020	+.0020
22.0269	22.0291	22.0291	22.0313	+.0022	+.0022
24.0166	24.0500	24.0190	24.0524	+.0024	+.0024
26.0011	26.0523	26.0037	26.0549	+.0026	+.0026
28.0200	28.4928	28.0227	28.4956	+.0027	+.0028
30.1276	30.0934	30.1304	30.0964	+.0028	+.0030
32.0594	32.1371	32.0624	32.1403	+.0030	+.0032
34.0023	34.1003	34.0055	34.1037	+.0032	+.0034
S/N	N/S	S/N	N/S	S/N	N/S

NOTE: OUTSIDE LASER READOUT COMPARED WITH COMPUTER ATTACHED LASER HEWLETT-PACKARD # 91192 - 005151.

TABLE 4 Z OR W AXIS CALIBRATION CHECK

sections on general description of how laser interoferometry works, a description of the laser transducer and optics, system electronics, programming, installation and checkout, and troubleshooting.

General diagnostic routines are also contained in software provided with the HP 9825A programmable controller (minicomputer). The HP 9825A is also equipped with builtin test equipment that can diagnose problems down to the chip level. Separate instruction manuals are also provided with all of the components of the HP 5501A LTS.

Daily and preventative maintenance requirements are spelled out in the operating and service manual as well as in the individual instruction manuals.

Northern Ordnance's experience, with the HP 5501A LTS and Hewlett-Packard, was that most of the maintenance expertise had to be supplied in-house. The major problem that currently exists with the system is in the area of alignment reliability.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions to be reached concerning the feasibility of using laser interferometry on large machine tools are:

1. The Laser Measuring System as supplied, (HP 5501A LTS), is not considered feasible for use on large machine tools in an uncontrolled environment. However, substantial cost savings could be provided on future weapon systems if a means to stabilize the system is explored and refined.

2. Avoidance of scrap, rework and repair can be attained through the use of laser interferometry.

3. Additional cost avoidance can be obtained, through the use of laser interferometry, by reducing the amount of material handling, energy costs, and costs associated with production delays when inspecting or machining parts in controlled, remote environments. Also, a "Hardfit" laser measuring system could eliminate the need for periodic linear calibration.

4. The use of the HP 5526A LMS can be a great asset to defining and characterizing machine geometry and tool point path accuracy.

Recommendations

1. Utilize information gathered during this phase of the project together with information from the National Bureau of Standards and Lawrence Livermore National Laboratory to initiate a second phase of the project that will help to analyze, define, model, and control error sources during machining in an uncontrolled environment. (Appendix A lists the variables to be analyzed and Appendix C lists factors that should be defined for attaining maximum real time machining).

2. Examine for feasibility of using fiber optics, iodine-stablized or infrared laser sources, helium-neon laser sources that can be made self-aligning through the use of servo-feed-back staging devices, or isolation of optics and laser sources, for cost effective implementation of laser interferometry.

3. Investigate the use of "off the shelf" staging devices that could simplify the task of calibration with the HP 5526A LMS.

APPENDIX A

VARIABLES IN ANALYZING MACHINE ACCURACY

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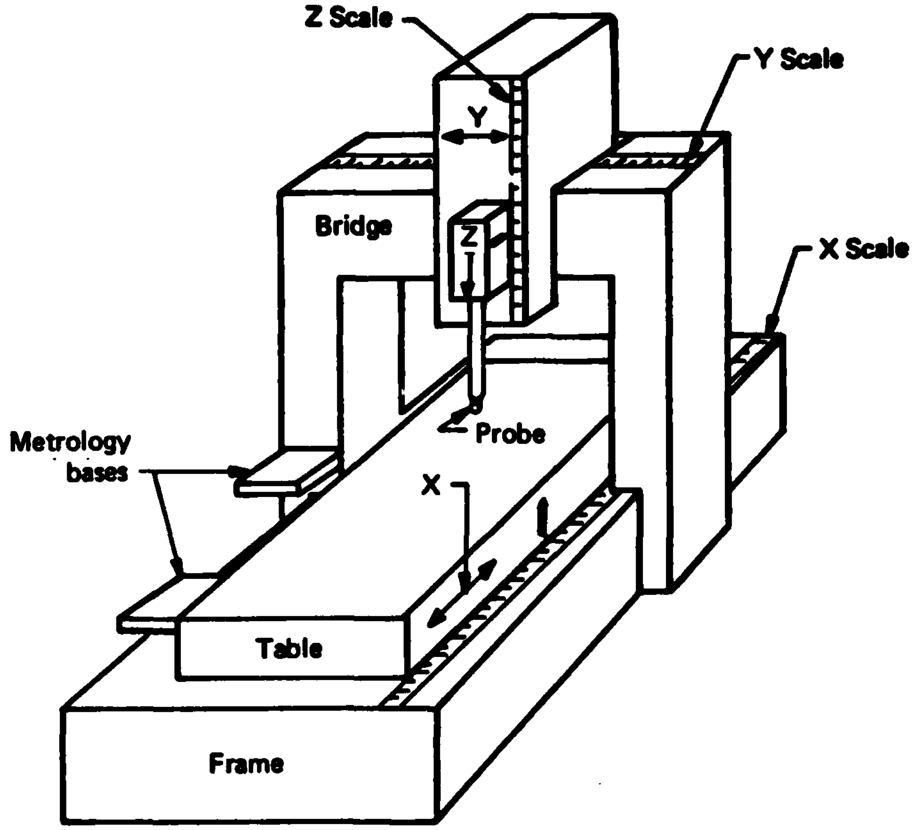
VARIABLES IN ANALYZING MACHINE ACCURACY

1. Mean Work Zone (MWZ) - The volume of work space taken up by the average part on any particular machine.

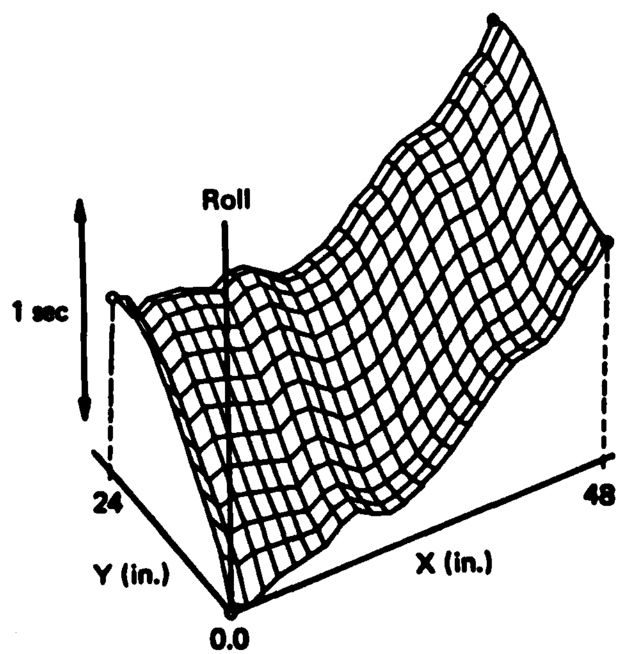
2. Mean Work Load (MWL) - The average dead load (defined either as a point load or continuous load) of parts run on any particular machine.

3. Mean Operating Temperature (MOT) - The average temperature difference between the machine and workpiece during normal operating conditions.

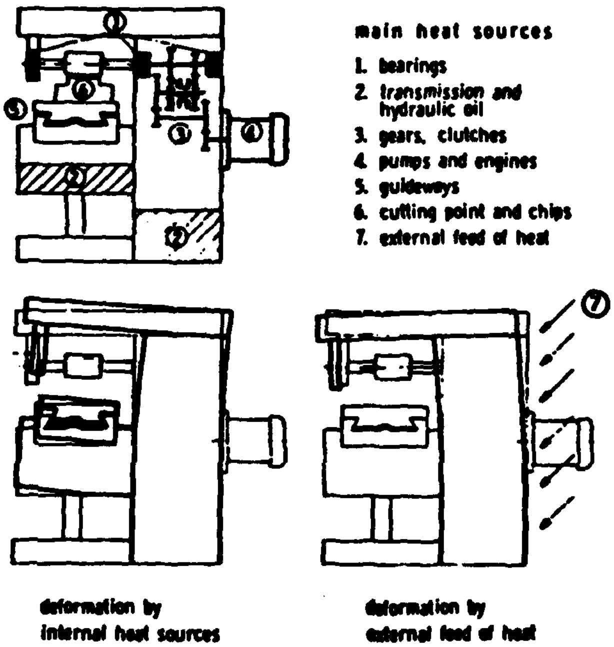
4. Mean Vibration Level (MVL) - The average vibration level of the tool point to workpiece under normal operating conditions.



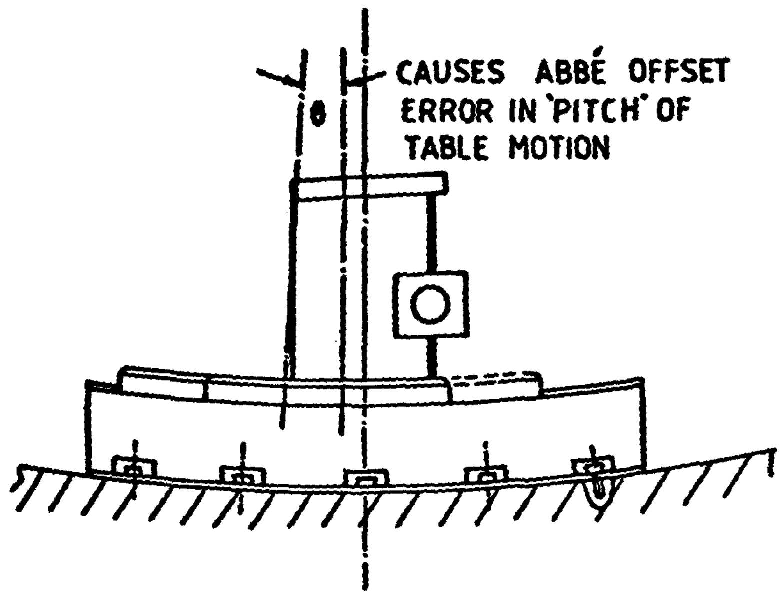
Schematic of bridge-type measuring machine.



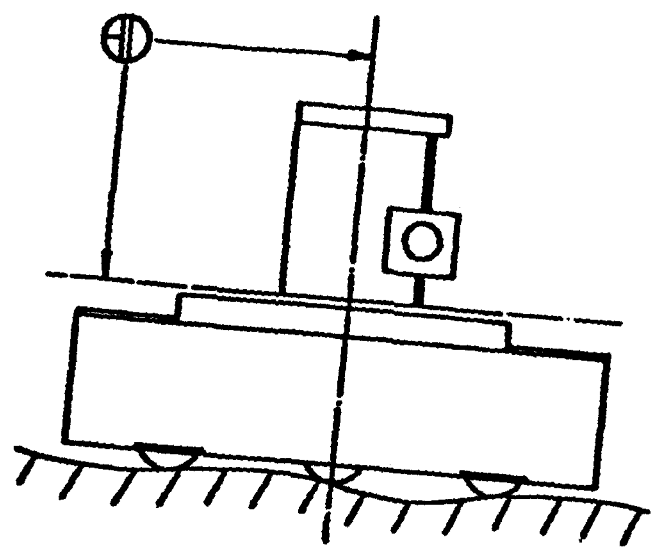
Roll of the table on the machine shown affects the X table position and the Y Cross carriage position. Coupling (the motion of one machine element influencing the motion of another) is clearly present.



Example of deformation arising from thermal conditions in a milling machine.



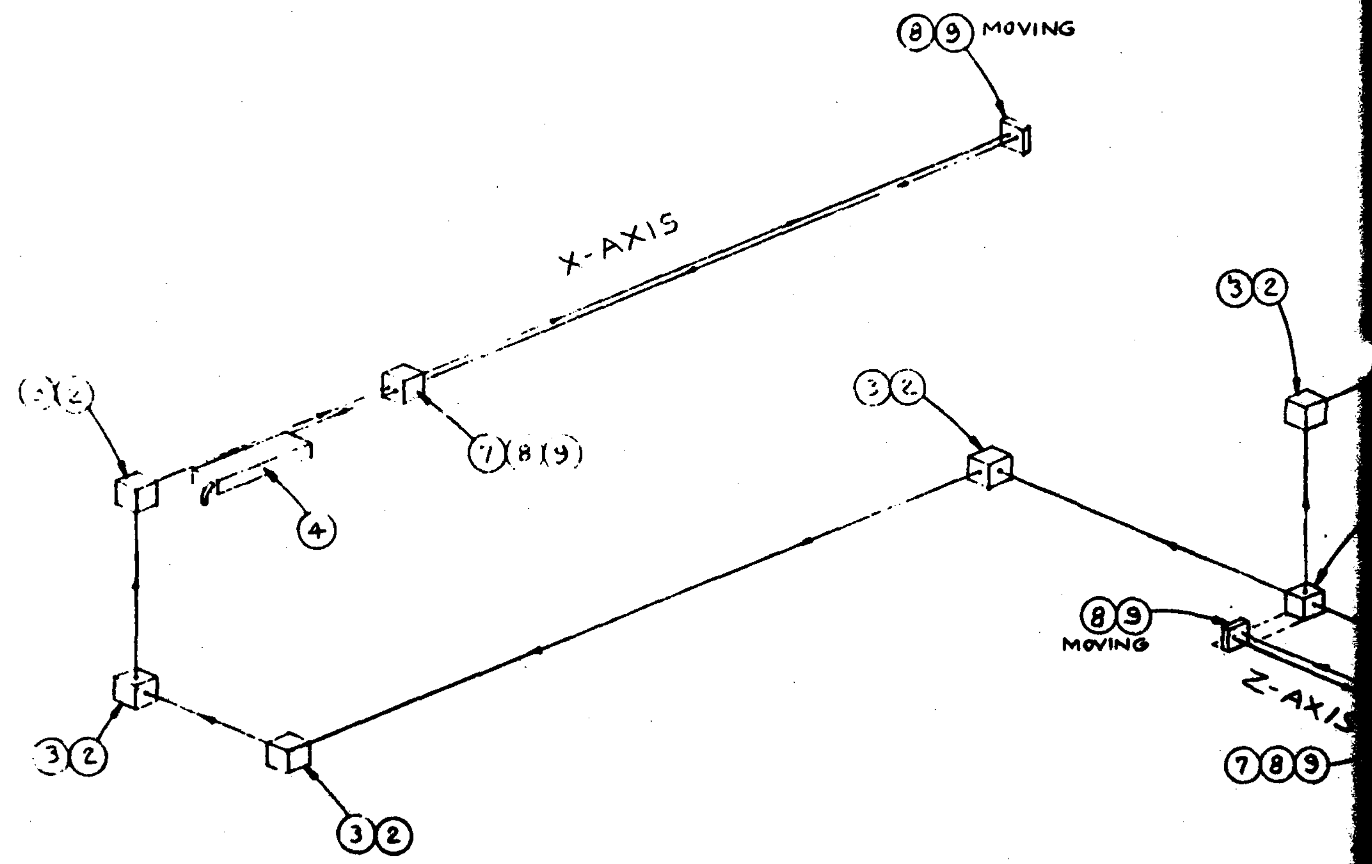
Multipoint support: foundation movement causes distortion of the machine structure.

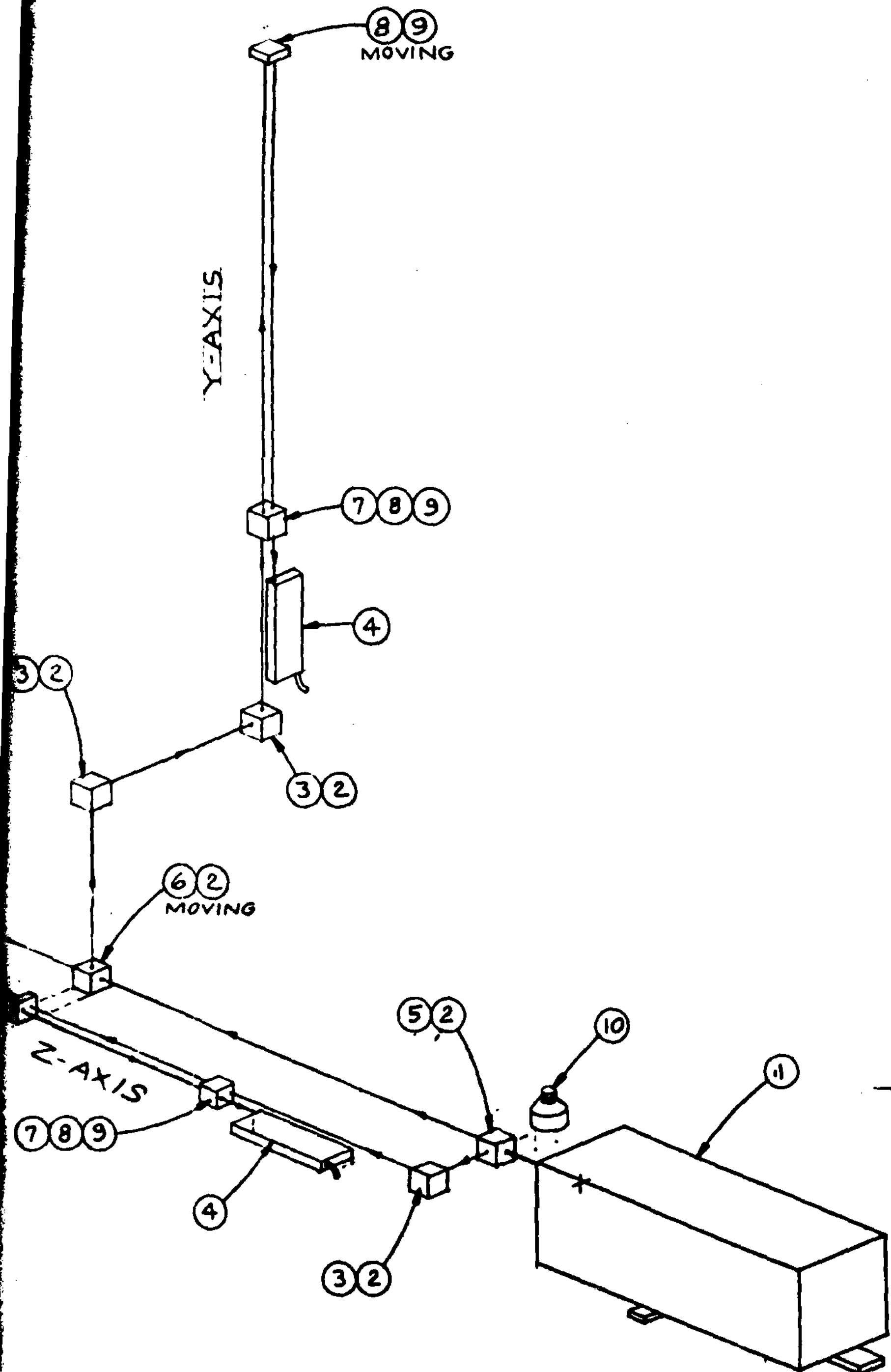


Three-point support: foundation movement does not distort the machine structure.

APPENDIX B

SCHEMATIC OF A LASER MEASURING SYSTEM
FOR A LARGE MACHINE TOOL





NOTE:
SCREWS AND WASHERS FOR MOUNTING OPTICAL EQUIPMENT ARE SUPPLIED BY HEWLETT PACKARD

CONTINUED ON SHEET 14

ITEM NO	QTY REQD	DESCRIPTION
10	1	SENSOR
9	6	ADJUSTABLE MOUNT, HP# 10711A
8	6	RETROREFLECTOR, HP# 10703 A
7	3	LINEAR INTERFEROMETER, HP# 10702A
6	1	50% BEAM SPLITTER, HP# 10701A
5	1	33% BEAM SPLITTER, HP# 10700A
4	3	RECEIVER, HP# 10780A
3	7	BEAM BENDER, HP# 10707A
2	9	ADJUSTABLE MOUNT, HP# 10710A
1	1	LASER TRANSDUCER, HP# 5501A

LIST OF MATERIALS OR PARTS LIST

CONTRACT NO. N00197-79-0095
KEN THIESEN 11-7-80
TOOL ENG

FMC Corporation
Northern Ordnance Division
Minneapolis Minnesota

SCHEMATIC DIAGRAM
LASER MEASURING SYST
FOR HORIZ. BORING MACH

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D 53711 USN-00515

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FACILITY 2

LTR	REV BY	DATE	USE WITH	PRODUCT
REVISIONS			APPLICATION	

1

NOTE: IF NECESSARY FOR HANDLING, TOOLMAKER MUST PROVIDE TAPPED HOLES IN PROPER LOCATION

APPENDIX C

AN APPROACH TO REAL-TIME ACCURATE AND PRECISE
MACHINING IN AN UNCONTROLLED ENVIROMENT

RECOMMENDED APPROACH TO REAL-TIME MACHINING:

1. Define degree of accuracy and precision required on DOD Weapon Systems (future).

2. Define variables to be considered in machining accurately and precisely in an uncontrolled environment.

3. Define equipment necessary to analyze, model, and control these variables.

4. Design, procure, and fabricate equipment.

5. Implement precision machining techniques by demonstrating capabilities on a large machine tool in an uncontrolled environment.

If it is found that the degree of accuracy and precision required for machining and measuring *future DOD weapon systems* is indeed high and a production line capability is deemed necessary, then this approach is advocated.

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4. Hewlett-Packard Operating and Service Manual For 5501A Laser Transducer System, Hewlett-Packard, 1501 Page MIll Road, Palo Alto, CA 94304.

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Interferometer
Measuring System
Calibration
Large Machine Tools

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The demand on machine tools today for higher productivity and accuracy requires the latest in technology for tool positioning and calibration. To meet this demand, modern day machine tools are built to more exact standards and are numerically controlled for accurate tool positioning. To remain competitive today in industrial machining requires large expenditures for new machine tools or the up-grading of existing tools.

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A large percentage of the Navy's machine tools were manufactured in the 1940's. The positioning system on these machines consist of lead screw graduated dials which are adequate when liberal tolerances are involved. To obtain a higher degree of accuracy, the time consuming use of pin gages, gage blocks, and dial indicators must be used or the machines have to be retrofitted with some type of modern measuring system.

With development of the Laser Interferometer, it was envisioned that older existing machine tools could be up-graded by retrofitting them with Laser Interferometer Measuring Systems. The Laser Interferometer provides the machine tool industry with a high accuracy length standard. The accuracy of the Interferometer is determined by the laser wave length which is known within 0.5 parts per million. This degree of accuracy is more than adequate for most machine tool measuring calibration and inspection requirements.

In conclusion, the Laser Measuring System presently available is not recommended for general implementation at this time. Results of this work indicate that the equipment and installation cost are very high and pay back would be very slow. Also, the reliability of the electronic components is in need of improvement. The system requires frequent realignment and maintenance due to it's lack of toleration to "Shop Floor" conditions.

This conclusion is made in view of the availability of electrical inductance measuring systems. These systems are more economical and with .001 inch accuracy would be satisfactory for a large percentage of machining requirements. However, where extreme accuracy (.000005 inch) is required, the Laser Interferometer System should be considered.

END

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