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RPI TECHNICAL REPORT MP-73

CONTROL ELECTRONICS FOR A MULTI-LASER/ MULTI-DETECTOR SCANNING SYSTEM

by

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ABSTRACT

The Mars Rover Laser Scanning system uses a precision laser pointing mechanism, a photo-detector array, and the concept of triangulation to perform 3 dimensional scene analysis. The system is used for real time terrain sensing for the RPI Mars Roving Vehicle. Another application is in the area of robot vision.

This report describes the final implementation of the Multi-Laser/Multi-Detector (ML/MD) laser scanning system. The system is controlled by a digital device call the ML/MD controller. This device is now operational and meets or exceeds all of the original design specifications. Included are the controller capabilities, interface specifications, and operating instructions.

Also included in this report is a description of a next generation laser scanning system. This next generation system is based on the Level II controller, which is microprocessor based. The new controller capabilities will far exceed those of the ML/MD device, with fewer parts and lower power consumption. This increase in function and flexibility is due to the fact that many of the controller's tasks will be implemented in software. The first draft circuit details and the general software structure are presented.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to those people who have helped bring this project to fruition.

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Glossary of Abbreviations

AZC	Azimuth Count
CLAC	Closed Loop Axis Controller
CSA	Center of Scan, Azimuth
CSE	Center of Scan, Elevation
DMT	Direct Memory Transfer
EOA	End of Azimuth
EOS	End of Scan
EPROM	Erasable Programable Read Only Memory
FIFO	First-in First-Out Memory
I/O	Input/Output
IRCS	Independant Robotics Control System
L.E.D.	Light Emitting Diode
LSB	Least Significant Bit
ML/MD	Multi-Laser/Multi-Detector
MSB	Most Significant Bit
NA	Number of Azimuth Shots
NE	Number of Elevation Shots
PIA	Peripheral Interface Adapter
RAM	Random Access Memory

PART 1

INTRODUCTION AND HISTORICAL REVIEW

The RPI Mars Rover Project was begun in 1968 under a NASA grant. The project goal was to develop concepts for an autonomous roving vehicle which would be capable of unmanned exploration of the Martian surface. The initial work centered around the mechanical design and construction of a radio-controlled roving vehicle. This vehicle was equipped with a two-way radio link which transmitted steering and propulsion commands to the vehicle, and returned telemetry information to an off-board computer.

In 1974 the project goals were refined. The new goal was to produce a truly autonomous vehicle, one capable of obstacle detection and avoidance under closed loop computer control. The implementation of this concept required the development of a new visual sensing system. A substantial software development effort was also undertaken to provide real time scene analysis and vehicle control.

The original terrain sensing system was based on a laser triangulation scheme. A pulsed laser, mounted at the top of a vertical mast, pointed down toward the ground at an angle of about 45 degrees from the horizon. A photo diode detector with a 3-degree field of view was mounted .5 meters below the laser and pointed to the expected intersection of the laser beam and level ground. If the terrain was indeed level, the detector would "see" the laser spot and that path would be labeled clear. If the laser beam struck an obstacle of sufficient size (approximately 10" above or below level terrain), the laser spot would fall outside the detector's field of view causing that path to be labeled blocked. The original laser mast fired 15 laser shots per scan. The shots were contained within a 140-degree arc centered about the vehicle's heading. The path clear or path blocked information for each laser shot was transmitted via telemetry to the off-board computer for analysis. This system underwent testing on the vehicle through 1978. The Single Laser/Single Detector system was tested with various computer heuristic algorithms, and performed with varying degrees of success. The Single Laser/Single Detector system was severely limited by its single shot per azimuth capabilities, and by the simple go/no-go output of its detector. With data collected at only 15 different azimuths per scan the computer could not generate a very detailed terrain map.

During the Spring of 1977 planning was begun for a next generation sensing system. The new system was still based on the triangulation concept but would be capable of multiple elevation shots per azimuth. The new system would take up to 32 elevation shots for each of 32 azimuths, for a total of 1024 terrain points per scan. In addition, multiple detector elements would generate point elevation information for each laser shot. The new system was called the Multi-Laser/Multi-Detector (ML/MD) system.

The design and development work for the ML/MD system was done during the 1977/78 academic year coincident with the final testing of the old Single-Laser/Single-Detector system. The new scanning system is based on a laser mast which rotates continuously instead of oscillating from side to side. This continuous rotation provides greater speed and flexibility in scanning, but it does require slip rings to transmit power, ground, and data to and from the mast. Mounted on the mast is a 100-watt pulsed laser diode aimed at a rotating 8-sided mirror. The mirror deflects the laser beam towards the ground into the detector's field of view. Both the mast and mirror axes are monitored by precision optical shaft encoders which give a laser point accuracy of 1.4 degrees in azimuth and .35 degrees in elevation. The detector is also mounted on the mast; it is located about 1 meter below the mirror. It consists of a 20-element linear photo diode array with suitable lensing to provide a 30 degree field of view. The detector system can discern elevation differences of about 4 cm.

The construction, debugging and system integration of the ML/MD scanner was a slow process, requiring most of the 78/79 and 79/80 academic years. The progress was slowed by a massive hardware overhaul on the vehicle, and by the changeover to a PRIME computer for real time control. However, the resulting system is much more flexible and reliable than the original design.

The objective of this report is to describe the modifications to and implementation of the ML/MD controller electronics. The controller is that portion of the system which monitors mirror and mast position, and outputs control signals to the laser, detector and telemetry. The present controller meets or exceeds all of the original design specifications. This report also includes a description of a next generation scanning system. This new scanning system uses the same mechanical hardware but is driven by a new controller. The Level II controller is microprocessor based, and provides a much more flexible controller. This controller is designed to take full advantage of the greatly increased command link and telemetry capabilities, which were the result of the hardware overhaul.

The scanning system described above has many applications beyond simple terrain scanning. The final section of this report will describe possible applications of the ML/MD scanning system in scene analysis and robot vision. These applications are present with the current controller, and would be greatly expanded by the implementation of the Level II controller.

PART 2

MULTI-LASER/MULTI-DETECTOR CONTROLLER

The complete ML/MD scanning system is depicted in Figure 2. The control electronics for this system were originally designed by J. Craig during academic year 1977/78. For a description of the controller specifications and an in-depth explanation of the elevation scanning concept, see Reference 1.

This report is concerned with the modifications to the original mast design, which were performed to achieve an operational system. The major modification to the system was the addition of the Command Link Interface Board. The addition of an on-board microprocessor to the vehicle electronics has resulted in a greatly improved command link. The Command Link Interface Board provides an interface between the command link and data registers on the individual controller cards. This board is the primary source of increased flexibility from the original design.

2.1 Capabilities

2.1.1 Azimuth Angles. The basic azimuth capabilities have not changed from the original design. There are 256 available azimuth angles spaced 1.4 degrees apart. These 256 azimuth angles are linearly mapped into the address space of a 1024 word by 8 bit EPROM. The available angles repeat four times, allowing four different scan patterns to be stored (Figure 2.1). Each pattern may have up to 32 azimuth fire angles.

The desired azimuth fire angles are programmed into the

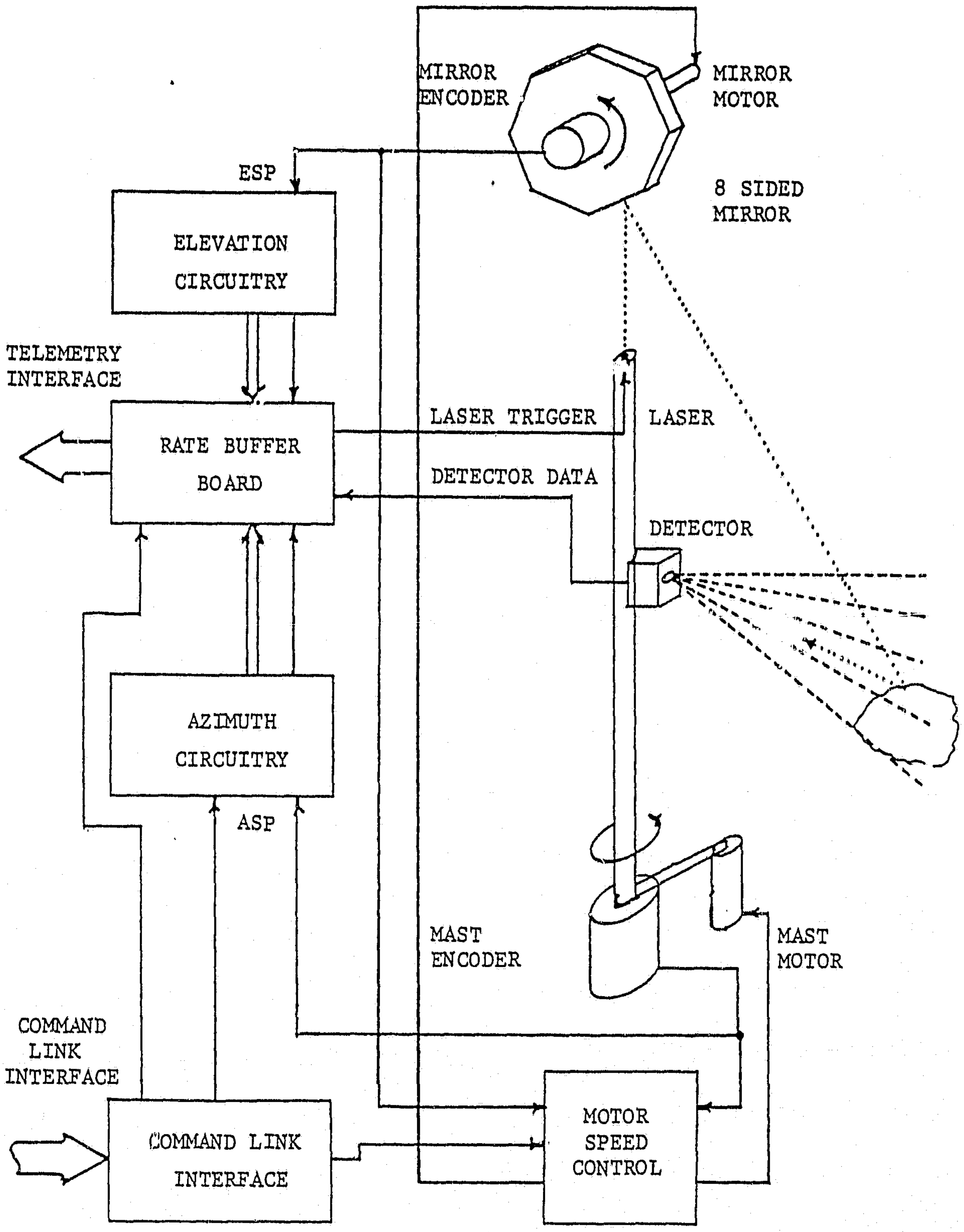

Fig. 2. ML/MD Scanning System.

Azimuth 255	1023
⋮ PATTERN 3	
Azimuth 0	768
Azimuth 255	767
⋮ PATTERN 2	
Azimuth 0	512
Azimuth 255	511
⋮ PATTERN 1	
Azimuth 0	256
Azimuth 255	255
⋮ PATTERN 0	
Azimuth 0	0

Fig. 2.1 Azimuth EPROM Packing.

EOS BIT	X	A4	A3	A2	A1	A0	FIRE BIT

MSB X = not used LSB

A4–A0 = Azimuth Shot Tag

Fig. 2.1a Azimuth EPROM Data Word Format.

azimuth EPROM by placing a 1 in the MSB of the corresponding memory location. The shot number is a unique 5 bit tag which is programmed into the five LSBs of the same memory location. This shot tag will be used to form the DMT address for the data transfer into the PRIME computer. For the last azimuth fire angle in a scan pattern, bit 7 is programmed to a 1 to generate an end of azimuth interrupt for the PRIME computer. Figure 2.1a shows the format of the azimuth EPROM data word. The four different azimuth scan patterns are selectable by computer control via the command link.

The capability exists to offset the entire set of azimuth angles by a fixed angle called the Center of Scan, Azimuth (CSA) angle. The available CSA angles correspond to every azimuth angle. The 256 CSAs and their associated command link data words are listed in Appendix I. The data word is immediately latched into a register on the azimuth board by the microprocessor handshake signals, so there is no longer a data hold time to contend with. On system initialization the CSA will be 0 degrees, and the scan pattern will be pattern 0.

The test and alignment procedures are unchanged from the original specifications.

2.1.2 Elevation Angles. The set of possible fire angles in the elevation axis forms a grid of 256 radials within the 90 degree scan quadrant. The angular separation between adjacent radials is .35 degrees. As for the azimuth angles, the possible elevation angles are mapped four times into a 1024 x 8 EPROM. The MSB of a memory location is programmed to a 1 for a desired fire angle and the five LSBs are programmed with a shot tag. The four elevation scan patterns are selectable by computer control via the command link. On system initialization, scan pattern 0 will be selected. For proper generation of the End of Azimuth (EOA) interrupt signal, the elevation shot count switch on the azimuth board must be set to N-1, where N is the number of elevation shots per azimuth for the current pattern.

The elevation patterns may contain from one to 32 shots per azimuth. The set of allowable patterns is determined by factors such as scanning speed, maximum laser firing rate, and beam width. For the current configuration of .5 scans per second, a 10 kHz maximum firing rate, and a .375" beam width, the allowable elevation fire angles are between 14.06 and 74.88 degrees inclusive. The minimum separation between fire angles is 1.05 degrees for this case. These pattern limitations are more fully described in Reference 1.

The test and alignment procedures are unchanged from the original specifications.

2.2 Operation

Circuit operation is discussed in reference to the circuit and timing diagrams in Appendix II. The circuit operation was extensively covered in the original design specifications (Reference 1), so I will principally cover the design modifications to the original controller.

2.2.1 Azimuth Board. The azimuth board is basically an address sequencer. Pulses from the azimuth encoder drive an 8 bit counter (D17-D18). The counter outputs are summed with the CSA and the result drives the address lines of a 1024 x 8 EPROM, so that each of the 256 mast positions corresponds to a particular memory location. When you desire to fire the laser at a particular azimuth angle, you simply program a fire bit in the corresponding memory location.

The modifications of the original azimuth board from the original design cover two areas, the CSA register and the generation of the End of Azimuth (EOA) and End of Scan (EOS) signals.

Due to the increased command link capabilities the CSA register was expanded to a full 8 bits. This allows the CSA to be set to any available azimuth angle. The CSA latch signal is now generated by the Command Link Interface card, so a 7474 chip (D7 in the original schematics) was removed from the board.

The circuitry to generate the EOA and EOS signals required extensive modification for proper operation. D21, D22, D5 and the Elevation Shot Count switch form a shot counter clocked by FIREUN. The counter is cleared by AFIREL being low; this initializes the counter to zero. At the start of an azimuth fire angle, AFIREL goes high enabling the counter; this transition inhibits the clock to D29, locking AFIREL high until all elevation shots are completed. The shot count switch should be set to N-1, where N is the number of elevation shots per azimuth. After N-1 shots the output of D5 goes low switching EOA and possibly EOS high. The next and last fire pulse latches EOA and EOS into R5 and clears D29, allowing AFIREL to go low until the next desired azimuth. This clears D21 and D22, and removes EOA and EOS.

This circuit has the limitation that the shot count switch must be changed if an elevation pattern with a different number of shots per azimuth is selected. To make this adjustment computer controllable would have required the addition of several IC packages to an already crowded circuit board. It is much simpler to require that all scan patterns contain the same number of shots per azimuth; unwanted shots can simply be ignored. On receiving the system initialize signal the CSA register is cleared to 0. The remaining circuit operation is unchanged from the original design.

2.2.2 Elevation Board. The elevation board was the first portion of the system to become operational. It required no major modifications from the original design. It was desired to make the Center of Scan, Elevation (CSE) angle computer controllable, but there were insufficient I/O pins to bring the command link data onto the board.

A minor wiring change was made in the FIFO portion of the board. The EOS signal is fed into the D0 input to R4 and from R4 the signal is latched into the D8 input of FIFO R1. This change stems from the current software requirements to have both EOA and EOS available to telemetry. The output enable lines of the FIFO buffer have been connected to the telemetry system to avoid contention on the telemetry bus.

2.2.3 Rate Buffer Board. The ML/MD controller was designed to interface with the Varian computer and its telemetry system. This telemetry system had a maximum data rate of 2.5K words per second. With a laser firing rate of 10 kHz it was possible to generate data much faster than it could be transmitted. This required the addition of a 40 word FIFO stack to store data for transmission, and placed some restrictions on the allowable scan patterns.

The new telemetry system designed by D. Cipolle has a word rate of approximately 7K words per second. This reduces the buffer requirements for the FIFO stack and eliminates the restrictions on scan patterns. The rate buffer board also provides the handshake signals for the new telemetry system.

Also present on the rate buffer board are the laser protection and software laser enable circuits. The laser protection circuit consists of a 74121 one shot which narrows the laser fire pulse to 1 microsecond. The software laser enable circuit is a 7403 gate which provides command link control of the laser enable line. The laser enable bit is the MSB of the scan pattern command data word.

2.2.4 Memory Board. The memory board contains two 1024 x 8 EPROMs, one for the aximuth scan patterns and one for the elevation scan patterns. Each memory will hold up to four complete patterns. The scan patterns are selectable by a software command. The Command Link Interface board latches the Scan word into a register on the memory board. The four LSBs of the command word are connected to the two MSBs of the azimuth and elevation memories. The MSB of the command word is the laser enable bit. On system initialization the register is cleared, selecting scan pattern 0 and disabling the laser.

2.2.5 Motor Speed Control Board. The Motor Speed Control Board is a Phase Locked Loop (PLL) motor speed controller. The controller is configured as two independent PLL speed controllers which are synchronized by a master clock. The control loop is closed by the pulse outputs of the mast and mirror encoders. During normal operation the ratio of mast velocity to mirror velocity is maintained at 1 to 24. This is achieved by dividing the mirror reference clock by 24 to synthesize the mast reference clock. The system scanning speed is controlled by a master clock of 12,228 hz.

The board has been modified to allow software control of mast scanning speeds. Available speeds are 0, .25, .5, and 1 scan per second. In addition each axis may be turned on or off independently, but the ratio between mast and mirror speeds may not be changed. For test purposes the system scanning speeds can be set manually.

The software control circuitry consists of an 8 bit latch, two dual 4 line to 1 line multiplexers, and a quad 2 input open collector NAND gate. The inputs to the multiplexers are ground, Ø/2, Ø/4, and Ø/8, where Ø is the system clock of 12,288 hz. One set of multiplexer select lines is driven by a DIP switch, the other set is driven by the two LSBs of the Speed latch. Another switch selects which multiplexer is enabled, providing manual or computer speed control. The output of the multiplexer is the reference clock for the mirror axis. Bits 2 and 3 of the speed latch drive open collector NAND gates which enable the DC amplifiers for the mirror and mast motors. On system initialization both amplifiers are enabled, and the master clock is grounded.

One additional circuit located on the Speed Control board is the over-voltage protection circuit for the +5 volt bus. This circuit monitors the controller +5 volt bus.

If the voltage rises above 6.8 volts a SCR crowbar pulls the bus down to ground. This circuit will protect the ICs from voltage transients.

2.2.6 <u>Command Link Interface Board.</u> The new command link system provided a much larger set of mast commands. Unfortunately the present controller cards had neither the room for more chips nor the I/O pins to accommodate more data. The only solution was to design a new card for the system.

The Command Link Interface board is responsible for buffering the command link data lines, generating data latch signals, and generating the handshake signals to interface with the microprocessor command link. IC chips D1 and D2 buffer the data and address lines respectively. D2 also provides the handshake data accepted ($\overline{DA}$) signal. Each data latch signal is generated by a 74LS266 quad exclusive NOR chip. The chip is wired as a 4 bit address decoder. There are currently three data latch signals being generated. They are CSA latch, Scan latch and Speed latch. The system is expandable to eight latch signals through the addition of more 74LS266 chips.

Only three address lines from the command link are used. $\overline{DAV}$ is treated as the fourth address line. When $\overline{DAV}$ goes low, the selected 74LS266 generates a positive pulse which clocks data from the command link data bus into a data register on one of the other controller cards.

Addresses 0, 1 and 2 correspond to the CSA, Scan Pattern/ Laser Enable, and Motor Speed Control registers.

2.3 Interface

The ML/MD controller interfaces with the vehicle electronics through two main connections. These connections are the command link and the telemetry system.

2.3.1 Command Link. The link for transmitting commands to the mast consists of eight data lines, four address lines and two handshake signals ($\overline{DAV}$ and $\overline{DA}$). Currently the only commands wired up are the CSA angle, the Scan Pattern/Laser Enable, and the Motor Speed command. The addresses and bit positions for these commands are shown in Figure 2.3.

The handshake sequence is as follows. The command link places an address on the bus, then data are placed on the bus, and $\overline{DAV}$ goes low. The controller latches the data into the appropriate data register and drives $\overline{DA}$ low. The command link acknowledges $\overline{DA}$ by raising $\overline{DAV}$ and removing the data and address from the bus. Finally the controller raises $\overline{DA}$, completing the transfer. The command link signals originate on the Peripheral Interface Adapter (PIA) of the M6800 microprocessor, and are connected to the mast umbilical cable by a 50 pin ribbon connector. The connector pinouts are listed in Appendix III.

2.3.2 Telemetry. The telemetry interface consists of a 22 bit data word, and the handshake signals Laser Data Here (LDH),

ADDRESS FIELD		
0	0	0

DATA FIELD							
D7	D6	D5	D4	D3	D2	D1	D0

D7-D0 = CSA angle

CENTER OF SCAN, AZIMUTH COMMAND

0	0	1

L	X	X	X	E1	E0	A1	A0

L = Laser Enable (1 = enabled)

XXX = not used

E1-E0 = Elevation Pattern Number

A1-A0 = Azimuth Pattern Number

SCAN PATTERN COMMAND

0	1	0

X	X	X	X	A		S1	S0

XXXX = not used

A = $\overline{\text{Azimuth Motor Enable}}$

E = $\overline{\text{Elevation Motor Enable}}$

S1-S0 = Motor Speed Select

MOTOR SPEED COMMAND

Fig. 2.3 Mast Command Format.

Shift Out (SO), and Output Enable ($\overline{OE}$). The telemetry word consists of 10 bits detector data, 10 bits shot address, and the interrupt signals EOA and EOS.

The handshake procedure is completely controlled by the telemetry system. LDH tells the telemetry system that data is available; it responds by clearing other devices off the telemetry bus, enabling the FIFOs onto the bus with $\overline{OE}$ and clocking the SO line until LDH goes low.

The telemetry system is connected to the mast umbilical cable by another 50 pin ribbon cable. The connector pinouts are listed in Appendix III.

2.4 Packaging

The controller electronics consist of six circuit cards located in a card basket which is mounted on the stationary portion of the mast. This card basket connects to the mast through connectors J1, J2 and J3. Figure 2.4 depicts the correct card positions and the connector locations. J1 is a 25 pin connector which links the controller data signals to the rotating portion of the mast through the slip rings. J2 is a nine pin connector which links the controller to the azimuth encoder, and the mast motor, and provides power and ground to the rotating portion of the mast. J3, a 50 pin connector, is the only connection between the mast and the vehicle electronics. This greatly simplifies the movement of the mast between the vehicle and the new Dynamic Test Platform. J3 is connected to a single umbilical cable which provides power, ground, and data to

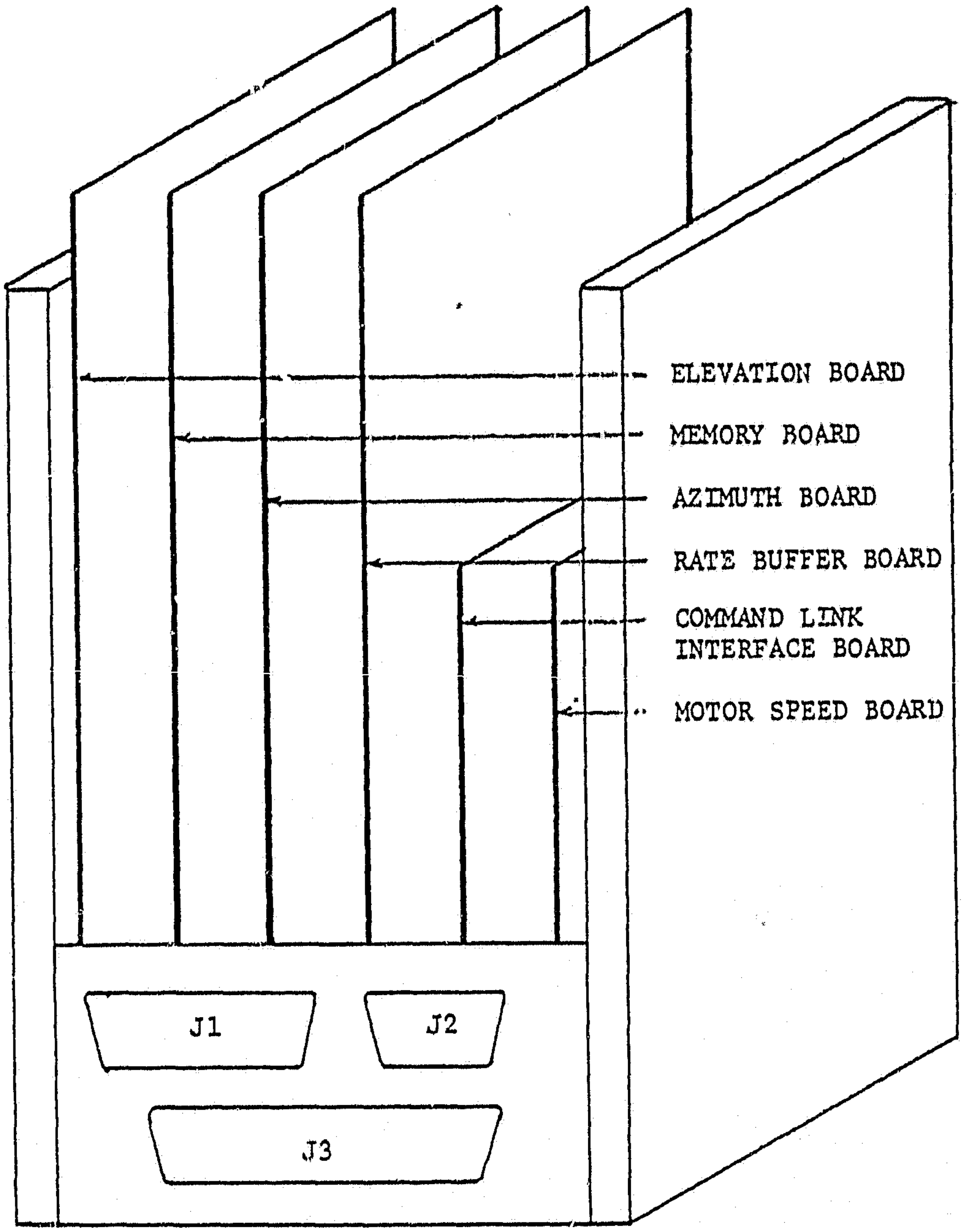

Fig. 2.4 ML/MD Controller Card Basket.

and from the mast. The vehicle end of the umbilical cable connects to the command link and telemetry via two 50 pin ribbon connectors. The power and ground connections are made separately. All board and connector pinouts are listed in Appendix III.

2.5 Operating Instructions

This section explains the function of the various switches and L.E.D.s on the controller; board layouts are included in Appendix II. Also discussed is the programming procedure for entering new scan patterns. For all boards an open switch or lit L.E.D. represents a binary 1, and a closed switch or unlit L.E.D. represents a binary 0. When a series of switches represents a binary word, switch 1 represents the LSB and the more significant bits are labeled in increasing numerical order.

2.5.1 Azimuth Board. The Azimuth Board has three modes of operation. They are test mode, single shot mode and automatic mode. Test mode is selected by opening the Override Azimuth switch; while in this mode the Override Azimuth L.E.D. will be off. In this mode the Azimuth Board is disabled and AFIREL is locked in the high state. This causes the Elevation Board to fire at all azimuths; it also allows the elevation axis to operate when the mast is not rotating. This feature is useful for calibrating the elevation axis. Test mode overrides all other controls on the Azimuth Board.

When the Override Azimuth switch is closed, the associated L.E.D. will be lit. With this switch closed the Azimuth Mode Select switch will enable either the single shot or automatic mode. If the mode select switch is open, the board will operate in single shot mode. In this mode there is only one azimuth fire angle; this angle is selected with the Azimuth Single Shot Mode Angle Select switch. The switch is loaded with the binary reference angle of the desired azimuth shot. The elevation board is not affected; the system will run as if the azimuth scan pattern contained only one fire angle. This mode is useful for the calibration of the azimuth axis. If the Azimuth Mode Select switch is closed the board will operate in automatic mode. This is the normal mode of operation; the scan pattern is read from the azimuth EPROM and may contain up to 32 azimuth fire angles. For all modes described above the Last Azimuth of Fire Display will read out the binary reference angle of the last azimuth that a laser shot was fired at.

For proper generation of the EOA and EOS interrupt signals the Elevation Shot Count switch must be set to N-1 where N is the number of elevation shots per azimuth. If a new scan pattern uses a different number of shots per azimuth this switch must be changed. It is easier to require that all patterns use 32 shots per azimuth, and simply ignore unwanted shots.

2.5.2 <u>Elevation Board.</u> The Elevation Board has two modes of operation, single shot mode and automatic mode. The mode is selected by the Elevation Mode Select switch. When the switch is open the elevation board is in single shot mode. As with the azimuth axis, single shot mode implies one elevation shot per azimuth. The single elevation fire angle is determined by the setting of the Elevation Single Shot Mode Angle Select switch. This switch is loaded with the binary reference angle of the desired elevation shot. This mode is useful for system calibration, or for simulating the old Single Laser/Single Detector scanning system. When the mode select switch is closed, automatic mode is enabled. This is the normal mode of operation. During automatic mode the elevation fire angles are read from the elevation EPROM. During any of the elevation boards' operational modes, the Last Elevation of Fire Display will show the binary reference angle of the last elevation shot fired. This diaplay is only useful during single shot mode; in automatic mode the L.E.D.s switch on and off too rapidly.

For calibrating the elevation axis the Center of Scan, Elevation (CSE) switch is used. This switch offsets the elevation scan pattern by any elevation reference angle. This feature is used to adjust for mis-alignment of the elevation encoder.

2.5.3 Rate Buffer Board. The Rate Buffer Board contains three switches which control the laser enable, and the laser fire protection circuit. The Master Laser Enable switch, when closed, enables the laser to receive FIREUN pulses. In this mode the command link cannot disable the laser. When this switch is open the command link can enable or disable the laser depending on the position of the Computer Laser Enable switch. If this switch is closed the command link enable is blocked, but if the switch is open the computer can turn the laser on or off via the command link. In any of these modes the red Laser Enabled L.E.D. will be lit if the laser is enabled.

The laser fire protect switch selects the maximum laser firing rate. If this switch is open the laser will be limited to a 5 kHz firing rate. When the switch is closed the laser can fire at the full 10 kHz limit. In the 10 kHz mode the yellow L.E.D. will be lit.

2.5.4 Memory Board. Changing the scan patterns in the memory board involves reprogramming the EPROMs. The 2708 UV erasable PROMs must be erased completely before reprogramming the entire 1024 x 8 memory space. The erasing operation is performed by an ultra-violet lamp. This lamp is available in the Computer Hardware Design Lab (JEC 3207); the EPROMs should be exposed for at least two hours to insure complete erasure. Reprogramming is done using a Cromenco BYTESAVER board and an IMSAI 8080 development system; both of these devices are available in JEC 3207. For assistance in using this equipment see R. Kraft (JEC 5001). The manual for the BYTESAVER board is available in the Mars lab.

2.5.5 Motor Speed Control Board. The Motor Speed Control Board has two operational modes, manual and computer controlled. S3, the Manual Override switch, is closed for manual mode and opened for computer control. In manual mode switches S1 and S2 form the Manual Speed Select switch. The binary representations of 0, 1, 2 and 3 correspond to mast scanning speeds of 0, .25, .5 and 1 scan(s) per second. In computer control mode the computer will select the scanning speed via the command link. S3 is a manual override to disable the mast motor; this disables the mast motor regardless of the operational mode. This feature is useful for system calibration purposes.

2.5.6 Command Link Interface Board. The Command Link Interface Board has no user accessable controls.

2.6 Future Modifications

The present ML/MD controller has been slightly modified from its original design. These modifications were made to take better advantage of the new command link and telemetry systems. There are further improvements which could be made to increase reliability and reduce power consumption, but further functional improvements would require substantial redesign and rewiring. The current controller boards are very densely packed with ICs, and I/O pins are at a premium.

The reliability and power consumption improvements center around replacing the present ICs with the newer low power CMOS and 74LS series chips. One simple modification would be to replace the 7485 comparitor chips with 74LS266 quad exclusive NOR chips. These chips use one tenth the power of the 7485s, yet perform the same function.

Desirable functional improvements to the controller would include greater elevation resolution, a steerable detector array, and software downloading of scan patterns. The present controller is simply not modifiable to perform all of these functions, and a hard-wired controller capable of performing all of these functions would be too complicated and restricted to be worthwhile. Because of this fact the conceptual work has been done on the next generation of mast controller. The Level II controller will be capable of all of the above plus 12 bit elevation and azimuth resolution, a 16 bit detector data path, self diagnostic and calibration capabilities, and possibly the capability for detector data preprocessing.

PART 3

LEVEL II CONTROLLER

The present controller, although greatly improved over the original design, has reached the limit of its capabilities. The current controller is several orders of magnitude more powerful than its predecessor, and is a great milestone in the Rover Project. Still, thought must be given to further improvements. These improvements should be in the areas of resolution, flexibility, reliability and power consumption. The new controller should be able to take full advantage of any new breakthroughs in detector, laser or encoder technology. The Level II Controller has been designed as a feasibility study for a microprocessor-based controller which fulfills these requirements.

3.1 Capabilities

When implemented, the Level II Controller will provide a great improvement in performance over the present ML/MD system. This controller will be able to take full advantage of the new telemetry system (16 bit data bus and 16 bit address bus), and the new command link (8 bit data bus and 6 bit address bus). The Level II controller will support computer downloaded scan patterns, self-calibration, and arbitrary scan patterns of N azimuths by M elevations where N x M is less than 1024. With minor modifications, the encoder resolution can be doubled to .703 degrees in azimuth and .175 degrees in elevation. Slightly more elaborate modifications can make this resolution software controllable with resolution up to

.087 degrees in azimuth and .022 degrees in elevation. The Level II Controller will be able to take advantage of this resolution increase immediately and without any additional modification.

3.1.1 Azimuth Angles. The Level II Controller will provide up to 4096 available azimuth angles, spaced .087 degrees apart. The exact number of angles is dependent on the encoder resolution. For the initial testing, 512 azimuths should be sufficient. This gives an angular resolution of .703 degrees.

The Level II Controller includes the CSA angle capabilities of the ML/MD controller and adds the feature of software downloaded scan patterns. A pattern may contain up to 128 azimuth shots per scan. The only restriction is that adjacent azimuth fire angles be spaced at least 1.875 degrees apart. This restriction is based on the current mast-to-mirror speed ratio of 1 to 24. A faster laser or greater speed ratio would ease this restriction.

Because the Level II Controller is microprocessor based, software downloading of the scan patterns does not require programming an entire 4096 word memory. For an azimuth pattern with NA azimuth shots per scan, 2NA + 1 data words must be transmitted via the command link. First the pattern number and NA are transmitted. Then the NA azimuth fire angles are transmitted, requiring two data words per angle. For proper operation these angles must be transmitted in the reverse order of occurrence. To transfer a 128 shot pattern from the PRIME to the mast would require 8.6 seconds. This is due to the slow data rate out of the PRIME. If the pattern were stored in the vehicle microprocessor, it could be loaded in about 20 ms.

There will be 256 words of memory for azimuth scan patterns. These 256 words will be organized as a stack of 128 16 bit words. This allows two 64 shot patterns, or any other combination of patterns with the restriction that the sum of all fire angles in all patterns must not exceed 128.

The controller can run in azimuth single shot mode via computer control, or manually via circuitry similar to the ML/MD controller. A three digit hexidecimal display reads the last azimuth angle at which a laser shot was fired.

3.1.2. Elevation Angles. In the elevation axis the Level II Controller can resolve up to 4096 different elevation angles within the 90 degree scan sector. This provides a theoretical accuracy of .022 degrees. Due to mechanical vibrations in the mast, the maximum practical resolution is probably .088 degrees or 1024 elevation radials. The present design is configured for a maximum resolution of .088 degrees, but this can be increased to .022 degrees simply by adding more memory.

The elevation axis will shoot up to 128 elevation shots per azimuth depending on scanning speed. The basic limitation on the scan pattern is the maximum laser firing rate. The minimum spacing between adjacent elevation angles $\Delta\beta$ is a function of the mirror velocity Wm, and the maximum laser firing rate Fmax; the function relating $\Delta\beta$ to Wm and Fmax is:

$$\Delta\beta = 2Wm/Fmax.$$

For a 10 kHz firing rate and a mirror velocity of 12 rev/s, the minimum separation between adjacent elevation angles is .864 degrees.

The new design retains the single shot capabilities of the ML/MD controller and adds software downloading of the elevation scan patterns. Like the azimuth axis, the pattern can be transmitted with 2NE + 1 commands, where NE is the number of elevation shots per azimuth. The data transfer follows the same procedure as for the azimuth axis.

In addition, the Center of Scan, Elevation (CSE) angle may be loaded by computer control. A three digit hex display will read the last elevation angle at which a laser shot was fired.

3.1.3 <u>Detectors.</u> The Level II Controller will interface with the present 20-element detector, the 1024-element RETICON detector, or practically any new detector system which may be developed. The controller will provide a 16 bit data path for the detector data and if necessary, can transmit multiple words of data. This allows for almost unlimited expansion of the detector resolution. Another capability of the controller is its ability to pre-process detector data before transmitting it to the telemetry system. This processing may consist of data formatting, or may include performing some simple transformations on the raw detector data.

3.1.4 <u>Peripheral Devices.</u> The motor speed controller, steerable detector array, and any other auxiliary systems will be treated like computer peripherals. An 8 bit bi-directional data register and an 8 bit address register will transfer data and commands to and from the peripheral devices. This allows powerful new mast subsystems to be developed independently of the controller, but provides a common interface for all.

3.2 Operation

The Level II controller is a microprocessor based design using the INTEL 8085 microprocessor chip and its associated support chips, the 8155 Random Access Memory (RAM) + I/O chip, and the 8755 Erasable Programmable Read Only Memory (EPROM) + I/O chip.

By going to a microprocessor based design it is possible to replace large portions of hardware with real time control programs. In particular the azimuth portion of the controller can be implemented almost entirely in software. With the microprocessor we gain flexibility without losing fuctionality.

In certain critical paths of the controller where high speed is a requirement, hardwired logic will remain. This is true for the elevation axis in particular which remains very similar to the original ML/MD design.

3.2.1 Controller Hardware. The Level II controller is a digital device based on the 8085 microprocessor family. The hardwired portions of the controller are designed around 7400 LS series TTL logic gates. This results in single +5 volt power supply operation with an estimated 40 percent reduction in power consumption over the ML/MD controller.

The controller is divisible into three major functional elements. They are the microprocessor, the elevation control circuitry, and the azimuth counter. A system block diagram is shown in Fig. 3.2. The following three sections refer to the hardware schematics included in Appendix IV.

3.2.1.1 Microprocessor. The INTEL 8085 is an 8 bit single

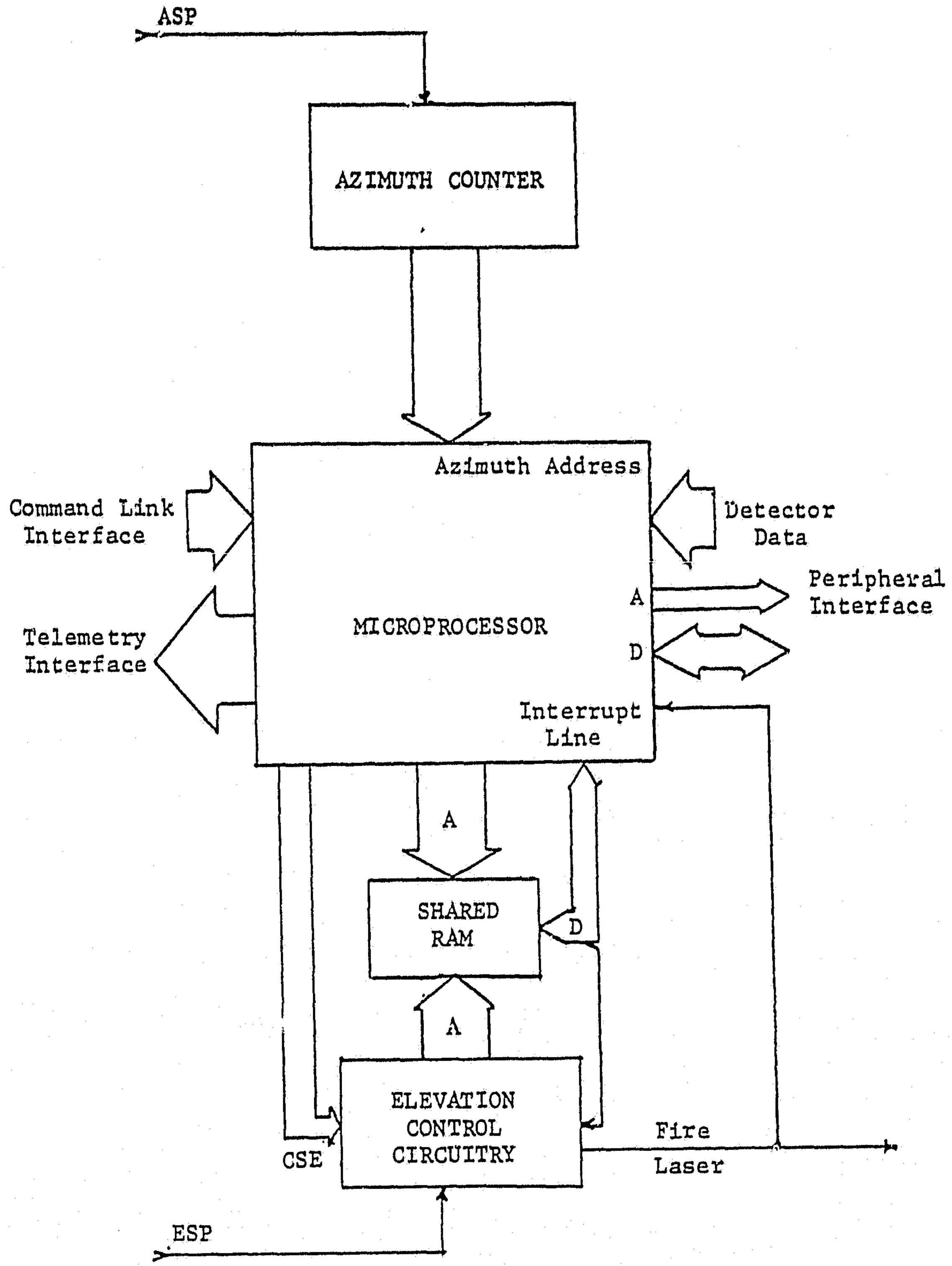

Fig. 3.2 Level II Controller Block Diagram.

chip microprocessor. The microprocessor planned for the Level II controller consists of an 8085 microprocessor chip, two 8155 RAM + I/O chips, and one 8755 EPROM + I/O chip. This configuration gives us a controller with 2048 bytes of EPROM storage, 512 bytes of RAM storage, 60 programmable I/O pins, and one serial I/O port. The actual operational details of the 8085 microprocessor are beyond the scope of this document and can be found in Reference 2.

The system memory is distributed as follows. The operational programs and interrupt vector addresses will reside in the 2048 byte EPROM. One 256 byte block of RAM storage is used as a stack to store azimuth scan patterns; the remaining 256 bytes of RAM serve as temporary variable and scratchpad storage, and serve as a stack to keep track of subroutine and interrupt return addresses.

In addition to the above memory the controller will contain a 1024 byte RAM shared between the microprocessor and the elevation control circuitry. This RAM stores elevation scan patterns. The microprocessor will access the shared RAM in two modes. In the first mode it treats the RAM as its own memory and controls both the address and data lines to it. In the second mode, which occurs during scanning, the microprocessor can only read the data at the output of the RAM, while in this mode the RAM address lines are driven by the elevation control circuitry.

The microprocessor interfaces to the hardwired logic through the shared RAM and through several data registers and bus drivers which are memory mapped into the microprocessor's address space. The complete memory map is listed in Table I. The command link and telemetry interfaces will be through the I/O pins on the 8155 and 8755 chips; the I/O port assignments are listed in Table II.

The serial input port on the 8085 chip is used to receive the Data Valid signal from the detectors, and the serial output port transmits the AFIRE signal to the elevation circuitry at the start of an azimuth fire angle.

3.2.1.2 Elevation Circuitry. The elevation circuitry of the Level II controller is based on the same design as the ML/MD elevation board. The available fire angles are mapped into the address space of a solid state memory. Where we wish to fire a laser shot we place a 1 in the LSB (the fire bit) of the corresponding memory location; we also place a binary shot tag in the MSBs of that same location.

In the Level II controller design, the EPROM memory of the ML/MD system has been replaced by a 1024 byte RAM which is shared with the microprocessor. The elevation counter has been expanded to 12 bits but otherwise remains identical to its ML/MD counterpart. Every mirror revolution the counter is preloaded with the contents of the Center of Scan, Elevation (CSE) register, giving software control of the CSE angle.

The elevation control circuitry will retain the single shot capabilities of the ML/MD controller. Switch S1 when in the single shot mode will select the fire bit not from the shared RAM, but from

Table I

Level II Controller Memory Map

Address (Hex)	Contents
0000 - 07FF	ROM - Program Storage
1000 - 10FF	RAM - Scratch Pad
2000 - 20FF	RAM - Azimuth Stack
3000 - 33FF	RAM - Elevation Pattern
4000 - 4FFF	Read Azimuth MSBs
5000 - 5FFF	Read Elevation Memory
6000 - 6FFF	Read Detector MSBs
7000 - 7FFF	Read Detector LSBs
8000 - 8FFF	CSE MSBs Out
9000 - 9FFF	CSE LSBs Out
A000 - AFFF	Peripheral Address Out
B000 - BFFF	Peripheral Data

Table II

Level II Controller I/O Port Assignments

Port	Function	I/O Address (Hex)	Signal(s)
PA1	OUTPUT	21	TELEMETRY DATA (MSBs)
PB1	INPUT	22	COMMAND LINK DATA
PC1	HANDSHAKE	--	--
PA2	OUTPUT	11	TELEMETRY DATA (LSBs)
PB2	INPUT	12	COMMAND LINK ADDRESS
PC2	INPUT	13	AZIMUTH COUNTER (LSBs)
PA3	OUTPUT	00	TELEMETRY ADDRESS (MSBs)
PB3	OUTPUT	01	TELEMETRY ADDRESS (LSBs)

a 12 bit comparator. This comparator will be constructed from 3 quad XNOR chips whose outputs have been wired ANDed together. When the elevation counter matches the setting on S2 (the Single Shot Mode Angle Select Switch), EFIRE will go high to trigger the laser. During all operating modes EFIRE is ANDed with AFIRE to generate the FIREUN laser trigger pulse.

In automatic mode, the fire bit is read from the LSB of the shared RAM. When the laser is fired the microprocessor's program will be interrupted, causing it to read the current shot tag from the RAM output lines. For debugging purposes there will be a 3 digit hexidecimal display which shows the last elevation the laser was fired at. These displays are driven by the 12 elevation counter bits and are latched by the FIREUN signal. The displays may be blanked by closing switch D1. This feature will conserve power.

3.2.1.3. Azimuth Control Circuitry. The azimuth portion of the Level II controller is to be implemented almost entirely in software. The only hardware devoted to this function will be a 12 bit azimuth counter and a 12 bit XNOR comparator.

As in the ML/MD controller the counter is incremented by azimuth encoder pulses, and is cleared once per revolution by the Azimuth Zero Reference (AZR) pulse. The 12 bit comparator is identical in form and function to the comparator in the elevation circuit.

The azimuth circuitry will have three operating modes, azimuth override, single shot and automatic. Azimuth override mode is enabled by opening switch S3, leaving the AFIRE signal in a high state which will cause the elevation circuitry to be continuously enabled. When S3 is closed, switch S4 selects single shot mode or automatic mode. In single shot mode AFIRE is generated by the 12 bit comparator (S5 is the Azimuth Single Shot Mode Angle Select Switch); in automatic mode AFIRE will be software controlled by the Serial output port on the 8085 microprocessor.

The azimuth counter interfaces to the microprocessor via two paths. The 6 LSBs of the azimuth counter are connected to I/O Port C2, and the 6 MSBs are memory mapped into the address space of the microprocessor. The Center of Scan, Azimuth function is implemented entirely in software providing a large reduction in hardware over the ML/MD design.

Like the elevation axis, the azimuth circuit design includes a 3 digit hexidecimal display which indicates the last azimuth of fire. This display may be blanked by closing switch D2.

3.2.2 Controller Software. The Level II controller derives its power and flexibility from its microprocessor based design. By changing parameters in the control program, the controller can be adapted and tuned for different encoder resolutions, new detector systems, and new scanning modes.

At this time the assembler level code has not been written, as this may change before the design is finalized. What has been developed is the general software requirements and program flow.

The two major blocks of code for the controller are the Command Polling routine, and the Scan routine. The Command Polling routine acknowledges controller commands and initiates appropriate actions. The Scan routine is that portion of code active during a terrain scan.

3.2.2.1 Command Polling. In the Level II controller, command interpretation and execution will be performed entirely in software. The commands currently envisioned for the controller are listed in Table III. The New Elevation Pattern, and New Azimuth Pattern commands control the loading of new scan patterns into controller memory, and have been discussed previously. At least one pattern must be loaded after initial controller power up, as the memories get cleared when they are powered down.

The Clear Elevation Patterns, and Clear Azimuth Patterns commands clear the Elevation memory and azimuth stack respectively; this is done before inputting a new pattern. The CSE and CSA commands shift the Elevation and Azimuth patterns by fixed reference angles. The Initialize, Calibrate and Diagnostic commands are not defined at this time; their functions will involve resetting the controller, calibrating the elevation and azimuth axes, calibrating the detector, and running general controller hardware diagnostics. Another possible Initialize function would be to load a stock scan pattern from EPROM memory to RAM.

The Start Scan command is the most important instruction in the controller's repertoire. This command will initiate a single terrain scan, or multiple scans depending on bit settings in the command data word. The start bit when set to a 1 initiates a

Table III

Level II Controller Commands

COMMAND	PARAMETERS IN DATA WORD
New Elevation Pattern	Number of shots per azimuth
Elevation Fire Angle MSBs	8 MSBs of Fire Angle
Elevation Fire Angle LSBs	4 LSBs of Fire Angle
New Azimuth Pattern	Pattern number, Number of Shots per Scan
Azimuth Fire Angle MSBs	8 MSBs of Fire Angle
Azimuth Fire Angle MSBs	4 LSBs of Fire Angle
Center of Scan, Azimuth MSBs	8 MSBs of CSA
Center of Scan, Azimuth LSBs	4 LSBs of CSA
Center of Scan, Elevation MSBs	8 MSBs of CSE
Center of Scan, Elevation LSBs	4 LSBs of CSE
Start Scan	Start Bit, Continuous Scan Bit, Scan Pattern Number, Single Shot Mode Bit
Initialize	-
Clear Elevation Patterns	-
Clear Azimuth Patterns	-
Calibrate	-
Run Diagnostics	-

terrain scan using one of 16 possible scan patterns (chosen by the scan pattern number). At the end of a scan the continue bit is tested; if it is a 1, a new scan is initiated. If the continue bit is 0, the scanning halts. The single shot mode bit, when set to a 1, places the azimuth axis into automatic single shot mode. This means that the only azimuth fire angle is 0 minus the CSA angle.

The command interpretation and execution will be performed by the Command Polling routine (Fig. 3.2a) and the Command Interrupt Service routine (Fig. 3.2b). Associated with these routines is a global buffer of 25 bytes. Twenty-two bytes provide double buffered storage for the command data words; two bytes are used to store 16 one bit flags corresponding to the 16 valid commands. A command flag set to a one indicates a command awaiting execution. The last byte of the global buffer will contain error flags to monitor buffer overflow, command parity errors and invalid command addresses.

When a command is received, a vectored interrupt is generated. This interrupt causes control to pass to the Command Interrupt Service routine. This routine sets the appropriate command or error flags, stores the command data word in the correct buffer, and echoes the command back through telemetry before returning control to the interrupted program.

During controller idle time the microprocessor loops through the Command Polling routine, testing the command flags in a priori-

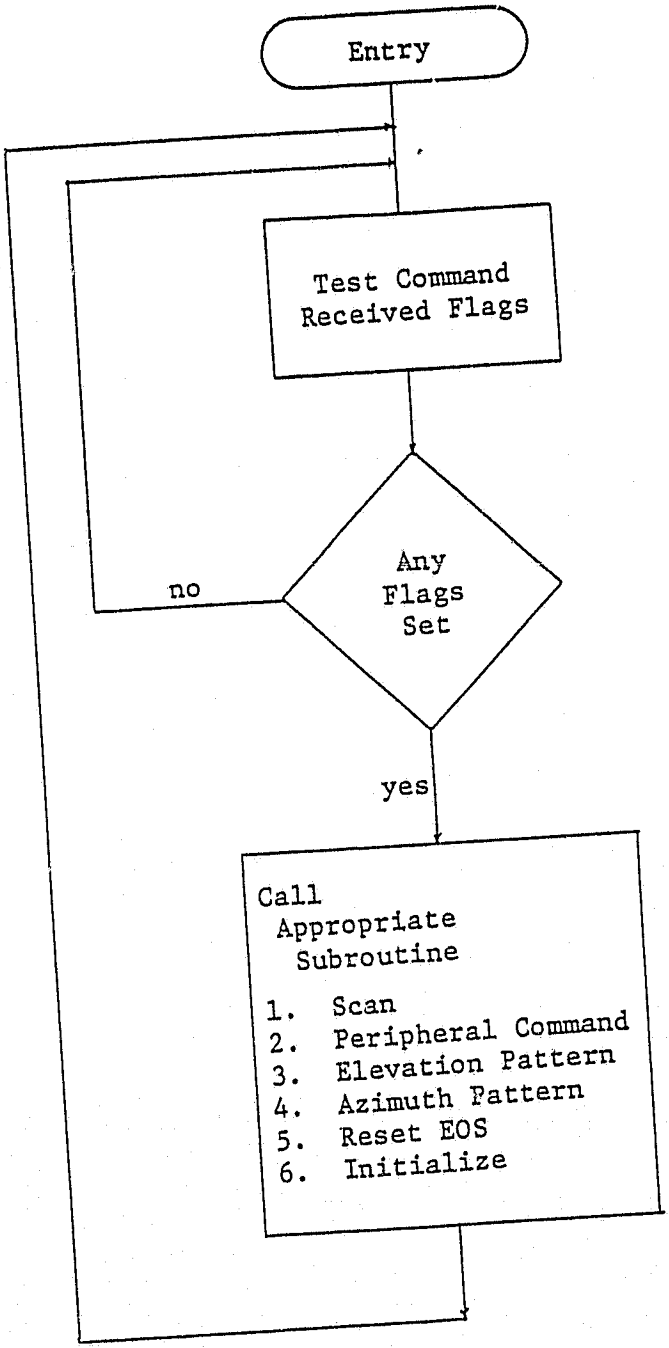

Fig. 3.2a Command Polling Routine.

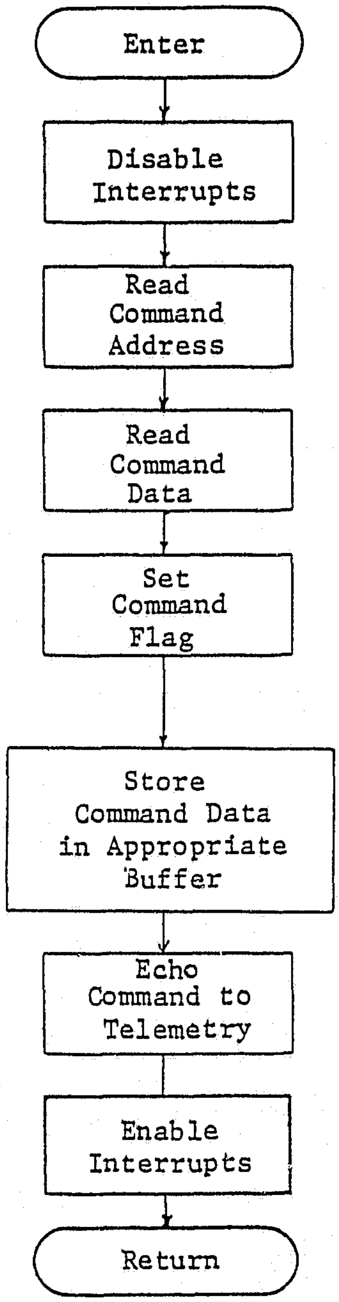

Fig. 3.2b Command Interrupt Service Routine.

tized order. If a flag has been set the program branches to the appropriate command subroutine. Control will not return to the Command Polling routine until the command subroutine is finished, however the Command Interrupt Service may continue to acknowledge commands and set flags.

3.2.2.2 Scan Routine. Perhaps the most important portion of the operational code will be the command subroutine called the Scan routine. This routine initiates and controls the automatic terrain scan. The program will coordinate the various hardware blocks of the controller to monitor azimuth and elevation position, fire the laser, and to generate the correct telemetry word.

This program is divisible into three major sections, the Scan Control Program (Fig. 3.2c), the Elevation Fire Subroutine (Fig. 3.2d), and the FIREUN Interrupt Service routine (Fig. 3.2e).

Upon acknowledgement of a scan command the Command Polling routine branches to the Scan Control program. This program will first initialize scratchpad constants, and unpack the data fields from the scan command data word. This initialization includes loading the CSA angle, the Number of Azimuths (NA) in the desired pattern, and loading the stack pointer with the address of the desired azimuth scan pattern. Other actions will include setting AFIRE to 0, clearing a temporary variable called AZimuth Count (AZC), along with the scan command flag and the start bit.

The first test in the program flow will be whether single shot mode has been enabled. If so the azimuth fire angle is set

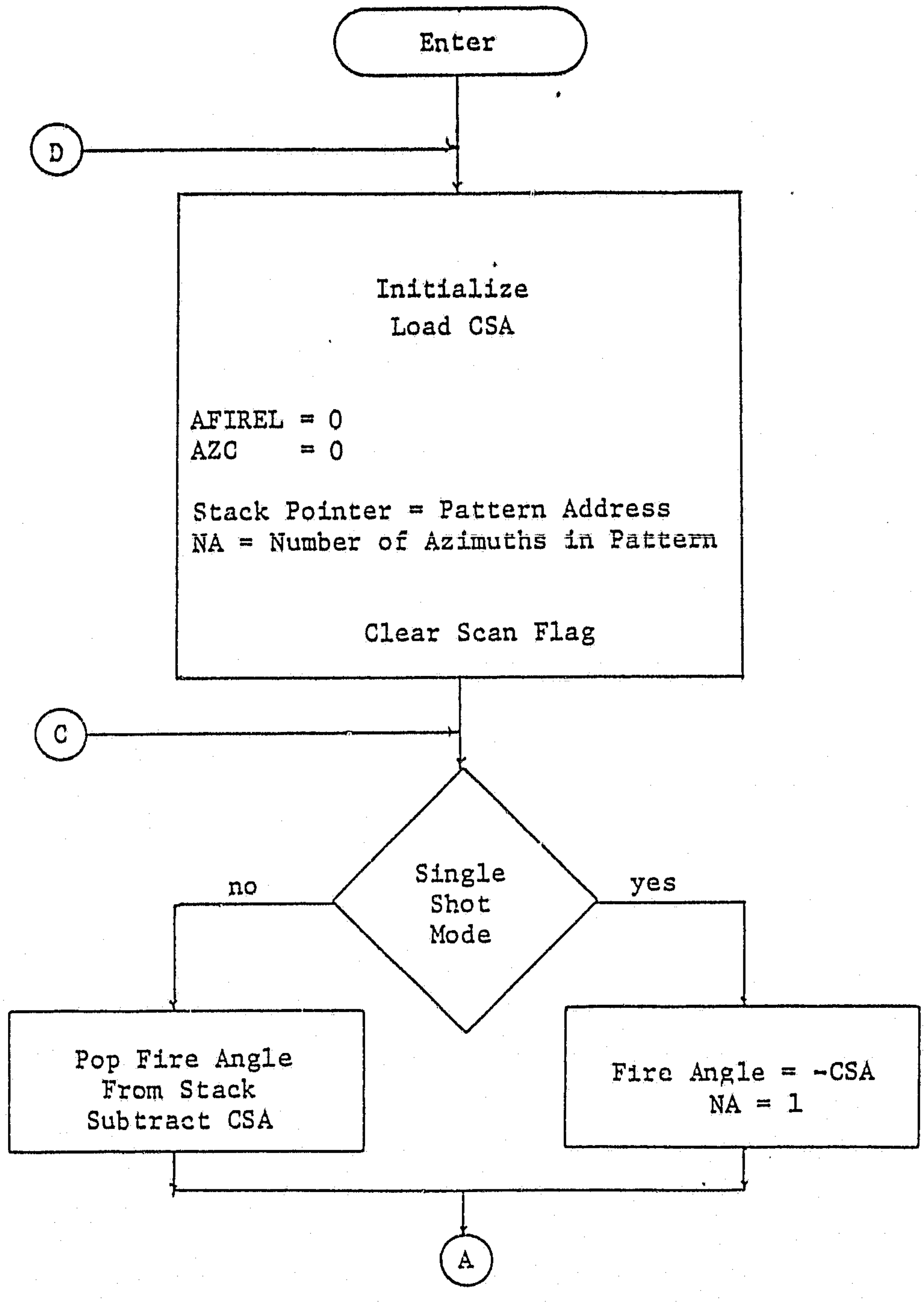

Fig. 3.2c Scan Control Program.

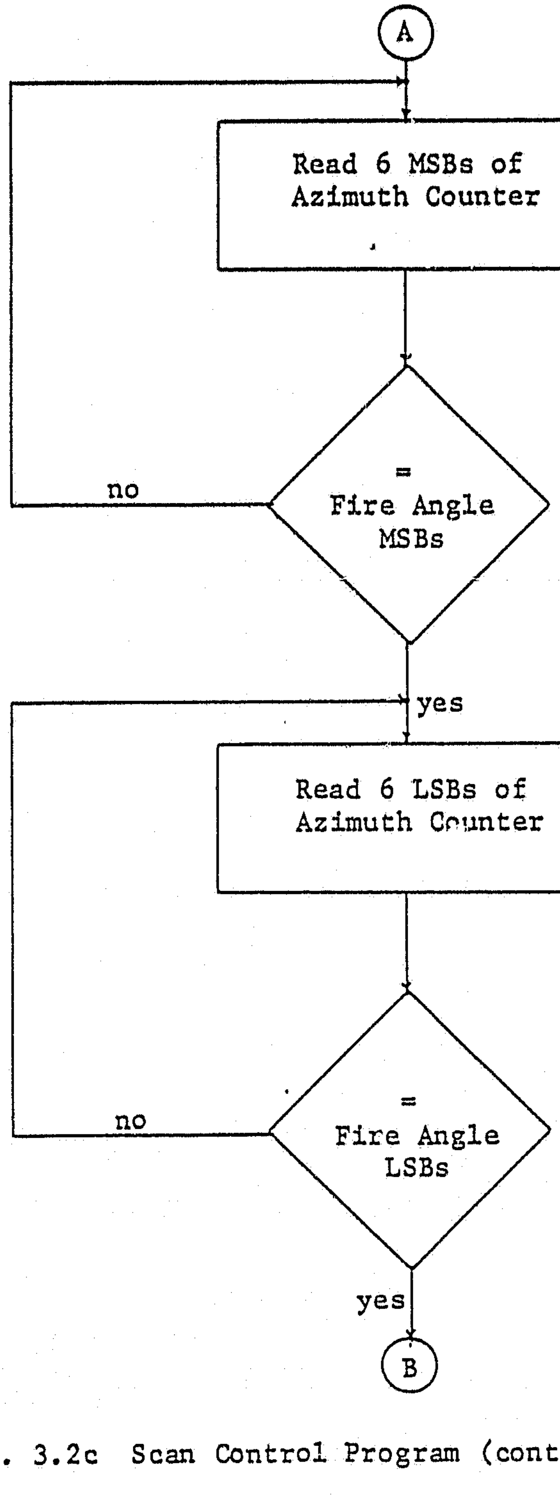

Fig. 3.2c Scan Control Program (continued).

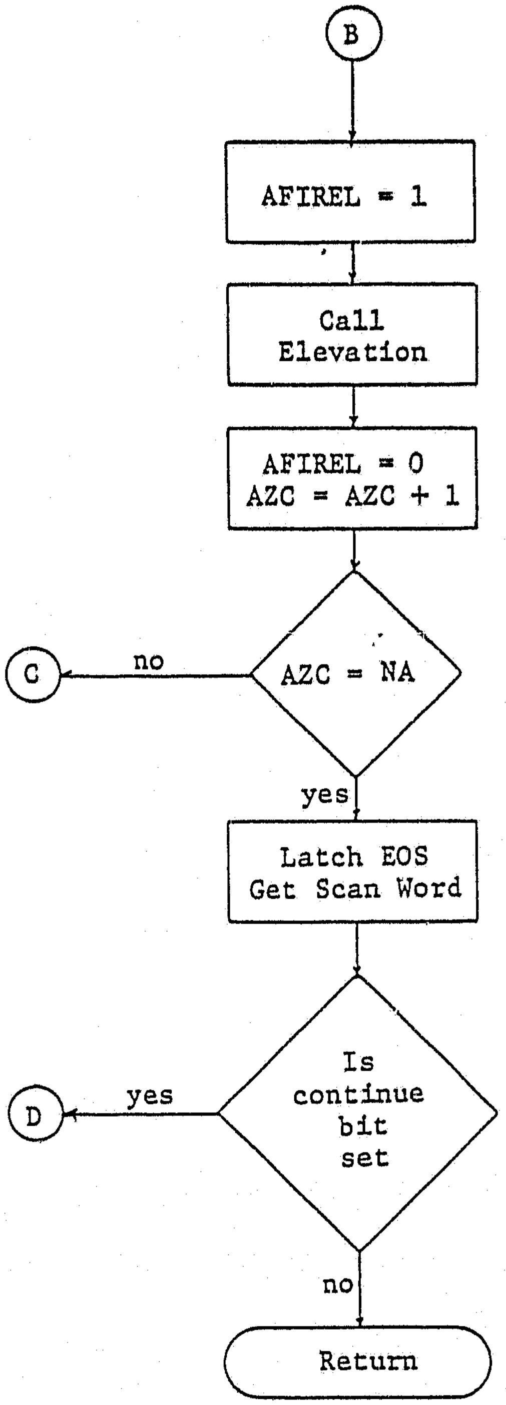

Fig. 3.2c Scan Control Program (continued).

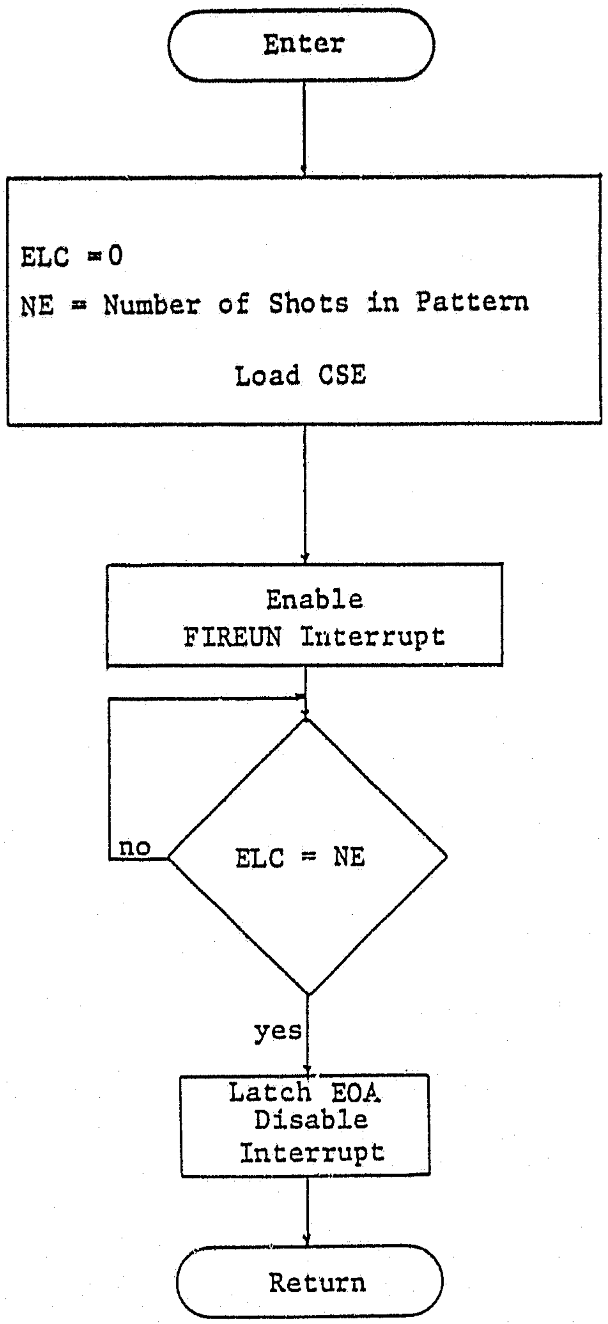

Fig. 3.2d Elevation Fire Subroutine.

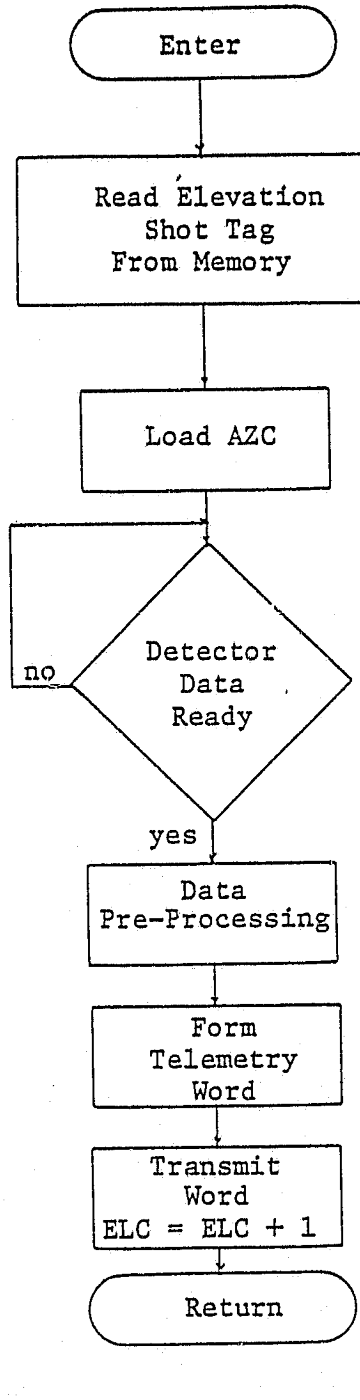

Fig. 3.2e FIREUN Interrupt Service Routine.

equal to -CSA, and NA is set to 1. If single shot mode is not enabled the first azimuth fire angle will be popped off the azimuth stack and the value of CSA will be subtracted from it. This gives the absolute encoder position of the desired fire angle. The program now loops until the mast reaches this desired fire angle. The loop is divided into two sections, the first compares only the 6 MSBs of the azimuth position, and the second compares only the 6 LSBs.

When the program detects the correct azimuth position, the AFIRE line will be driven high enabling the elevation circuitry. At this time control will branch to the Elevation Fire subroutine. After all elevation shots have been taken control returns to the Scan program, and AFIRE is returned to the low state. After AZC is incremented it is compared with NA; if AZC is less than NA the program loops back to pop the next azimuth fire angle off the stack and repeat the process. If AZC equals NA then the scan is completed and the End of Scan (EOS) signal is generated for the telemetry system. After generating the EOS signal the program fetches a new copy of the Scan data word from the command buffer; if the continue bit is set to 1, the whole scan program will repeat (possibly with a different pattern or scan mode). If the continue bit is 0 the scanning is terminated and control returns to the Command Polling routine.

The Elevation Fire subroutine will not be interruptable by the Command Interrupt Service routine. This is necessary due to tight timing constraints in this portion of code. During the elevation scan events occur much more rapidly than during azimuth scans.

The Elevation Fire subroutine first initializes the Elevation Count (ELC) to zero, and loads the Number of Elevation shots (NE) and the CSE angle. The FIREUN interrupt is now enabled; this will cause a vectored interrupt to the FIREUN Interrupt Service routine every time the elevation circuitry fires the laser. The program will now loop until ELC is equal to NE (ELC is incremented by the FIREUN Interrupt Service routine). When ELC equals NE all elevation shots will have been taken so the End of Azimuth (EOA) signal is generated and the FIREUN interrupt is disabled. Control returns to the Scan Control routine.

The FIREUN Interrupt Service routine is the portion of code which will be executed after each laser shot. This service routine reads the elevation shot tag from the shared RAM and combines it with the azimuth count AZC to form the telemetry address. The routine will then loop until the detector data is ready (signaled by a logic 1 on the serial input port of the 8085). When the detector data has settled it will be read, processed and formatted into the telemetry data word and transmitted with the telemetry address to the PRIME computer. ELC is then incremented and control returns to the Elevation Fire subroutine.

This package of three subroutines along with the simplified elevation and azimuth hardware will simulate and surpass the functionality of the hardwired ML/MD controller.

3.3 Implementation

This section has presented the first level design for a microprocessor based mast controller. The implementation of this device will require revisions and refinements in both the hardware and software areas. This task is currently outside of the MARS Project goals but could play a vital part in expanding the application of the ML/MD Laser Scanning concept.

PART 4

ALTERNATIVE APPLICATIONS

The ML/MD Laser Scanning concept is a powerful one, and hazard detection for an autonomous roving vehicle is only one of many possible applications for it.

The task of object recognition has traditionally been performed using stereoscopic cameras and specialized signal processing hardware. This camera approach also requires that the scene contain suitable contrast to discern edges. Our system is free from these limitations; what we have developed is a general purpose 3-dimensional vision system. Without the use of stereoscopic techniques our system can locate objects and define their shapes in three dimensions regardless of scene contrast. To be fair, it must also be stated that where contrast is the only differentiating feature our system is ineffective.

The key to our system's power is its flexibility. Our operational system is only a first level implementation of the ML/MD concept; it is a test bed for trying new ideas. In its present form the laser mast can be tailored and tuned to a specific application in terms of range and resolution. Currently the system has a step resolution of 5 cm to 10 cm corresponding to ranges of 2 to 4 meters. This resolution can be changed simply by changing the detector lensing. New areas to be explored include increasing encoder and detector resolution, and the implementation of a Level II controller.

Once one frees oneself from thinking only in the reference frame of a rotating mast on a moving vehicle, a whole new set of applications come to mind. In particular I see strong applications in the area of vision systems for industrial robots, and as a sensing system for automatic assembly of space structures. In these areas our scanning system has several strong advantages over the standard stereoscopic television system.

4.1 Industrial Robot Vision

The ML/MD scanning system is an ideal candidate for inclusion in a robotics vision system. The scanner can assume the function of workspace hazard detection (for both mobile and immobile hazards) and can be tailored to act as the primary vision system for an intelligent robot arm system.

There is currently a project on the RPI campus which would be an ideal candidate for our scanning system. The Bendix Arm project at RPI is concerned with the hierarchical control of an industrial robot arm (Reference 3).

The hardware consists of a 6 axis robot arm, with each axis controlled by a 6800 microprocessor called a Closed Loop Axis Controller (CLAC). Each CLAC controls the dynamics of its axis, given the inputs of desired position and velocity envelope. The 6 CLACs receive their commands from an LSI-11 processor called an Independent Robotics Control System (IRCS). One LSI-11 IRCS controls all 6 axes coordinating their operation to produce concerted action. The topmost level of control will be the IPL PRIME 750 computer located in the Jonsson Engineering Center. The IPL PRIME will coordinate the robot arm with a vision system and will eventually provide a high level user interface with command primitives such as MOVE, PICK and PLACE.

Our system suitability becomes apparent when one realizes that the MARS project also uses the IPL PRIME for its high level processing. All the required interfaces have been built and are operational. Our scanning mast and electronic support systems were designed with portability in mind for use with the Dynamic Test Platform (Reference 4); the ML/MD scanner could easily be moved to the robotics lab for testing purposes. The only additional work necessary would be to pull additional cable from the IPL room to the robotics lab.

The system level software for this new vision system already exists in the form of T$ROVR (Reference 5). The higher level software requirements could be satisfied through modifications to existing MARS project software. Some early Mars path selection algorithms were based on a Kalman filter and Bayesian estimation scheme (Reference 6). This early scheme used these techniques for the analysis of a planetary surface to find the optimum path through it. This concept is directly applicable to the problem of optimally guiding a robot arm through a workspace filled with obstacles or hazards (boxes, tables, people, etc.). With the Kalman filter approach, successive scans (perhaps slightly perturbed in center of scan) improve the modeler's estimation of the scene.

Another application of the mast in this project would be in first level conveyor belt recognition experiments. Instead of rotating, the mast would remain at one azimuth, shooting a dense scan pattern across a moving conveyor belt. If the belt's velocity is known the scanner can determine an object's size and shape without resorting to stereoscopic techniques. The arm scanner system could identify, grasp and sort a collection of objects moving down a conveyor belt.

4.2 Space Assembly

Although the robotic assembly of space structures is a subset of the industrial robot area I feel that our vision system has some specific advantages over current techniques which warrant special mention.

The ML/MD scanning system is capable of operation in a hostile space environment, but this is not a particular advantage over a conventional TV system. Our system does not require external illuminiation of its scanning area (a definite energy saver). Additionally, the computer processing to extract 3-dimensional co-ordinates from the scan data is trivial compared to the processing requirements for most other vision systems. These advantages along with the independence from contrast limitations make the ML/MD scanner a strong contender for space applications.

A possible space application would involve a laser mast with a servo controlled azimuth axis (easily interfaced with the Level II controller). This would give the azimuth axis the ability to rotate continuously, oscillate about a fixed azimuth, or lock at any desired azimuth. This mast would scan an area for some drifting object (a tool, truss, or piece of space junk). The mast would initially use a wide scan pattern. After initial object acquisition the scanner would use a denser pattern to characterize the object. A third scan would provide additional detail and would provide object velocity and direction information. This information could then be transmitted to a manipulator arm to retrieve or possibly avoid the object.

This same device using a dense pattern in an oscillating azimuth scan could act as the primary vision system for a robotics eye-hand coordination system for space assembly.

PART 5

DISCUSSION AND CONCLUSION

After three years of time and effort by many dedicated people, the Multi-Laser/Multi-Detector laser scanning system is now operational. The task has taught us well the difficulties involved in the development of a complex hybrid system which involves electrical, mechanical and optical components.

During the development process the controller electronics were enhanced to take full advantage of new vehicle electronic systems being developed concurrently; these new systems included new telemetry and command links, and an on-board microprocessor. The ML/MD scanner will be the primary tool in the MARS Project goal of developing short range hazard detection capabilities in an autonomous roving vehicle.

We should not remain idle, however. Although the ML/MD system provides a thousand-fold increase in capabilities over the previous Single-Laser/Single-Detector scanner, we should attempt to increase the system's power and flexibility even further. When the software development group can utilize the ML/MD controller's capabilities to the fullest, we should be ready with a next generation of mast controller providing even more capabilities. This is why I have done a preliminary study on the Level II controller. The design included in this report is merely a first cut at the concept of a microprocessor based scanning system. This first draft must be polished and refined into the successor to the ML/MD controller.

The key concept for the next generation of controller is flexibility. Flexibility will allow the controller to quickly take advantage of any new developments in encoder, detector or laser technology.

The current capabilities of the ML/MD controller and the further improvement possible with the Level II controller has opened my eyes to alternative applications for the scanning mast. Our scanner has great potential in robot vision applications. The capability to discern 3-dimensional scene information without stereoscopic sensors is a strong advantage over other vision systems. True the device cannot discern contrast differences in a 2-dimensional image, but neither does it need contrast differences to generate the coordinates of a 3-dimensional scene.

I would like to see work done in this area, perhaps in conjunction with one of the robotics groups presently working on campus. An interesting vision system would be the combination of a conventional TV camera with our scanning mast. The laser mast would discern 3-dimensional detail while the camera could perform 2-dimensional scene analysis on the planar surfaces.

The laser scanning concept is and will continue to be the backbone of the MARS project, but perhaps it is time to share our developments to fully explore the capabilities and limitations of the ML/MD laser scanning concept.

PART 6

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APPENDIX I

Available Center of Scan Angles

AVAILABLE AZIMUTH CENTER OF SCAN ANGLES

CENTER OF SCAN ANGLE	REF. ANGLE OCTAL	REF. ANGLE BINARY	COMPUTER COMMAND WORD OCTAL	COMPUTER COMMAND WORD BINARY
-180.0000	200	10000000	200	10000000
-178.5938	177	01111111	177	01111111
-177.1875	176	01111110	176	01111110
-175.7813	175	01111101	175	01111101
-174.3750	174	01111100	174	01111100
-172.9688	173	01111011	173	01111011
-171.5625	172	01111010	172	01111010
-170.1563	171	01111001	171	01111001
-168.7500	170	01111000	170	01111000
-167.3438	167	01110111	167	01110111
-165.9375	166	01110110	166	01110110
-164.5313	165	01110101	165	01110101
-163.1250	164	01110100	164	01110100
-161.7188	163	01110011	163	01110011
-160.3125	162	01110010	162	01110010
-158.9063	161	01110001	161	01110001
-157.5000	160	01110000	160	01110000
-156.0938	157	01101111	157	01101111
-154.6875	156	01101110	156	01101110
-153.2813	155	01101101	155	01101101
-151.8750	154	01101100	154	01101100
-150.4688	153	01101011	153	01101011
-149.0625	152	01101010	152	01101010
-147.6563	151	01101001	151	01101001
-146.2500	150	01101000	150	01101000
-144.8438	147	01100111	147	01100111
-143.4375	146	01100110	146	01100110
-142.0313	145	01100101	145	01100101
-140.6250	144	01100100	144	01100100
-139.2188	143	01100011	143	01100011
-137.8125	142	01100010	142	01100010
-136.4063	141	01100001	141	01100001
-135.0000	140	01100000	140	01100000
-133.5938	137	01011111	137	01011111
-132.1875	136	01011110	136	01011110
-130.7813	135	01011101	135	01011101
-129.3750	134	01011100	134	01011100
-127.9688	133	01011011	133	01011011
-126.5625	132	01011010	132	01011010
-125.1563	131	01011001	131	01011001
-123.7500	130	01011000	130	01011000
-122.3438	127	01010111	127	01010111
-120.9375	126	01010110	126	01010110
-119.5313	125	01010101	125	01010101
-118.1250	124	01010100	124	01010100
-116.7188	123	01010011	123	01010011
-115.3125	122	01010010	122	01010010
-113.9063	121	01010001	121	01010001
-112.5000	120	01010000	120	01010000

-111.0938	117	01001111	117	01001111
-109.6875	116	01001110	116	01001110
-108.2813	115	01001101	115	01001101
-106.8750	114	01001100	114	01001100
-105.4688	113	01001011	113	01001011
-104.0625	112	01001010	112	01001010
-102.6563	111	01001001	111	01001001
-101.2500	110	01001000	110	01001000
-99.8438	107	01000111	107	01000111
-98.4375	106	01000110	106	01000110
-97.0313	105	01000101	105	01000101
-95.6250	104	01000100	104	01000100
-94.2188	103	01000011	103	01000011
-92.8125	102	01000010	102	01000010
-91.4063	101	01000001	101	01000001
-90.0000	100	01000000	100	01000000
-88.5938	077	00111111	077	00111111
-87.1875	076	00111110	076	00111110
-85.7813	075	00111101	075	00111101
-84.3750	074	00111100	074	00111100
-82.9688	073	00111011	073	00111011
-81.5625	072	00111010	072	00111010
-80.1563	071	00111001	071	00111001
-78.7500	070	00111000	070	00111000
-77.3438	067	00110111	067	00110111
-75.9375	066	00110110	066	00110110
-74.5313	065	00110101	065	00110101
-73.1250	064	00110100	064	00110100
-71.7188	063	00110011	063	00110011
-70.3125	062	00110010	062	00110010
-68.9063	061	00110001	061	00110001
-67.5000	060	00110000	060	00110000
-66.0938	057	00101111	057	00101111
-64.6875	056	00101110	056	00101110
-63.2813	055	00101101	055	00101101
-61.8750	054	00101100	054	00101100
-60.4688	053	00101011	053	00101011
-59.0625	052	00101010	052	00101010
-57.6563	051	00101001	051	00101001
-56.2500	050	00101000	050	00101000
-54.8438	047	00100111	047	00100111
-53.4375	046	00100110	046	00100110
-52.0313	045	00100101	045	00100101
-50.6250	044	00100100	044	00100100
-49.2188	043	00100011	043	00100011
-47.8125	042	00100010	042	00100010
-46.4063	041	00100001	041	00100001
-45.0000	040	00100000	040	00100000
-43.5938	037	00011111	037	00011111
-42.1875	036	00011110	036	00011110
-40.7813	035	00011101	035	00011101
-39.3750	034	00011100	034	00011100
-37.9688	033	00011011	033	00011011
-36.5625	032	00011010	032	00011010
-35.1563	031	00011001	031	00011001
-33.7500	030	00011000	030	00011000

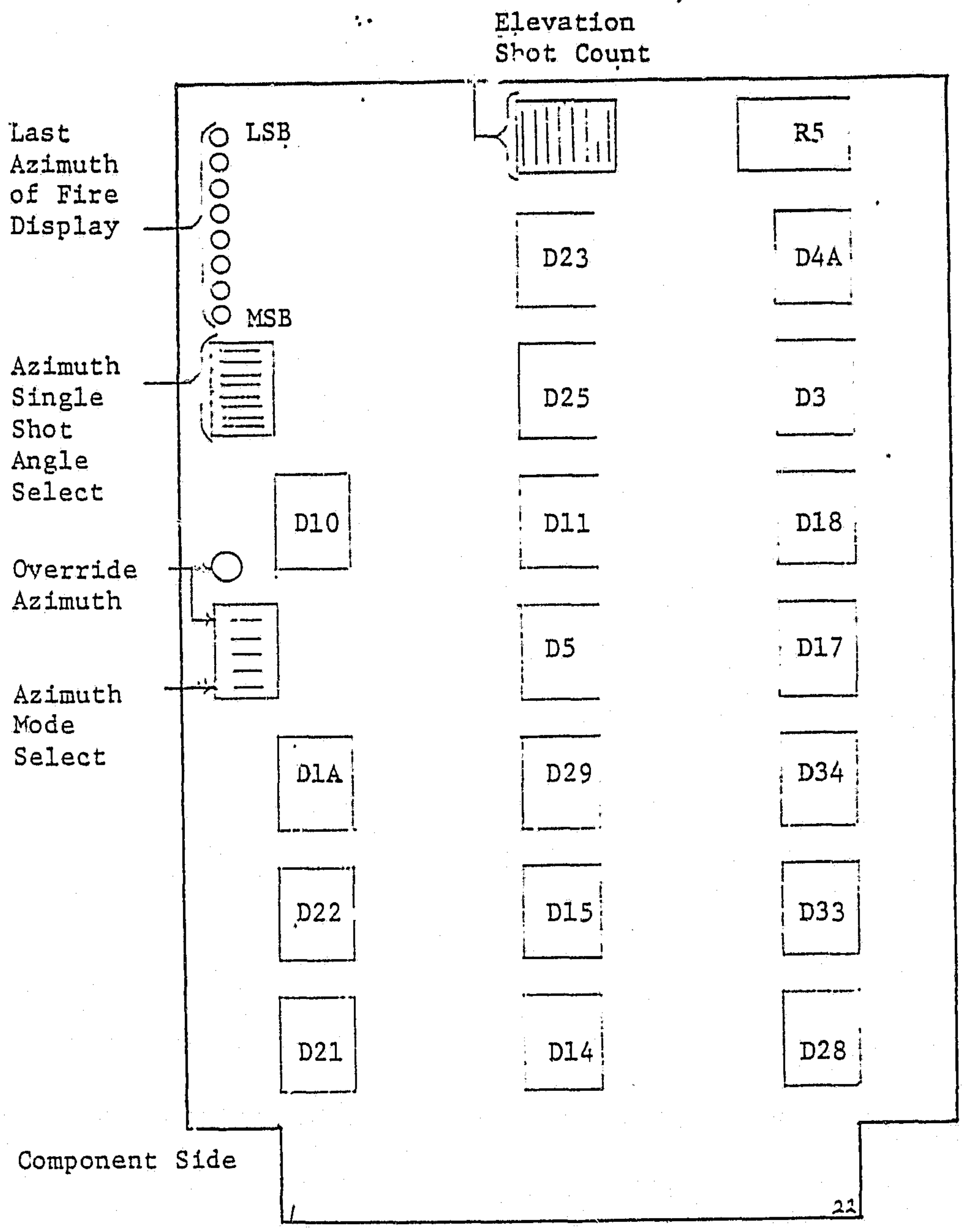
-32.3438	027	00010111	027	00010111
-30.9375	026	00010110	026	00010110
-29.5313	025	00010101	025	00010101
-28.1250	024	00010100	024	00010100
-26.7188	023	00010011	023	00010011
-25.3125	022	00010010	022	00010010
-23.9063	021	00010001	021	00010001
-22.5000	020	00010000	020	00010000
-21.0938	017	00001111	017	00001111
-19.6875	016	00001110	016	00001110
-18.2813	015	00001101	015	00001101
-16.8750	014	00001100	014	00001100
-15.4688	013	00001011	013	00001011
-14.0625	012	00001010	012	00001010
-12.6563	011	00001001	011	00001001
-11.2500	010	00001000	010	00001000
-9.8438	007	00000111	007	00000111
-8.4375	006	00000110	006	00000110
-7.0313	005	00000101	005	00000101
-5.6250	004	00000100	004	00000100
-4.2188	003	00000011	003	00000011
-2.8125	002	00000010	002	00000010
-1.4063	001	00000001	001	00000001
0.0000	000	00000000	000	00000000
1.4063	377	11111111	377	11111111
2.8125	376	11111110	376	11111110
4.2188	375	11111101	375	11111101
5.6250	374	11111100	374	11111100
7.0313	373	11111011	373	11111011
8.4375	372	11111010	372	11111010
9.8438	371	11111001	371	11111001
11.2500	370	11111000	370	11111000
12.6563	367	11110111	367	11110111
14.0625	366	11110110	366	11110110
15.4688	365	11110101	365	11110101
16.8750	364	11110100	364	11110100
18.2813	363	11110011	363	11110011
19.6875	362	11110010	362	11110010
21.0938	361	11110001	361	11110001
22.5000	360	11110000	360	11110000
23.9063	357	11101111	357	11101111
25.3125	356	11101110	356	11101110
26.7188	355	11101101	355	11101101
28.1250	354	11101100	354	11101100
29.5313	353	11101011	353	11101011
30.9375	352	11101010	352	11101010
32.3438	351	11101001	351	11101001
33.7500	350	11101000	350	11101000
35.1563	347	11100111	347	11100111
36.5625	346	11100110	346	11100110
37.9688	345	11100101	345	11100101
39.3750	344	11100100	344	11100100
40.7813	343	11100011	343	11100011
42.1875	342	11100010	342	11100010
43.5938	341	11100001	341	11100001
45.0000	340	11100000	340	11100000

46.4063	337	11011111	337	11011111
47.8125	336	11011110	336	11011110
49.2188	335	11011101	335	11011101
50.6250	334	11011100	334	11011100
52.0313	333	11011011	333	11011011
53.4375	332	11011010	332	11011010
54.8438	331	11011001	331	11011001
56.2500	330	11011000	330	11011000
57.6563	327	11010111	327	11010111
59.0625	326	11010110	326	11010110
60.4688	325	11010101	325	11010101
61.8750	324	11010100	324	11010100
63.2813	323	11010011	323	11010011
64.6875	322	11010010	322	11010010
66.0938	321	11010001	321	11010001
67.5000	320	11010000	320	11010000
68.9063	317	11001111	317	11001111
70.3125	316	11001110	316	11001110
71.7188	315	11001101	315	11001101
73.1250	314	11001100	314	11001100
74.5313	313	11001011	313	11001011
75.9375	312	11001010	312	11001010
77.3438	311	11001001	311	11001001
78.7500	310	11001000	310	11001000
80.1563	307	11000111	307	11000111
81.5625	306	11000110	306	11000110
82.9688	305	11000101	305	11000101
84.3750	304	11000100	304	11000100
85.7813	303	11000011	303	11000011
87.1875	302	11000010	302	11000010
88.5938	301	11000001	301	11000001
90.0000	300	11000000	300	11000000
91.4063	277	10111111	277	10111111
92.8125	276	10111110	276	10111110
94.2188	275	10111101	275	10111101
95.6250	274	10111100	274	10111100
97.0313	273	10111011	273	10111011
98.4375	272	10111010	272	10111010
99.8438	271	10111001	271	10111001
101.2500	270	10111000	270	10111000
102.6563	267	10110111	267	10110111
104.0625	266	10110110	266	10110110
105.4688	265	10110101	265	10110101
106.8750	264	10110100	264	10110100
108.2813	263	10110011	263	10110011
109.6875	262	10110010	262	10110010
111.0938	261	10110001	261	10110001
112.5000	260	10110000	260	10110000
113.9063	257	10101111	257	10101111
115.3125	256	10101110	256	10101110
116.7188	255	10101101	255	10101101
118.1250	254	10101100	254	10101100
119.5313	253	10101011	253	10101011
120.9375	252	10101010	252	10101010
122.3438	251	10101001	251	10101001
123.7500	250	10101000	250	10101000

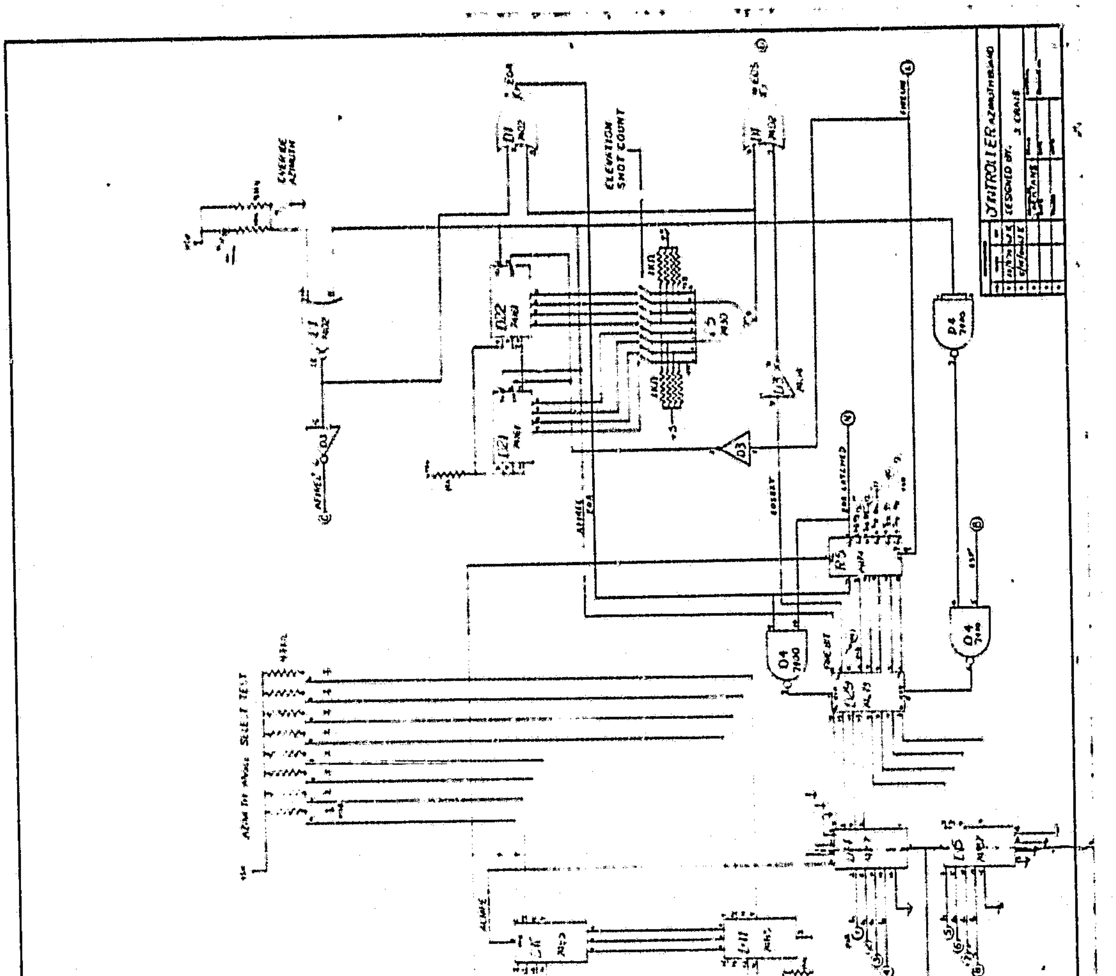
125.1563	247	10100111	247	10100111
126.5625	246	10100110	246	10100110
127.9688	245	10100101	245	10100101
129.3750	244	10100100	244	10100100
130.7813	243	10100011	243	10100011
132.1875	242	10100010	242	10100010
133.5938	241	10100001	241	10100001
135.0000	240	10100000	240	10100000
136.4063	237	10011111	237	10011111
137.8125	236	10011110	236	10011110
139.2188	235	10011101	235	10011101
140.6250	234	10011100	234	10011100
142.0313	233	10011011	233	10011011
143.4375	232	10011010	232	10011010
144.8438	231	10011001	231	10011001
146.2500	230	10011000	230	10011000
147.6563	227	10010111	227	10010111
149.0625	226	10010110	226	10010110
150.4688	225	10010101	225	10010101
151.8750	224	10010100	224	10010100
153.2813	223	10010011	223	10010011
154.6875	222	10010010	222	10010010
156.0938	221	10010001	221	10010001
157.5000	220	10010000	220	10010000
158.9063	217	10001111	217	10001111
160.3125	216	10001110	216	10001110
161.7188	215	10001101	215	10001101
163.1250	214	10001100	214	10001100
164.5313	213	10001011	213	10001011
165.9375	212	10001010	212	10001010
167.3438	211	10001001	211	10001001
168.7500	210	10001000	210	10001000
170.1563	207	10000111	207	10000111
171.5625	206	10000110	206	10000110
172.9688	205	10000101	205	10000101
174.3750	204	10000100	204	10000100
175.7813	203	10000011	203	10000011
177.1875	202	10000010	202	10000010
178.5938	201	10000001	201	10000001

APPENDIX II

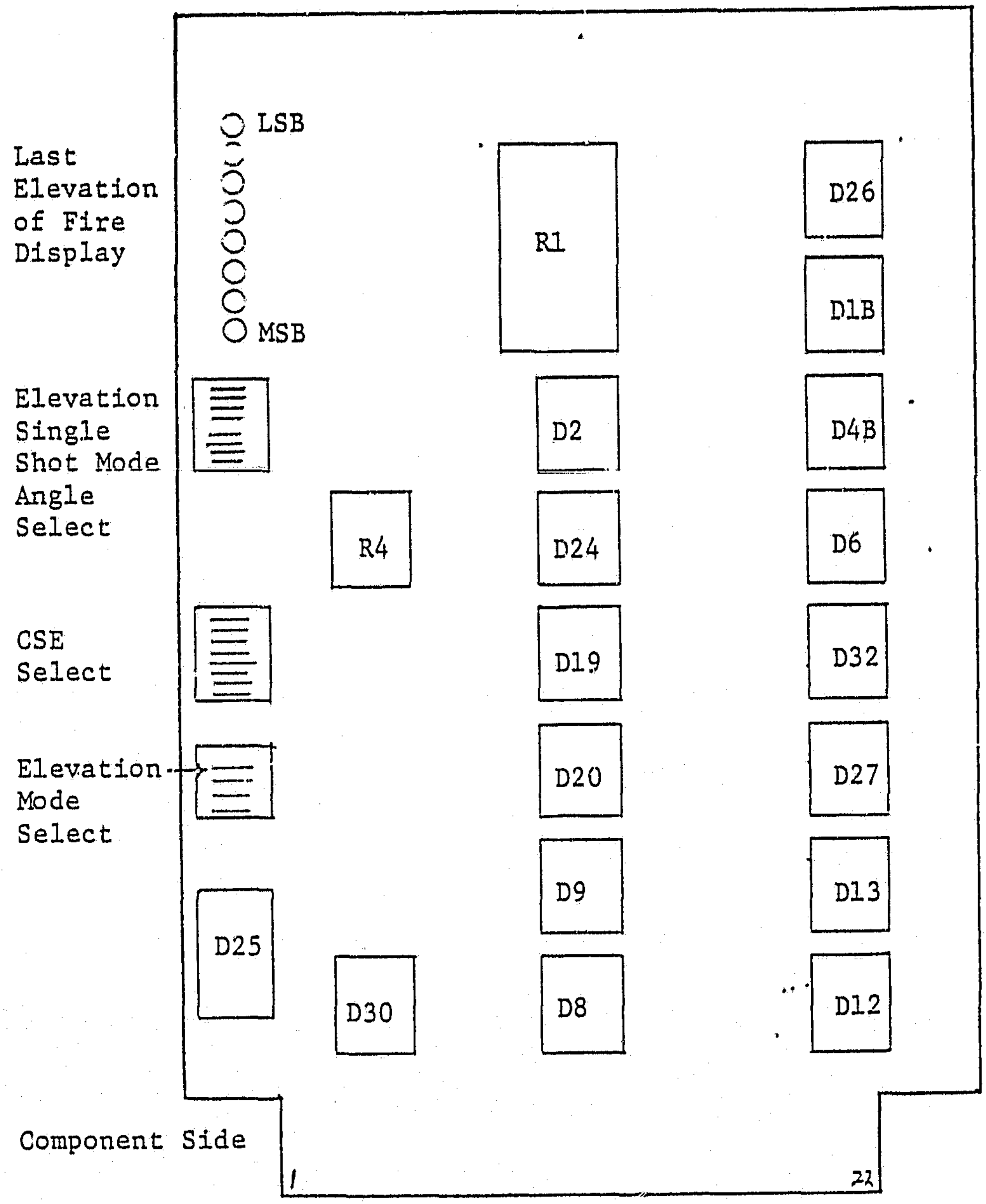
ML/MD Board Layouts, Schematics and
Timing Diagram



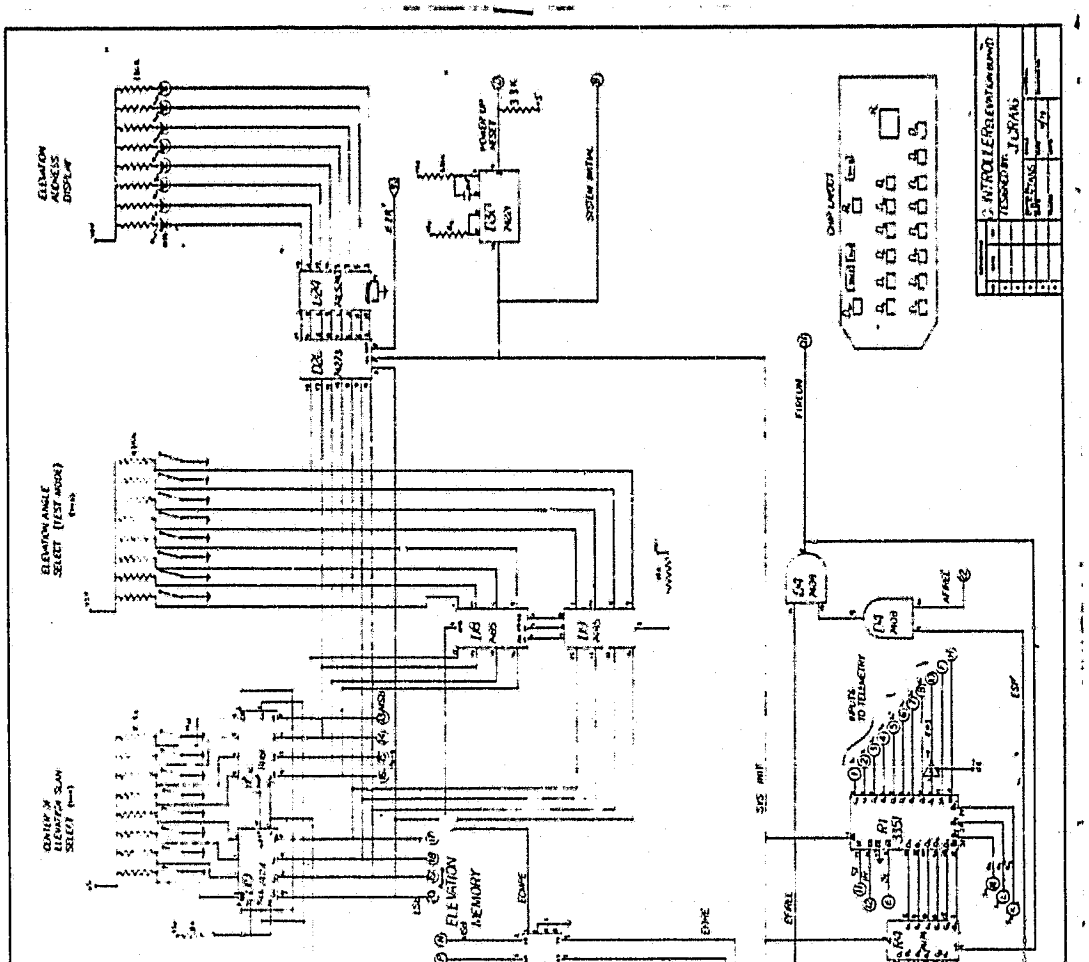
Azimuth Board Layout



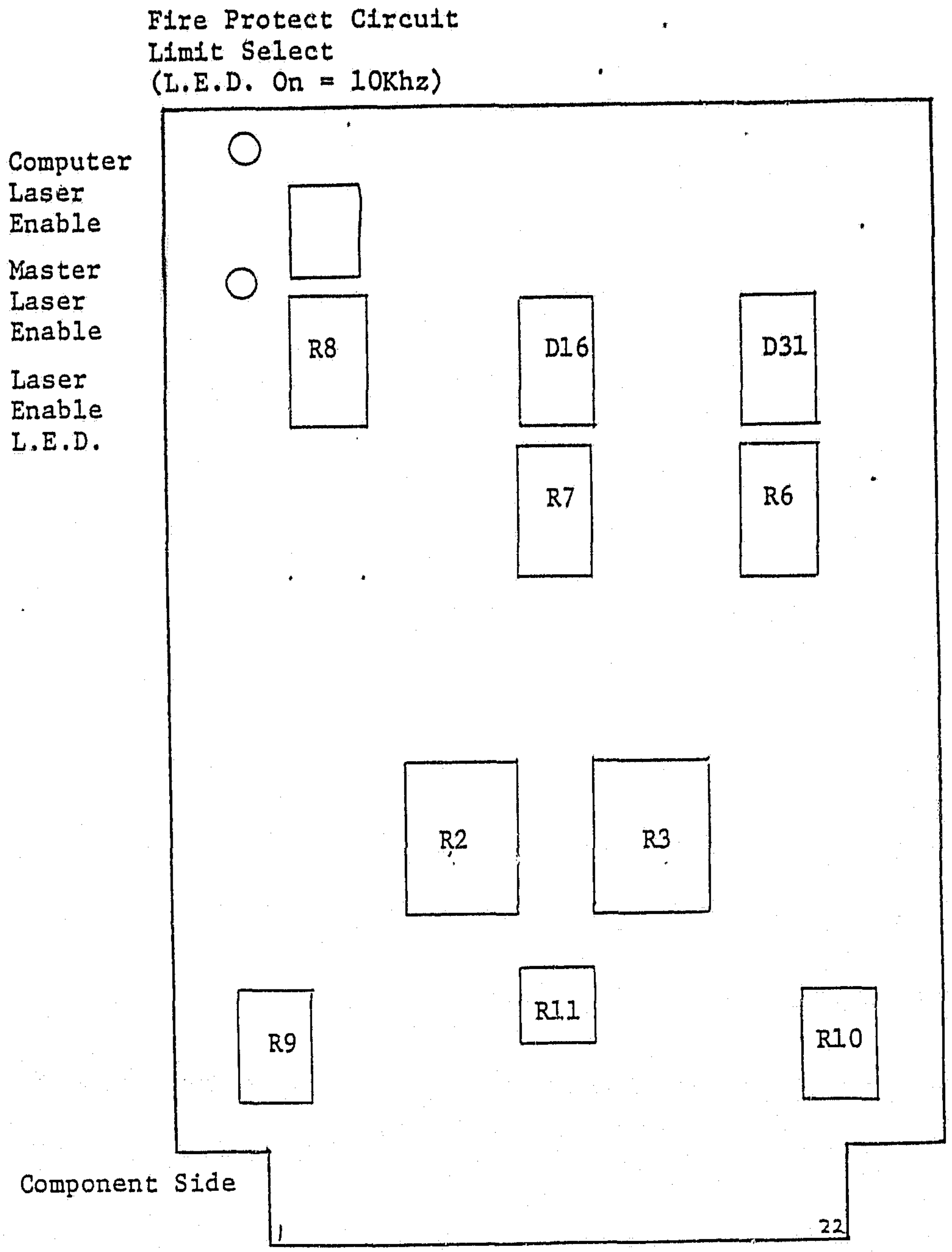
Azimuth Board Schematic



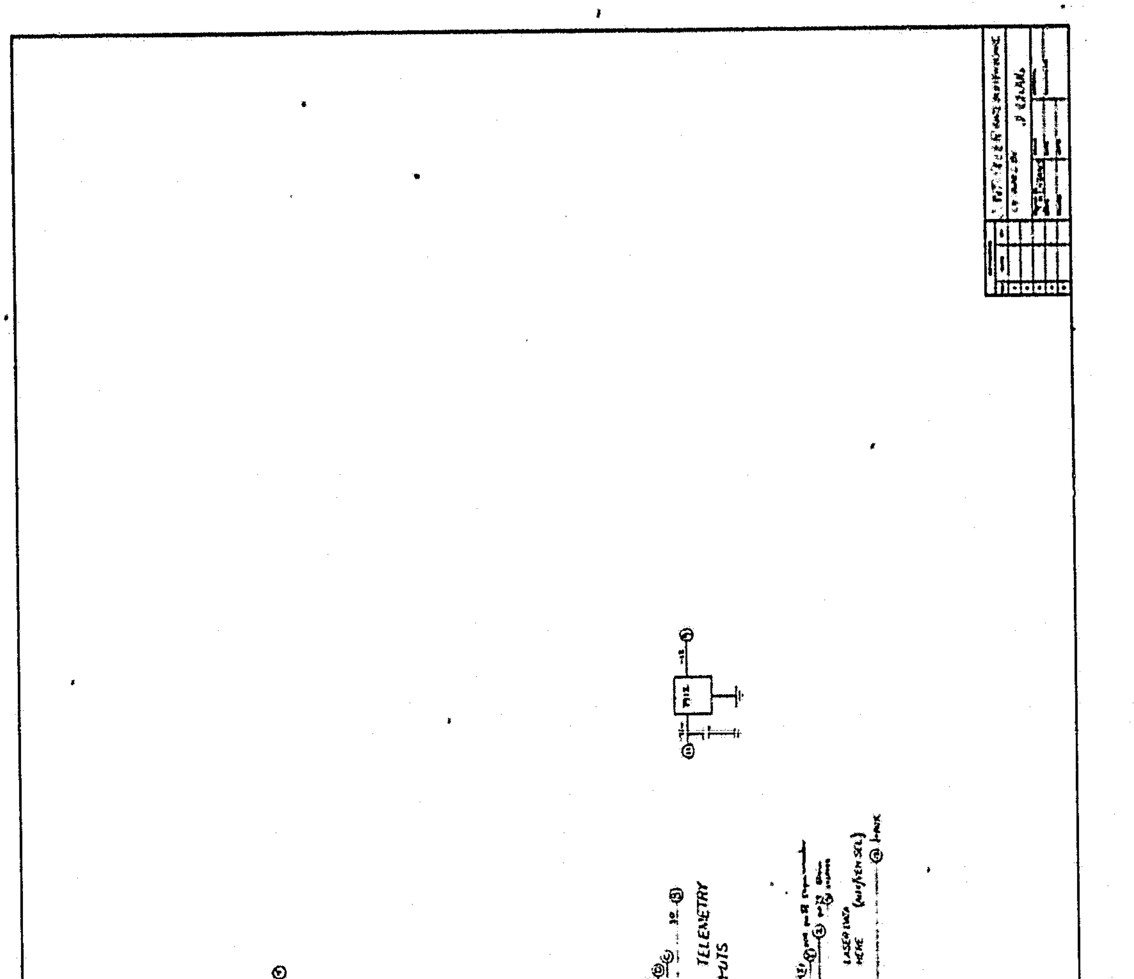
Elevation Board Layout



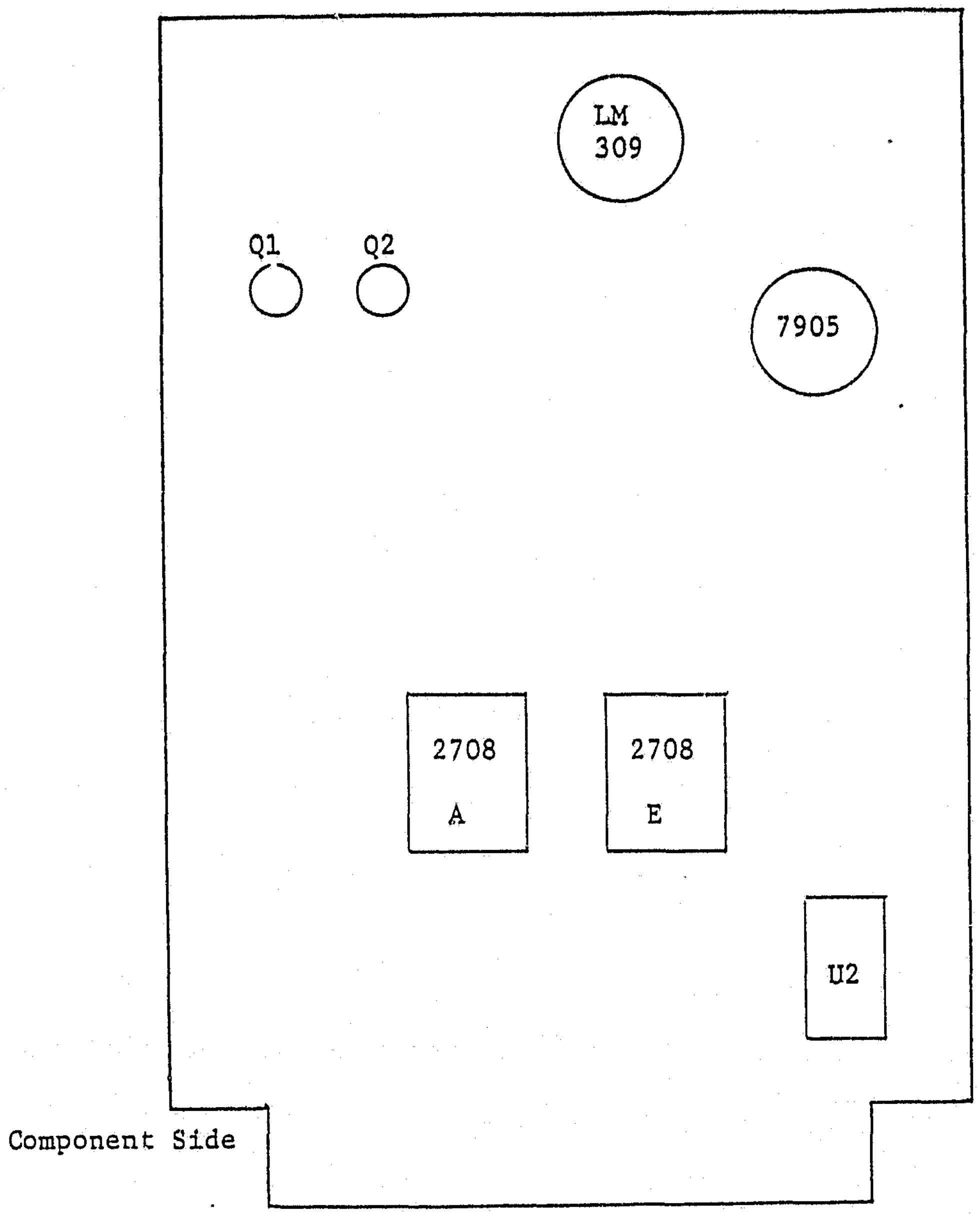
Elevation Board Schematic



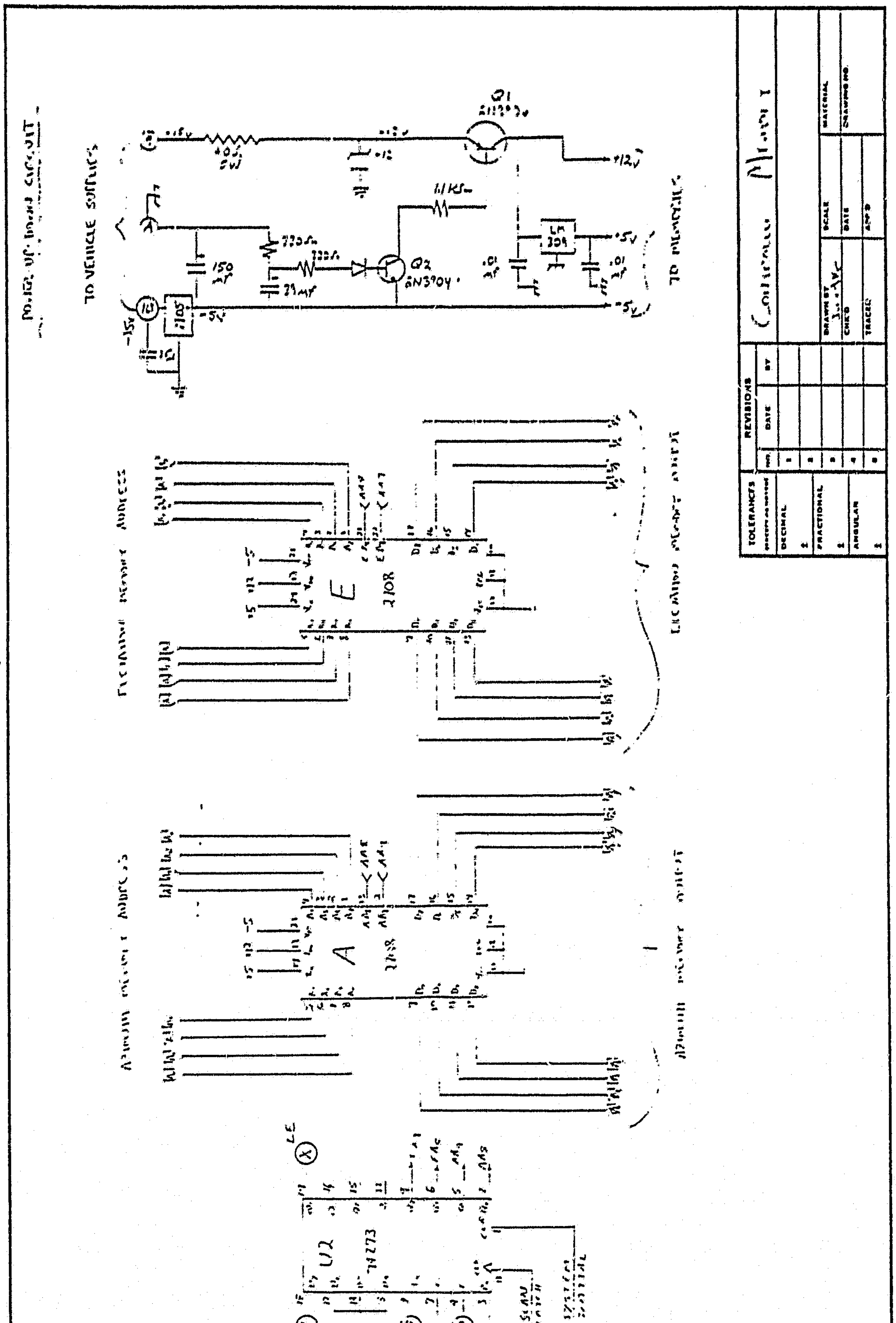
Rate Buffer Board Layout



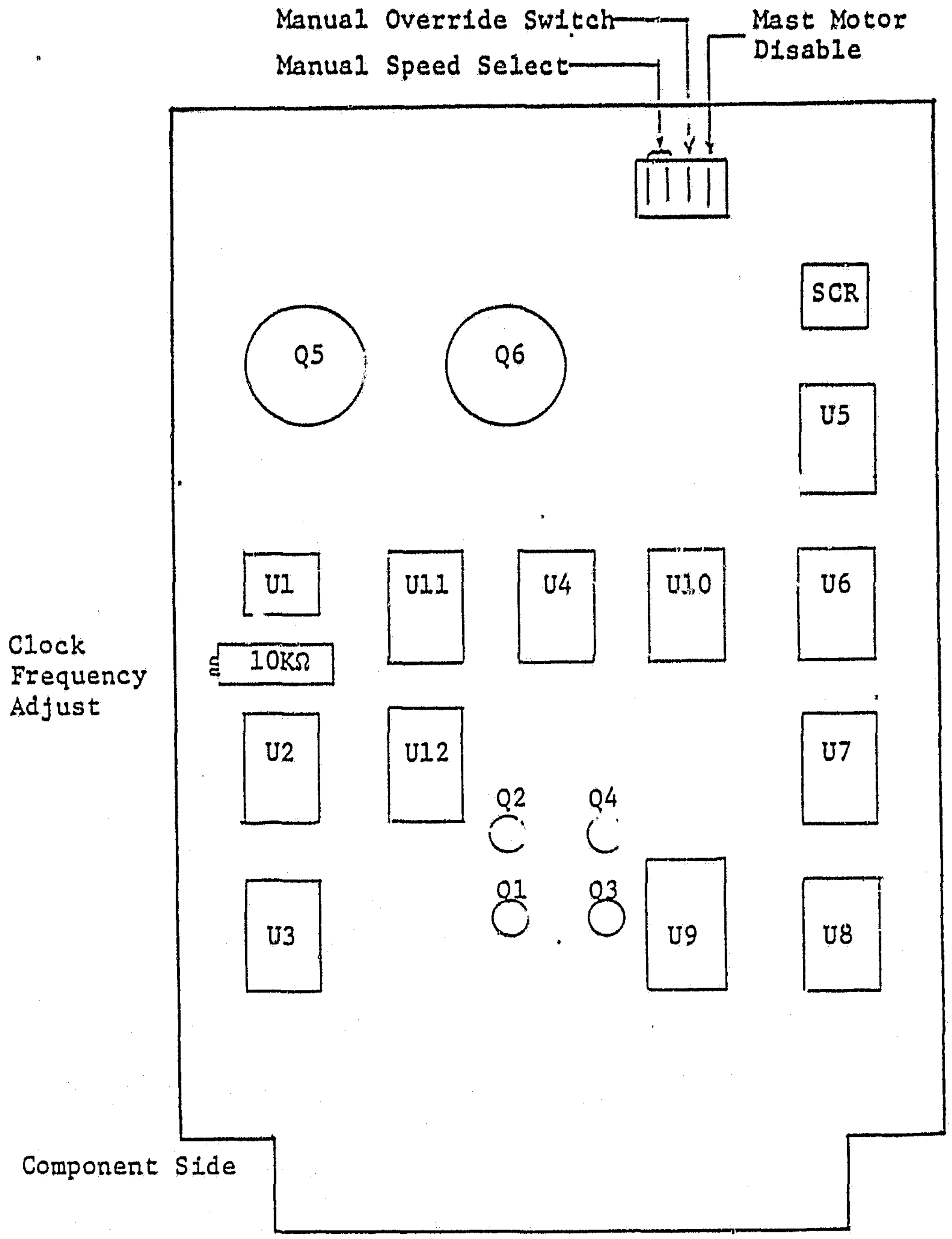
Rate Buffer Board Schematic



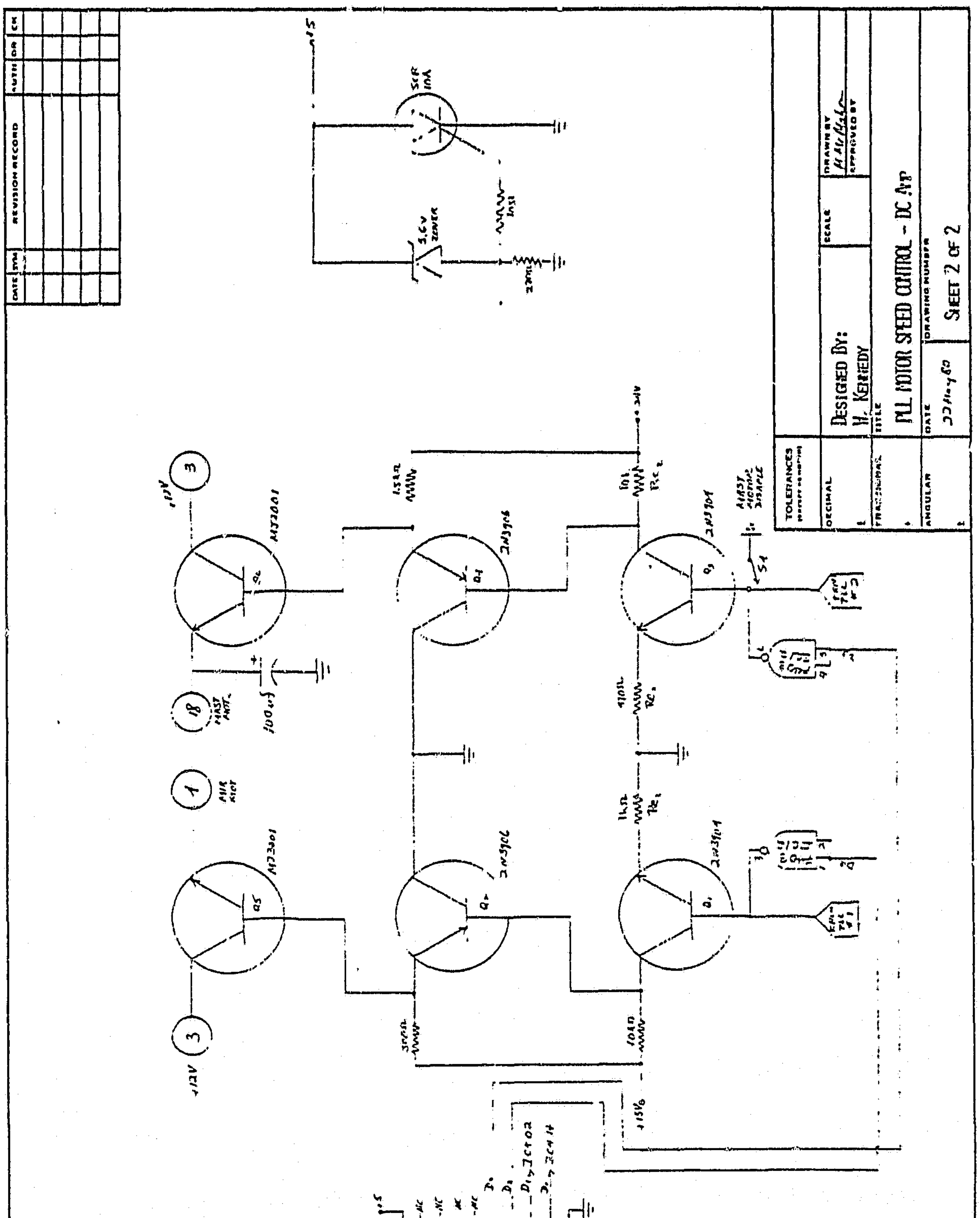
Memory Board Layout



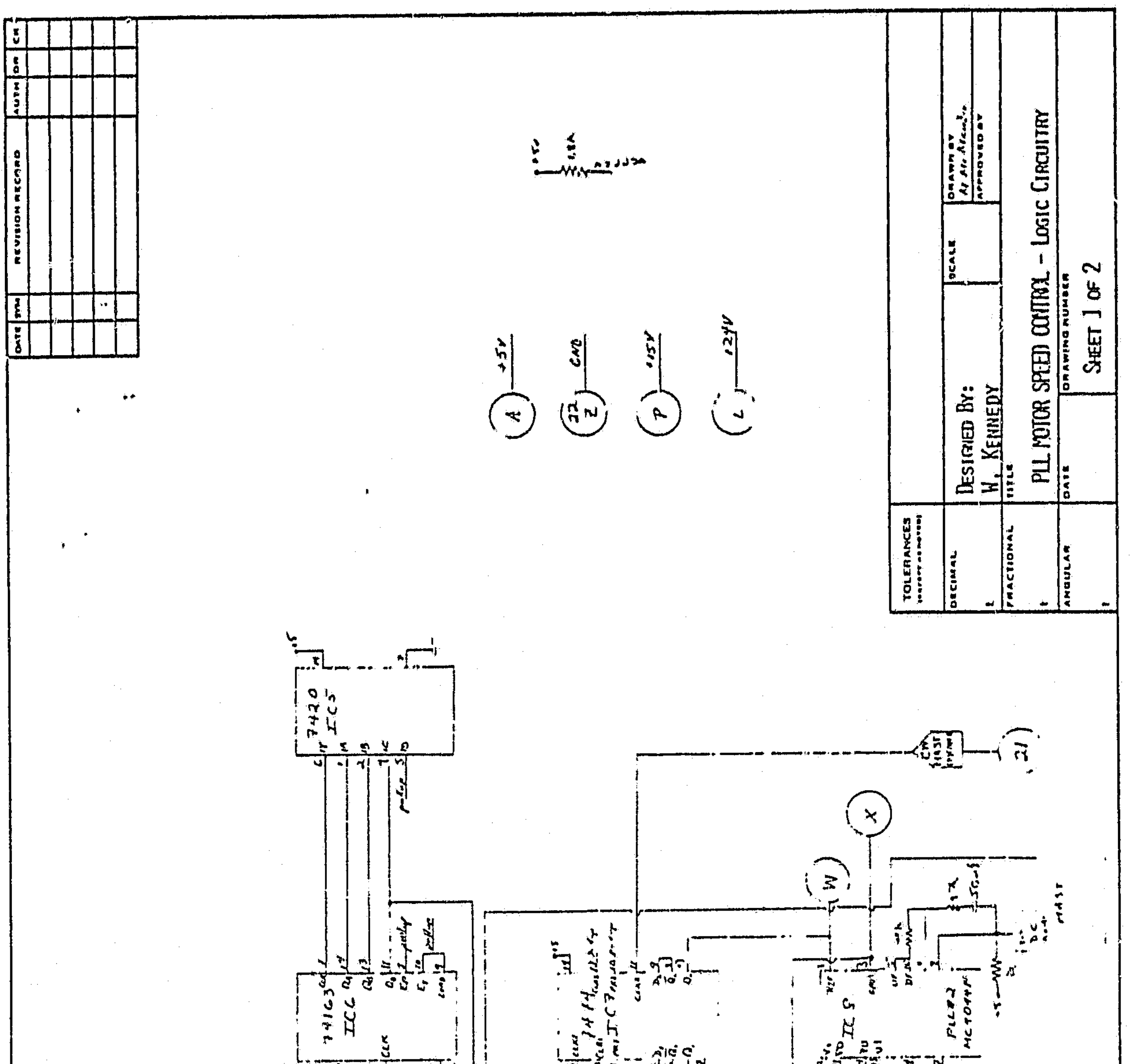
Memory Board Schematic



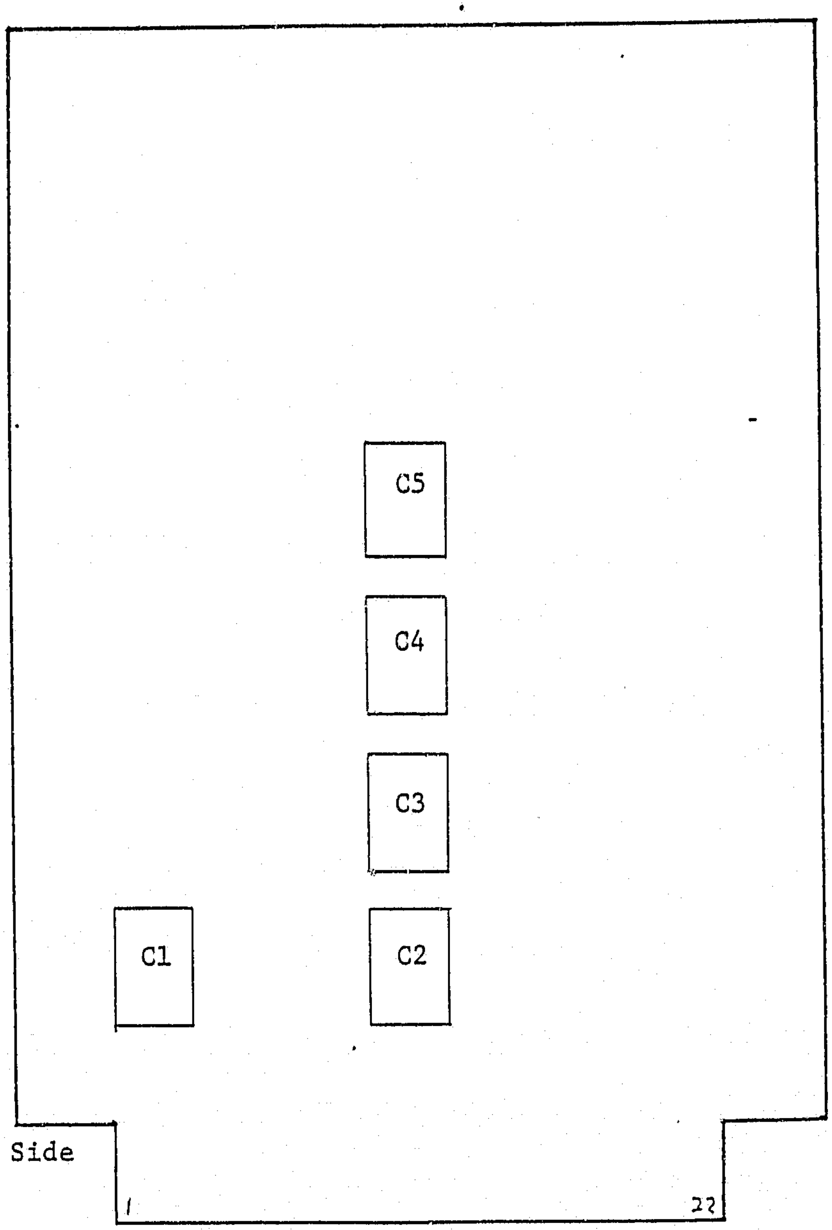
Motor Speed Control Board Layout



Motor Speed Control Board Schematic

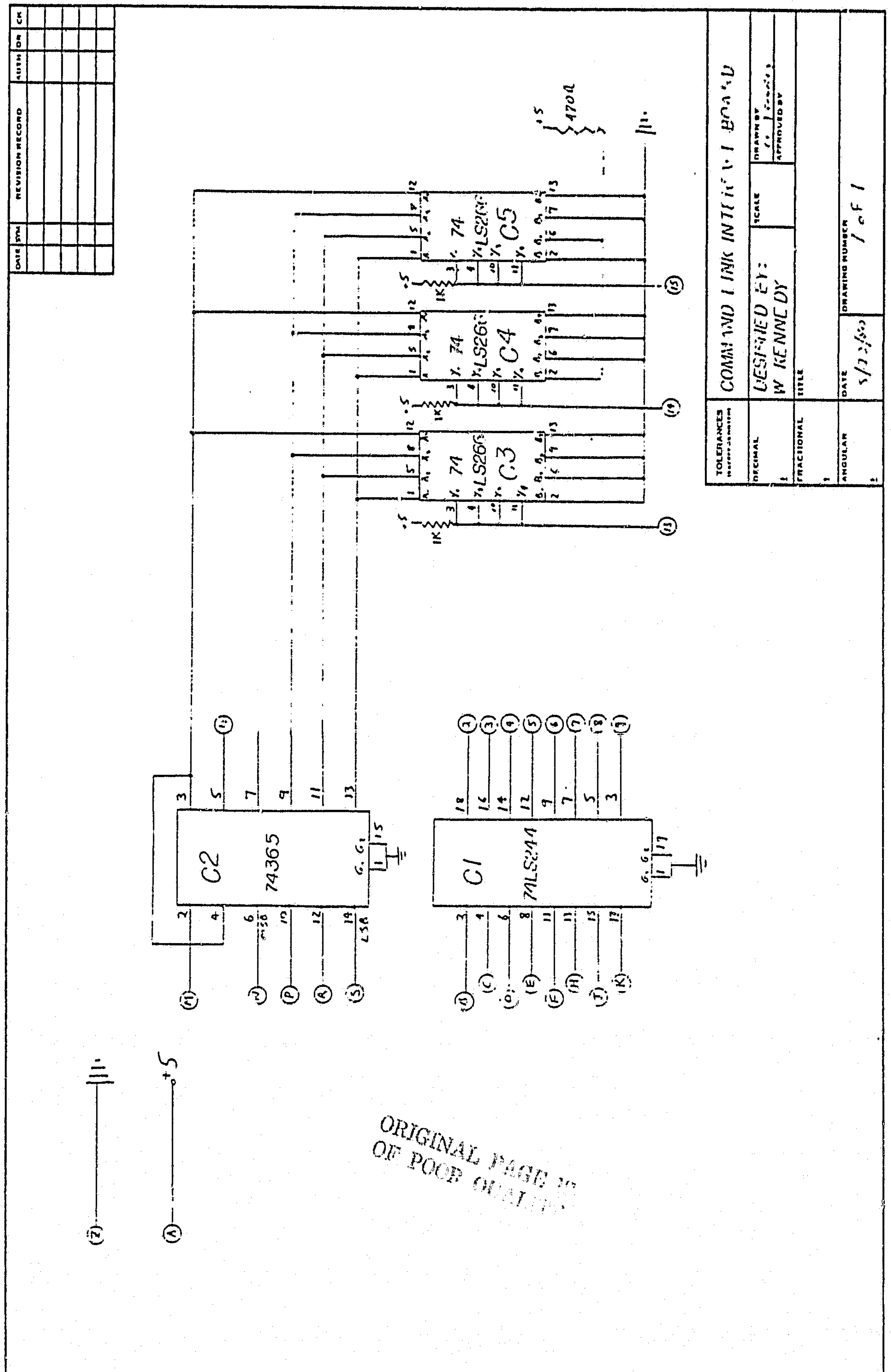


Motor Speed Control Board Schematic

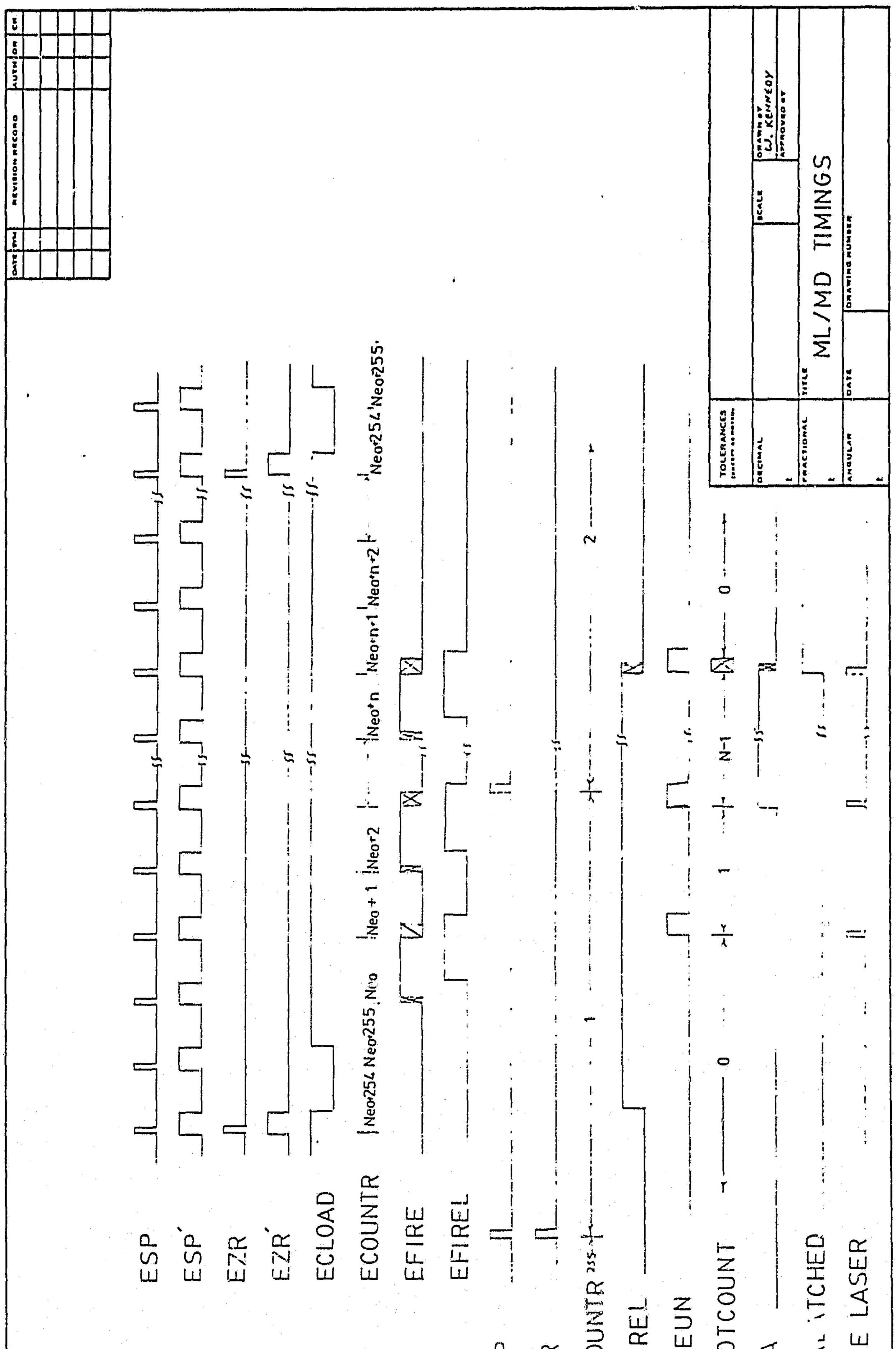


Component Side

Command Link Interface Board Layout



Command Link Interface Board Schematic



ML/MD Controller Timing Diagram

Appendix III

ML/MD Board and Connector Pinouts

A	GROUND	1	$A\phi_7$
B	ESP'	2	$A\phi_6$
C	AFIREL'	3	$A\phi_5$
D	EOS	4	$A\phi_4$
E		5	$A\phi_3$
F		6	$A\phi_2$
H	AZR	7	$A\phi_1$
J	ASP	8	$A\phi_0$
K	SYSTEM INITIALIZE	9	S_5L
L	FIREUN	10	S_6L
M		11	S_7L
N	EOA LATCHED	12	S_8L
P	CSA LATCH	13	S_9L
R	AA_7	14	SSA
S	AA_6	15	C_7
T	AA_5	16	C_6
U	AA_4	17	C_5
V	AA_3	18	C_4
W	AA_2	19	C_3
X	AA_1	20	C_2
Y	AA_0	21	C_1
Z	+5 VOLTS	22	C_0

Azimuth Board Pinouts

A	GROUND	1	T_0
B	SYSTEM INITIALIZE	2	T_1
C	ESP'	3	T_2
D	POWER UP RESET	4	T_3
E	OUTPUT ENABLE $\overline{OE}$	5	T_4
F	SO'	6	T_5
H	OR'	7	T_6
J	EOS	8	T_7
K	S_7L	9	-12 VOLTS
L	S_6L	10	T_{20} - EOS
M	S_5L	11	SI'
N	$E\phi_7$	12	IR'
P	$E\phi_6$	13	EA_7
R	$E\phi_5$	14	EA_6
S	$E\phi_4$	15	EA_5
T	$E\phi_3$	16	EA_4
U	$E\phi_2$	17	EA_3
V	$E\phi_1$	18	EA_2
W	$E\phi_0$	19	EA_1
X	EZR	20	EA_0
Y	ESP	21	FIREUN
Z	+5 VOLTS	22	AFIREL'

Elevation Board Pinouts

A	+5 VOLTS	1	S_8L
B	LASER ENABLE - LE	2	T_8
C	T_{17}	3	OUTPUT ENABLE - $\overline{OE}$
D	T_{16}	4	EOA LATCHED
E	T_{18}	5	S_9L
F	T_{15}	6	"LASER = 1"
H	T_{14}	7	
J	T_{13}	8	$\overline{SO}$
K	T_{11}	9	-12 VOLTS
L	T_{12}	10	SI'
M	T_9	11	-15 VOLTS
N	α_0'	12	SO'
P	α_1'	13	LASER DATA HERE
R	α_2'	14	OR'
S	α_3'	15	FIRE LASER
T	α_4'	16	RECEIVER DATA READY
U	α_0	17	α_2
V	α_1	18	α_3
W	T_{19}	19	α_4
X	T_{21}	20	IR'
Y	T_{20}	21	FIREUN
Z	GROUND	22	SYSTEM INITIALIZE

Rate Buffer Board Pinouts

A	GROUND	1	$A\phi_0$
B	AA_0	2	$A\phi_1$
C	AA_1	3	$A\phi_2$
D	AA_2	4	$A\phi_3$
E	AA_3	5	$A\phi_4$
F	AA_4	6	$A\phi_5$
H	AA_5	7	$A\phi_6$
J	AA_6	8	$A\phi_7$
K	AA_7	9	+12 VOLTS
L	SYSTEM INITIALIZE	10	-15 VOLTS
M	EA_0	11	$E\phi_0$
N	EA_1	12	$E\phi_1$
P	EA_2	13	$E\phi_2$
R	EA_3	14	$E\phi_3$
S	EA_4	15	$E\phi_4$
T	EA_5	16	$E\phi_5$
U	EA_6	17	$E\phi_6$
V	EA_7	18	$E\phi_7$
W	SCAN LATCH	19	C_0
X	LASER ENABLE - LE	20	C_1
Y	C_7	21	C_2
Z	+5 VOLTS	22	C_3

Memory Board Pinouts

A	+5 VOLTS	1	ESP
B	TEST POINT - REF. CLOCK	2	SYSTEM INITIALIZE
C	TEST POINT - MIRROR REF.	3	+12 VOLTS
D	TEST POINT - MIRROR ERROR	4	MIRROR MOTOR DRIVE
E		5	
F		6	C_7
H		7	C_6
J		8	C_5
K		9	C_4
L	+24 VOLTS	10	C_3
M		11	C_2
N		12	C_1
P	+15 VOLTS	13	C_0
R		14	SPEED LATCH
S		15	
T		16	
U		17	
V		18	MAST MOTOR DRIVE
W	TEST POINT - MAST ERROR	19	
X	TEST POINT - MAST REF.	20	
Y		21	ASP
Z	GROUND	22	GROUND

Motor Speed Board Pinouts

A	+5 VOLTS	1	
B	D_7	2	C_7
C	D_6	3	C_6
D	D_5	4	C_5
E	D_4	5	C_4
F	D_3	6	C_3
H	D_2	7	C_2
J	D_1	8	C_1
K	D_0	9	C_0
L		10	
M	$\overline{DAV}$	11	$\overline{DA}$
N	A_3	12	
P	A_2	13	CSA LATCH
R	A_1	14	SCAN LATCH
S	A_0	15	SPEED LATCH
T		16	
U		17	
V		18	
W		19	
X		20	
Y		21	
Z	GROUND	22	

Command Link Interface Board Pinouts

PLUG NO. J1

MALE x FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS SLIP RINGS TO ML/MD CONTROLLER

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
1	-			
2	ESP	RED/YELLOW	ELEVATION	Y
3	EZR	GREEN/YELLOW	ELEVATION	X
4	α_1	BLUE/YELLOW	RATE BUFFER	N
5	α_2	BLACK/YELLOW	RATE BUFFER	P
6	α_3	VIOLET/YELLOW	RATE BUFFER	R
7	-			
8	-			
9	-	ORANGE		
10	-	GREEN		
11	-	BLACK		
12	-	BLUE		
13	FIRE LASER	BROWN	RATE BUFFER	15

PLUG NO. J1

MALE X FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS SLIP RINGS TO ML/MD CONTROLLER

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
14	α_{10}	GREEN/BROWN	RATE BUFFER	19
15	α_9	GREEN/RED	RATE BUFFER	18
16	α_8	BLACK/ORANGE	RATE BUFFER	17
17	α_7	BLACK/VIOLET	RATE BUFFER	V
18	α_6	BLACK/BLUE	RATE BUFFER	U
19	α_5	BLACK/GREY	RATE BUFFER	T
20	α_4	BLACK/GREEN	RATE BUFFER	S
21	-			
22	-	BLACK/RED		
23	MIR. GND	RED	SPEED CONTROL	22
25	MIR. DRIVE	GREY	SPEED CONTROL	4

PLUG NO. J2

MALE X FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS ML/MD CONTROLLER TO STATIONARY MAST CIRCUITRY

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
1	ASP		AZIMUTH	J
2	AZR		AZIMUTH	H
3	ENCODER GROUND		AZIMUTH	A
4	+24 VOLTS		J3	50
5	GROUND		SPEED CONTROL	22
6	+5 VOLTS		AZIMUTH	Z
7	-15 VOLTS		J3	48
8	+12 VOLTS		SPEED CONTROL	P
9	MAST DRIVE		SPEED CONTROL	18

PLUG NO. J3

MALE X FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS ML/MD MAST TO VEHICLE ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
1	D_0		COMMAND LINK	K
2	D_1		COMMAND LINK	J
3	D_2		COMMAND LINK	H
4	D_3		COMMAND LINK	F
5	D_4		COMMAND LINK	E
6	$T_0 - \beta_0$		ELEVATION	1
7	$T_1 - \beta_1$		ELEVATION	2
8	$T_2 - \beta_2$		ELEVATION	3
9	$T_3 - \beta_3$		ELEVATION	4
10	$T_4 - \beta_4$		ELEVATION	5
11	T_{22} - "1 = LASER"		RATE BUFFER	6
12	POWER UP RESET		ELEVATION	D
13	A_0		COMMAND LINK	S

PLUG NO. J3

MALE X FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS ML/MD MAST TO VEHICLE ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
14	GROUND			
15	NC			
16	NC			
17	+12 VOLTS		SPEED CONTROL	3
18	D_5		COMMAND LINK	D
19	D_6		COMMAND LINK	C
20	D_7		COMMAND LINK	B
21	$T_5 - \theta_0$		ELEVATION	6
22	$T_6 - \theta_1$		ELEVATION	7
23	$T_7 - \theta_2$		ELEVATION	8
24	$T_8 - \theta_3$		RATE BUFFER	2
25	$T_9 - \theta_4$		RATE BUFFER	M
26	$\overline{DA}$		COMMAND LINK	11

PLUG NO. J3

MALE x FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS ML/MD MAST TO VEHICLE ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
27	$T_{10} - \alpha_1 - \alpha_0'$		RATE BUFFER	N
28	T_{21} - EOS		ELEVATION	10
29	A_1		COMMAND LINK	R
30	GROUND			
31	NC			
32	+15 VOLTS		SPEED CONTROL, MEMORY	P, 9
33	A_2		COMMAND LINK	P
34	$T_{11} - \alpha_2 - \alpha_1'$		RATE BUFFER	P
35	$T_{12} - \alpha_3 - \alpha_2'$		RATE BUFFER	R
36	$T_{13} - \alpha_4 - \alpha_3'$		RATE BUFFER	S
37	$T_{14} - \alpha_5 - \alpha_4'$		RATE BUFFER	T
38	$T_{15} - \alpha_6 - \alpha_0$		RATE BUFFER	U
39	$T_{16} - \alpha_7 - \alpha_1$		RATE BUFFER	V

PLUG NO. J3

MALE X FEMALE ___

LOCATION ML/MD CARD BASKET

CONNECTS ML/MD MAST TO VEHICLE ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
40	$T_{17} - \alpha_8 - \alpha_2$		RATE BUFFER	17
41	$T_{18} - \alpha_9 - \alpha_3$		RATE BUFFER	18
42	$T_{19} - \alpha_{10} - \alpha_4$		RATE BUFFER	19
43	T_{20} - EOA		RATE BUFFER	Y
44	$\overline{SO}$		RATE BUFFER	12
45	LASER DATA HERE		RATE BUFFER	13
46	OUTPUT ENABLE $\overline{OE}$		RATE BUFFER	3
47	$\overline{DAV}$		COMMAND LINK	M
48	-15 VOLTS		RATE BUFFER, MEMORY	11,10
49	GROUND			
50	+24 VOLTS		J2	4

PLUG NO. J4

MALE ___ FEMALE X

LOCATION BASE OF ROTATING MAST

CONNECTS POWER TERMINAL BLOCK TO ROTATING MAST ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	DESTINATION PIN
1	GROUND	GREEN		
2	GROUND	GREEN		
3	GROUND	GREEN		
4	-15 VOLTS	BLACK		
5	-15 VOLTS	BLACK		
6	NC			
7	+24 VOLTS	PINK		
8	+24 VOLTS	PINK		

PLUG NO. J4

MALE ___ FEMALE X

LOCATION BASE OF ROTATING MAST

CONNECTS POWER TERMINAL BLOCK TO ROTATING MAST ELECTRONICS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
9	+15 VOLTS	BLUE		
10	+15 VOLTS	BLUE		
11	NC			
12	+5 VOLTS	RED		
13	+5 VOLTS	RED		
14	NC			
15	NC			
16	NC			

PLUG NO. J5

MALE ___ FEMALE X

LOCATION BASE OF ROTATING MAST

CONNECTS SLIP RINGS AND POWER TO ENCODER, MOTOR, AND LASER

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
1	NC			
2	LASER FIRE			
3	NC			
4	MOTOR GROUND			
5	NC			
6	ENCODER ESP			
7	NC			
8	ENCODER EZR			

PLUG NO. J5

MALE ___ FEMALE X

LOCATION BASE OF ROTATING MAST

CONNECTS SLIP RINGS AND POWER TO ENCODER, MOTOR, AND LASER

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
9	ENCODER GROUND			
10	ENCODER GROUND			
11	ENCODER +5 VOLTS			
12	NC			
13	MOTOR DRIVE			
14	NC			
15	NC			
16	LASER +24 VOLTS			

PLUG NO. J6

MALE ___ FEMALE X

LOCATION BASE OF ROTATING MAST

CONNECTS SLIP RINGS AND POWER TO DETECTORS

PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
1	α_0'			
2	α_1'			
3	α_2'			
4	α_3'			
5	α_4'			
6	α_0			
7	α_1			
8	α_2			

PLUG NO. J6

MALE ___ FEMALE X

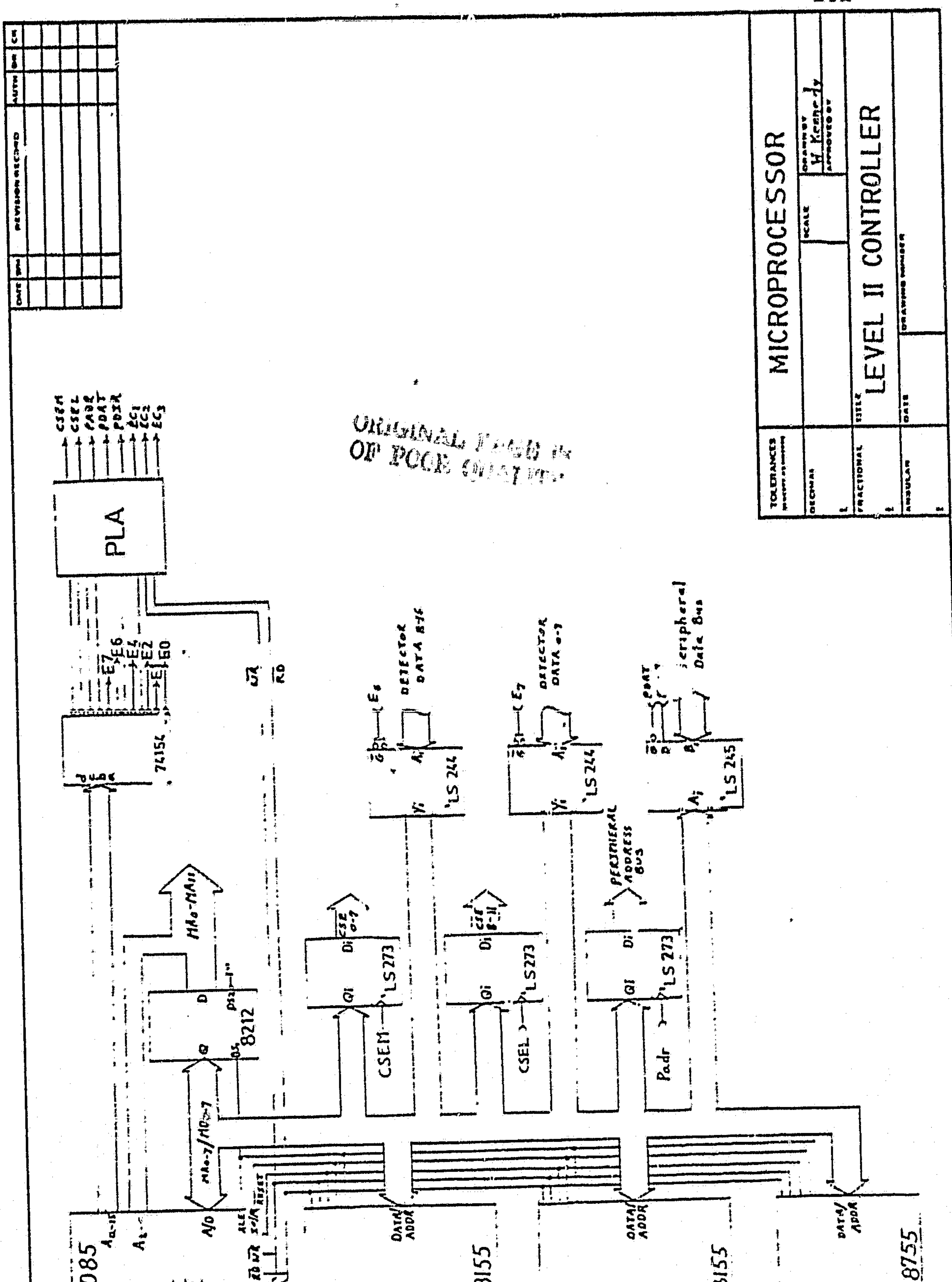
LOCATION BASE OF ROTATING MAST

CONNECTS SLIP RINGS AND POWER TO DETECTORS

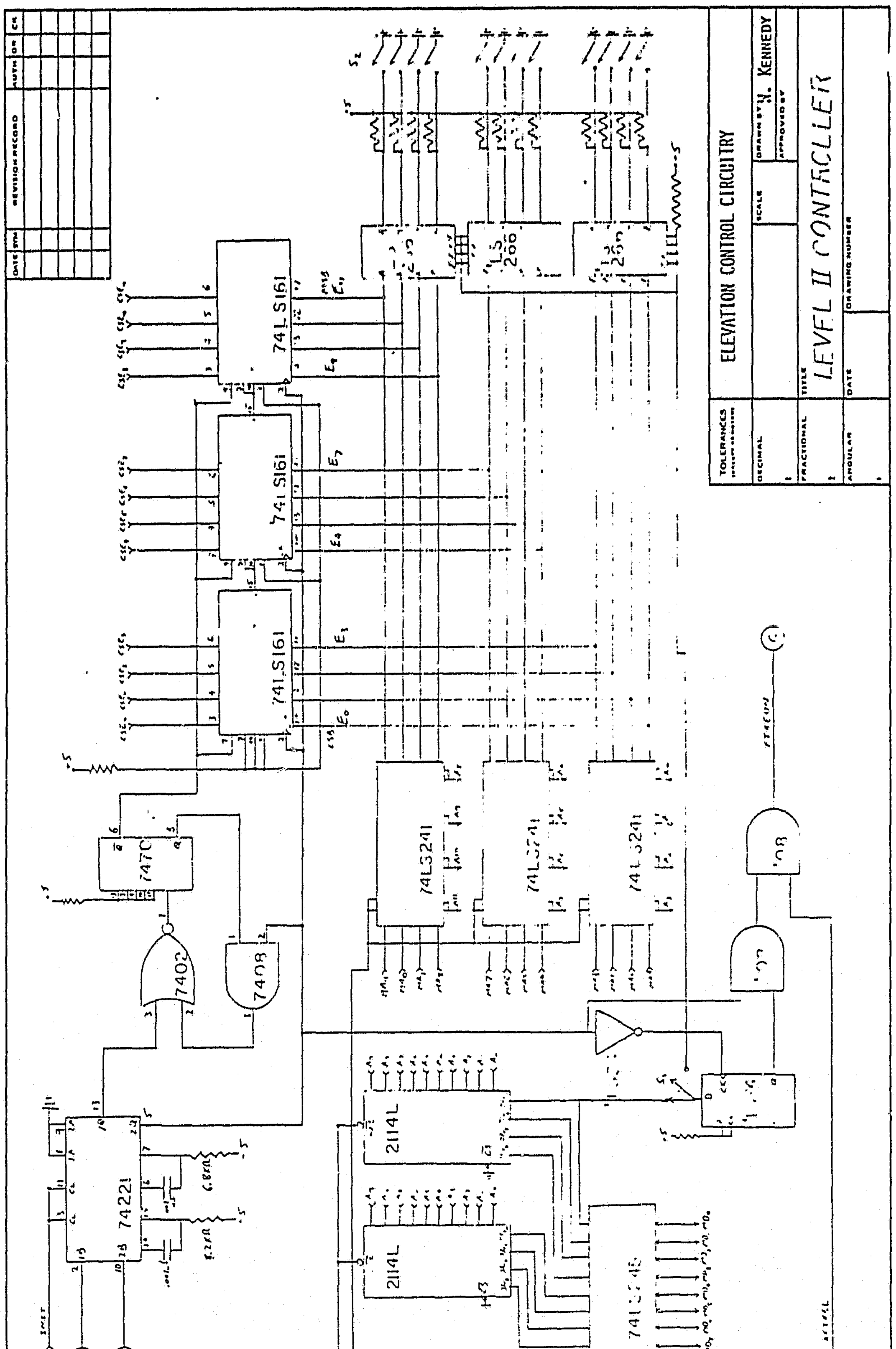
PIN	SIGNAL	WIRE	DESTINATION BOARD OR CONNECTOR	PIN
9	α_3			
10	α_4			
11	GROUND			
12	LASER FIRE			
13	+24 VOLTS			
14	+15 VOLTS			
15	+5 VOLTS			
16	-15 VOLTS			

APPENDIX IV

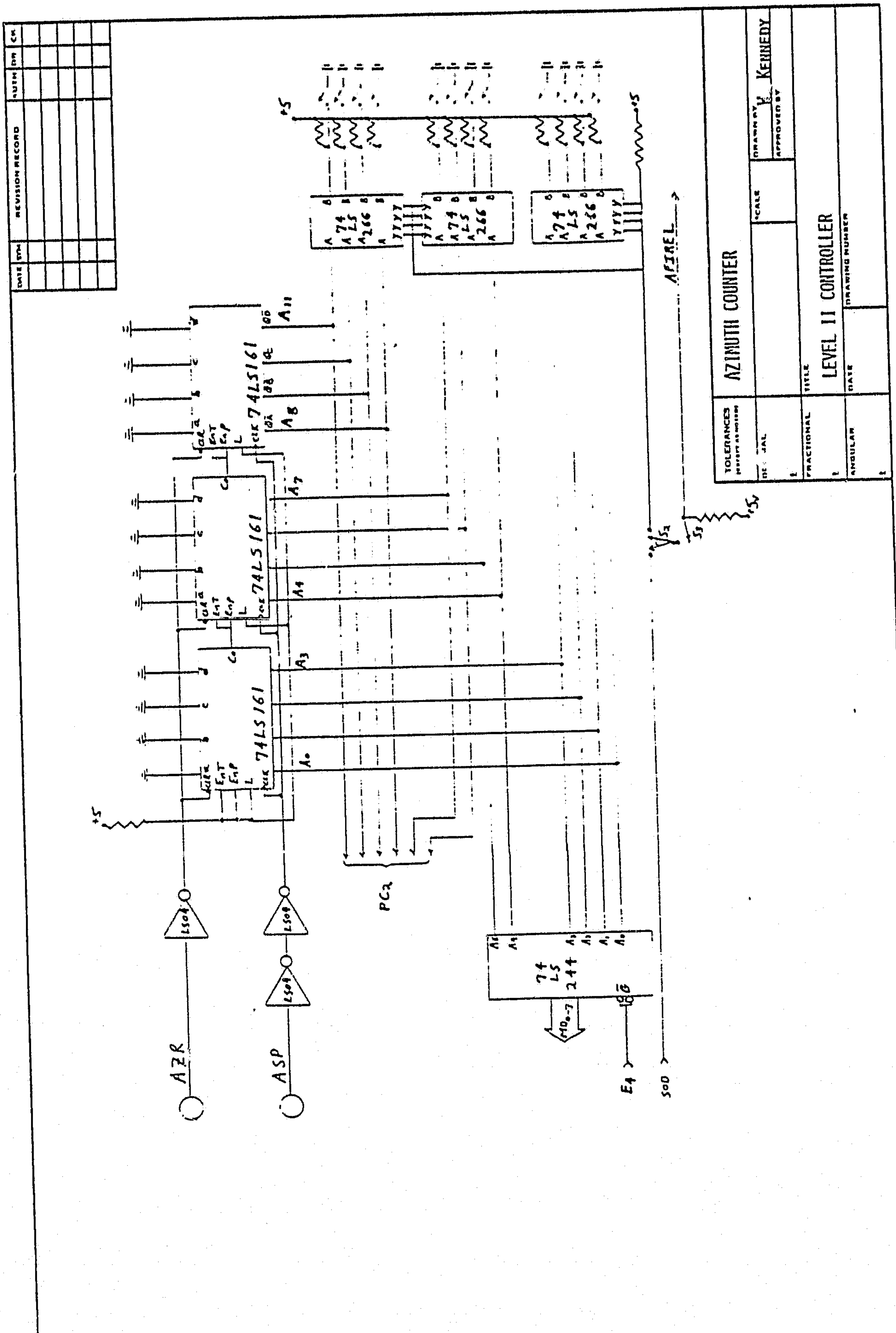
Level II Controller Schematics



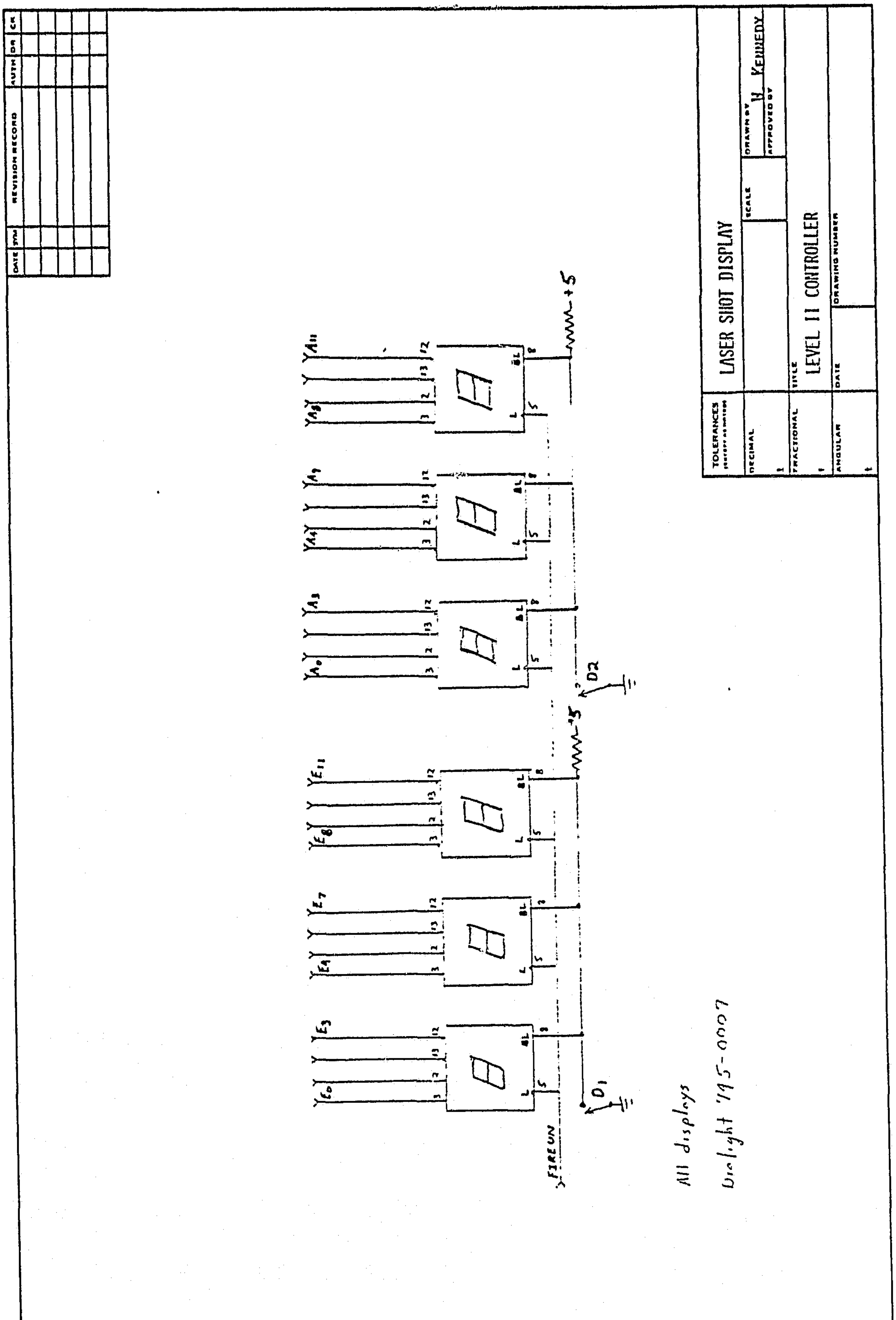
Microprocessor Schematic



Elevation Control Schematic



Azimuth Counter Schematic



Shot Display Schematic