IMPROVED CONTROL OF HYDRAULICALLY ARTICULATED MINING BOOMS

To Jean

IMPROVED CONTROL OF HYDRAULICALLY ARTICULATED MINING BOOMS

by

J. H. Knight, MSc. Cert. Ed.

A thesis submitted for the degree of
Doctor of Philosophy

in

The Department of Mechanical and Production Engineering

at

THE UNIVERSITY OF ASTON IN BIRMINGHAM

May 1984

IMPROVED CONTROL OF HYDRAULICALLY ARTICULATED MINING BOOMS

by

JOHN HENRY KNIGHT

PhD 1984

SUMMARY

The machines used for the removal of coal and mixed strata have hydraulically articulated booms. This project is concerned with one particular type of machine, that is, the boom mounted ripper, which is used for the construction of roadways. These machines are presently open-looped controlled, with all control inputs originating from the machine operator.

A dual microprocessor system has been developed which provides automatic and improved hand controlled operation. Feedback is introduced to monitor the position of the boom for controlled positioning and continuous path operations.

Multiprocessor system configuration, feedback systems, analogue to digital conversion and the microprocessor based information retrieval system is developed and the results demonstrated. The hazardous environment of the coal mine required the electronic components of the system to have low level current consumptions etc., in order to meet intrinsic safety requirements.

Ergonomic and environmental considerations were involved in developing the machine operator interface. This led to a novel solution for tunnel profile definement to the system and limitation of hand controlled movement of the boom. The tunnel profile can readily be changed and the system re-programmed, by unskilled personnel, in a mining environment.

The hydraulic valves for control of direction and velocity of the boom movement are of the soft seat poppet design. This provides for high contamination tolerance of the dilute (5/95, oil in water) emulsion. These requirements were stipulated by the National Coal Board. Computerised simulations of inertia load control and valve response times with bench test confirmations are included, and a bang-bang (on/off) control philosophy has been adopted.

Determination of boom velocity, required for optimal switching of the valves for boom positioning, is carried out using angular displacement transducers, a timer IC and software routines.

The kinematic equations have been developed for referencing the boom, which is mounted on a free ranging chassis, to the tunnel coordinates.

KEYWORDS

Multiprocessor System Design.
Mining Boom Ripper Positioning.
Bang-bang (on-off) control.
Optimal switching of hydraulic poppet valves.
Digital computer based simulation.

ACKNOWLEDGEMENTS

Reference to many books, journals, proceedings, learned societies and business concerns has been necessitated by the multi-discipline nature of the project. Indebtedness is acknowledged to all those concerned for the assistance they have provided.

The author wishes to thank Professor K. Foster and Mr G. A. Jones for their encouragement, help, guidance many suggestions and constructive criticism throughout the project.

Gratitude is also expressed to Mr J. D. Kibble and Mr J. Leahy of the National Coal Board for help in identifying and defining the requirement, and to the National Coal Board for sponsoring the project.

The project was carried out jointly with Mr C. W. Chuen, whose constant companionship and computing expertise were an invaluable aid.

The manufacture and assembly of various items of mechanical and hydraulic hardware was carried out in the Department of Mechanical Engineering at The University of Aston. The author is indebted to the many technical staff involved, in particular; Mr A. G. Evitts, Mr M. Clark, Mr T. Horton, Mr N. Moss, Mr P. Pizer, Mr L. Beddall, Mr D. Green and Mr A. Jones.

CONTENTS.

CHAPTER SIX: ACTUATOR DIRECTIONAL CONTROL WITH POPPET VALVES.

CHAPTER SEVEN: VOLUME FLOW CONTROL AND SIMULATION OF A PULSE WIDTH MODULATED POPPET VALVE.

LIST OF FIGURES.

LIST OF TABLES.

ABBREVIATIONS AND NOTATIONS

The following abbreviations and notations are used in this thesis. Not all suffices are listed. The Chapters containing mathematical modelling for hydraulic valves and system incorporate drawings indicating the full notations with suffices. Notations are re-defined in the local text.

Microprocessor System.

IC	Integrated Circuit.
ROM	Read Only Memory.
PROM	Programmable Read Only Memory.
EPROM	Erasable Programmable Read Only Memory.
EAROM	Electrically Alterable Read Only Memory.
RWM	Read/Write Memory.
RAM	Random Access Memory.
I/O	Input/Output.
PCB	Printed Circuit Board.
ICE	In-Circuit Emulation.
PIC	Programmable Interrupt Controller.
DMA	Direct Memory Access.
VLSI	Very Large Scale Integration.
LCD	Liquid Crystal Display.
BCD	Binary Coded Decimal.
APU	Arithmetic Processing Unit.

Signal Conditioning and Conversion.

SNR	Signal to noise ratio.
RMS	Root mean squared.
DC	Direct current.

CMRR	Common mode rejection ratio.
DMG	Differential mode gain.
CMG	Common mode gain.
Ed	Differential signal.
Ecm	Common mode signal.
dB	Decibel.
CAZ	Commutating auto-zeroing.
ADC	Analogue to digital Conversion.
A/D	Analogue to digital.
LSB	Least significant bit
MSB	Most significant bit.

Electricity and Magnetism.

I, i	Current.
R	Resistance.
V	Voltage.
C	Capicitance.
W	Watts.
F	Farods.
Ω	Ohms.
L	Self inductance.
ϕs	Self induced flux.
ϕm	Mutual flux.
B	Flux density.
μr	Relative permativity.
μo	Absolute permativity.
m.m.f.	Magneto motive force.
E	Electric field strength.
U-V	Ultra-violet.

e.m.f.	Electromotive force.
tc	Time constant.
H	Magnetic field strength.

Kinematics.

X	Linear directional notation.
Y	Linear directional notation.
Z	Linear directional notation.
αx	Angular directional notation.
αy	Angular directional notation.
αz	Angular directional notation.
R	Revolute pair.
P	Prismatic pair.
S	Spherical pair.

Fluid Power.

A	Area.
P	Pressure.
Ps	System supply pressure.
Pse	Servo pilot pressure.
Pt	System exhaust pressure.
V	Volume.
β	Bulk modulas of the fluid.
Q	Fluid flow rate.
k	Fluid column stiffness.
F	Force.
M	Mass.
ρ	Density of fluid.
t	Time
Cd	Flow discharge coefficient.

Non-dimensional notations use the lower case letter in all cases, except for time, which is:

τ Non-dimensional time.

MAIN TEXT

CHAPTER ONE

INTRODUCTION

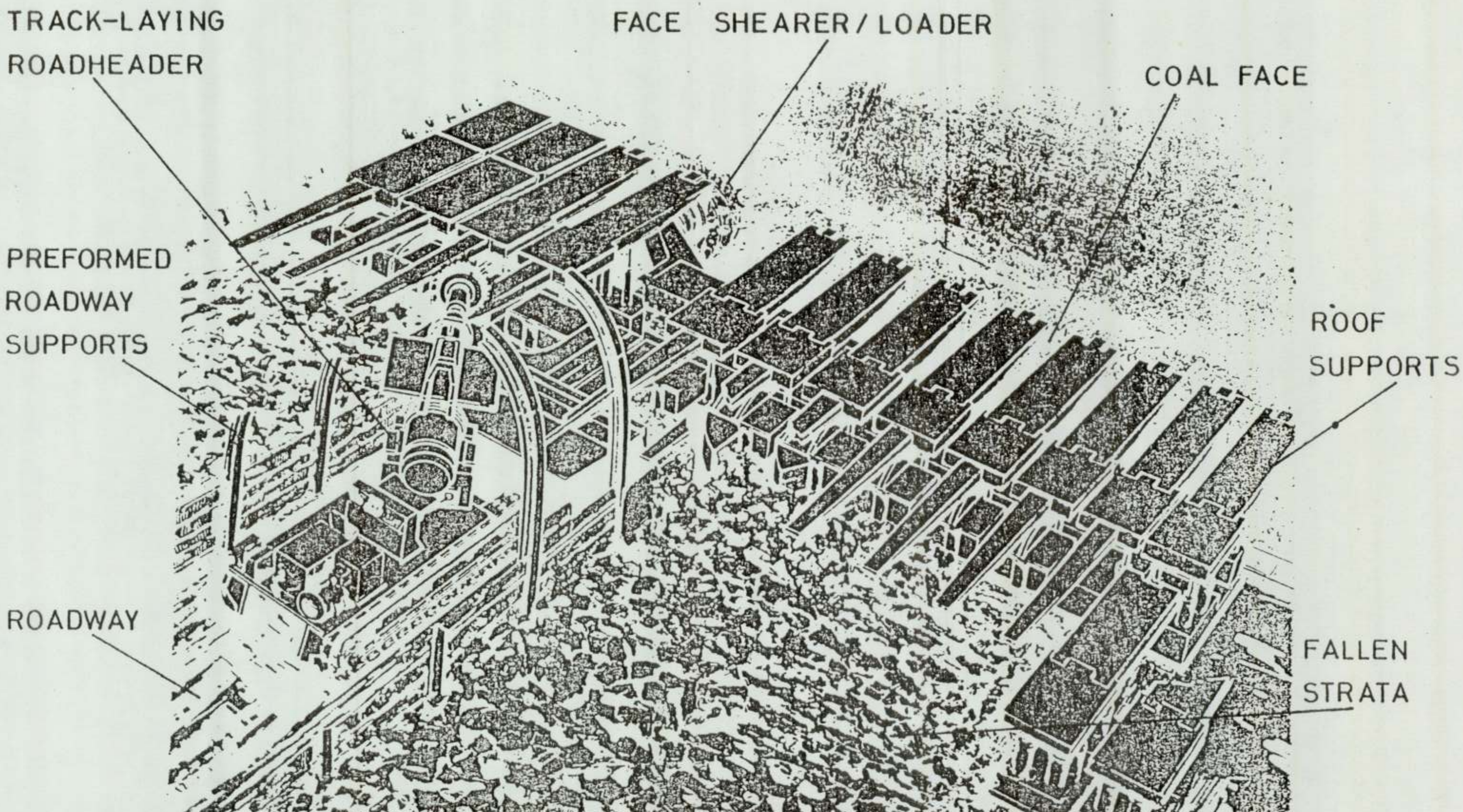


FIGURE 1.1. LONGWALL COALFACE OPERATIONS.

1.1 THE MINING OF COAL-HISTORICAL INTRODUCTION.

The mining of coal is a long standing traditional industry in the United Kingdom. Initially, and for many years, coal extraction remained a hand operation, with the very simplest of tools. New technologies have led to an increase in recent years in the level of mechanisation (Ref.1).

Power hydraulics, as we think of it today, had its inception towards the end of the last century (Ref.2 & 3). The mechanisation of the modern longwall coal face makes extensive use of hydraulic power.

The longwall system is shown in Figure 1.1. The electrically driven shearer traverses the face, removing coal which falls onto a conveyor. The void, left by the removal of coal, is supported by a continuous row of hydraulic roof supports. These roof supports are advanced forward as coal is removed, and the strata is allowed to fall behind. Roadways are constructed at each end of the face for ventilation, to house the conveyors and to provide access for personnel, services and machinery. The roadways are constructed by hydraulically powered roadheading machines, which, once access is gained to the coal seam from the shaft, are required to increase the height of the seam to form the tunnel. The tunnel is held in place by preformed rolled steel supports.

Productivity in the coal mining industry increased significantly in the 1960's as a result of face mechanisation, but in the 1970's it remained relatively static. The new equipment had the potential to produce more, but problems of reliability and complex control operations led to under-utilisation.

A recent technology which is beginning to have an impact on coal mining operations is micro-electronics and associated computer-based systems. MINOS (MINe Operating System) (Ref.4) is a computer-based system, developed jointly by the Mining Research and Development Establishment (MRDE) and several industrial organisations, to automatically monitor and control various colliery operations. Several versions of the system are now working, each tailored to suit a particular mine. Automated coal transport, production and face monitoring, environmental monitoring and fixed plant control and monitoring can all be incorporated. A surface central control and secondary management computer, make for a system which will increasingly aid productivity as full potential is realised. Several systems are now installed which are undergoing tests and further development.

Free ranging machines, such as track-laying roadheaders, are not incorporated in the MINOS.

1.2 ROADWAY CONSTRUCTION MACHINES.

Tunnelling, required for the construction of roadways, is carried out by a variety of methods (Ref.5), each suited to a particular type of strata. The machines at present in use are:-

1) Boom mounted rippers.
2) Shielded machines.
3) Boom mounted drilling machines.

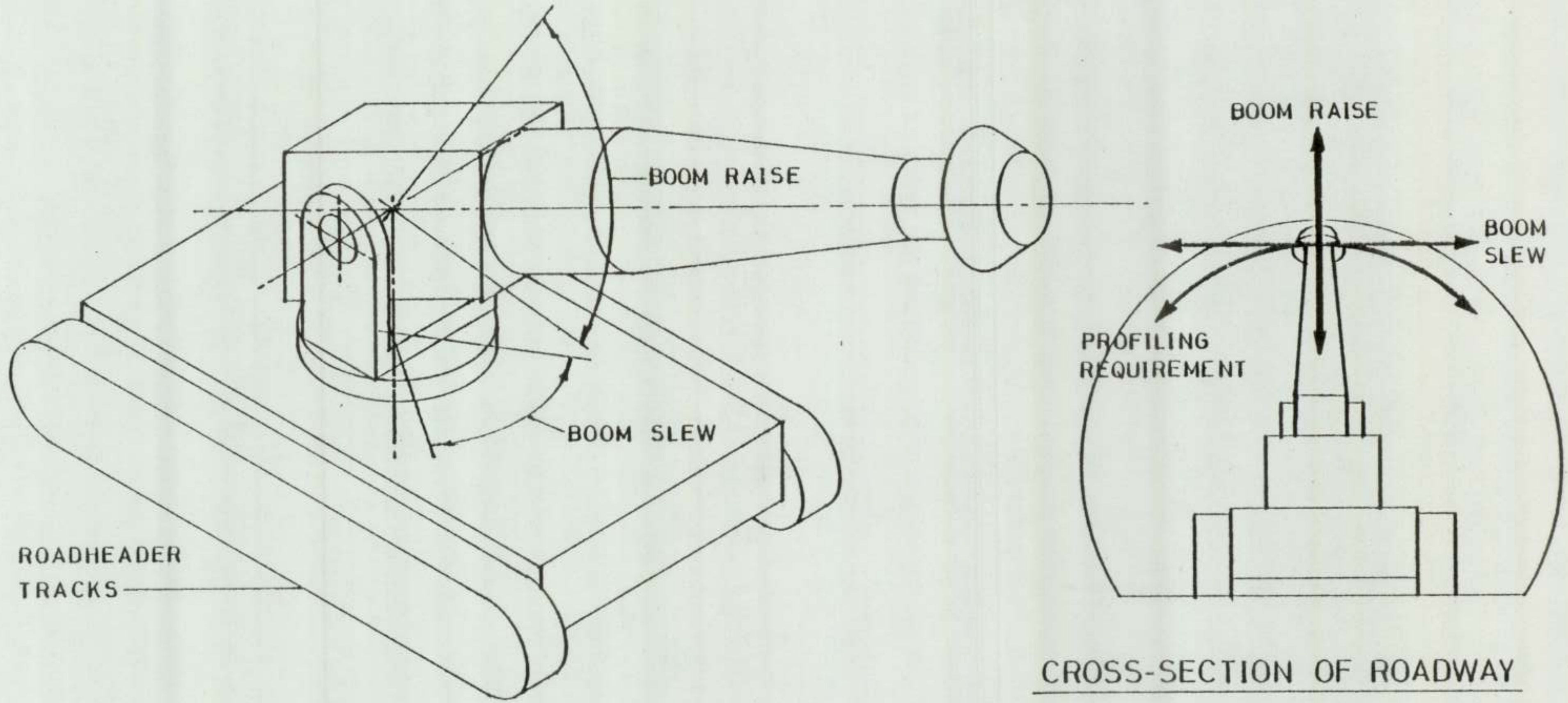


FIGURE 1.2. ROADHEADER DEGREES - OF - FREEDOM

4) Impact type rippers.

It is necessary to understand the variety of strata which has led to the development of these different machines. The average compressive strength of coal is between 21 N/mm^2 and 28 N/mm^2, with a maximum of about 42 N/mm^2. The strata above the coal may include any combination of fireclay, mudstone, shales and varieties of sandstone. The compressive strength of these materials can vary from approximately that of coal, to as much as 200 N/mm^2. The nature of the rock, that is, extent of lamination, pre-existent cracks and fractures and abrasivity all have a bearing on the method used for the construction of roadways.

The ripping machine was first introduced in 1960/61 (Ref.6). This led to the development of the boom ripping machine, which was first tried at a Midlands colliery in 1967. The NCB now owns several hundred of these machines, which are now referred to as roadheaders. Similar machines are used in the quarrying and cival engineering industries.

Figure 1.2 shows a diagramatic representation of a typical roadheader, and degrees-of-freedom of the boom, relative to the machine frame. The cutting head is carried at the end of the boom which is held in position, relative to the machine body, by hydraulic rams. The machine relies for stability on its weight and adhesion between the caterpiller tracks and the floor. The actuation of the two degrees-of-freedom of the boom is by hand operated spool valves. This gives complete flexibility of movement, allowing freedom of cutting action and choice of cutting pattern. Almost any

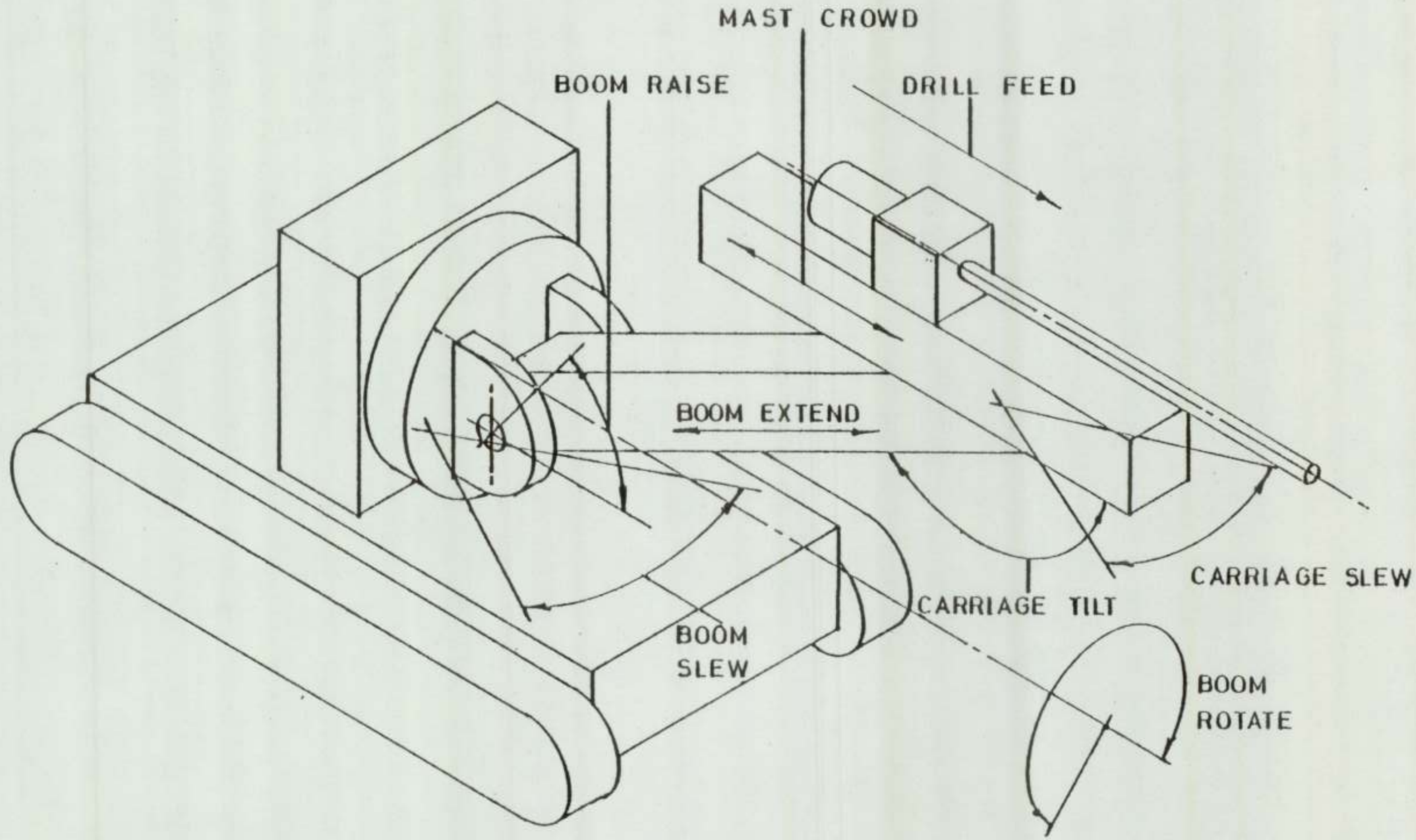


FIGURE 1.3. BOOM MOUNTED DRILLING MACHINE DEGREES-OF-FREEDOM.

shape of roadway profile may be excavated, but only to a limited degree of accuracy. This accuracy depends on the skill of the operator and the type of strata. The roadway supports are preformed, and any inaccuracy in ripping the profile requires backfilling.

Shielded machines (Ref.7) were developed initially for the civil engineering industries for the cutting of circular, concrete shielded, tunnels. These machines are similar, in principle, to the roadheader, except they are generally of a more robust construction, mounted on skids and held rigid within precast concrete tunnel shields. A considerable amount of ancillary mechanical hardware is required, and the system is generally less flexible. The NCB have a shielded machine system at present under trial for evaluation.

Prior to the direct cutting machines, drilling and shotfiring was used. The drilling, for the construction of tunnels, is now carried out using machines of the type depicted in Figure 1.3. This method is applicable today for hard rock areas. The operation requires two men, one at the drilling end, who indicates the position for the drill, and the machine operator. It is not a continuous operation, since it is necessary for the machine to move back from the explosion. A mechanical shovel is then used to scoup up the debris.

Impact type rippers (Ref.8) are also used, but to a much lesser extent, in the construction of roadways. The hydraulically powered impact unit is mounted on a machine which is similar to the boom mounted drilling machine.

1.3 HYDRAULIC POWER.

In mining operations, hydraulic power is predominant, due mainly to its ability to produce high, readily controlled, forces in small packages.

Strength and robustness is essential for all hydraulic equipment and materials must be chosen carefully to avoid corrosion in a wet environment with the presence of chemicals, such as sulphur.

Dusts, slurries and lumps of rock or coal are all present during underground operations. They present an ongoing risk of contamination for all hydraulic systems. Tunnelling machines, including the hydraulic components, are assembled, operated and maintained in these conditions. The ventilation airflow is usually from the cutting head back across the machine. A good standard of oil filtration is normally achieved, with 5 micron filters and magnets in the tank and on the suction side, and 5 or 10 micron filters on the pressure side. High maintenance standards are difficult to achieve in an underground situation, and it has long been realised that the better solution is to provide contaminant tolerant hydraulic components. This is particularly applicable to the valves controlling fluid flow (Ref.9).

With the ever present risk of fire and explosion in coal mines, due to methane and coal dust in the atmosphere, the appropriate choice of hydraulic fluid is of paramount importance. There are numerous fire resistant fluids now available, and their effect on equipment and circuit design has been researched (Ref.10 and 11). Aqueous fluids are

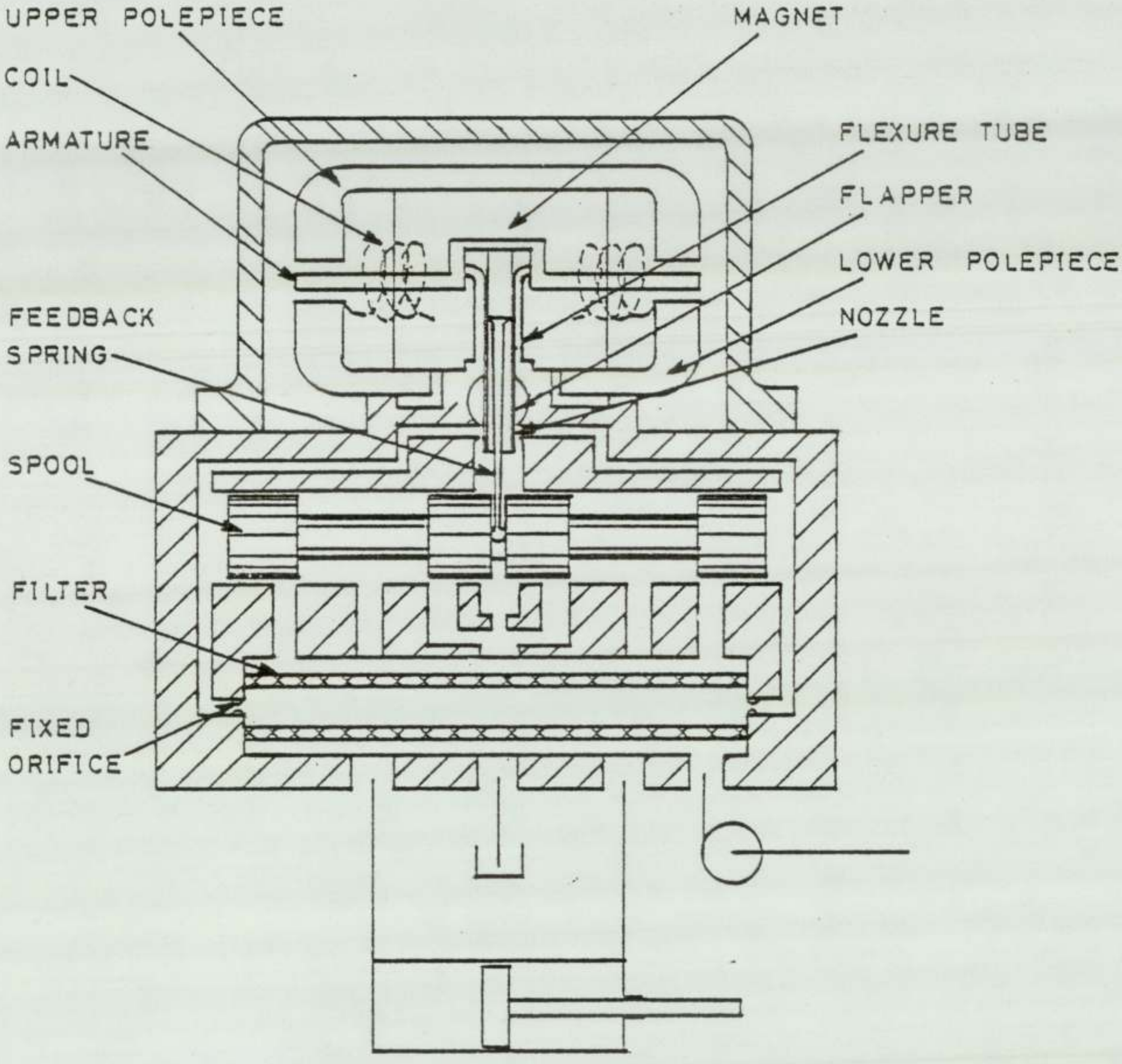


FIGURE 1.4. ELECTRO-HYDRAULIC SERVO VALVE.

widely used in mining machinery in this country, and abroad (Ref.12). Roof supports are now working with dilute (5/95, oil-in-water) emulsion, and mobile machinery, including roadheaders, are using invert (40/60, water in oil) emulsion.

1.4 ELECTRO-HYDRAULIC CONTROLS.

Automation is fast becoming a natural consideration, following mechanisation. The application of electro-hydraulic controls in coal mining is closely related to the development of automation in the mining industry. The system intelligence is provided by the electronics, and the muscles by the hydraulics. There must at some point be an interface between the two, for the system to be operational. A fundamental part of the system is the servo valve. This unit converts an electrical signal into an amplified hydraulic flow. The development of electro-hydraulic valves has made major strides in recent years (Ref.13). Added impetus for further development is provided by the onset of the microprocessor.

The servo valve is usually a four port unit with a three land spool and one of the more common designs is shown in Figure 1.4. The bushing has rectangular slots to achieve a linear relationship between spool movement and flow. Internal feedback is provided between electrical input and spool displacement by the armature of the electrical torque motor, which positions a flapper between two nozzles, thus creating two variable orifices. Movement of the flapper results in a differential pressure at the spool ends,

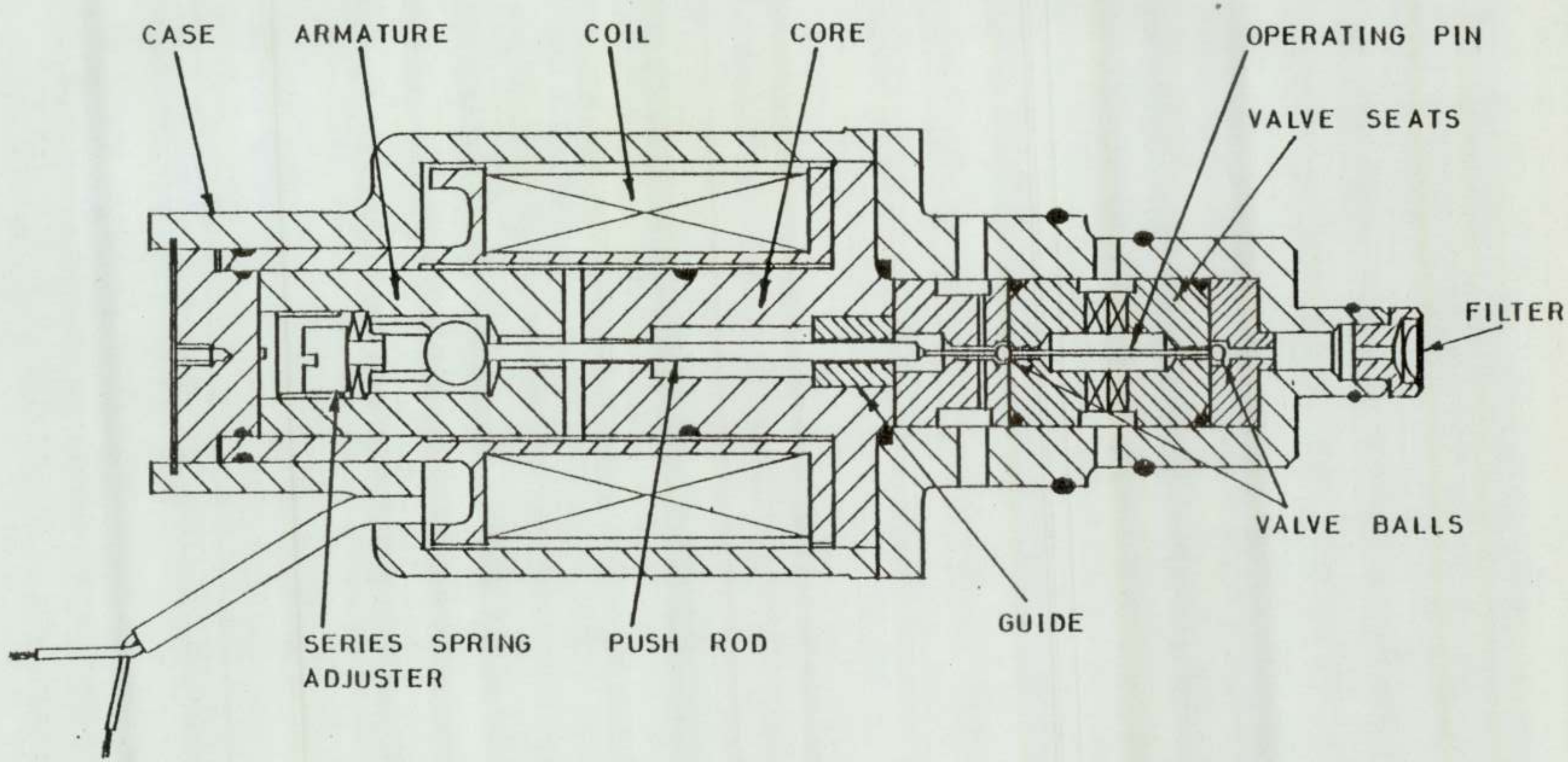


FIGURE 1.5. SOLENOID OPERATED CARTRIDGE BALL VALVE.

causing it to move. A feedback wire is attached to the flapper and the spool. This has a linear rate to ensure that the torque generated by the electrical signal is balanced by a proportional displacement of the spool.

The application of servo valves is generally in closed loop control systems (Ref.14), where feedback from a sensor is compared to a reference. The valve can be used to control the displacement and velocity of a hydraulic actuator. Pressure and load are also parameters which can be controlled.

Systems of this type have been applied to control mining operations. The valves were initially developed for use with mineral oils, but will operate with a reduced life on invert emulsion. This type of valve requires a precision machining capability in manufacture, and 10 micron filtration for both the pilot and main flow. The filtration requirement is an undesirable feature for a mining application.

In roof support systems, continuously proportional control is unnecessary and simple on/off, or bang-bang, control is used. Solenoid operated ball valves, as shown in Figure 1.5 have been developed for this purpose. The quality of control with this method is ultimately limited by the response of the valve. A dead band is imposed on the error signal and the valve only operates after a threshold value is exceeded. These valves have given satisfactory service with dilute emulsion with improved contamination tolerance, having an integral 55 micron filter.

Electrical equipment for use underground in coal mining must be either intrinsically safe or flameproof. Intrinsic safety requires that the available energy is reduced so that a discharge could not cause ignition, while flameproofing is achieved by the strength and design of the enclosure. Intrinsic safety is a total system consideration requiring a close degree of understanding between manufacturer, user and safety authorities. Intrinsic safety is preferred when alternatives are possible.

1.5 PROJECT REQUIREMENT.

The NCB requested that the control of articulated booms should be researched, and an improved system be designed and developed. The hydraulic system should be contaminant tolerant and suitable for operation using dilute (5/95 oil in water) emulsion. A Dosco Mk 2 boom ripper was provided, and the work carried out is relevant to this type of machine, with "spin offs" for other machines which use large inertia, hydraulically operated, booms.

The boom ripper has been described (Ref.6), as " a good example of the successful adaptation of an apparently unsuitable design in circumstances where operational and geological considerations dictate a compromise between conflicting requirements". The success of the machine can be measured by the number now in operation with the NCB and the vast capital investment represented. There are two manufacturers of this type of machine in this country, Dosco and Anderson Maver, and approximately 60% of production goes for export, throughout the world.

The machine is moved forward, on its caterpillar tracks, causing the cutting head to sump into the ripping. When the required depth of sump has been achieved (usually 0.4m to 0.5m) the head is traversed over the rip. The machine is then moved forward on its tracks to remove the sides and top from the concave section, formed by the arcing motion of the boom, to leave a relatively flat faced rip. The boom traversing is carried out by the operator, who is provided with a hand control for slewing the boom, and a separate hand control for raising and lowering the boom.

Point to point and continuous path control is required. The latter is difficult to obtain, except on horizontal and vertical surfaces. Most tunnel profile shapes are curved, or a combination of interspersed, straight and curved sections.

1.6 MICROPROCESSOR SYSTEMS.

The recent advances in large-scale-integration (LSI) semiconductor process technology has led to substantial reductions in the cost and size of digital logic circuits. Computer systems have progressed from discrete components, such as single transistors, to complex functional integrated circuits (IC´s) containing many logic gates on a single "chip".

The first commercial microprocessor appeared on the market in 1971. The understanding and market acceptance of this revolutionary new product was slow. It was some years before the advantages of the microprocessor were fully comprehended by digital systems designers. In 1976 there were over two dozen microprocessors commercially available and incorporated in computer terminals, laboratory instruments and consumer products. Control and process monitoring systems were also being implemented using the microprocessor.

The early microprocessors were of 4-bit design. The avalanche of technology quickly brought about the 8-bit, and todays technology of very large scale integration (VLSI) has led to the 16-bit and 24-bit microprocessors (Ref. 15). 32-bit microprocessors will be available in early 1984. The increased functional density has led to high performance for computing applications and this is available to the control systems engineer.

These new advanced devices demand a high level of expertise in their application and manufactures have developed a range of card modules for the implementation of configurable control systems (Ref.15).

Digital control techniques had been used previously in control engineering using fluidic logic elements. These are still used today in particular applications, but by and large, microelectronic logic has taken over with all the advantages it has to offer.

The underlying principle of any control system is the feedback loop. Microelectronics enable measurements to be made and the microprocessor system can analyse and provide the required control action. This can eventually lead to the fully automatic control of machinery and industrial process.

1.7 PREPARATION AND ORGANISATION OF THESIS.

The improved control of the ripping boom involves the application of multi-discipline engineering principles. All are of equal importance in producing a working system and the order in which the thesis is presented does not imply any particular decision-making weighting.

A multi-microprocessor system was designed and developed, and a chapter is devoted to the design philosophy of system architecture, multiprocessor configurations, communication techniques and comparison of systems built from integrated circuit (IC) level with systems constructed using card modules. The hardware and software of the system developed for the roadheader, together with system input devices, signal conditioning, analogue to digital conversion and signal amplification are described in this thesis.

It was intended to "de-skill" the human requirement for the operation of the boom, whilst obtaining an improvement in production and quality of finished tunnel profile. This involved ergonomic considerations requiring familiarization with present operating methods and conditions. Visits were made to several different mines, with varying geological conditions, and mining equipment repair workshops. Discussions were also had throughout the project, with the various mining equipment, and methods experts at the MRDE.

The redesign of the hydraulic system has concentrated on valve redesign to improve contaminant tolerance, to operate on dilute emulsion and to be controlled by intrinsically safe electronic signals. The contaminance and fluid characteristics do not present any particular problem for the hydraulic actuators. Pumps have been developed by various manufacturers, and tested by the MRDE, and are now providing satisfactory service for roof support systems. These pumps are of the diaphragm and piston type.

The actuator directional switching valves, and the volume flow control valves, are all of the poppet type and digital computer based simulation of their performance is discussed. Comparison is made between predicted and actual performance.

The switching of the valves for optimal positioning of the boom formed a major part of the thesis carried out by C. W. Chuen. A simplified analogy is made in this thesis which incorporates a delay in the closing of the supply poppet behind the exhaust poppet to an actuator to avoid possible cavitation conditions and to provide improved stiffness to the locked hydraulic fluid columns.

All valves have solenoid actuation for the servo module and electro-magnetism is discussed, with particular respect to analysing and improving the response time.

The Appendices contain the electronic hardware diagrams, the system software, computerised simulation programmes, details of the hydraulic circuits, ripping boom kinematics and a display suitable for the machine operator and use in a mining environment.

CHAPTER TWO

MICROPROCESSOR AND MULTIPROCESSOR SYSTEM DESIGN

2.1 INTRODUCTION.

The application of the microprocessor to the general purpose microcomputer, minicomputer or computer has made tremendous advances in recent years. This is evident in all aspects of life from the home and business user, to use as a tool in high level scientific research. However, the microprocessor, despite the fact that it has the technical capability, has been slow in making the expected impact in manufacturing and control systems engineering. This is not only due to the high level of technology involved in the application, but that economic and management factors provide other limitations.

A digital electronic system used for a control engineering application does not need to be designed using a general purpose microcomputer, minicomputer or computer. Each system is developed for a particular application, usually with real-time control requirements and a specific operating environment. These specifications can often be satisfied by using a relatively simple microprocessor system. Bespoke hardware may be necessary and special software will be specifically required.

The level of possible entry for the design of a microprocessor control system has broadened considerably in recent times, to include the use of special purpose interconnected card modules to form a configurable "open system" (Ref.15). This is an attempt to combine the convenience of the general purpose computer with the versatility of the system conceived using individual IC´s. The number of special purpose modules now available, for interconnection to form a configurable system, is said to be at least nine hundred. There is no doubt that this approach will find increasing application, particularly as a total system solution to complex control problems.

The application of microprocessor based control systems, at any entry level, requires an understanding of system architecture, hardware interfacing to the real world and the advantages to be gained between hardware and software trade-offs.

The design and development of microprocessor based control systems require complex, closely integrated design procedures which can vary depending on the complexity and level of entry. If the system is to be constructed from IC level then the work entails the understanding of the individual IC functions. Any level of entry requires the development of system operation software, although for the configurable "open system", software modules are becoming available. These however can entail the payment of royalties for each time they are used in a system sold to the end user (Ref.16).

The computer based control systems implemented in the late 1960´s and early 1970´s were generally of the centralized type where interfacing costs to external events often required long runs of screened cable with complex signal amplification and conditioning. A breakdown in the centralized computer could result in a complete shutdown of the process. The reducing cost and availability of the microprocessor led to their use in distributed computing systems. Improved system performance is a key objective in the implementation of these multiprocessor systems.

This chapter will discuss briefly the fundamental elements of a microprocessor system and the available system development aids. The fundamental system design decisions, including the choice of microprocessor, multiprocessor configurations, data transfer techniques and communication methods, with particular emphasis to control engineering applications will be analysed.

2.2 BASIC SYSTEM ELEMENTS.

The basic elements that comprise a minimum microprocessor system whether for computing or control are :-

1) Central controller.

This task is carried out by the microprocessor. It can be described as the heart of a system and is an IC component. The basic functional elements are an arithmetic logic unit (ALU), instruction decoder and control and synchronization. The von Neumann type architecture (Ref.33) is the basis for almost all present day microprocessors. The microprocessor has evolved as a result of tremendous advances in digital systems technology (Ref.15). Although all microprocessors of a particular type are identical, they can perform vastly different tasks according to the other elements of the system and the programme instructions.

2) Store for Information Which Dictates The System Behaviour.

The tasks to be performed by the system are specified by the programme code. These fixed instructions, and data values that do not change, are stored in read only memory (ROM). The microprocessor can randomly access this non-volatile semiconductor memory. The mask programming (Ref.33) requirement of ROM makes it unsuitable for prototype development, or one-off applications.

Programmable read-only memory (PROM) IC's overcome this problem by allowing programming using a suitable PROM programmer. The bit pattern is usually implemented by blowing of selected fusible links. They can only be programmed once by the user.

At the programme development stage it is often necessary to make numerous changes to instructions and data values. Erasable progammable read-only memory (EPROM) and electrically alterable read-only memory (EAROM) provide this facility. EPROM's are erased by exposure of the large scale integrated (LSI) circuit to ultra-violet light and only the entire memory contents can be erased. The memory contents of EAPROM's are electrically erasable and it is possible to alter one word or a block of memory.

3) Short Term Store For "Transient" Information.

This is termed the read/write memory (RWM) or random access Memory (RAM). It is generally used for the temporary storage of data, as the memory is volatile.

There are available two categories of RAM - static RAM and dynamic RAM. In static RAM the data is maintained, providing power is applied, and there is no need for refreshing. Dynamic RAM is time degrading which requires the refreshing of the memory contents after a specified period. The access time is greater for dynamic RAM, but so is the density for a given size chip of silicon.

4) Communication with Electro-Mechanical Equipment.

The requirement of data transfer between sensors, actuators and other peripherals and the microprocessor is an essential system element. This can be carried out using parallel input/output (I/O) ports, serial I/O, memory mapped I/O, etc.

5) Miscellaneous Interconnection Components.

These are many and varied and are used for interfacing the various elements within the microprocessor system, as well as external devices to the I/O ports.

2.3 SYSTEM DESIGN CRITERIA.

The criteria, that must be established at an early stage and have a bearing on any design decisions throughout the system development operation, can be broadly defined as :-

1) Cost.

The hardware cost of a system cannot be precisely determined before actually constructing and testing the initial system. However, the electronic industry does have empirical rules for estimating costs. It would be lower for systems constructed from the IC level as redundant elements are avoided. This cost is repeated for each system built.

The cost of design and development is by far the major element in building the prototype of a system and would be highest for systems built from IC level. These, however, are once only costs and the greater the number of systems the lower the per-unit design and development cost.

2) Flexibility.

This is a major advantage of microprocessor based systems. The engineer often has a choice between hardware implementation of logic functions, or software defined behaviour. Hardwired logic systems can only be changed with different interconnections and probably with different components. Software defined behaviour changes, which include both programme and data base changes, can readily be made by reprogramming and insertion of another EPROM, without any physical changes to the interconnections of the system.

Systems configured using single board modules are weighted towards software defined behaviour and for this reason they are considered to offer the greatest flexibility. There is however, no reason why flexibility should not be built into a system constructed from IC level.

3) System Reliability.

The mean time between failure of a microprocessor based system depends on :-

a) Hardware faults.

b) Software errors, and probability of data flow/process state involving error sequence leading to fault.

Most manufacturers of IC´s publish reliability reports (Ref.17). Typical failure rates are approximately, one in every 500 years. It is the assembly of these into a system where an element of unreliability can creep in. Wired and soldered joints can give rise to trouble, and require attention at the assembly stage. Control of reliability is more easily achieved in systems constructed from IC level since the designer can select whether to use :-

a) Sockets or IC´s connected direct to printed circuit boards (PCB).

b) IC´s of either industrial grade or military grade (Ref.16).

c) Ceramic or plastic IC´s.

d) Wire wrapping or soldered connections.

e) A single PCB or multiple PCB´s using edge connectors etc.

f) Encasement of the boards in an epoxy resin block, or similar. This is often used in vibration or high humidity situations.

g) Multiple IC´s or multi-function IC´s. There is an increasing number of multi-function IC´s becomming available. These not only simplify the system development, but can also give improved reliability due to the reduction in system connections.

Hardware reliability is both design stage and time dependent, whereas software error is caused at the design stage. The writing of software is discussed in Chapter 5.

4) Compatibility.

This must be ensured between the various IC´s, comprising the microprocessor system. This is not generally a problem when implementing a system configured using card modules.

Unlike the design of a desk top computer, where most of the external compatibility is limited to compatibility with humans, the control system must operate with a variety of mechanical and electrical components of the system. These may be any of many different types of input sensors and output actuators, with real time characteristics.

5) Speed.

The speed of microprocessors has increased with development. Computational speed of control logic and arithmetic operations may dictate the use of a high speed microprocessor and accompanying system IC´s.

6) Size.

The physical size of the system may be an important consideration for some applications. Microprocessors possess the unique advantage of ultracompact size, and multi-function IC´s can further reduce the component count, and hence, system size. Systems "tailor built" from IC level, with a minimum of redundant features would be more compact than a system configured using card modules.

2.4 SYSTEM FEASIBILITY AND CHOICE OF MICROPROCESSOR.

Having established the total electro-mechanical system design criteria, it is necessary to examine the feasibility of implementing a microprocessor control system as part of that total system.

The three aspects which need evaluating, in broad terms, are :-

1) Hardware Structure.

This consideration begins initially by examining what is required of the system for a particular control engineering application and choosing a microprocessor to suit the requirements (Ref.18). The consideration should include :-

a) Number of bits.

b) Speed.

c) Available compatible system support IC's.

d) Power supply requirement.

e) Type and number of interrupts.

f) Clock frequency.

g) Arrangement of control logic.

h) Bus formation.

i) Availability of tri-state outputs and semaphore I/O for multiprocessor system applications.

j) Availability now and in the future and existing expertise within the company.

Single board computer modules are available with various different microprocessors (Ref.15).

2) Software Structure.

This concerns the operational characteristics of the microprocessor, and is an important initial system feasibility consideration. Basic to any application, particularly when designing from IC level and using assembly language programming is :-

a) The number and types of registers.

b) Word length.

c) Bit manipulation.

d) Addressing mode.

e) I/O facilities

f) Instruction set and arithmetic ability.

g) Inequality conditional jumps.

h) Proper indexing.

i) Ability and method of indexing stack.

Compilers are available to allow the use of high-level languages such as PASCAL, FORTRAN, PL/M and RTL-2 etc. The aspect of these languages, particularly with respect to control systems applications, is discussed in Chapter 5.

3) Complete Electro-Mechanical System Integration.

This is particularly relevant to the application of microprocessor control in mechanical engineering. Microprocessors must be interfaced to suitable memory, I/O devices and other system logic. In addition to the microelectronic components, sensors are required to feed the data to the system, and actuators are necessary for carrying out the systems instructions. These can often be many times the cost of the microelectronic components and can render the economics of the system unfeasible.

2.5 SYSTEM DEVELOPMENT AIDS.

The implementation of a microprocessor system can be described as a two part operation. The hardware must be designed, assembled and tested, and secondly, the user programme must be conceived, written and debugged. They mutually rely on each other. The microprocessor manufacturers, as well as the realistic potential users, have realised that the development of an operable system, starting from the microprocessor and a few associate parts, is a formidable task.

To simplify the problem, most of the microprocessor manufacturers, and some of the companies which build microprocessors into systems, market a range of equipment to help in the design and development task (Ref.19).

The mechanical engineer is concerned with systems which respond to the time scale of the process being controlled. The response time depends on the process dynamics or time constants which operate in a real-time mode. The fundamental concepts required in the design of real-time systems form a necessary, but not sufficient, set of axioms for the design of microprocessor based control systems.

The process of engineering the microprocessor based control systems includes the specification, design, implementation, integration, commissioning and maintenance tasks. Validification tests are required at each stage, making use of analysis tools. Many of the system development aids can be used as both design and analysis tools.

2.5.1 System Design Kit (SDK).

This falls at the lower end of the market, costing only a few hundred pounds. It generally comprises a single board with a microprocessor, ROM, RAM, I/O ports, keyboard and simple display. The ROM is programmed with a primitive system monitor for general software utilities and system diagnostics.

They form an excellent level at which a mechanical engineer can start to learn, understand and evaluate the fundamentals of microprocessor system design (Ref.20). The built-in flexibility of these boards make for simple interface to the users system for simple intelligent control applications.

It is both a design and an analysis tool of primitive form and is not usually used for final system implementation.

2.5.2 Logic Analyser.

This is a device which can be connected into the user system to act as a development and debugging tool. A logic analyser can simultaneously acquire digital data from a number of channels and display them. The number of channels will vary between analysers, but it is normally possible to acquire access to up to 32 channels. A record can be kept of recent events and when a failure occurs, the analyser can display the digital data. This data is examined to determine the cause of the failure. Most logic analysers allow the data to be displayed in different formats, e.g. binary, hexadecimal or timing diagrams. It is also possible to use some logic analysers with particular microprocessors, to decode the binary machine code and show the assembly language code. Oscilloscope facilities are also usually available.

The fundamental operational aspect of a microprocessor system is the manipulation of logic levels in a sequential manner. The logic levels, at any particular instance, can be examined allowing a state analysis to be made. The timing of the elements of each sequential change and the timing of control line states during each change, such as read/write lines etc., is of vital importance. The logic analyser allows a real-time analysis for any particular signal and a sequential comparison analysis for a number of signals.

2.5.3 Development System.

The microprocessor development system is a sophisticated, expensive and versatile development aid. Initially these systems were dedicated to a particular microprocessor, but universal development systems are now available. These provide a facility using different plug-in modules, which allow the development and emulation of a range of microprocessors. This makes the initial investment cost of such systems more acceptable to the user who is likely to deal with a variety of microprocessors.

Typical modules included in a microprocessor development system are :-

An alpha-numeric keyboard.

Assemblers.

Disc operating system.

High-level language compilers/interpreters.

Text editors.

Debug monitors.

File handling routines.

Loaders.

Linkers.

Besides their use in the writing and development of the application software (Ref.21), a major advantage of these systems is that they help in the time consuming, testing and debugging process. Development systems aid engineering solutions involving the microprocessor.

2.5.4 In-Circuit Emulation (ICE).

This is an important item for use, in conjunction with the development system, during the testing and debugging of the complete system at the system integration phase. It is also useful for intermediate testing and debugging enabling the simulation of system elements in software.

The one end of the ICE is plugged into the users system microprocessor socket, and the other end is connected to the development system. The hardware system to be tested has access to all the resources of the development system and programmes can be run from either source, or a mixture of both. Alteration of the contents of memory or registers, together with hardware/software interchange, is possible at any point in the programme.

The hardware of the system being developed has access to all the resources of the development system and can be tested in real-time. Step by step debugging of the hardware and software with the response of I/O systems to particular events is a very powerful tool. Programme execution can be interrupted at any point and the contents of memory locations and registers etc. can be examined.

2.5.5 EPROM Programmer.

This is most conveniently used as an accessory, or peripheral, to the development system. It is an essential development system tool which enables the application

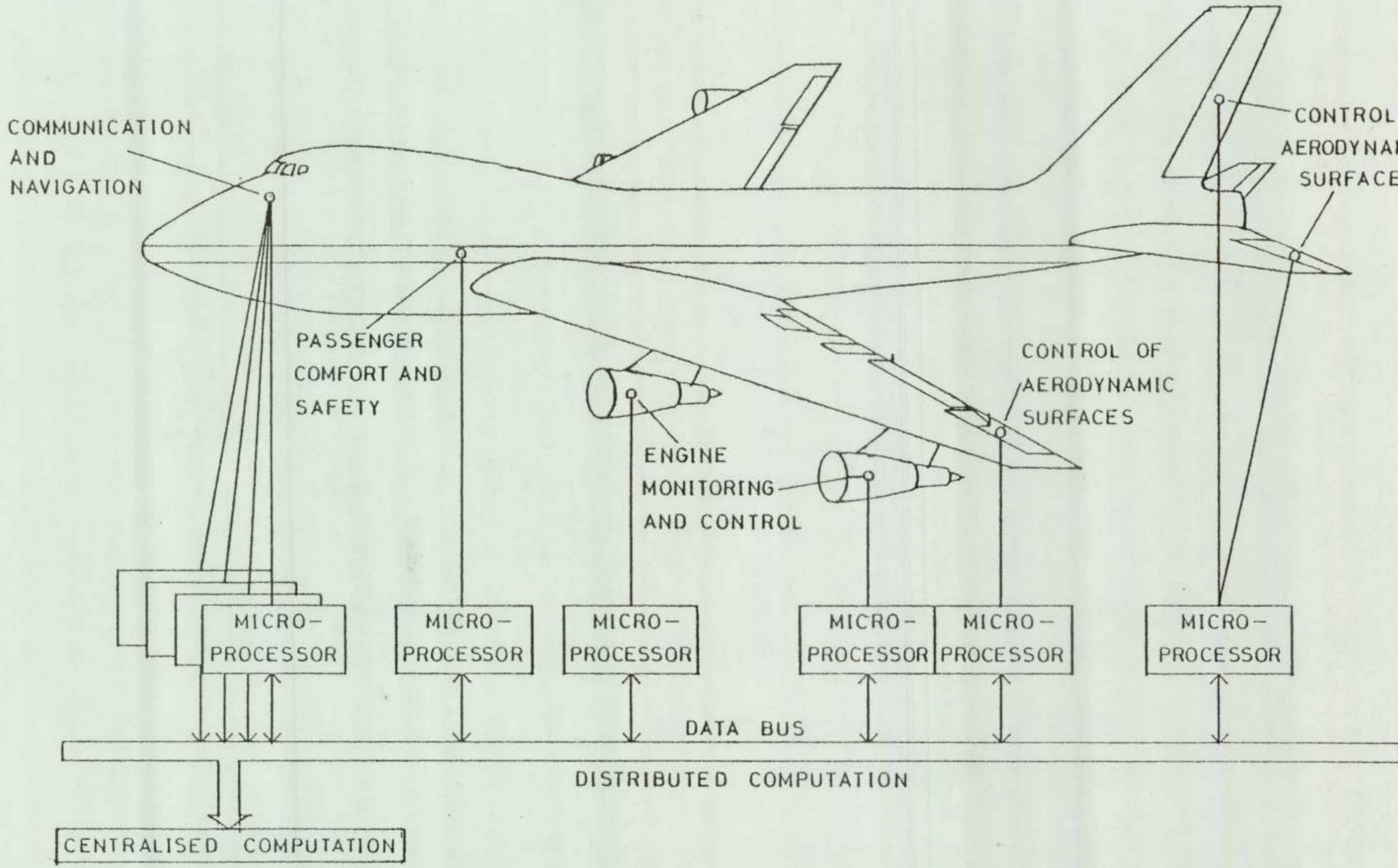


FIGURE 2.1 MODERN AIRCRAFT MICROPROCESSOR CONTROL AND MONITORING.

"firmware" to be down loaded, from the development system, into non-volatile memory.

There are several different types of PROM, including fusible link PROM´s and EPROM´s. Also there are numerous different IC´s of each type. Different PROM varieties or families are programmed by using plug-in "personality modules".

2.6 MULTIPROCESSOR SYSTEM CONFIGURATION.

Improved system performance, enabling it to cope with real-time requirements, is the key objective in the implementation of multiprocessor systems. The performance requirements are met by partitioning system functions and sharing them across more than one processor system or using more than one processor system to fulfill a particular function.

There are many possible configurations that can be applied to meet the required objectives of a control system. The height of the technology for a control and monitoring application is best demonstrated by the modern day jet airliner as shown in Figure 2.1 (Ref.22).

The conceptual systems design engineer must be familiar with the many different multiprocessor configurations and their various advantages and disadvantages, if effective system implementation is to be achieved.

2.6.1 "Pipeline" Processing.

In a pipeline processing system all the sequential functions required to execute an instruction are divided and carried out simultaneously by a number of separate

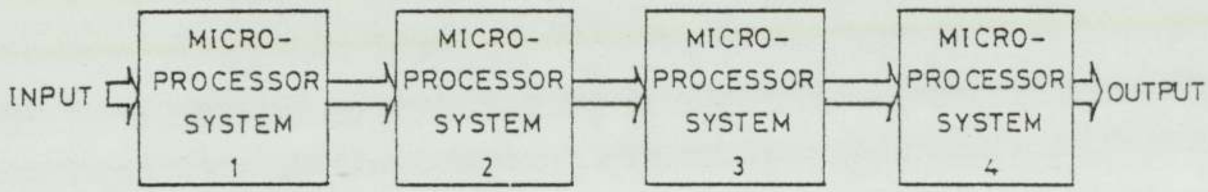


FIGURE 2.2 PIPELINE PROCESSING SYSTEM.

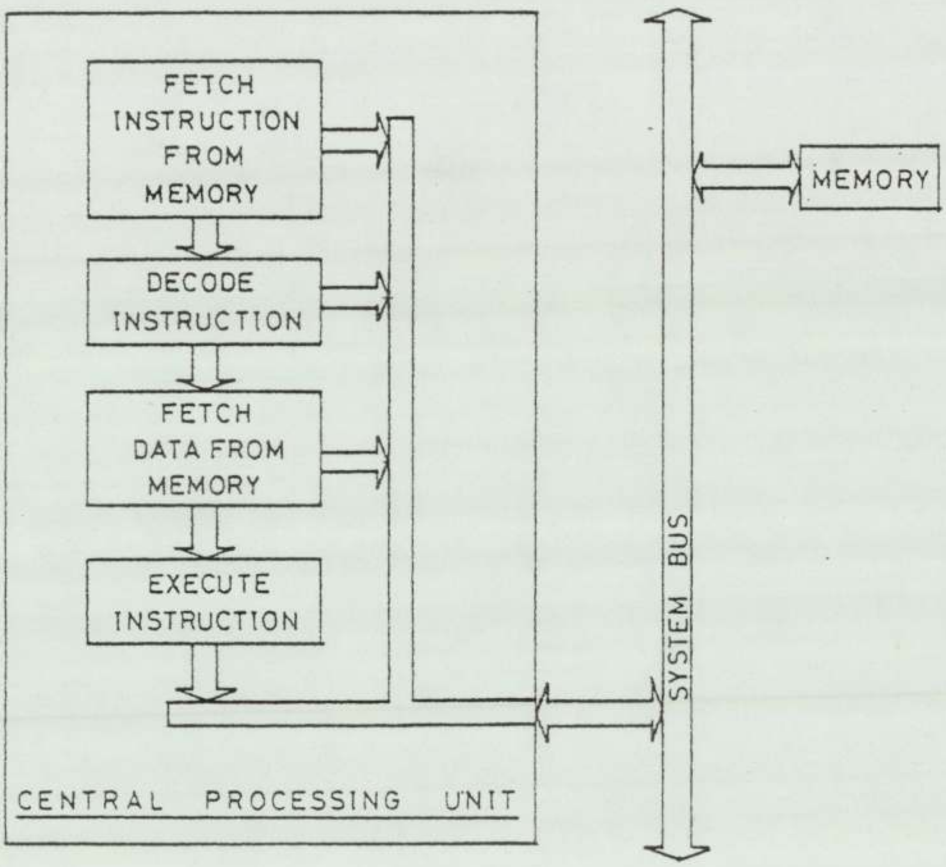


FIGURE 2.3 PARALLEL PROCESSING WITHIN A CENTRAL PROCESSING UNIT.

processor systems. This type of parallel processing system is shown in Figure 2.2 and is analogous to a factory assembly line. A pipeline processor system gains efficiency for the same reasons as the assembly line, viz - functions are specialized and communications are minimized. Pipelining, for example, can enable arithmetic sections of fast computers to process sequences of numbers with a high overall speed (Ref.23).

Some microprocessors incorporate parallel processing features. This is demonstrated by the Intel 8086 (Ref.24), which can implement multiple processing operations, internally. This is shown represented by Figure 2.3. The approach with this processor is fetching an instruction, decoding it, fetching data and executing an instruction. These are carried out in parallel so that on execution of the previous instruction, the next one is ready for execution. The overall throughput rate, as for pipeline multiprocessing, depends on the slowest element.

The throughput processing rate is increased, but this approach does not enable the simultaneous execution of a number of instructions on a number of data values.

2.6.2 Matrix Processing.

This array of processors is effective when much identical processing is to be carried out on many items of data. A matrix system is shown in Figure 2.4 where all the processors receive the same instructions, similar to a company of soldiers carrying out drill duty. A limitation is that individual computations depend only on the data in

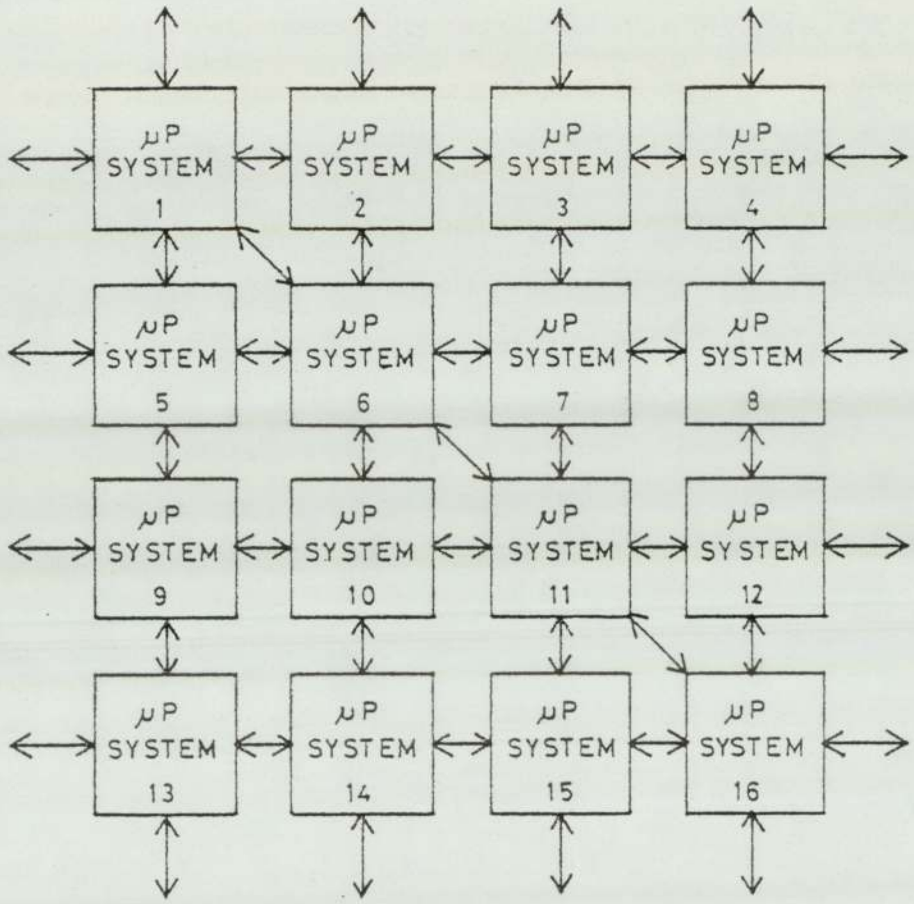


FIGURE 2.4 MATRIX PROCESSING SYSTEM.

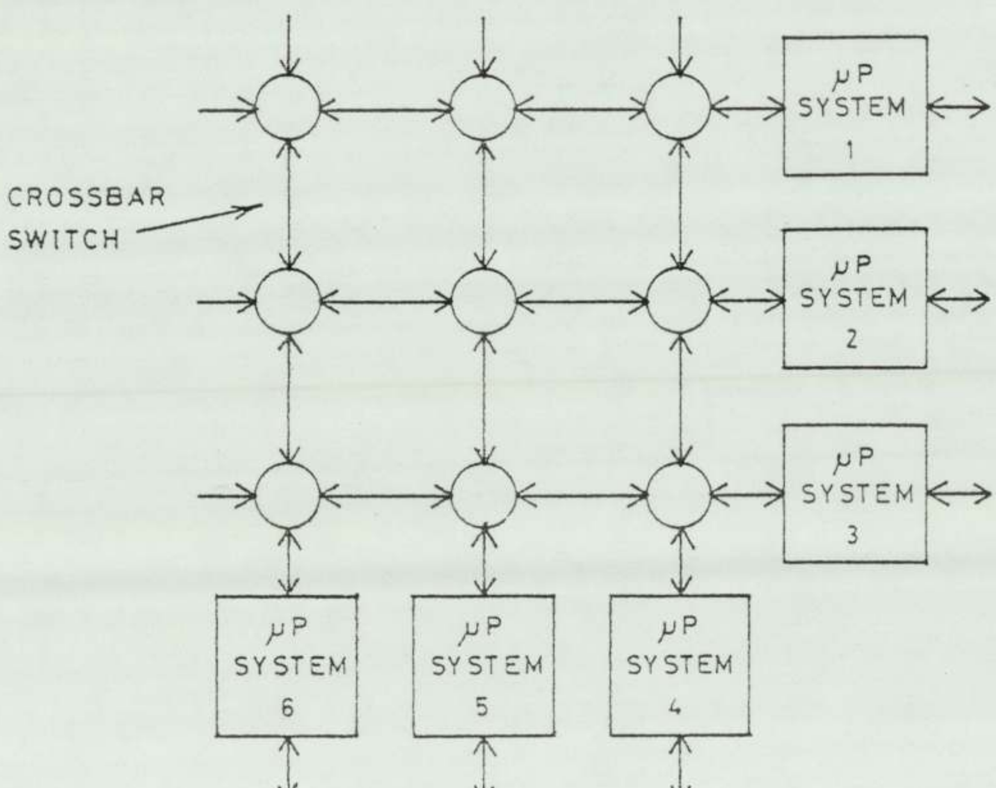


FIGURE 2.5 SWITCHED PROCESSING SYSTEM.

a particular element and its immediate neighbours. This has been effective in operations such as weather simulation, where local atmospheric interactions are significant (Ref.23).

2.6.3 Switched Processing.

A switched processing system is shown in Figure 2.5. An array of processors are connected by a crosspoint switch that directly connects any one processor system element to any other processor system element. This can be useful if a number of processor system elements must have contact with each other.

2.6.4 "Ring" System.

A further form of array processing, where the processor systems are distributed along a ring, is shown in Figure 2.6. Data are transferred around the ring, often by a serial unidirectional link, and captured by a particular processor system, according to predetermined criteria. The processor system for which the message is intended can remove it from the ring or pass it along if the message is also meant for another processor system. A message can be sent to all systems on the ring. Problems can be caused by the malfunction of any of the network processor systems. Reliability of ring networks can be increased by using double loops (Ref.25). There are many varying implementations of the ring or loop systems, including multiple loops where a processor may form part of more than one loop.

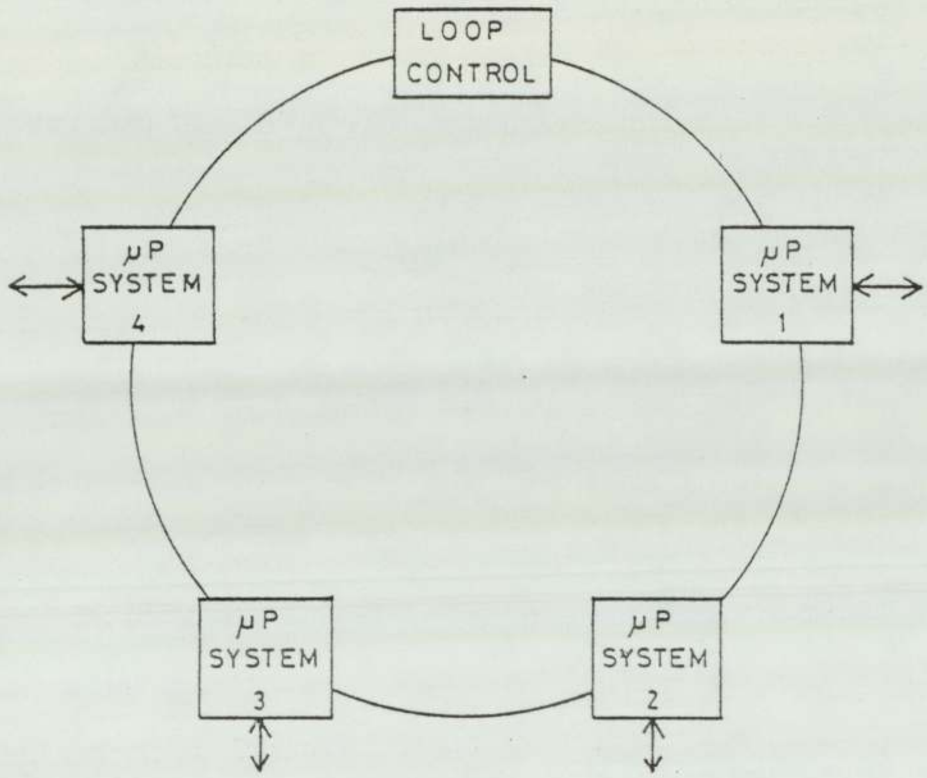


FIGURE 2.6 RING PROCESSING SYSTEM.

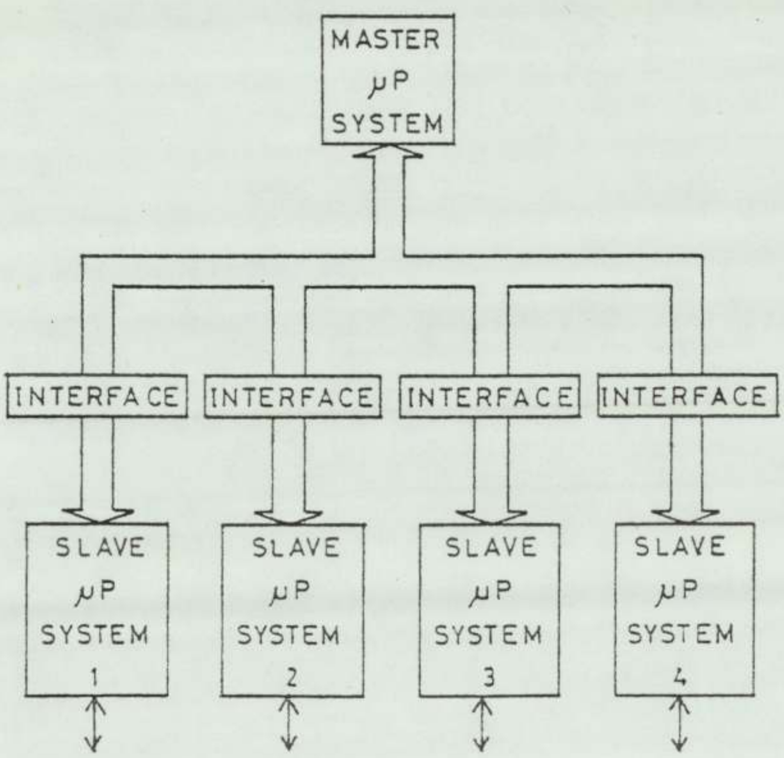


FIGURE 2.7 HIERARCHICAL PROCESSING SYSTEM.

2.6.5 Hierarchical Processing.

Figure 2.7 shows a system which is based on one "master" and four "slaves" in a hierarchical relationship. The master processor can control or supervise the operation of the slave processors in either a "tightly" or "loosely" coupled manner.

Hierarchical systems can be implemented where there are more than two levels. Thus the master processor at one level may be the slave for the next higher level.

2.6.6 Tightly Coupled Systems.

A system is considered to be tightly coupled if the processors access a common memory and peripherals. Any of the processors can access any of the memory locations and execute the necessary instructions. The access by different processors to common memory can not be simultaneous. Events have to be synchronized or the priority of access decided by handshaking operations.

2.6.7 Loosely Coupled Systems.

These may not have access to common memory. Each processor generally has its own memory and peripherals. The functions of loosely coupled systems are clearly defined. The operating system of a number of processors may be identical.

2.7 DATA TRANSFER TECHNIQUES.

Multiprocessor system design requires that various processor system elements receive servicing in an efficient manner, so that data and control information can be transferred with a minimum effect on throughput. The design, development and implementation of data transfer between processors, can be a time consuming operation that requires thought and careful planning to achieve the optimum solution for each application. A number of techniques can be used, either individually or in combination.

2.7.1 Polled Input/Output.

A common method used for detecting whether devices require servicing is the polled approach. This is where the processor, controlling the polling, must check each system element in sequence, to see whether it needs servicing. A large proportion of the main programme can be taken in needlessly looping through the polling cycle. This could have a detrimental effect on system throughput, thus limiting the tasks that could be assumed by the multiprocessor system and hence reducing the cost effectiveness of such methods. It might not be possible to respond to the real-time requirement criteria of control systems.

Hardware flags are used to indicate the send, or receive, condition of the system elements. If data is to be transferred, then an appropriate software routine is used to service that particular system element. The polling, status indication and data transfer can all be carried out between processor systems with simple input/output (I/O) ports. The hardware interface between systems is simple, requiring little, if any, additional logic, and with an efficient programme, executed at high speed, this method has found many applications.

2.7.2 Interrupted Input/Output.

The output of a multiprocessor system can be increased significantly if, instead of polling, it only stopped to service system elements when requested and usually when it is convenient to do so. The request can occur at any time, that is, in an asynchronous mode. The system element indicates this by setting up an interrupt flag in the other systems processor. The processor, if the interrupt is enabled, will acknowledge the interrupt, complete the execution of the current instruction, save the processor status and then service the requesting system by transferring the control to an appropriate I/O routine. Once the requesting system has been serviced the control is transferred back to the original programme. The interrupt service routine needs to be re-entrant.

Interrupt systems vary greatly from processor to processor and typical characteristics are :-

1) Number of interrupt lines.

2) How sources are identified.

If only one requesting line is connected to a single receiving interrupt then there is no problem with identification. When a number of requesting lines are attached to a given interrupt line, each requiring its own servicing routine, the interrupting line must be identified. This can be carried out by using a polling interrupt routine. A preferred alternative is to use a vectored interrupt where the interrupting line is directly identified. Some vectored interrupts not only identify, but also provide the starting memory address of the service routine to which the programme should jump.

3) Priority.

Some interrupts may be recognized first or interrupt the other´s service routine.

4) How interrupts are enabled and disabled.

Most real-time control applications involve critical routines that must not be interrupted during their execution. Some interrupts, depending on the application, can be classified as trivial whilst others have to be serviced. Different types of interrupts, known as maskable and non-maskable, can be used to overcome these difficulties. In maskable interrupts, software routines are used to enable or disable an interrupt. If disabled the processor will ignore the interrupt request. A non-maskable interrupt has to be acknowledged and serviced by the processor.

If more interrupts are required than are available on the processor and polling interrupt techniques are to be avoided, because of real-time requirements, then a programmable interrupt controller (PIC) integrated circuit may be used. A PIC, such as the Intel 8259A (Ref.26), functions as an overall manager in an interrupt driven data transfer system. It accepts requests from the interrupting systems, determines which of the incoming requests has the highest importance, ascertains whether an incoming request has a higher priority level than the level currently being serviced, and issues an interrupt based on this determination. Up to eight levels of request are managed and there are features enabling expansion, using additional PIC°s, to 64 levels. It is programmed by the systems software as an I/O peripheral and a selection of priority modes are available so that the interrupt requests can be configured to match the system requirements. The priority modes can be changed, or reconfigured, dynamically at any time during the main programme. This enables the complete interrupt structure to be defined as required for the total system requirement. The PIC, after interrupting the processor, can point the programme counter to the address of the start of the service routine associated with the requesting system element.

2.7.3 Direct Memory Access (DMA).

The I/O technique for the transfer of data, might not be suitable for many applications requiring fast data transfer. DMA, as the name implies, enables the processor of one system to gain direct access to another system's memory. The data transfer rate can be as high as the memory cycle time allows. There are various different ways of implementing DMA.

The buses of two or more processors may be interconnected for communication between systems. To enable each processor system to carry out its individual task there must be a means, usually under software control, of isolation between the buses. The processor whose bus is being accessed must be isolated from its bus before access can be gained by another system. Some of the more recent processors (Ref.25) can be placed in a HOLD state. They then become isolated from their buses. On linking of the two buses high-speed data transfer can take place. The mode is suitable for transfer of large blocks of data or for data of a byte or two. This type of DMA operation, referred to as the visible or burst mode, is frequently used in microcomputer systems. The speeds of operation of the microprocessors are reduced and this can be detrimental for some applications.

Another mode of DMA involves the stealing of cycles during which the processor is carrying out other tasks which do not require access to its memory and the bus is not being used. It is usual to transfer data one byte at a time, and this can be transparent to the system in that normal operations of the microprocessor are not suspended except for the inhibiting of the clock for a wait cycle. It is left to the systems designer to implement the necessary front-end logic (Ref.27) for cycle steal operations, as it is not an integral part of the processor. This is carried out by using the DMA facilities available on most processors. The stealing of cycles mode of data transfer, whilst not delaying the processor whose system memory has the data, can delay the transfer rate. Normally the bus is only relinquished for a few clock cycles which only allows transfer of a byte or two of data at a time.

Programmable DMA controller integrated circuits, such

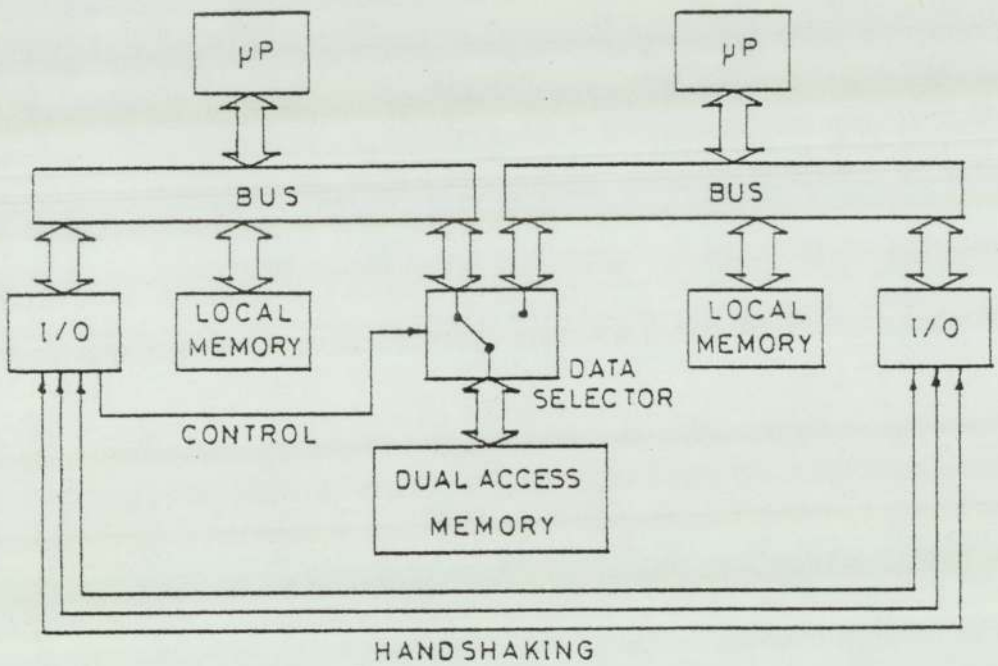


FIGURE 2.8 DUAL ACCESS MEMORY SYSTEM

as the Intel 8257 (Ref.26), are obtainable. This I.C. has four channels of DMA control. Upon a request, a sequential memory address is generated which will allow the reading or writing of data directly to or from memory. Acquisition of the system bus is obtained by use of the processors HOLD function. Sophisticated systems can make use of dedicated processors as DMA controllers and card modules containing these system elements are available for use in the configured open system (Ref.15).

A further form of DMA would be a method where a block of volatile memory could be accessed or isolated, from either system, under logic control. This would mean that at no time would the processors be isolated from their buses which would enable other tasks to be carried out, such as the control of I/O ports or an analogue to digital converter (ADC). Depending on the structure of the system, relatively long periods could be obtained for data transfer without slowing down the throughput rate. A typical layout using this method is shown in Figure 2.8 with handshaking and data selector control using I/O ports. The communication control could be configured in many different ways. For example, priority interrupts could be used and the data selector could be controlled from both or either system.

Dual port memory I.C´s., incorporating the data selector controls, are now becoming available.

2.8 COMMUNICATIONS BETWEEN MICROPROCESSOR SYSTEM MODULES.

The address, data and control bus are fundamental for communication within any processor system. The use of bi-directional bus drivers are often implemented, if large blocks of memory etc. are accessed within a system, to increase the drive capability of the local bus. These can also be used, with the tri-state facility, for the communication between two processor systems that are local to each other. A major problem with this method can be not only the distance and driving ability limitation, but also that only identical microprocessor buses may be interfaced. This problem can be overcome by using additional cicuitry and a standardised data communication bus. Manufacturers and other organisations have developed various standardised methods to enable the inter-connection of a wide variety of peripherals.

Buses can be categorised, depending whether they have parallel or serial communication. Parallel communication is faster than serial communication, because of simultaneous transmission of a number of data bits. Parallel transmission is practical only over relatively short distances. If data can be accepted at a slower speed then a serial bus with fewer lines can be used.

There are currently available a large number of data communication standards. Typically, the S100 bus, Intel Multibus, Standard bus, 6800 bus, LSI 11 bus, TRS 80 bus and Apple II bus, are examples. It is only intended to mention the more salient features of those which are particularly relevant to multiprocessor communication.

1) S100 Bus.

This bus is poorly defined and there are a number of different S100 implementations that are not necessarily compatible with each other. There are 100 lines and the function of some of the lines has not been specified. The bus is based on the Intel 8080 processor and its popularity has resulted in its official recognition by the Institution of Electrical and Electronic Engineers (IEEE). The IEEE have produced a revised standard for the S100 bus. This reduces the compatibility problems and offers a transmitted data distance of 635 mm, at a maximum frequency of 6 MHz. It is suitable for the new 16-bit processors, such as the Intel 8086 and the Zilog Z-8000. Up to 21 card modules can be connected to the bus. 24 address lines are available, allowing addressing to 16.384 megabytes of memory. Data can be transferred on the parallel lines in the form of 16-bit words, 8 lines are used for handling vectored interrupts and the remaining lines can be used for I/O, control functions and possible future specification.

2) Intel Multibus.

This bus system was introduced by Intel and has become an industry standard. It was specifically intended for use with the single board computer and boards for the control of periferal devices (Ref.15). Complex control problems have been solved using this approach (Ref.28). The Multibus was designed to support three generations of VLSI technology and has 24-bit compatibility. It has an element of defined system architecture and can support up to 16 processors, either in a master/slaves configuration, or a priority structure can be used to resolve the conflicts which arise when a number of processors of equal hierarchy are implemented. There are a total of 86 lines and the functions include, 16 address lines, 16 data lines, 8 interrupt lines, 9 status control lines, 6 multi-master control lines, 16 power lines, 8 ground lines and the remaining lines are user definable. The bus is 100 mm long with up to 5 board locations.

Recently Multibus II has been introduced by Intel. This has 32-bit processing capacity and is intended to support VLSI into the 1990's. It is not intended as a replacenent for the standard Multibus.

3) The Standard Bus.

This was introduced by Mostek and Pro-log Corporation. It has 56 clearly defined lines. The first 6 are logic power lines, the next 8 are used for data transfer, the next 16 for address, the next 22 for control and the remaining 4 are used for power. This bus structure is particularly suitable for the smaller system.

4) The User Defined Backplane.

Backplanes are available in various sizes and consist of a card with numerous parallel printed circuit tracks, generally double sided, with plated through holes for standard multi-way sockets for plug-in boards. The backplane is intended for systems designed and constructed from component level as all lines are user definable.

An attempt has been made to introduce industrial standards (Ref.29) for various other backplane configurations. When designing from component level the user definable backplane can offer many advantages, but it is necessary to anticipate any future possible system expansion to avoid inflexibility.

2.9 NETWORK COMMUNICATIONS.

The technology developed initially for the interfacing of the microcomputer to external devices, such as display units, printers, plotters etc., can be used for the communication between multiprocessor systems. Just as the peripherals may be local, that is, in the immediate vicinity of the computer system, or remote, so could the various processor systems, or system elements, developed for control or monitoring applications which require inter-communication. A number of standard interface methods have been introduced in an attempt to provide reliable transmission of signals.

1) The IEEE Std 488 Bus.

This is suitable for the transmission of 8-bit data in the parallel mode, over a maximum distance of 2 metres. 24 lines allow for bi-directional data transfer, data transfer control and general management and control. The standard defines the timing as well as the signals. It is not suitable for use in a noisy environment.

2) The EIA RS 232.

Communication by the Electrical Industries Association (EIA) RS 232 is via serial interfaces, whereby the data is transferred serially one bit at a time. Data can be transmitted at various standard rates from 50 baud (bits per second) to a maximum of 19 200 baud, over extended distances. There are a total of 25 pins in the socket, but it is usual to find the number of pins used for the data transmission ranging from 2 to 9. These are, transmit data, receive data, signal ground, request to send, data set ready status, carrier detect, clear to send, data terminal ready and secondary request to send. The RS 232 standard is somewhat anomalous and hence systems that satisfy the standard might not be compatible.

Development has led to the EIA RS 422 and EIA RS 423 which offer improved noise immunity.

3) 20 Milliamp (mA) Current Loop Standard.

Transmission is in the serial mode and logic 1s and 0s are indicated by closing and opening the 20mA current loop. The asynchronous transmission of the data can be over extended distances. Only 4 wires are used and the system has good noise immunity.

Devices for converting the current loop standard to RS232 are available.

2.10 SUMMARY.

The tremendous growth in microprocessor and associated products technology in recent years is continuing at an ever increasing pace. The development of commercial and technically viable control systems incorporating the latest techniques is necessary if products and entire companies are to avoid obsolescence. The microprocessor systems application engineer, having first identified and defined the requirements, must make many decisions at an early stage as to the system architecture.

The design criteria, choice of microprocessor, system development and de-bugging aids, multiprocessor configurations and inter-system communication techniques have received appraisal, with respect to the design and analysis tasks, in this Chapter.

2.10.1 Level of Entry.

This is fundamental to the development process and has a bearing on the initial and each subsequent system. The choice is between IC level, Configured "open systems" built from selected modules, or ready configured minicomputers. The latter has only a limited application to complex control engineering applications and only the initial two levels will receive comment. It is possible to combine these two levels for an overall system. The level of entry may be decided by distinct system requirements.

The design and construction of a system from IC level would have the following characteristics :-

1) Low cost for multiple production due to a minimum of redundant features.
2) High initial development cost.
3) Extended time to market with possible investment risk.
4) Low overall power consumption and small physical system size due to a "highly tailored" system.
5) Requires a high degree of hardware expertise particularly if the requirement is for VLSI.

6) High degree of flexibility in hardware and software trade-offs.

7) High degree of multi-sourcing of IC's guaranteeing availability in the future.

8) Very easy to produce a system tailored to present day needs alone and not possible future requirements. This can be avoided by adopting an "open system" approach from the beginning.

The Characteristics of the "open system" configured from card modules are :-

1) Reduced time to market reflecting a lower investment risk.

2) High multiple production costs.

3) Lower system development costs, although the initial cost in purchasing the development equipment would be higher.

4) High power consumption and larger physical system size because of redundant elements.

5) Less flexibility in tailoring the system to meet the exact requirement, although this will become less of a problem as more modules become available.

6) Possible future requirements are more easily introduced avoiding product redesign costs.

7) Open to future VLSI.

8) Complex operating systems, such as those required for multiprocessor applications, are simpler to apply.

9) Comprehensive libraries of software modules are becoming available.

2.10.2 Multiprocessor Systems.

The layout and characteristics of multiprocessor configurations have been discussed in this Chapter.

The multiprocessor system can offer many advantages over the more conventional single processor system. The total system requirement must be defined and a decision made as to whether to divide the overall task between a number of processors. The advantages that can accrue can be defined as follows :-

1) Faster response to real-time control requirements can be obtained since several tasks can be carried out simultaneously. Interruption of a single processor need not interfere with the tasks of other processors, or the main operating system.
2) The cost of design, development and construction of a multiprocessor system can be less than the cost of a centralised system with equivalent computing power. 8-bit devices could provide the real-time control requirement provided by a single 16-bit processor.
3) Multiprocessor systems, correctly configured, can be more easily adapted to suit changed requirements. It is therefore easier to provide for an increase or change in system demands.
4) Multiprocessing systems with shared memory and a common bus can simplify the task of communications between different processors. The same data required by several systems can easily be accommodated, with minimum communication network costs.

5) The modular construction of multiprocessor systems enables the development task to be more easily divided and individually defined. This can result in a reduction in time for implementation of the working system.

CHAPTER THREE

MICROPROCESSOR SYSTEM FOR CONTROL OF ROADHEADER - HARDWARE

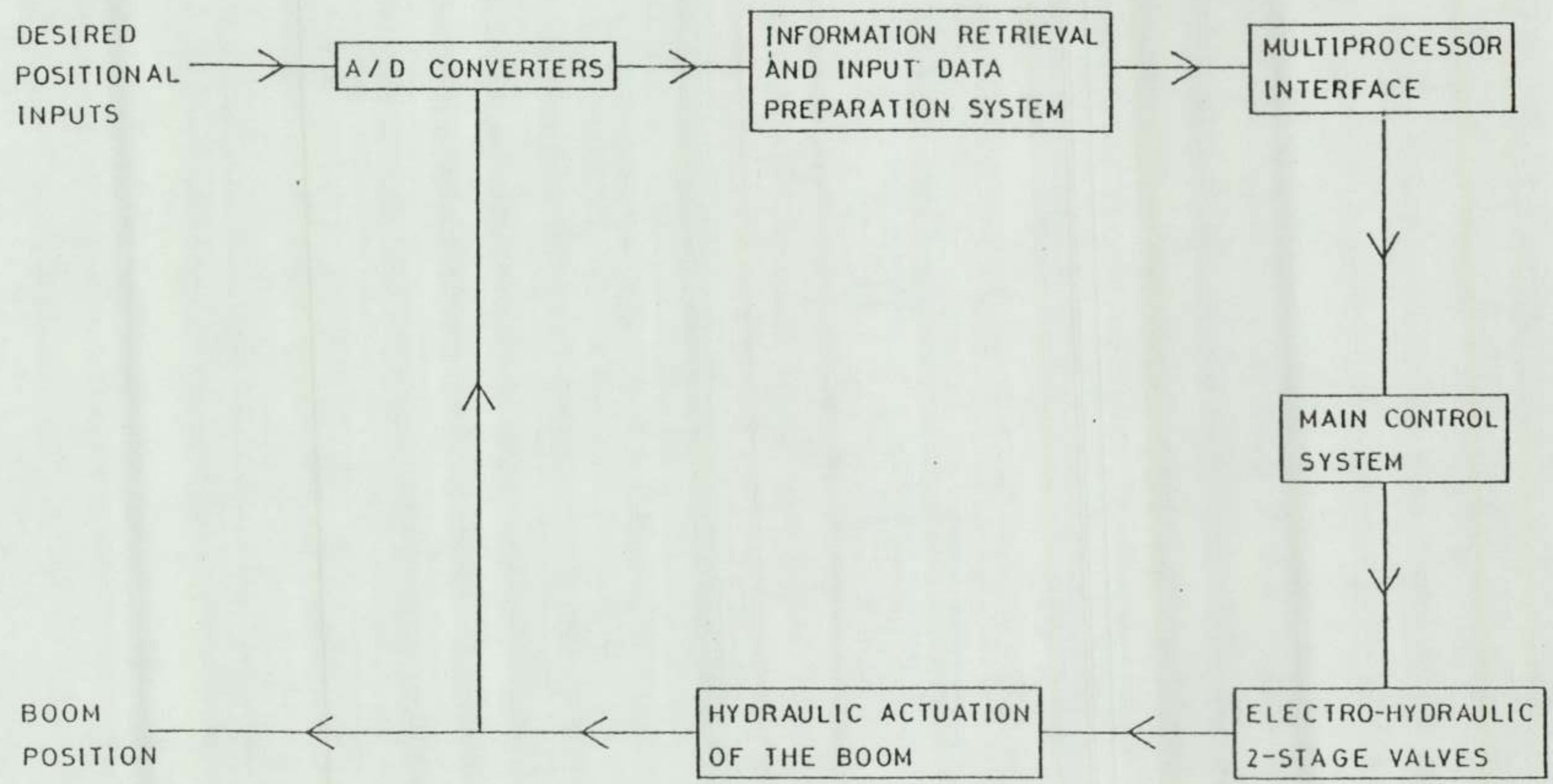


FIGURE 3.1 BLOCK DIAGRAM OF CONTROL SYSTEM FOR ROADHEADER BOOM.

3.1 INTRODUCTION.

The roadheader is a free ranging machine with distinct requirements for control of the boom and also for actual control system characteristics. The choice of microprocessor and compatible ICs that form the system, are fundamental to both of these aspects. The system design criteria, overall control system concept, choice of microprocessor and multiprocessor interaction for the roadheader are contained in this chapter.

A description of the elements, with detailed reference to the more salient features, of one of the microprocessor systems is also contained in this chapter.

3.2 SYSTEM DESIGN CRITERIA.

The initial step in the design of the microprocessor system began by applying the criteria, outlined in Section 2.3, to the roadheader machine. The system criteria are defined as :-

1) Control Requirement.

The system is required to give manual and automatic point-to-point and continuous path control to the hydraulically actuated boom of the roadheader.The valves for control of the hydraulic fluid are simple on/off, solenoid operated, poppet type valves. The valves are switched using control data which has been either pre-programmed or operator defined to the system. The boom position is continually monitored and closed-loop control is implemented. The complete overall system is shown in block diagram form in Figure 3.1.

2) Compatibility.

This must be ensured within the electronic systems, between the microprocessor system and the electro-hydraulic components, between the machine operator and the system control requirement of the boom and also between the total system and the environment.

The mining environment dictated that the system must have a low overall power requirement in an attempt to achieve intrinsic safety approval (Ref.30). To meet this requirement it was necessary to develop a system with a minimum of redundant elements. Hence, the system was developed using individual ICs which allowed the highest possible level of purpose designed system configuration. Other advantages and some disadvatages (discussed in Section 2.10.1) accrue from this entry level. These are particularly relevant to the roadheading machine and receive mention in other parts of this system design criteria description.

3) Cost.

There are approximately 600 roadheading machines of the boom mounted ripper type in use in the British coal mines, each representing a capital investment of between approximately £200 000 and £700 000. The export market for these machines represents approximately 60% of production.

The cost of the hardware is repeated for each application and is minimal for a control system constructed from IC level. If the system had been configured using pre-built card modules, as discussed in Chapter 2, the cost of the hardware would have been considerably higher. The extra initial system development costs for the IC level of entry would be repayed many times over when related to 600 machines. On cost alone, a case is made for this system to be constructed from individual IC component level.

4) Flexibility.

The development of the roadheader control system is likely to be an ongoing operation. Several aspects of the final system, described in this thesis, were not envisaged at the initial stage. It was possible to incorporate most of these without any major modification being necessary to the hardware. Software modification was readily implemented. The one exception to this, which came about after the system was built and working, proved to be the liquid crystal display (LCD) for the operator, described in Appendix C. The flexibility of the system is discussed further in Chapter 8.

Generally, the flexibility of the development of microprocessor based control systems was demonstrated.

5) Reliability and Safety.

In event of a roadheader becoming inoperable, the cost, to bring the machine to the surface and take down a replacement, can amount to 80,000. This does not include the cost of loss in production, which could amount to millions of pounds.

The mining environment dictated that the system should operate with reliability and safety, as specified for underground machinery (Ref.31).

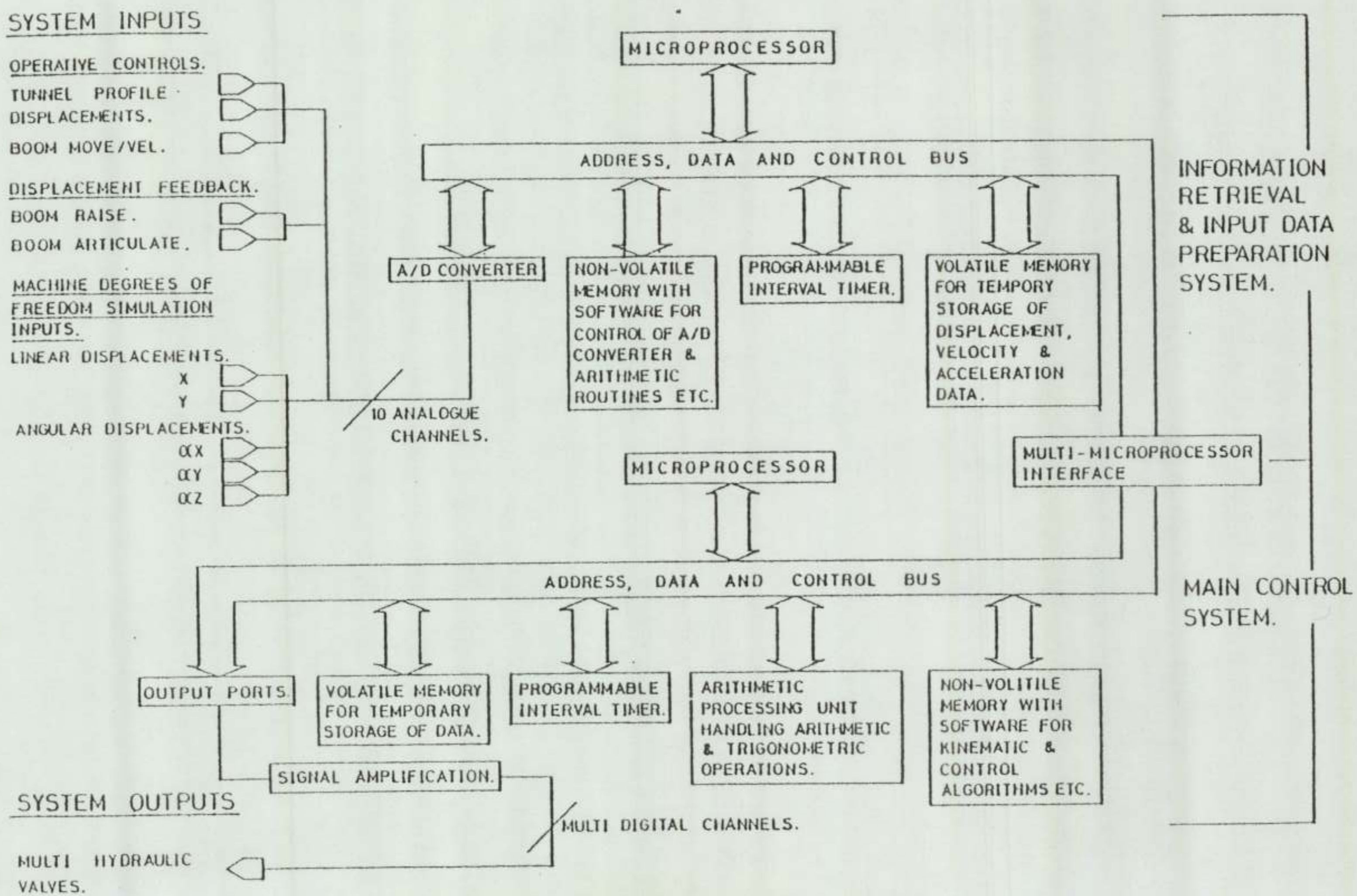


FIGURE 3.2 ROADHEADER CONTROL SYSTEM ARCHITECTURE.

The electro-hydraulic valves incorporate direct manual operation, which provides a rudimentary form of control in the event of a control system failure. Microelectronic systems are compact, and hence, easily replaceable. Despite this, system reliability remained an important criterion.

Safety in the designed operational performance of the system was of paramount importance and was considered throughout the design, development and testing operations.

There is an implication of unsafe performance if the system operates outside the designed mode. This was considered at all stages of system development in an attempt to design out the possibility of any unpredictable operational modes. Signal conditioning is applied to the analogue feedback lines as described in Chapter 4 and the usual precautions were taken in the selection of ICs and the design of the digital electronic systems as discussed in this chapter.

The structure of the software operating system is also relevant to safe operation and is discussed in Chapter 5.

The overall safety aspect of the electronic and hydraulic systems are described in Section 8.6.

3.3 CONTROL SYSTEM CONCEPT.

The architecture of the complete system is shown in Figure 3.2. Two microprocessors are used, one for the control of the input data retrieval system and one for the system which controls the switching of the hydraulic valves from this data. Two processors were necessary to enable real-time control of the boom.

The data input to the system includes feedback and machine operator defined information of analogue voltage representation. The inputs, including the signal conditioning and analogue to digital conversion (ADC), are described in Chapter 4.

The control of the ADC, storing of displacement information, and calculation of the velocity of the boom using an interval timer IC, requires a system with volatile memory for temporary storage of data and non-volatile memory for the system operational software. The microprocessor operates the sequential control of the entire data input system with parallel operations from the ADC and the programmable interval timer hardware elements.

The microprocessor system which generates the signals for switching the hydraulic valves is covered by the complementary thesis carried out by C. W. Chuen. The digital operation of the valves makes for a simple output interface requiring power amplification only.

3.4 CHOICE OF MICROPROCESSOR.

The selection of the microprocessor was a crucial step in the system design procedure. Having determined that a microprocessor based control system implementation was feasible for control of the roadheader, the Intel 8085A microprocessor (Ref.26) was selected on the basis of well established criteria. The criteria are :-

1) Accuracy and Speed.

An 8-bit device can give the accuracy of a 32-bit device, but will require multi-byte handling of data which

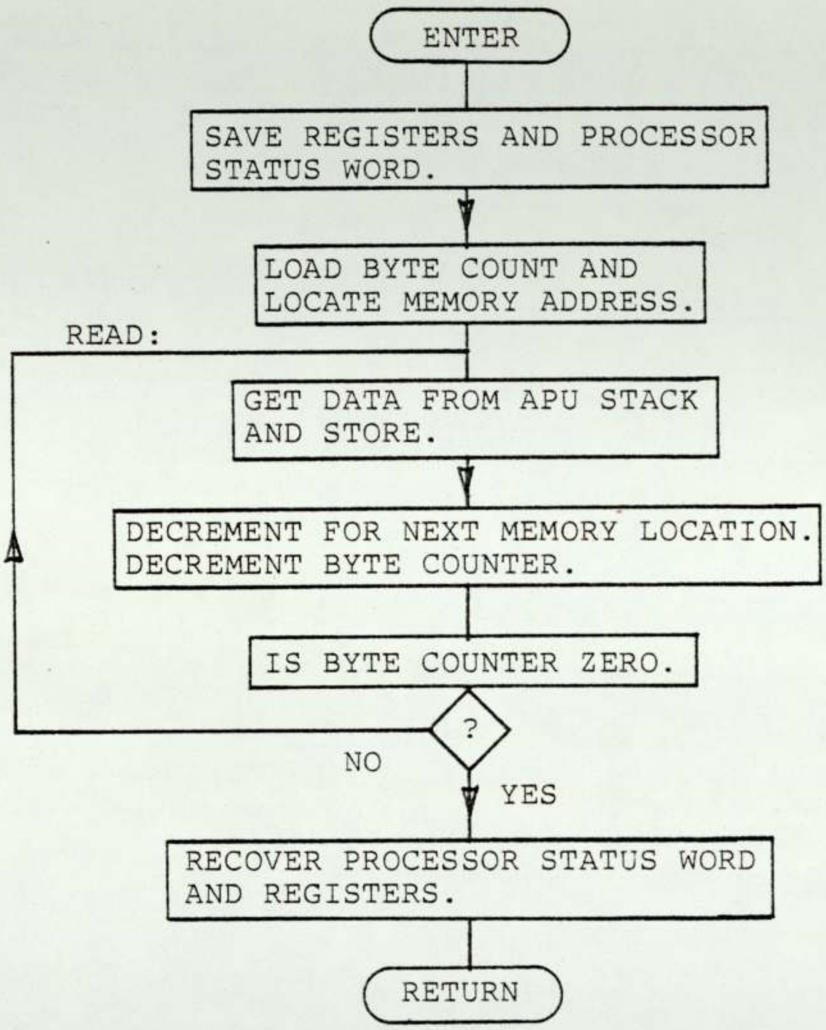


FIGURE 3.3 BENCHMARK PROGRAMME FLOW CHART.

			MEM. BYTES	CLOCK CYCLES
	PUSH H	; SAVE H,L REGISTERS.	1	12
	PUSH B	; SAVE B,C REGISTERS.	1	12
	PUSH PSW	; SAVE PROC. STATUS WORD.	1	12
	LXI H, STADD:	; LOCATE MEM. ADDRESS.	3	10
	MVI B, 04H	; LOAD COUNT VALUE.	2	7
READ:	IN APUD:	; GET DATA FROM APU STACK.	2	10*4
	MOV M,A	; STORE DATA INTO MEMORY.	1	7*4
	DCX H	; DECRE-T FOR NEXT MEM ST.	1	6*4
	DCR B	; DECREMENT BYTE COUNTER.	1	4*4
	JNZ READ:	; LOOP BACK IF NOT ZERO.	3	(10*3)+7
	POP PSW	; RECOVER PSW.	1	10
	POP B	; RECOVER B,C REGISTERS.	1	10
	POP H	; RECOVER H,L REGISTERS.	1	10
	RET	; RETURN TO CALLING PROG.	1	10
		TOTALS :-	20	238

Total time = $238 \times 0.3255 \times 10^{-6} = 77.47\ \mu s$

FIGURE 3.4 8085 ASSEMBLY LANGUAGE BENCHMARK PROGRAMME.

			MEM. BYTES	CLOCK CYCLES
	PUSH CX	; SAVE CX REGISTERS.	1	10
	PUSH BX	; SAVE BX REGISTERS.	1	10
	LAHF	; LOAD REG AH WITH FLAGS.	1	4
	PUSH AX	; SAVE ACCUMULATOR & REGS.	1	10
	MOV BX,STADD:	; LOCATE MEM STORE ADDRS.	3	4
	MOV AH, 02H	; LOAD COUNT VALUE.	2	4
READ:	IN AL, APUD:	; GET DATA FROM APU STACK.	2	10*2
	MOV CL,AL	; STORE UPPER BYTE.	2	10*2
	IN AL, APUD:	; GET DATA FROM APU STACK.	2	10*2
	MOV CH,AL	; STORE LOWER BYTE.	2	10*2
	MOV [BX],CX	; STORE DATA TO MEM.	3	10*2
	DEC BX	; DECR-T. FOR NEXT MEM ST.	1	2*2
	DEC AH	; DECREMENT COUNT VALUE.	2	3*2
	JNZ READ:	; LOOP BACK IF NOT ZERO.	2	16+4
	POP AX	; POP ACCUMULATOR & REGS.	1	8
	SAHF	; STORE REG AH TO FLAGS.	1	4
	POP BX	; RECOVER BX REGISTERS.	1	8
	POP CX	; RECOVER CX REGISTERS.	1	8
	RET	; RETURN TO CALLING PROG.	1	8
		TOTAL :-	30	208

Total time = $208 \times 0.2 \times 10^{-6} = 41.6\ \mu s$

FIGURE 3.5 8086 ASSEMBLY LANGUAGE BENCHMARK PROGRAMME.

infers a slower speed.

32-bit arithmetic data is handled within the system, using both software routines for velocity calculation (refer to Chapter 5) and an arithmetic processing unit (APU) is used for handling the valve switching criteria (refer to the thesis by C. W. Chuen). Multi-byte operations are required to handle the information.

A comparison of the performance of different processors is best carried out using a simple benchmark programme (Ref.33). Different processors utilize different instruction sets and such programmes are usually specified by a functional flow chart. The programme should represent time critical operations relevant to the intended application. The two parameters that are then considered for comparison are, the number of memory bytes occupied by the programme and the speed of execution of the programme.

An example, as applied to this application, is for the reading and storing of 32-bit information from the APU. The functional flow chart for this operation is shown in Figure 3.3.

The programme using 8085A assembly language to carry out this operation is shown in Figure 3.4. The programme using 8086 assembly language for the same operation is shown in Figure 3.5.

The 8085A, 8-bit processor, clocked with a 6.144 MHz crystal takes 77.47 μs to carry out the APU read routine, and the 8086, 16-bit processor, clocked with a 5 MHz crystal takes 41.6 μs for the same operation.

The 32-bit stack of the 8231A APU (Ref.26) can only be accessed with 8-bit bytes. The 8085A has four programmed passes of the READ loop and stores the data to four decremented bytes of memory. The 8086 reads two 8-bit bytes from the APU stack for each pass of the READ loop, and stores them as a 16-bit word. Only two passes of the loop are required and the information is stored as two 16-bit words.

The 16-bit processor demonstrates a considerable improvement in time performance in handling the reading of the APU. The 32-bit data would also be handled at increased speed within the 16-bit processors system. Despite this fact, the higher speed was not necessary for the roadheader real-time control application. Increased speed of operation could however be imperatve for other control engineering applications (Ref.28).

2) Power Requirement.

The 8085A N-channel device has a power requirement of 5V and 170mA. The single voltage is particularly useful for this intrinsically safe application as it avoids the linking of multi-voltage lines other than by optical means (Ref.30).

Ideally it would have been preferrable to use a complementary metal oxide semiconductor (CMOS) processor. These have inherently lower current ratings. At the time of beginning this project there were few CMOS processors available - namely the Intersil IM6100 and the RCA 1802 family. Neither of these processors suited the application as ideally as the 8085A and would have required investment in new development aids. In 1982 OKI introduced a CMOS version of the 8085A which has a current rating of only 18mA. This processor will operate at the same speed and has an identical architecture, instruction set and driving ability as the Intel 8085A processor. It can therefore be used as a direct replacement.

There are now many more CMOS processors and supporting ICs available and the technology is advancing at an ever increasing pace.

3) Hard-wired Interfacing Facilities.

These are of particular concern in the selection of a processor for an engineering control system application. Besides the address, data and control lines, the 8085A has five hardware interrupt inputs and DMA control facilities.

The interrupts are used to inform the processor of the occurrence of external events which require immediate action. They are in an order of priority and are individually maskable by software control except for the TRAP interrupt which is of highest priority. This is useful for detecting catastrophic events requiring immediate control system close-down, such as hydraulic power failure. The application of the interrupts for the roadheader control is detailed in Section 3.5.4.

The DMA facility allows external devices to gain control of the bus and is discussed further in Section 3.5.

The 8085A is a 40 pin, dual-in-line (DIL), IC. The high density of functions is made possible by the use of multiplexed data and eight least significant address lines.

4) Instruction Set.

All processors have a set of unique instructions that are closely related to each processor´s architecture. The greater the number of instructions in the set infers the better it is, since a larger variety of operations may be performed using one basic instruction. If the instruction set is small, then a number of basic instructions might be used to perform the action performed by one of the instructions of a larger set. Correctly configured benchmark programmes allow comparisons to be made.

The 8085A has a comprehensive set of instructions which are discussed further in Chapter 5.

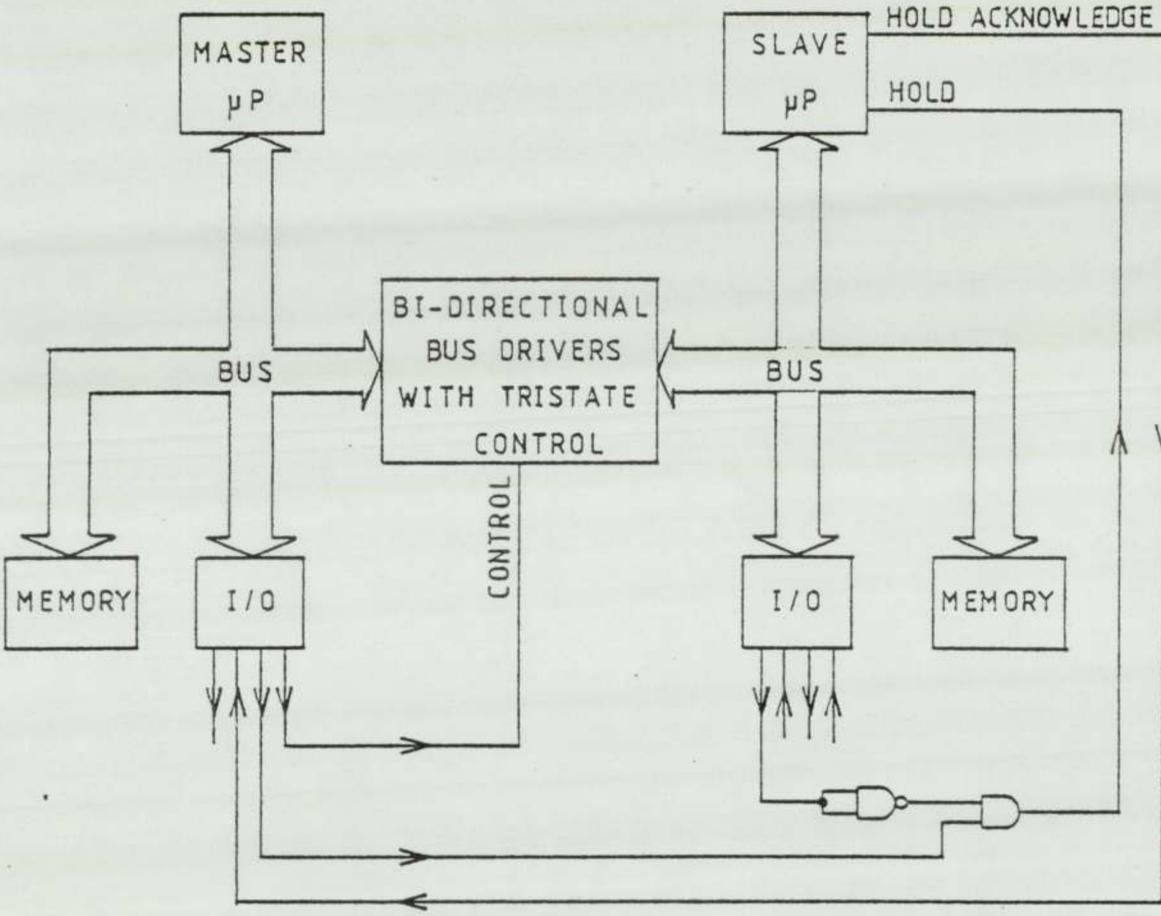
It is essential for the system designer/programmer to have a good knowledge of the instruction set.

5) Viability.

For a product as complex as a microprocessor viability is not always immediately demonstrated. Some original equipment manufacturers have found it necessary to abandon costly development projects because the prototype microprocessor, around which they were designed, did not materialize into a viable product. The Intel 8085A has found widespread application in the computing and control engineering fields since its introduction several years ago and its viability is confirmed.

6) Availability.

Availability now and in the future is of concern. Intel guarantee availability for a minimum of twenty-five



HOLD REQUEST (MASTER SYSTEM)	OUTPUT PORT (SLAVE SYSTEM)	HOLD (SLAVE SYSTEM)
0	0	0
0	1	0
1	0	1 (ACTIVE HOLD SIGNAL)
1	1	0

FIGURE 3.6 MULTIPROCESSOR INTERFACE AND TRUTH TABLE.

years. Second-source availability of the 8085A is a further guarantee.

7) Systems Design, Develop and Build Support.

A comprehensive range of compatible system support ICs, such as ROM, RAM, I/O, programmable interval timer and suitable system interface logic such as decoders etc. are available for the 8085A microprocessor.

A development system with an assembler and an in-circuit emulator and other software development aids were available within the University. These are important considerations when selecting the microprocessor, since to purchase such items would be a high initial cost. Some of the more recent VLSI microprocessors will reportedly be made available prior to the supporting system development aids. This delay in availability of development aids would considerably complicate the system implementation task.

3.5 MULTIPROCESSOR INTERACTION.

The system adopted for the roadheader is shown in Figure 3.6, with the retrieval systems processor referred to as the "slave" and the main processor for the valve switching criteria referred to as the "master". There is an element of hierarchy in the system, in that the main processor can access the retrieval processors system, but not vice-versa.

The important features are the controls which enable isolation of the retrieval processor from its address bus, data bus and control lines, and the controls which enable isolation and linking of the two processor systems buses.

For normal operation, when the retrieval processor is monitoring the feed in and feedback information and updating its memory and the main processor is controlling the switching of the valves, the two system buses are isolated from each other. To enable direct memory access (DMA) the retrieval systems processor must first be placed in a HOLD state, and on acknowledgement of this, the two buses are interconnected.

The information to be accessed by the main processor consists of multi-byte tunnel profile definition data, groups of four 8-bit bytes of velocity data and single 8-bit bytes of displacement data. During the period when the retrieval systems memory is being accessed the retrieval processor relinquishes use of the bus and only internal processing can continue. The instance and period of HOLD of the processor required careful consideration to minimise the effect on the accuracy and real-time control requirement of the boom.

The tunnel profile data is obtained by the retrieval processor. It is accessed and sorted by the main processor. These operations take place when the systems are first powered-up or on press of the reset button. During these periods the boom is rendered inoperable and it is not until the sorting is completed that the operator is able to place the system into either an automatic or manual mode of operation. It is only the four byte and single byte data which is accessed during the control period.

The moment in time of the receipt of HOLD for the reading of single byte data was of no account since the

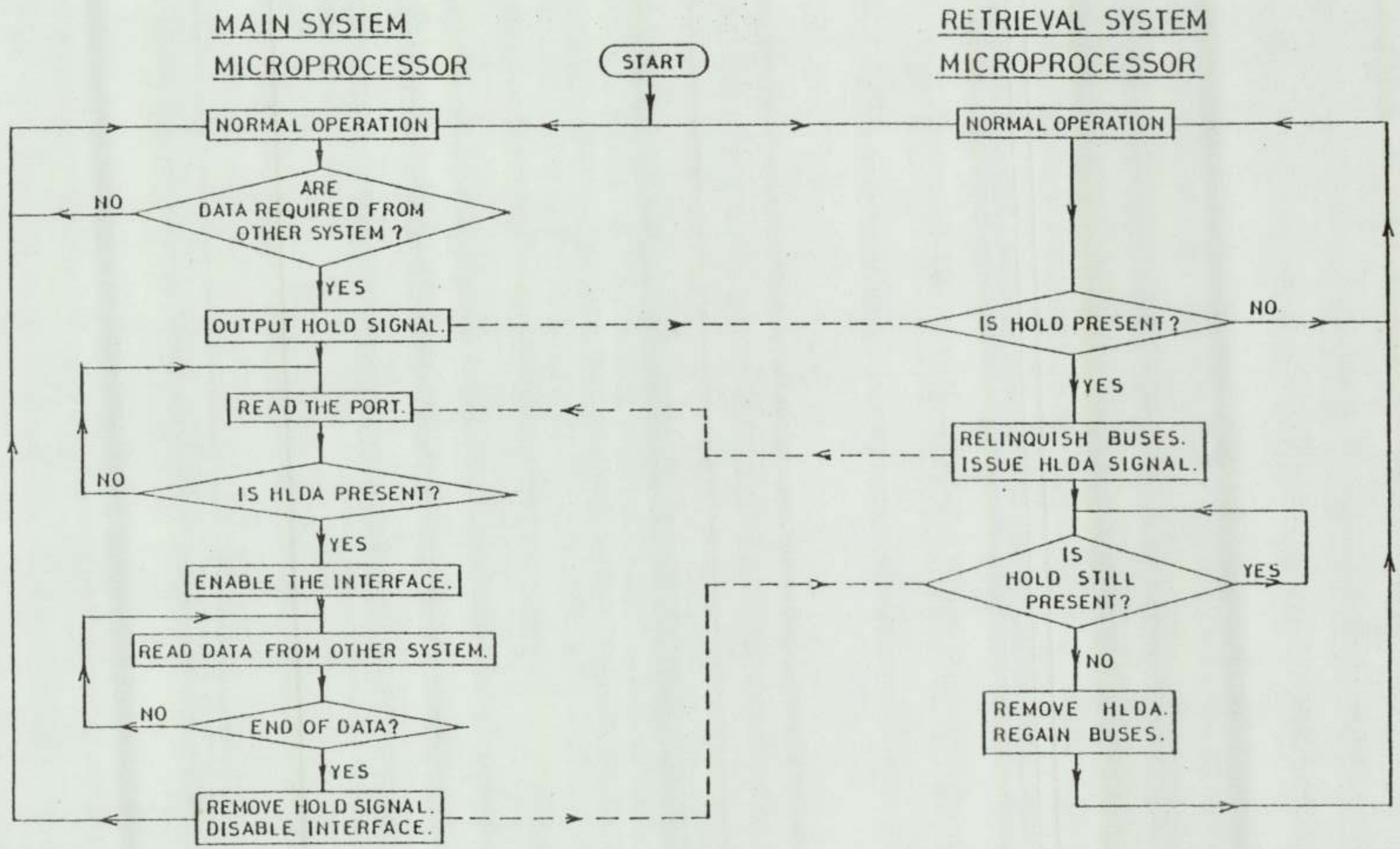


FIGURE 3.7 FLOW DIAGRAM FOR THE ACTIONS TAKEN BY THE TWO MICROPROCESSORS IN COMMUNICATING WITH EACH OTHER.

frequency of update and access of each byte of displacement data was approximately 32 times per second (refer to Section 4.7). The hydraulic valve opening and closure response times were measured to be approximately 200/350ms, respectively.

The instance of access of the four-byte velocity data required consideration, since to have accessed this data during a period of update could have provided incorrect information for the valve switching criteria algorithms. Handshaking was therefore implemented, as shown in Figure 3.6, whereby the retrieval processor could inhibit the HOLD during the period of update.

The handshaking and communication control between the systems was carried out using I/O ports. The flow diagram for the communicating actions taken by the two processors is shown in Figure 3.7 and is autonomous, that is, controlled by the software of the systems.

3.6 MICROPROCESSOR SYSTEM - DESCRIPTION OF PARTS.

This section describes the IC's and the salient features pertinent to the retrieval and data preparation system for the operation and control of the roadheader. The power amplification for the operation of the hydraulic valve solenoids and opto-isolation circuits are also described. The main processor system is described in the complementary thesis carried out by C. W. Chuen.

The circuit connections for the retrieval system can be found in the Appendix A on Hardware Diagrams Nos. 1, 2, 3 and 7 and the power amplification circuits are shown on

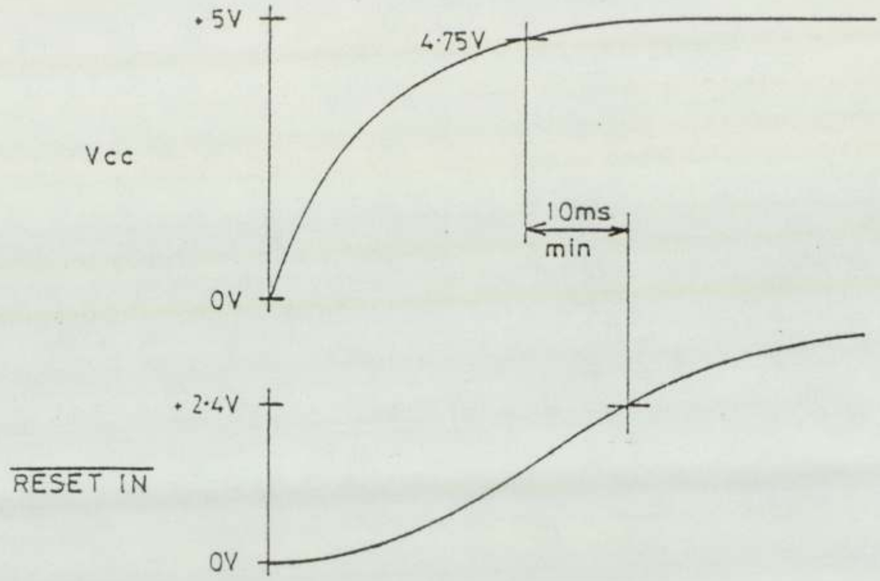


FIGURE 3.8 'POWER ON' TIMING.

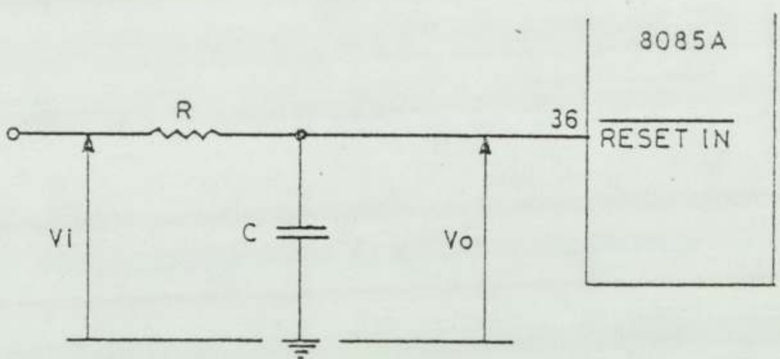


FIGURE 3.9 RC NETWORK FOR $\overline{\text{RESET IN}}$.

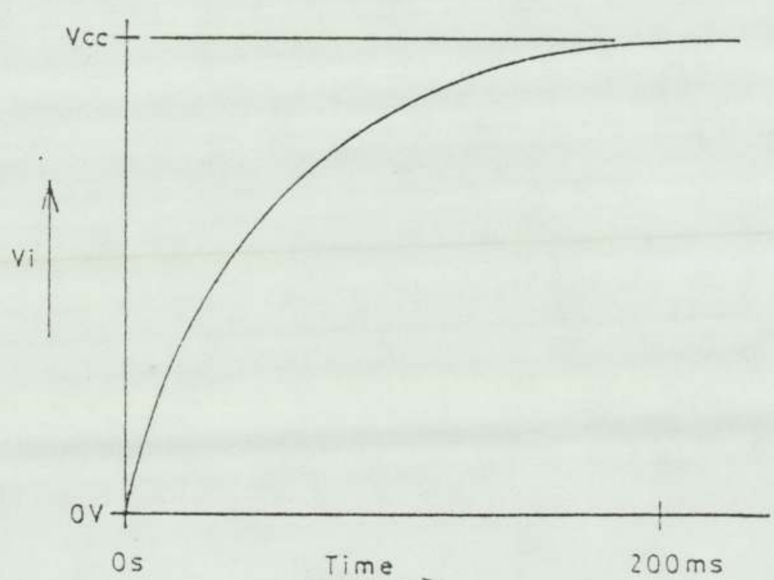


FIGURE 3.10 U-V RECORDING OF SYSTEM POWER SUPPLY OUTPUT VOLTAGE.

Hardware Diagram 6.

3.6.1. $\overline{\text{RESET IN}}$ and Power On.

Automatic start up on "power up" of the processor is desirable for this system. It saves having to implement some form of reminder to the operator to reset the system.

$\overline{\text{RESET IN}}$ sets the programme counter to zero and resets the Interrupt Enable and HLDA flip-flops. During $\overline{\text{RESET}}$ the buses and control lines are 3-stated, and the processor's internal registers and flags could be altered, with unpredictable results.

Within the 8085A is a special circuit to increase its speed and this requires a certain amount of time to stabilize after POWER ON. It is not guaranteed to work until 10ms after Vcc reaches 4.75V. $\overline{\text{RESET IN}}$ should be kept low during this period (See Figure 3.8). This is explained in further detail in Ref.25.

A simple RC network can satisfy the POWER ON requirement, but it is evident that a slow rise of Vcc would have a bearing on the delay required for $\overline{\text{RESET IN}}$ to reach 2.4V.

For the RC network shown in Figure 3.9.

$$\frac{Vo}{Vi} = \frac{1}{1 + sRC} \qquad (3.1)$$

Therefore the time taken for Vo to reach 63.2% of Vi, assuming infinite impedance at $\overline{\text{RESET IN}}$ and no internal resistance in the capacitor, is

$$t = RC \qquad (3.2)$$

and

$$\frac{Vo}{Vi} = 1 - e^{-\frac{1}{RC}t} \tag{3.3}$$

Transformer/regulated power supplies with smoothing capacitors will not give an instantaneous rise for Vi to equal Vcc immediately after "switch on". An U-V recording was made of the system POWER ON characteristic of Vi with a load of 3 amps (Figure 3.10).

A time of approximately 200ms from "switch on" is required for Vi to equal Vcc. Taking this as the time for Vo, or $\overline{\text{RESET IN}}$, to reach 2.4V, assuming an instantaneous Vi = Vcc (This is erring on the "safe" side, but is not detrimental to the system.), then from Eq. 3.3, using a capacitor of 1.0 μF,

$$R = 272k\Omega$$

A 300kΩ resistor was used.

3.6.2 Restart Interrupts.

The restart interrupts used for this application are RST5.5, RST6.5 and RST7.5. They are direct connections to the 8085A that are used to inform the processor of the occurrence of external events. Such inputs cause the suspension of normal operations and immediate response to the routine allocated to the interrupt which has been received. They may be individually masked out, and enabled or disabled, by software control. Full details of the priority, restart address and sensitivity of the interrupts are given in Ref.26.

For the retrieval system the allocated functions for the interrupts are shown in Table 3.1.

NAME	FUNCTION
RST5.5	"ENTER DATA" Push Button.
RST6.5	"END OF DATA" Push Button.
RST7.5	End of Analogue to Digital Conversion.

TABLE 3.1 Interrupt/Function Allocation.

3.6.3 Clock Generation (X1 and X2).

In microprocessor systems the clock is an essential element for the synchronising of data manipulation. Time reference is inherent for all operations carried out.

To drive the clock inputs, X1 and X2, of the 8085A, a quartz crystal clock driver of 6.144MHz is used. This is immediately divided by two, thus providing an internal clock frequency of 3.072MHz, which is available for use by other parts of the system at the CLK(OUT) pin.

3.6.4 Chip Select Decoding.

Decoding of the address is essential for selecting memory locations and other devices, such as the memory mapped analogue to digital converter. To avoid bus contention each device connected to the address bus must have a set range of addresses when it alone is selected.

A single, Intel 8205, high speed, 1 out of 8 binary decoder, is used for this purpose. It decodes A11, A12, A13, A14 and A15 to give a total of eight 2K blocks of selected addresses, beginning at 0000H through to 3FFFH, making a a total of 16K x 8-bit. The allocation of the Chip Select

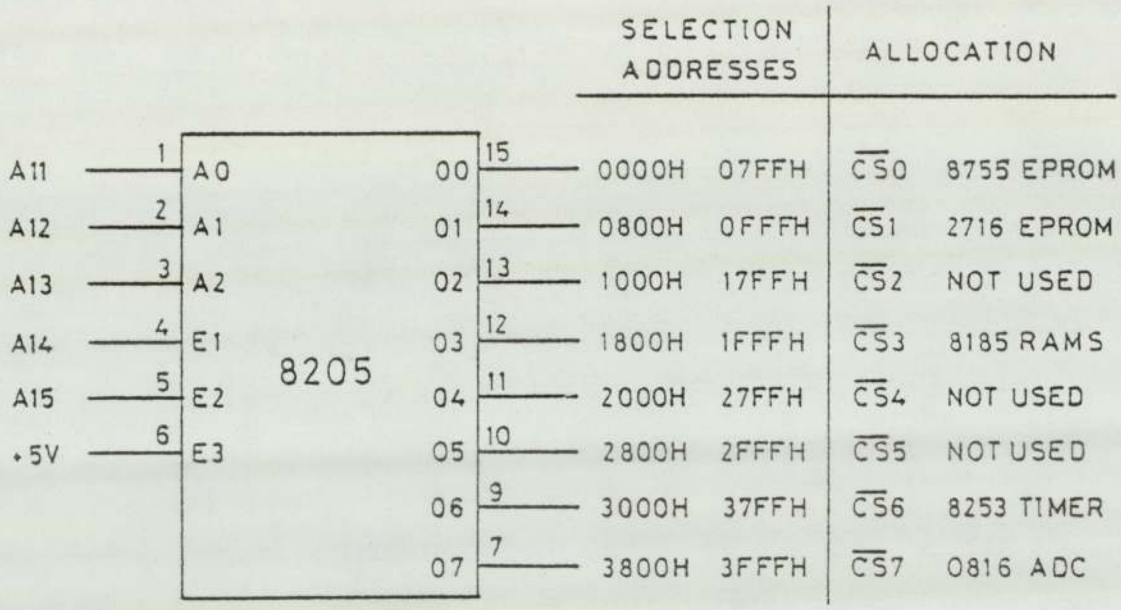


FIGURE 3.11 $\overline{CS}$ ALLOCATIONS.

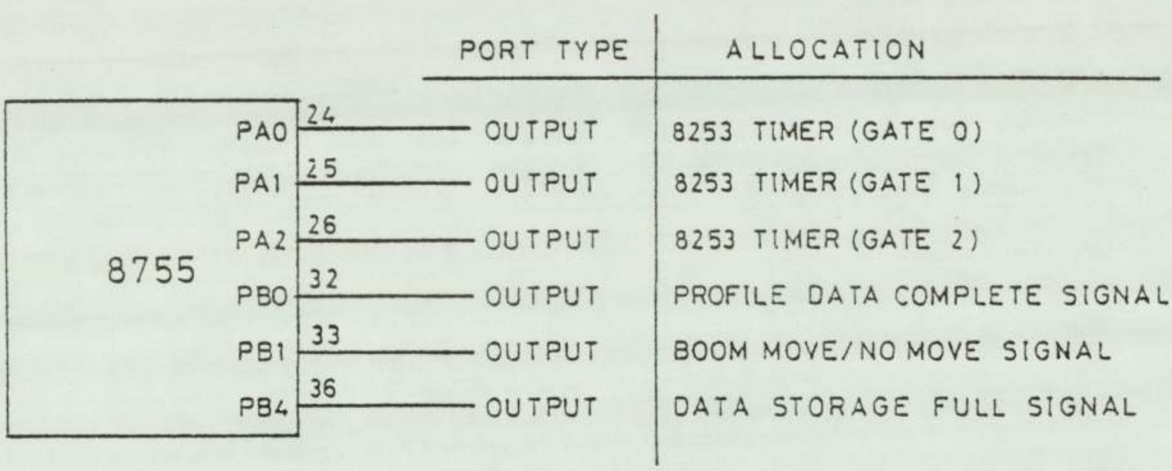


FIGURE 3.12 PORT ALLOCATIONS.

lines is shown in Figure 3.11. Further details of the 8205 will be found in Ref.26.

3.6.5 Low Order Address Latch.

An Intel 8212, 8-bit I/O Port, is used in an output gated buffer mode for supplying the 8 low bits of address from the multiplexed bus of the 8085A.

The output address is obtained from eight D-type flip-flops. The address latch enable (ALE) signal is provided by the 8085A and is used by the 8212 to latch the address so that it is available through the remainder of the machine cycle. The multiplexed address/data bus contains the low order 8-bits of address information during the first part of a machine cycle. The same bus contains the data, at a later time in the cycle. The IC´s that require the de-multiplexed address lines are the 2716 erasable, programmable read only memory (EPROM) and the 0816 analogue to digital converter (ADC).

3.6.6 EPROM With I/O.

An 8755A U-V erasable, programmable read only memory (EPROM), with I/O, contains the software, beginning at address 0000H through to 07FFH (2K x 8-bit). A 2716 (2K x 8-bit) EPROM contains the remainder of the retrieval system operating software, beginning at address 0800H.

The I/O portion consists of two general purpose ports. Each I/O port has 8 lines, and each line is individually programmable as input or output using software instructions. The port allocations are shown in Figure 3.12. The ports not shown are left unconnected.

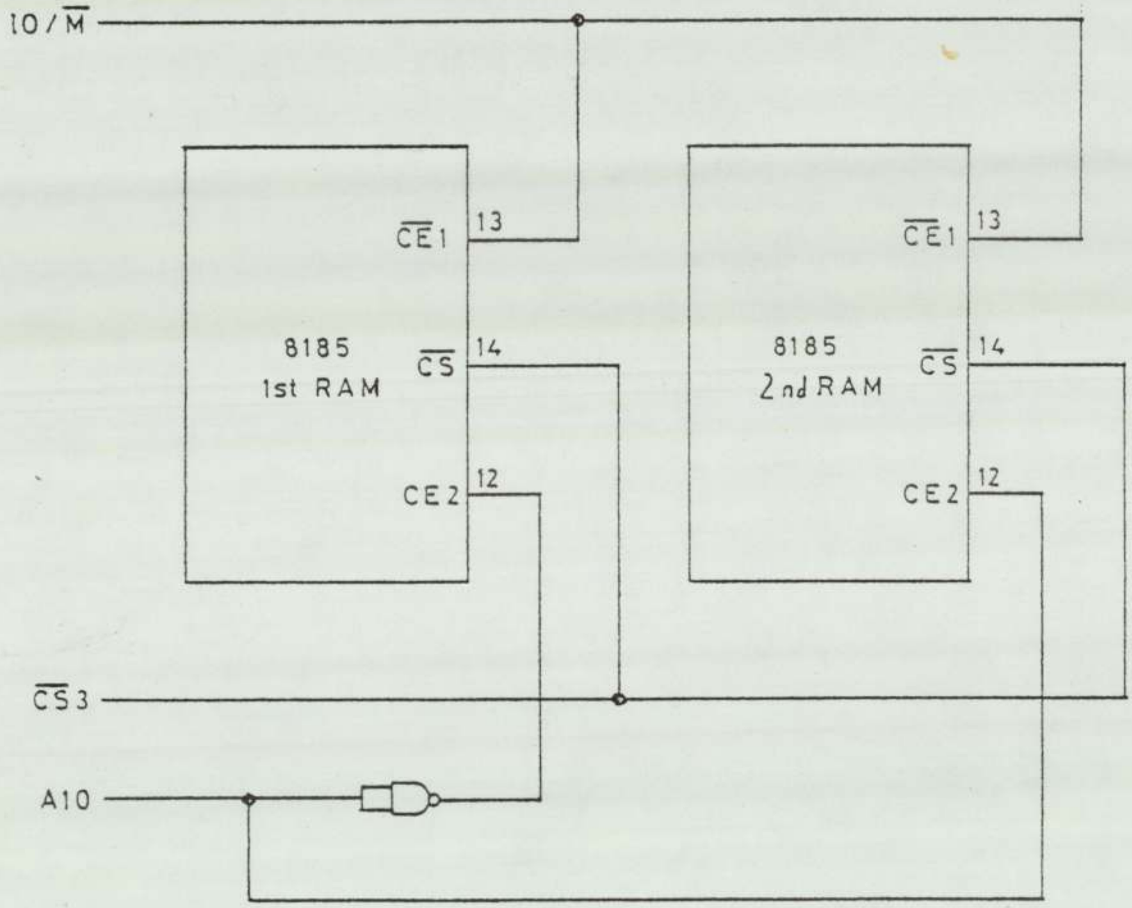


FIGURE 3.13 RAM DECODING.

The 8755A has a multiplexed address and data bus. This, together with a maximum access time of 450ns, makes it directly compatible with the 8085A, with no wait states.

The 2716, also with a maximum access time of 450ns, is directly compatible with the de-multiplexed 8085A processor system. A stand-by mode reduces the active maximum power dissipation of 525mW, by 75% when the IC is not selected.

3.6.7 RAM.

Two 8185 RAM IC´s are used for storing the captured tunnel profile data, the stack and all other temporary data. Both 8185´s are selected by $\overline{CS}3$, and additional decoding is carried out using address line A10 as shown in Figure 3.13. This ensures two consecutive 1K bytes of RAM. The first RAM is selected from address 1800H to 1BFFH, and the second RAM from 1C00H to 1FFFH.

Connected in this way, the low standby power mode of the 8185, is utilized. Powered up, the IC absorbs a maximum of 100mA. In the standby mode this reduces to 25mA. The 8185 IC´s use a multiplexed address and data bus and are directly compatible with the 8085A microprocessor system.

3.6.8 Programmable Interval Timer IC.

The 8253 is a versatile IC, offering five listed (Ref.26) modes of time referenced operations and either binary or BCD counting. The three 16-bit counters are completely independent. A common problem found in processor systems is the timing of events, or generation of accurate

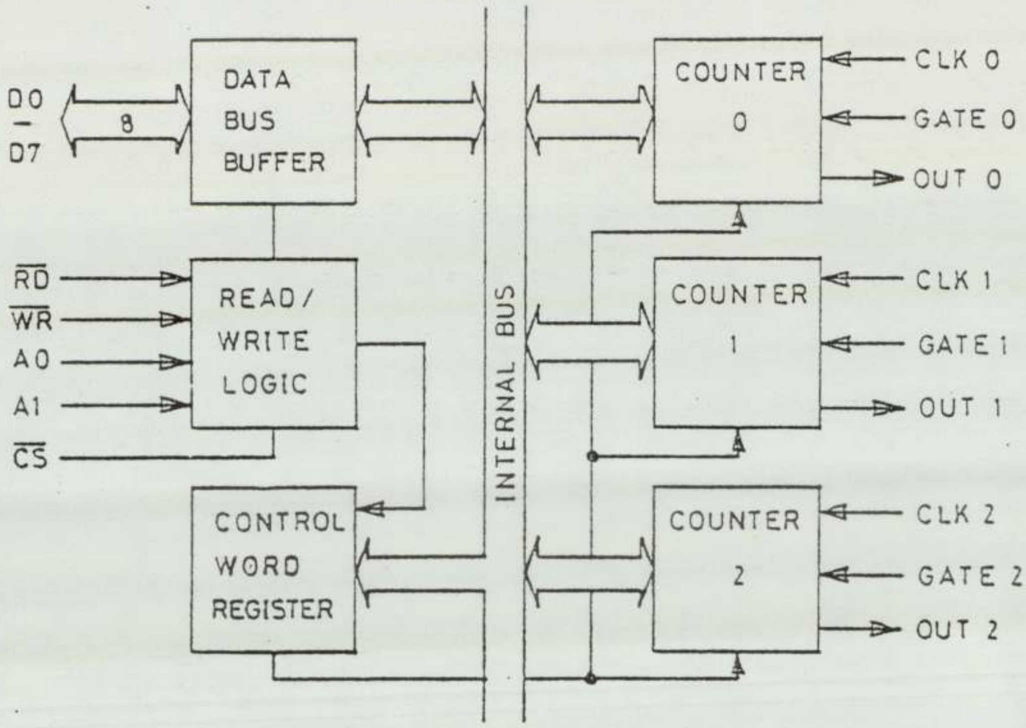
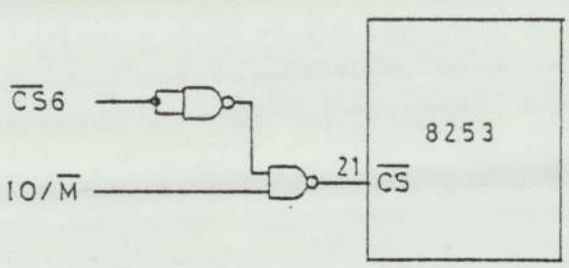


FIGURE 3.14 BLOCK DIAGRAM OF THE 8253.

$\overline{CS}$	$\overline{RD}$	$\overline{WR}$	A0	A1	
0	1	0	0	0	LOAD COUNTER No. 0
0	1	0	0	1	LOAD COUNTER No. 1
0	1	0	1	0	LOAD COUNTER No. 2
0	1	0	1	1	WRITE MODE WORD
0	0	1	0	0	READ COUNTER No. 0
0	0	1	0	1	READ COUNTER No. 1
0	0	1	1	0	READ COUNTER No. 2
1	X	X	X	X	DISABLE 3-STATE

FIGURE 3.15 CONTROL WORD REG. LOGIC.



IO/$\overline{M}$	$\overline{CS6}$	$\overline{CS}$
0	0	1
0	1	1
1	0	0
1	1	1

FIGURE 3.16 $\overline{CS}$ LOGIC AND TRUTH TABLE.

time delays, under software control, without tying up the microprocessor. The 8253 IC solves this problem.

The timers within the 8253 are numbered 0, 1 and 2. For this application timer 2 is used as a square wave generator (Mode 3) to clock timers 0 and 1 at a pre-determined rate. Timers 0 and 1 are used as rate generators (Mode 2) to give real time indication for velocity calculation. These are required by the main system for optimum control of the two axes of the boom.

Hardware and software are closely interlinked in the application of the 8253 and the description that follows will take this into account.

The block diagram showing data bus buffer and read/write logic functions is shown in Figure 3.14 and the logic required for setting up the control word register is shown in Figure 3.15.

$\overline{CS}6$ from the 8205 decoder and the IO/$\overline{M}$ signal, are together used for the $\overline{CS}$ of the 8253. $\overline{CS}6$ is taken low between addresses 3000H and 37FFH. To carry out all software operations on the 8253, an address within this range must be on the bus. The truth table for the $\overline{CS}$ logic is shown in Figure 3.16.

Writing to the 8253 is achieved by the execution of an OUTput instruction. This instruction places the contents of the accumulator on the data bus and the 8-bit port number is duplicated on the 16-bit address bus. An INput instruction, where the information on the data bus becomes the accumulator contents, is used to read the

D7	D6	D5	D4	D3	D2	D1	D0
SC1	SC0	RL1	RL0	M2	M1	M0	BCD

CONTROL WORD FORMAT

SC1	SC0	SC – SELECT CONTROL
0	0	SELECT COUNTER 0
0	1	SELECT COUNTER 1
1	0	SELECT COUNTER 2

RL1	RL0	RL – READ/LOAD
0	0	COUNTER LATCHING OPERATION
1	0	READ/LOAD MSB ONLY
0	1	READ/LOAD LSB ONLY
1	1	READ/LOAD LSB FIRST, THEN MSB

M2	M1	M0	M – MODE
X	1	0	MODE 2. RATE GENERATOR
X	1	1	MODE 3. SQ. WAVE GENERATOR

DEFINITION OF CONTROL

BCD = 0, FOR 16-BIT BINARY COUNTER.

BCD = 1 FOR 4-DECADE BCD COUNTER.

FIGURE 3.17 CONTROL WORD FORMAT & DEFINITIONS.

A1	A0	D7	D6	D5	D4	D3	D2	D1	D0	
1	1	1	0	1	1	X	1	1	0	COUNTER 2
1	1	0	1	1	1	X	1	0	0	COUNTER 1
1	1	0	0	1	1	X	1	0	0	COUNTER 0

FIGURE 3.18 MODE CONTROL WORDS.

8253. The $\overline{WR}$ line is active at some time during the execution of the OUTput instruction and the $\overline{RD}$ line is active at some time during the execution of the INput instruction (Ref.26). The $\overline{RD}$ and $\overline{WR}$ lines of the processor are directly connected to the $\overline{RD}$ and $\overline{WR}$ lines of the 8253. High speed operation of the programmable timer is obtained with this method of interface and all control is by simple software operations.

Each counter of the 8253 is individually programmed by writing a control word to the Control Word Register, with the IC selected throughout this operation. Figure 3.17 gives details of the Control Word Format and definitions of the individual bits. The Mode control words required for this application are shown in Figure 3.18.

Following setting up of the Mode control word, it is necessary to load the Count Register Bytes, that is, LSB then MSB.

The maximum clocking rate for the 8253 is 2MHz. The clock output of the 8085A being 3.072MHz is divided by two using a 74LS74 Type D Flip-Flop as shown on Hardware Diagram 2 in Appendix A. This square-wave signal of 1.536MHz is connected to CLK 2 of counter 2.

Counters 0 and 1 are clocked from the output of counter 2. A clocking rate of 60kHz was decided for counters 0 and 1, giving a period of 1.09225s for a full 16-bit down count.

The output for Counter 2, which operates in MODE 3, will remain high until one half of the count has been

A1	A2	D7	D6	D5	D4	D3	D2	D1	D0
1	1	SC0	SC1	0	0	X	X	X	X

SC1, SC0 – SPECIFY COUNTER TO BE LATCHED.

D5, D4 – 0 0 DESIGNATES COUNTER LATCHING OPERATION.

FIGURE 3.19 MODE REGISTER CODE FOR LATCHING COUNT.

A1	A0	RD	
0	0	0	READ COUNTER 0
0	1	0	READ COUNTER 1

FIGURE 3.20 READ COMMANDS.

completed, and go low for the other half.

$$\frac{\text{CLK 2 Rate}}{\text{OUT 2 Rate}} = \frac{1.536 \text{ MHz}}{60 \text{ KHz}} = 25.6$$

The counter was loaded with 001AH (26 decimal). The clocking frequency for counters 0 and 1 then became 59.077kHz. This was sufficiently accurate for this application where only approximate figures are required for the velocities of the boom. The Count Register Bytes for counters 0 and 1, working in Mode 2, for a full 16-bit down count is simply FFFFH.

The GATE of Counter 2 is connected to output port PA2 on the 8755 and remains permanently enabled following initialization. The GATEs of Counters 0 and 1 are connected to ports PA0 and PA1 respectively and software control is used to gate these timers (see Chapter 5). The GATE control is used for enabling, disabling and reloading.

A further feature of the versatility of the 8253, is the ability to be read whilst counting. This is used for counters 0 and 1. The contents of either counter is read "on the fly", that is without affecting the counting operation. This is carried out by writing the code, which latches the count, to the MODE register. The special code (see Figure 3.19) latches the count value, at that moment, into the storage register of the 8253. A read command to the selected counter releases the contents of the latched register to the system.

For normal reading of counters 0 and 1, the GATE inputs are taken low and the necessary read commands issued. These are shown in Figure 3.20.

3.6.9 Power amplification.

All outputs requiring power amplification are from the ports of the main system descibed in the thesis by C. W. Chuen. These outputs are to the solenoid operated hydraulic servo pilot valves discussed in Chapters 6 and 7 of this thesis. The power requirement to drive each solenoid is 80mA at 12V and the system is entirely digital. This makes for a very simple interface, where the only requirement is for amplification of each digital signal and opto-isolation between the 5V and 12V systems. A total of ten solenoid operated valves are used for the directional and velocity control of the boom.

This amplification is achieved using Darlington driver transistor ICs and is shown together with the opto-isolation on Hardware Diagram 6 in Appendix A.

The opto-isolation is essential to ensure the 12V level does not get shorted to the 5V circuits, in event of a failure in the Darlington drivers. Intrinsic safety requirements also demand opto-isolation between all components which are powered from separate power supplies.

3.6.10 System Assembly.

The system was assembled using Eurocards plugged to a backplane which is common to both the main system, and the retrieval and data preparation system. The backplane was configured as shown on Hardware Diagram 7 in Appendix A. By cross-referencing with the other hardware diagrams the individual functions assigned to each track on the backplane can be obtained.

The wire wrapping technique was used throughout for the connections on each card and care was taken in the placing of decoupling capacitors (Ref.32). The wire wrapping simplified modification to the circuits, which is particularly useful at the system development stage.

CHAPTER FOUR

CONTROL SYSTEM INPUTS

4.1 INTRODUCTION.

The successful application of a microprocessor based system, with real-time data acquisition and control, requires careful planning of the sensors and interface circuitry. They are fundamental to the overall accuracy of the system.

The control of the roadheader required a variety of inputs. These are considered in two parts, the inputs defined by the machine operator and the boom positional feedback. Simply, one informs the control system what is required, and the other, how it is performing its task.

It is important that the transmitted signals, from the point of generation back to the control system, are not corrupted. Noise - unwanted signals that obscure the desired signal - can affect the ultimate limit of detectability of weak signals, and if the signal being transmitted is not weak, the presence of noise degrades the accuracy of the signal and hence the control. Transducer output amplitude normally corresponds to some measurement of interest, such as temperature and pressure, or as in this application, angular displacement. The primary concern is the acquisition by the control system of true amplitude measurements in an acceptable form.

The signals from the boom angular positional feedback transducers and from the operator´s joysticks are of analogue voltage form, and hence require conversion to a weighted digital scale for the processor system. The device ultimately selected to carry out the conversion must suit

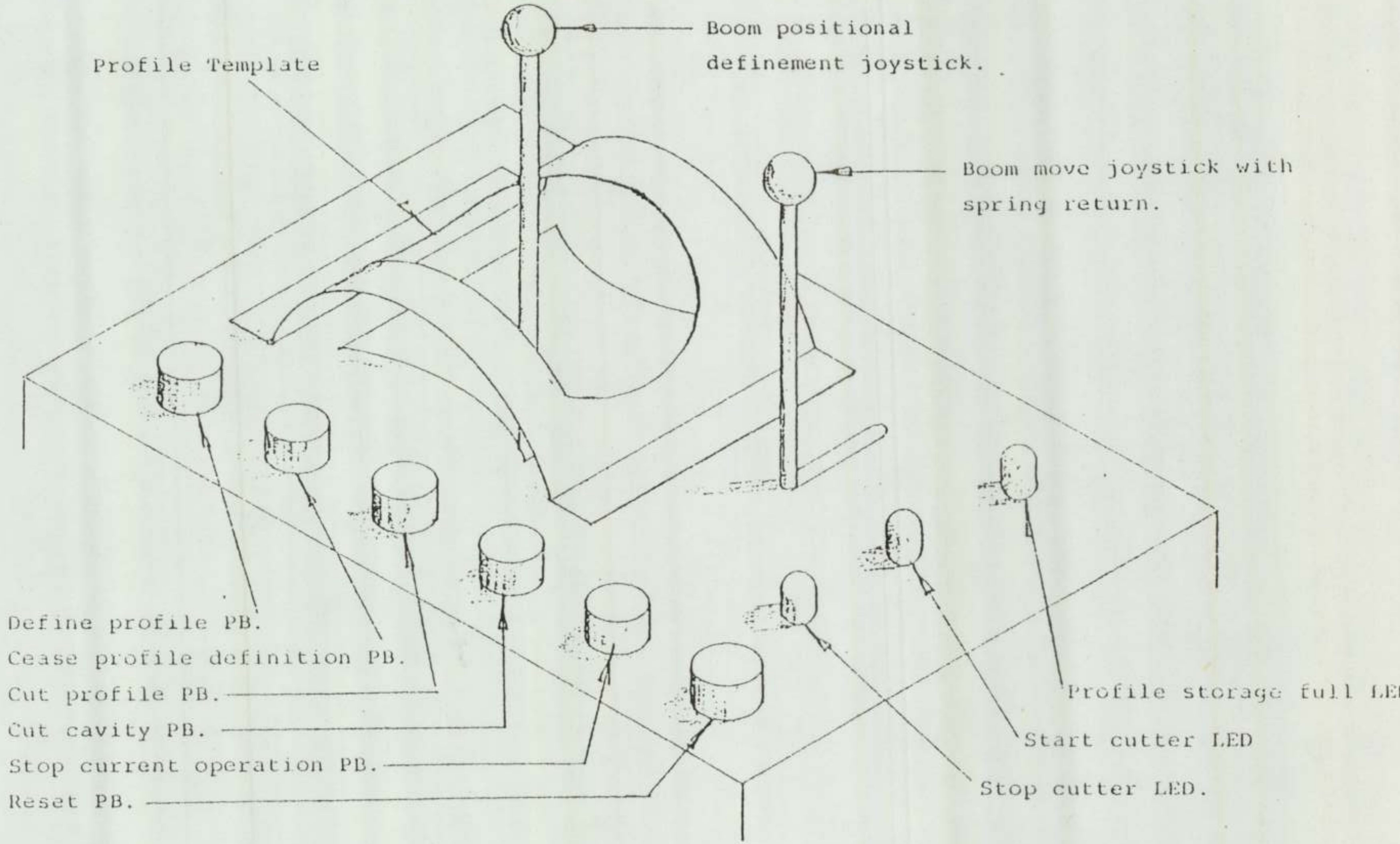


FIGURE 4.1 CONTROL CONSOLE LAYOUT.

this particular application. Many different types of analogue to digital converters (ADC) are now available, and the decisions involved for correct selection are outlined. These decisions are typical to most processor control system applications requiring ADC.

4.2 MACHINE OPERATOR DEFINED INPUTS.

It was never intended to fully automate the operation of the roadheader at this stage, although much of the technology used in developing this system would be relevant to a fully automated machine.

The operator interface was the subject of much conceptual thought, because of its highly weighted importance.

The layout of the control console implemented for the boom is shown in Figure 4.1. It contains the following control system input elements.

4.2.1 Tunnel Profile Definement.

The roadheader is used for cutting tunnels with a variety of shapes and sizes. It was necessary to define the profile of the tunnel to the control systems memory and also provide a means of readily re-programming for new profile shapes. This could be carried out in a variety of ways, such as from cassette tape, floppy disc, programmed EPROM´s or generating the information from a keyboard. The easiest to implement in a way suitable for the underground environment would be the keyboard using the new generation of fully enclosed touch sensitive keys.

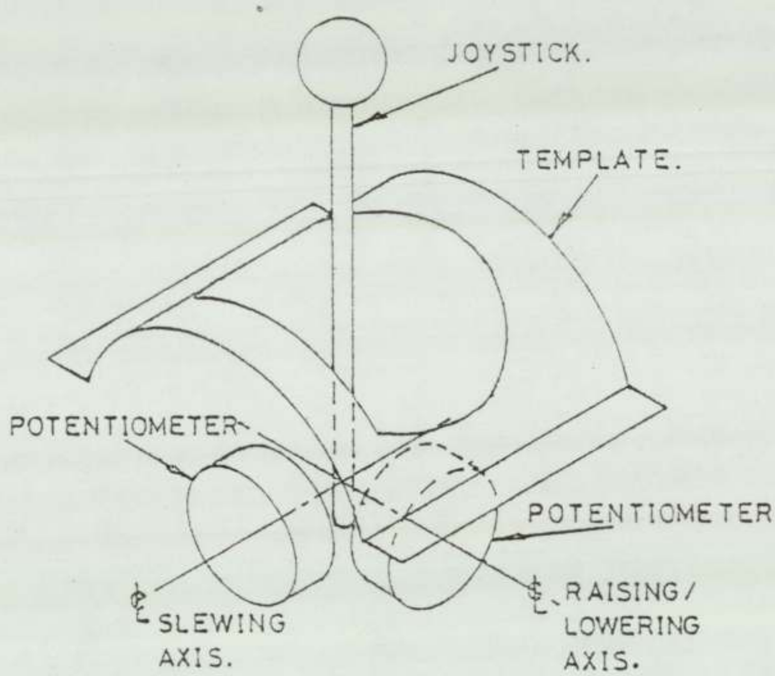


FIGURE 4.2 JOYSTICK, POTENTIOMETERS AND TEMPLATE.

However, the programming would have to be carried out by a skilled operator in the underground situation.

Considering the requirement of reprogramming the profile within the mining environment, a profiling template method was conceived and adopted.

The boom has two axes of movement, with respect to the machine frame. These are a raising/lowering axis and a slewing axis. Within the profile is placed a joystick with two axes which are in exact representation of the boom axes. The template, being representative of the tunnel profile, defines the limits of the angular movement of the joystick. The joystick position is detected by rotary linear potentiometers, fixed to the two axes. The profile is, therefore, defined to the system in angular terms, corresponding to the angular movement of the boom, with respect to the machine frame. The arrangement of the joystick, potentiometers and template are shown in Figure 4.2.

This method of profile definition has the following characteristics :-

1) An easy implementation of a change of profile by unskilled personnel, suitable for the mining environment.

2) Provides the machine operator with a system, where, for hand controlled movement of the boom, the joystick angle and position within the profile are representative of the boom angle and ripping head position.

3) Ripping heads comprise a number of special steel picks arranged radially and keyed in a headstock mounted on the boom shaft. Ripping heads of various diameters are

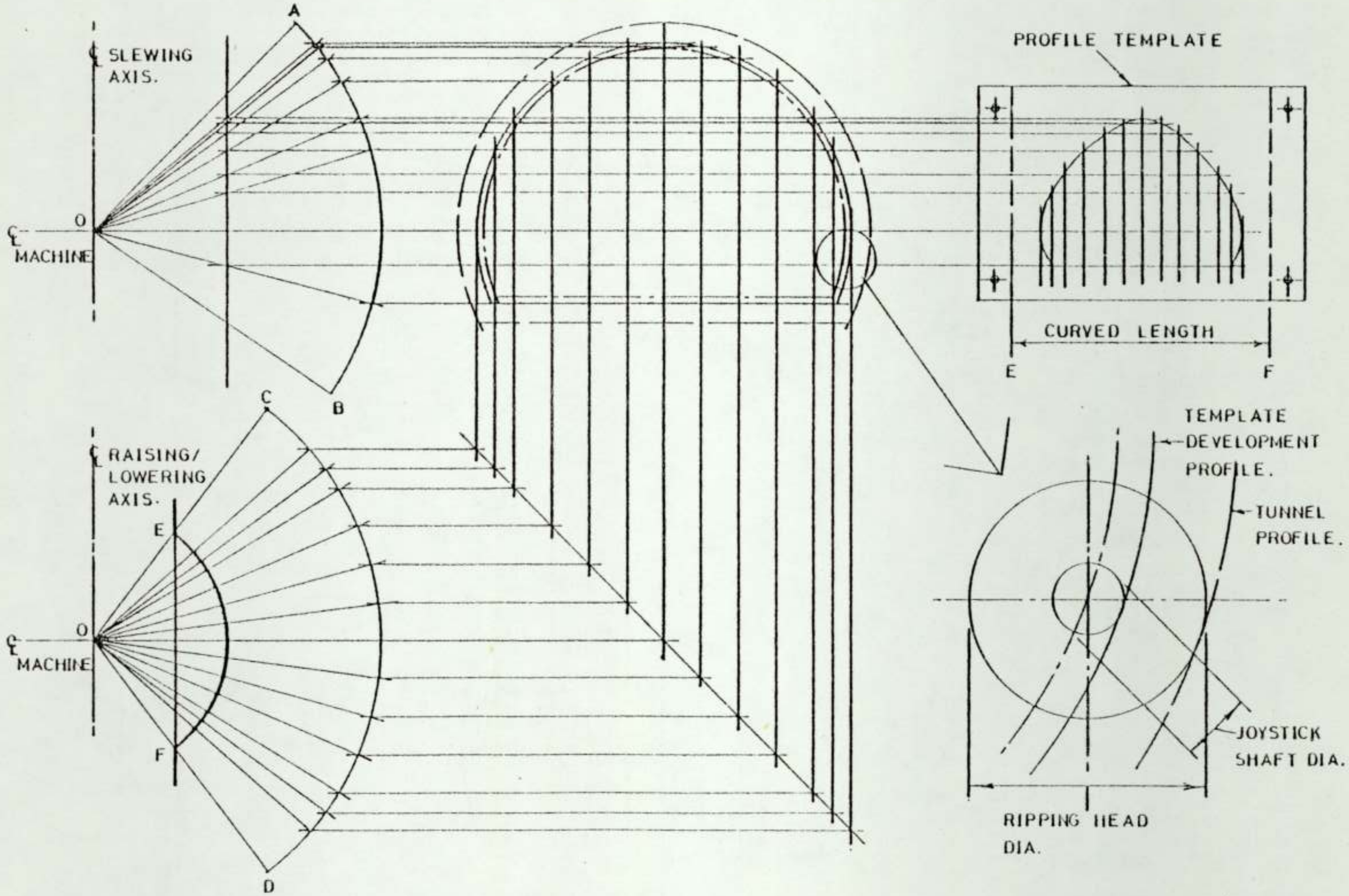


FIGURE 4.3 DEVELOPMENT OF CURVED TEMPLATE.

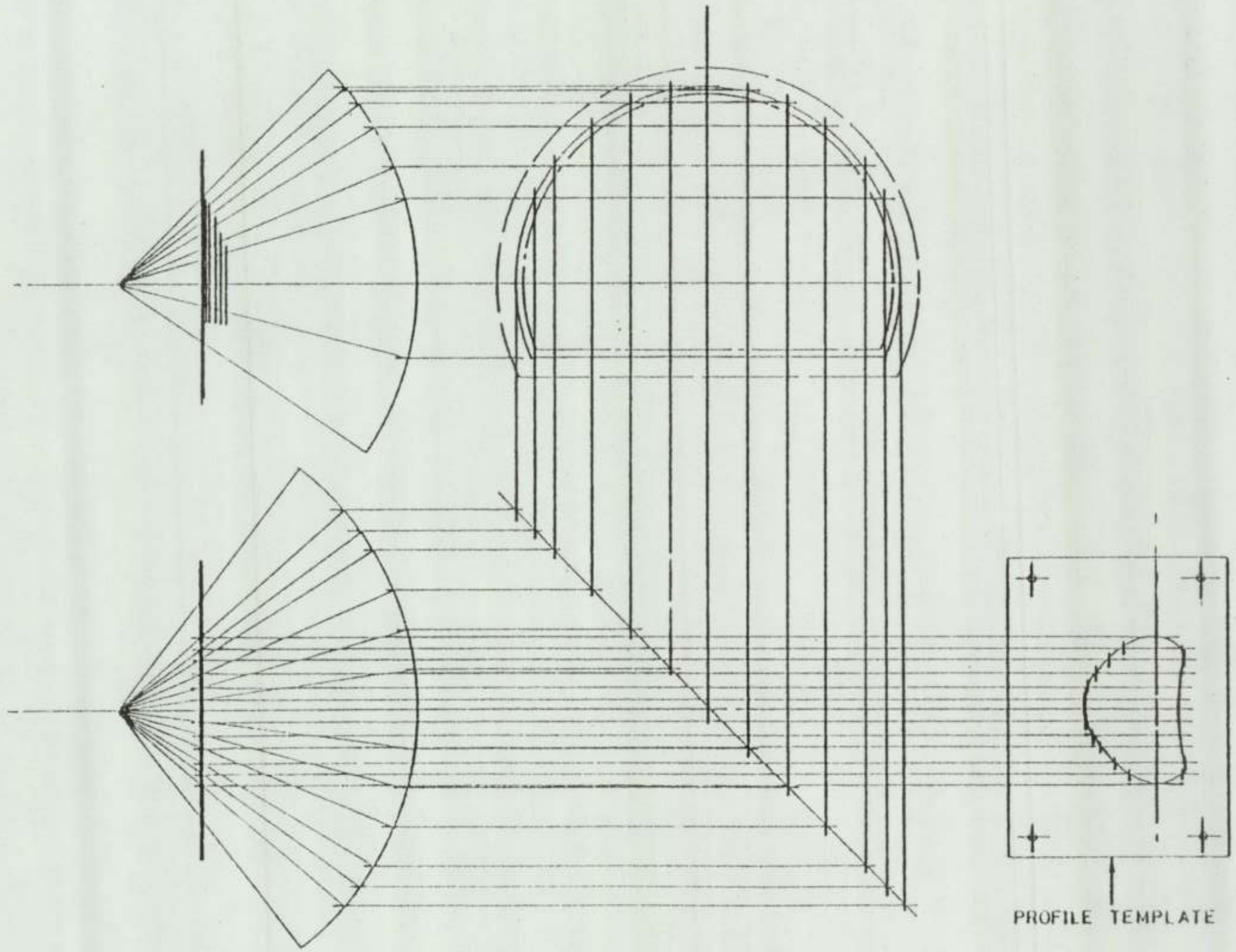


FIGURE 4.4 DEVELOPMENT OF FLAT TEMPLATE.

available, and the picks can be removed for sharpening which could also affect the diameter. The change in diameter would require revised profile definition data. This change would be accomodated simply by fitting different diameter sleeves to the joystick and re-defining the profile.

Two templates were developed and manufactured for the same tunnel profile. One was curved at a radius about the slewing axis and the development of this template is shown in Figure 4.3. The arc subtended by the angle COD represents the slewing arc of the boom, and the arc subtended by the AOB, the raising/lowering arc. The curved portion of the template is shown lying between points E and F. The flat template is shown in Figure 4.4.

The operator has a more realistic presentation of the tunnel profile with the curved template and this was adopted for the system.

A full scale development drawing was done of the template, taking care to accurately scale down the required tunnel profile and the boom length. The boom length is represented by lines O-A, O-B, O-C and O-D.

The Dosco Mk.2 boom, in the laboratory, had intersecting slewing and raising/lowering axes. This is not the case for many other models of roadheading machines. To use a similar method on these machines it would be necessary to offset the joystick potentiometer axes accordingly, or use the software technique of look-up tables.

The distance between the plane E-F and the axes centre-lines must be exactly related in the mounting of

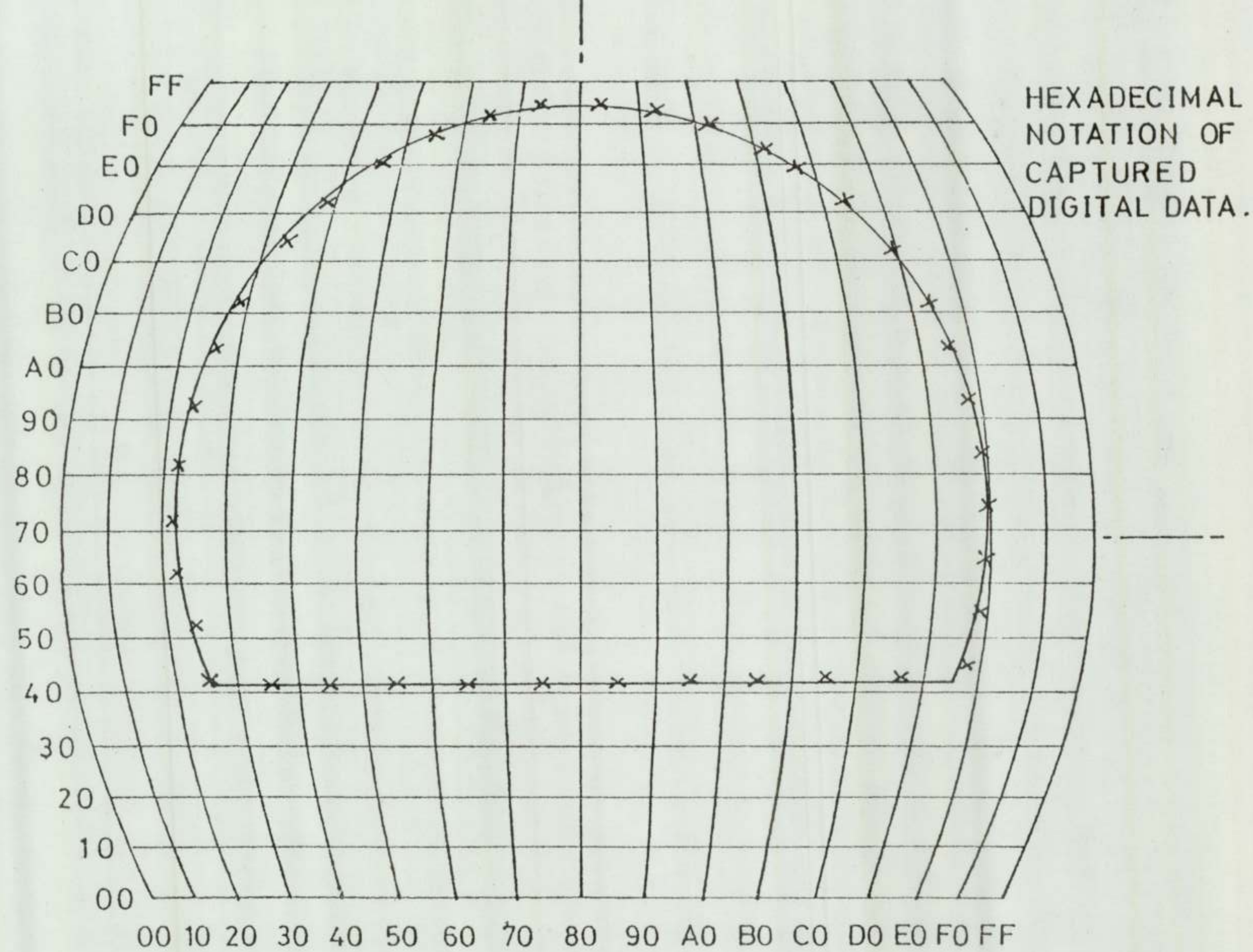


FIGURE 4.5 PLOT OF PROFILE DATA OBTAINED FROM TEMPLATE.

the template and joystick.

The template and joystick used for the laboratory application was small compared to what would be required for a machine in service. Despite this, reasonable accuracy was initially obtained as shown in Figure 4.5. A few minutes spent filing the template gave an accurate tunnel profile. Digital representation of the profile data was obtained using the Intel Microcomputer Development System (MDS-231) and the In-Circuit Emulator (ICE-85). The system was initialised, and the run terminated on push of the "Cease Profile Definition" push button. A print out was obtained of the captured data stored in the control systems volatile memory.

4.2.2 Speed Control Joystick.

This is a single axis joystick fitted with a rotary potentiometer. When the boom is not in an automatic control mode, the movement of this joystick will cause the boom to move to the position defined by the "boom positional definement" joystick. The "speed control" joystick displacement is divided into three discrete areas of control :-

1) Initial 10% - no movevement of boom takes place.
2) Next 50% - boom moves at slow speed to defined position.
3) Final 40% - boom moves at high speed to defined position.

The operator is able to move the boom to any point within the tunnel profile, defined by the template.

A potentiometer was used to provide the flexibility of software definement for the point of change in speed relative to the joystick angle. It also facilitates an increase in the number of speeds for movement of the boom, should this be required at a later stage.

4.2.3 Profile Definition Push Buttons.

When the system is initially powered up, or if the reset button has been pressed, there is no response to any of the control inputs until after the profile has been stored in memory. This is achieved by the operator pressing the "define profile" push button, and then moving the "boom positional definement" joystick around the profile. To complete the operation the "cease profile definition" push button must be pressed.

4.2.4 Cut Profile, Cut Cavity and Stop Current Operation Push Buttons.

These are all connected to the main control system. See the thesis carried out by C. W. Chuen for details.

4.3 BOOM FEEDBACK.

Various methods were investigated for obtaining the boom positional feedback signals. It was important that the the adopted system was suitable for a mining application.

One possible method was to detect the extension of the hydraulic rams using displacement transducers, placed within the cylinders, for protection. At the time of our enquiries (Summer 1980), suitable transducers were not available. Penny and Giles Ltd. are now (Spring 1983) marketing a potentiometric transducer suitable for mounting within a hydraulic actuator. Software operations would have

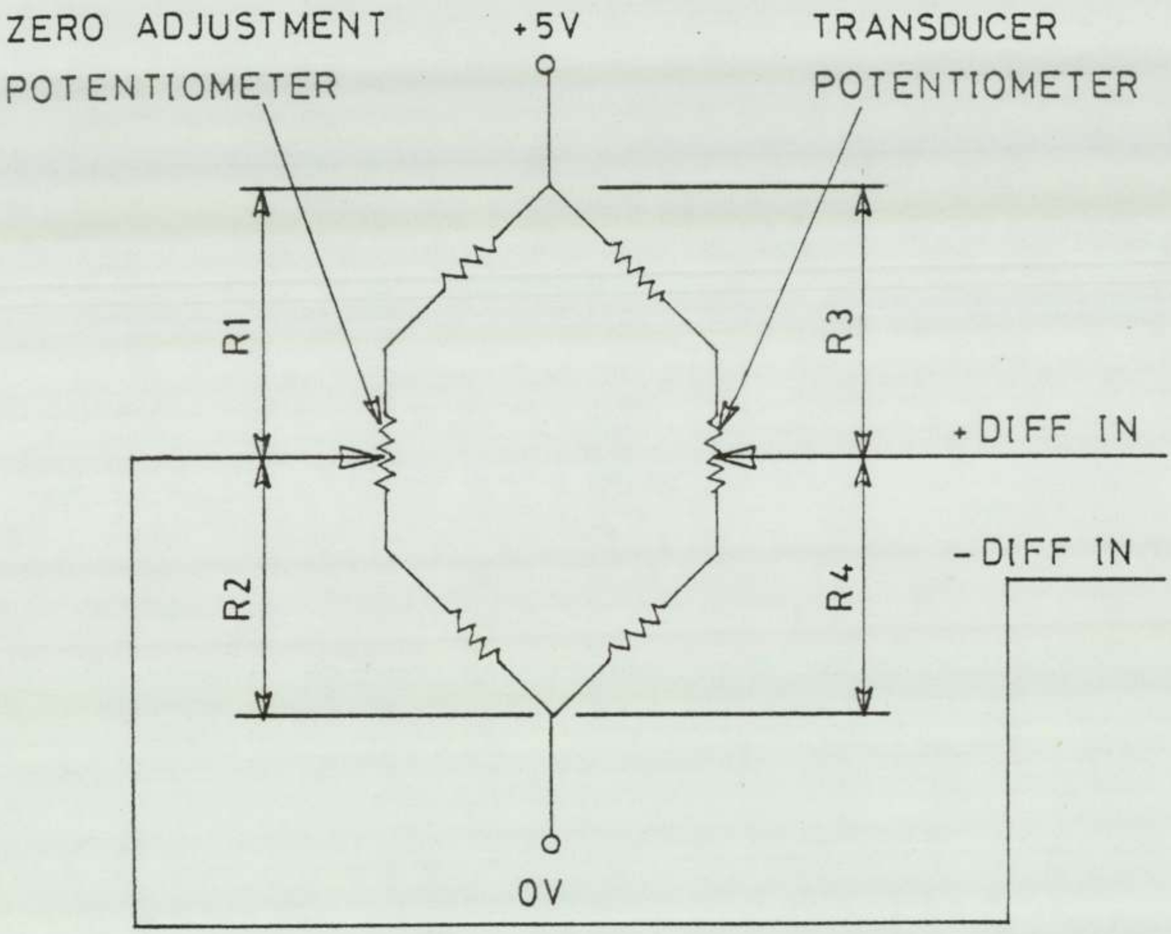


FIGURE 4.6 POTENTIOMETER BRIDGE CIRCUIT.

been required for relating the hydraulic ram extentions to the angular movements of the positional definement joystick.

A method was adopted using linear angular transducers fitted to each of the booms axes. These are simple devices and could be housed in a steel enclosure, approximately the size of a matchbox, for protection. The spindles of the potentiometers are attached to the shafts of the booms axes, and the bodies of the transducers are rigidly attached to the boom pedestal.

The potentiometers used were of the precision, screened conductive plastic, type, with a linearity of plus or minus 0.5%, good repeatability and a rotational life of > 100 million shaft rotations.

4.4 CONTROL SYSTEM INPUT CIRCUIT CONNECTIONS.

All transducer and joystick potentiometers are mounted in a bridge, as shown in Figure 4.6. The differential voltage of the bridge ((+ DIFF IN) - (- DIFF IN)) is fed along screened cables to the signal conditioning circuits described in the following section.

The resistance of the arms of the bridge are sized to take account of the total operational variation in the transducer/joystick potentiometer resistance to give a 1V to 4V single-ended analogue signal from the signal conditioning, constant gain, amplifiers.

The calculations involved for the bridge are as set out below.

Referring to Figure 4.6 and with,

$$(R1 + R2) = (R3 + R4)$$

R1, R2 and (R3 + R4) are constants.

R3 and R4 are varying.

$$(+\ \text{DIFF IN}) - (-\ \text{DIFF IN}) = \frac{5V}{R1 + R2}(R4 - R2) \qquad (4.1)$$

Then, with this relationship and a constant gain, G,

$$\frac{5V \times G}{R1 + R2}(R4\ \text{min.} - R2) = 1V \qquad (4.2)$$

$$\frac{5V \times G}{R1 + R2}(R4\ \text{max.} - R2) = 4V \qquad (4.3)$$

These equations were used to determine the resistance ratios of the transducer and joystick circuits. (R1 + R2) and (R3 + R4) were made 30k , giving a bridge current consumption, assuming infinite impedance at the amplifier inputs, of 33mA. Full circuit details are shown on Hardware Diagram 5 in Appendix A.

The "Profile Definition" push buttons are connected to RST5.5 and RST6.5 interrupts on the 8085A microprocessor as indicated on Hardware Diagram 1 in Appendix A, and as discussed in Chapter 3.

4.5 SIGNAL QUALITY CONSIDERATIONS.

Signal quality can be expressed as a signal to noise ratio (SNR), measured from the analogue output signal of the transducer/joystick potentiometers to the digital output word from the ADC (Ref.34). Each analogue input control signal to the processor system is of concern, and the SNR should be upgraded as the signal progresses to the ADC.

The characteristics of the analogue input signal,

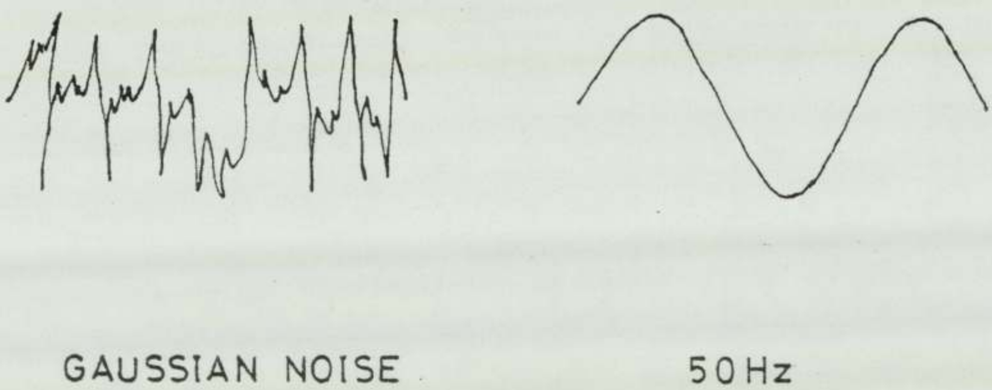


FIGURE 4.7 NOISE CATAGORIES.

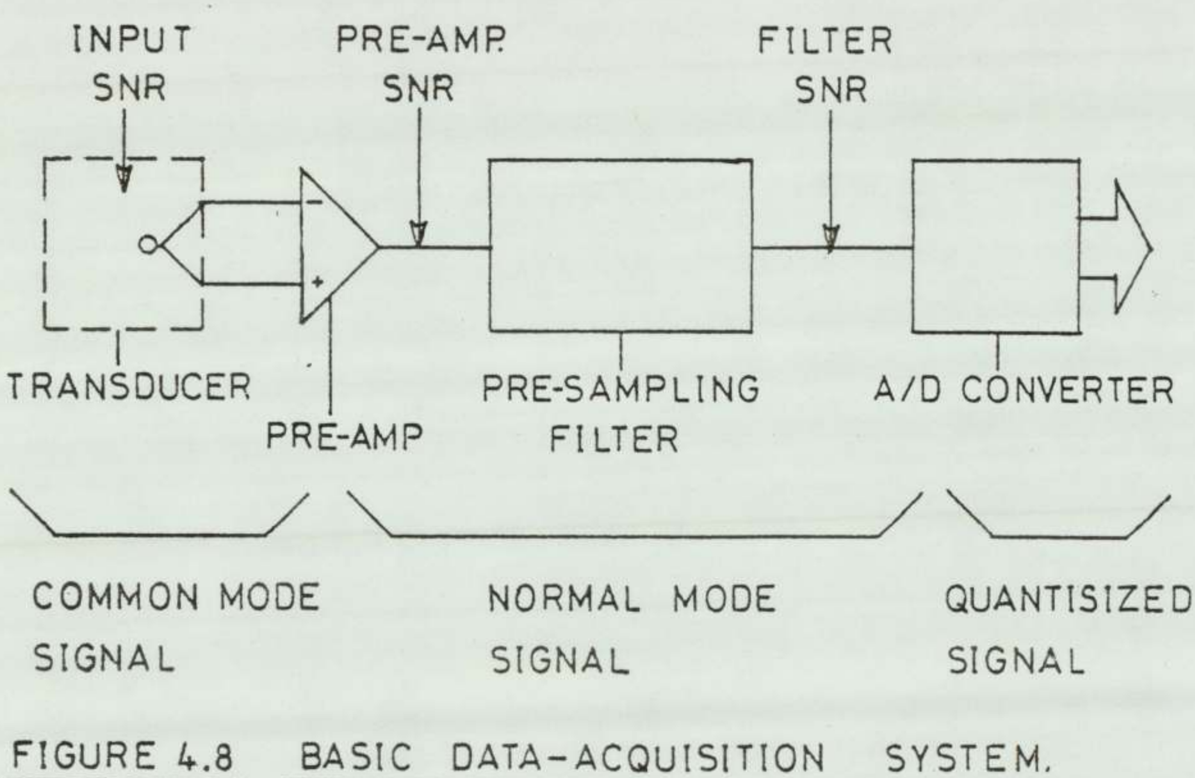


FIGURE 4.8 BASIC DATA-ACQUISITION SYSTEM.

plus noise, can be evaluated to determine the input SNR.

$$\text{Input SNR} = \left[\frac{\text{DC Signal}}{\text{RMS Interference}}\right]^2 \qquad (4.4)$$

The interference can be measured with an oscilloscope or true rms voltmeter, with the signal cable terminated in the transducer source impedance, but with the transducer disconnected. The oscilloscope, however, is not necessarily accurate if the interference is predominantly Gaussian noise rather than 50/60Hz (see Figure 4.7). The varying crest factor of Gaussion noise precludes a simple "peak voltage measurement" to "rms" mathematical relationship. An approximate rms value can be obtained with an averaging responding voltmeter (Ref.35) calibrated for sine waves, where:-

$$\text{rms (noise)} = \text{reading} \qquad (4.5)$$

The probability that the signal, which is corrupted by added interference, is within a specified difference region centered about the true value, can be determined from probability relationships (Ref.36)

Figure 4.8 shows a typical basic data-acquisition channel. The preamplifier may be either an operational, instrumentation or isolation amplifier, depending upon the application requirements. Generally of interest is the preamplifier in-circuit common mode rejection ratio (CMRR).

$$\text{CMRR} = \frac{\text{DMG}}{\text{CMG}} \qquad (4.6)$$

Where :-

DMG is the differential-mode gain of the amplifier and is the same as the closed loop gain.

CMG is the common mode gain and is primarily determined by the tolerance of the gain determining resistors associated with each circuit (Ref.35).

We are mainly concerned, in a mining environment, with 60Hz, electrostatically and electromagnetically coupled, interference. For unsheilded cables, a useful rule of thumb (Ref.35), is that, 1mV of interference will be coupled, per kilowatt of load in a 0.3M spaced signal cable, per 0.3M of parallel cable run.

Taking the roadheader total electrical power as 100kW, a cable run of 3m and a 0.3m parallel spaced signal cable, then applying the above relationship, the coupled interference (E_{CM}) would be 1V. This should allow for plenty in hand for other sources of interference, particularly since sheilded cable would reduce the figure.

With an input analogue voltage range of approximately 2.2V to 2.7V from the boom angular positional transducers, an accuracy of 1 in 256 gives a 2mV differential signal (E_d). (This represents a 1-bit accuracy in an 8-bit binary weighted scale. Refer to Section 4.7 for the accuracy at the boom end related to the tunnel cross-sectional plane).

The equation which expresses the required CMRR for a specified error is :-

$$\text{CMRR required} = \frac{1}{\text{CM error}} \times \frac{E_{CM}}{E_d} \qquad (4.7)$$

Selecting a CM error of 1%

$$\text{CMRR required} = \frac{1}{0.01} \times \frac{1\text{V}}{0.002\text{V}}$$

$$= 50{,}000 \text{ or } 94\text{dB}$$

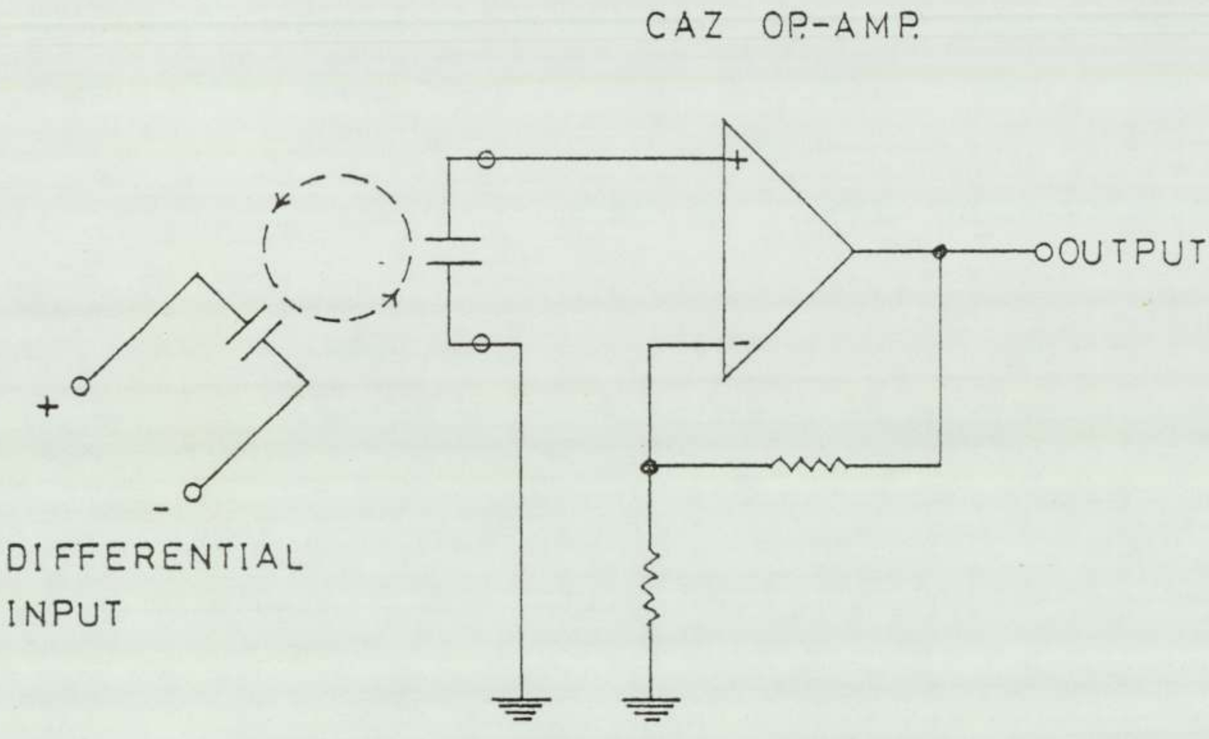


FIGURE 4.9 CAZ OPERATIONAL AMPLIFIER WITH "FLYING CAPACITOR" SWITCHING TECHNIQUE.

Potentiometric devices can usually be designed to give relatively high level signals which possess good noise rejection qualities, but this does call for low level gain at the filtering stage.

The single and the classic instumentation amplifiers (Ref.35) were investigated and found not to be suitable for this type of application, where a relatively low gain was required, without additional pre-sampling filtering. It was desirable to keep the electronic circuits as simple as possible with a low power level in an attempt to meet intrinsic safety approval.

4.6 COMMUTATING AUTO-ZEROING AMPLIFIERS.

The commutating auto-zeroing (CAZ) technique is a recent development and according to Horowitz and Hill (Ref.37) will revolutionize instumentation amplifier technology. The technique was pioneered by Intersil and the ICL7605 (Ref.38) was used for filtering all joystick and transducer analogue inputs for this project.

The ICL7605 uses the basic CAZ operational amplifier with a "flying capacitor" switching technique. This is shown in Figure 4.9.

The main advantages of this type of amplifier, which are particularly relevant to this application, are :-

1) Low input offset voltage temperature drift - 0.05μV/°C (Many times better than ordinary MOSFET operational amplifiers).
2) Low long term input offset voltage drift - 0.2 μV/year
3) High CMRR - 100dB for DMG of 1 to 1000.

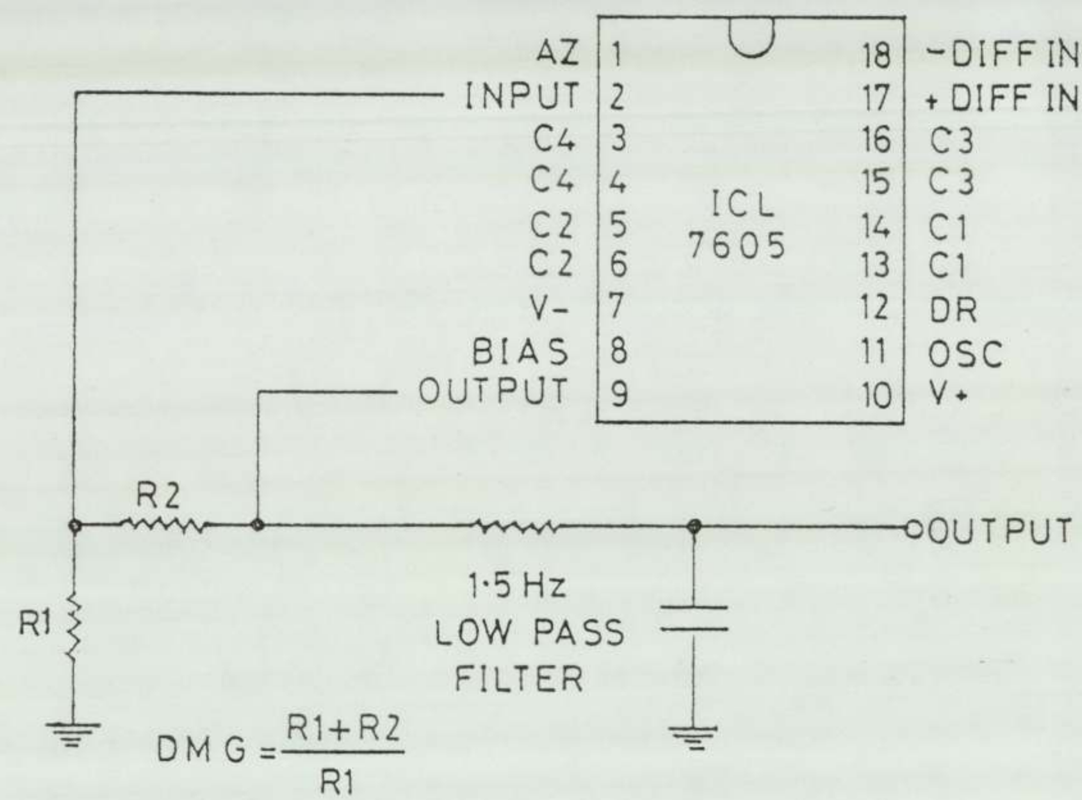


FIGURE 4.10 CAZ OPERATIONAL AMPLIFIER CIRCUIT.

4) No trimming, except for gain, thus avoiding ultra-high accuracy in resistor tracking and matching. This no-adjustment feature makes the CAZ amplifier suitable for operation in severe environments, such as are found in a mine, where equipment service is difficult.
5) The CMOS structure ensures a low supply current - typically a maximum of 5mA for a medium bias setting.
6) Wide operating supply voltage range. + and -4V to + and -10v for a medium or low bias setting. This obviates the need for a separate power supply.
7) Short circuit protection on outputs for + and - 5V operation.

There are two characteristics of the CAZ operational amplifier which would rule it out for some applications :-

1) It is only suitable for low-frequency operation as the bandwidth of the input voltage translator is from DC to 10Hz.
2) The nominal commutation frequency is typically from 160Hz to 2560Hz depending on the voltage level of the Division Ratio (DR). This would rule out the CAZ operational amplifier for some rapidly multiplexed A/D converter systems. For this application where the conversion time is typically 100 μs per channel, with multi-channel conversions interspersed with software routines, the individual channel commutation is within the commutational frequency requirement of the CAZ operational amplifier.

The ICL7605 is an 18 pin DIL package with pin configuration as shown in Figure 4.10. The simplicity of the interface requirements for this device are evident.

In many applications it is desirable to include a low-pass filter at the output of the CAZ operational amplifier to reduce high frequency noise which is outside the desired signal passband. The solution with conventional operational amplifiers is to place a capacitor across the feedback resistor. This concept is not possible with CAZ operational amplifiers because of the nature of the commutation spikes. The effect of a large load capacitor produces an area error in the output wave form, and hence an effective gain error. The output low pass filter must have a high impedance. For example, a 1.5Hz filter would require a 100kΩ resistor and a 1.0 μF capacitor, or a 1MΩ resistor and a 0.1 μF capacitor.

Further information for the ICL7605 can be found in the manufacturers data sheet (Ref.38).

The positive supply voltage of +5V was obtained direct from the main system power supply. Dual ICL7660 voltage converter integrated circuits are used to provide the negative supply voltage -5V from the +5V rail. They are connected in parallel to reduce the output resistance.

The circuit connections for the signal conditioning operations can be found on Hardware Diagrams 4 and 5 in Appendix A.

The necessary signal quality of the ADC input in terms of an adequate filter output SNR can be equated to one binary bit quality. For an analogue signal input range of 1V to 4V and an 8-bit converter, then :-

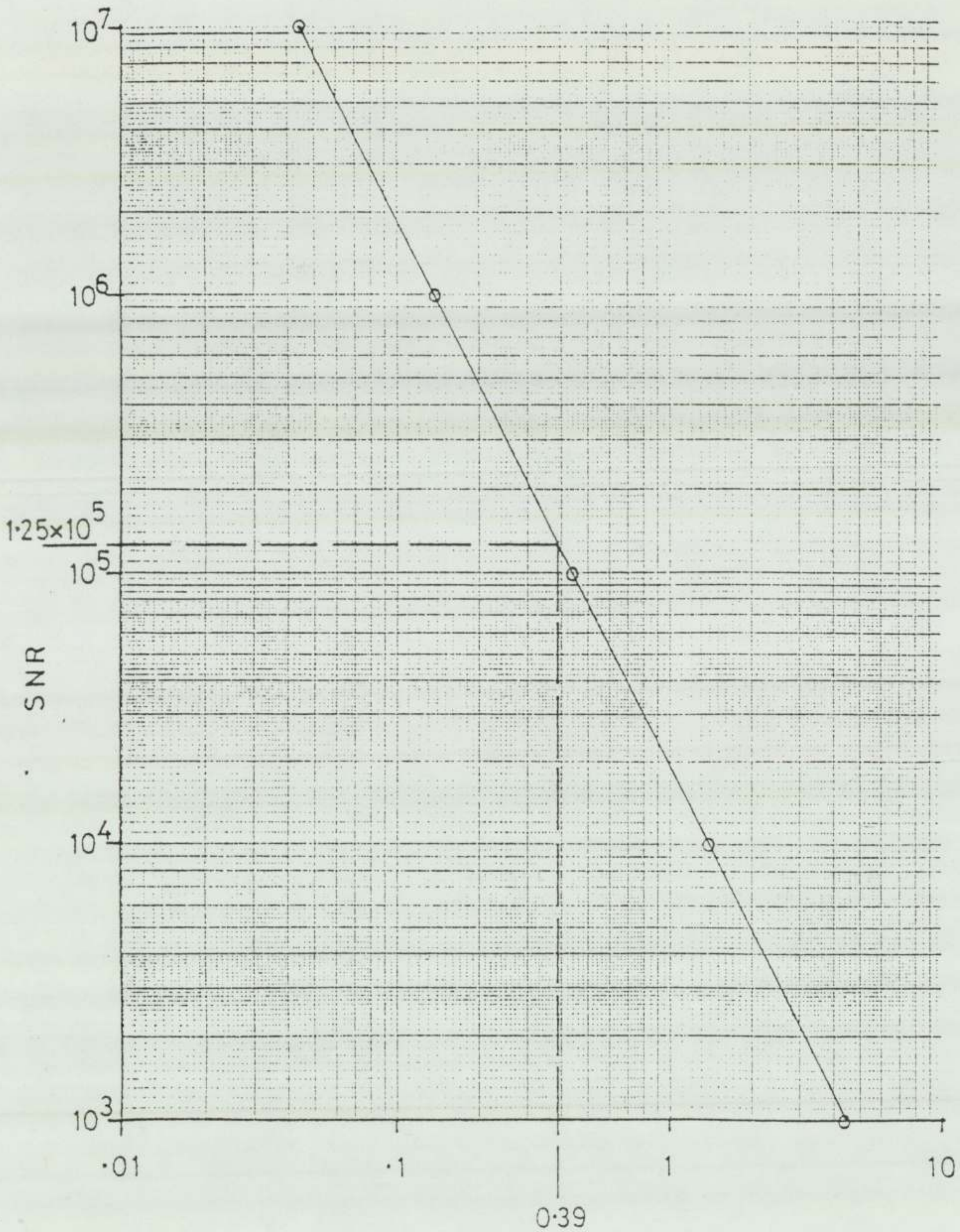


FIGURE 4.11 SNR VERSUS AMPLITUDE ERROR.

$$\frac{1}{2}\ \text{LSB} = \frac{\text{Full scale (FS) value}}{\text{No. of step changes}} \times \frac{1}{2} \qquad (4.8)$$

$$= \frac{4V - 1V}{256} \times \frac{1}{2} = 11.72\ \frac{mV}{2}$$

$$\%\ \text{of FS amplitude} = \frac{+\ \text{or}\ -\ \frac{1}{2}\ \text{LSB}}{\text{FS value}} \times 100\% \qquad (4.9)$$

$$= \frac{0.01172}{4V - 1V} \times 100\% = 0.39\%$$

A useful expression is available for the confidence in the measurement of an amplitude as a function of SNR (Ref.35). To aid interpolation, the figures for specified amplitude and for 68% confidence in the measurement of one standard deviation are shown plotted in Figure 4.11.

From Figure 4.11, an amplitude error of 0.39% calls for a filter output SNR of 125000 or 101dB.

Pre-amp output SNR = CMRR x Input SNR (4.10)

Where from Equation 4.4,

$$\text{Input SNR} = \frac{0.0002V}{1.0V} = 0.000004$$

Therefore :-

Pre-amp output SNR = 100,000 x 0.000004 = 40,000 or 92dB

With the severe input SNR assumed, an 8 bit binary quality signal is not available from the CAZ op-amp pre-amplifier alone. It would be possible to meet the criteria with the addition of a presampling filter in the circuit, as shown in Figure 4.8.

Without any additional filtering, the circuit would give an 8 bit binary quality signal for an rms interference of 0.55V. This was felt to be adequate for use in the laboratory and would possibly be suitable for use in the mine with shielded signal lines.

4.7 ANALOGUE TO DIGITAL CONVERSION.

There are many different types of devices available for carrying out the analogue to digital conversion (ADC), all with different characteristics. The device ultimately selected must suit the particular application. This involves the following decisions to be made :-

1) Type of weighted scale and number of bits.
2) Number of channels.
3) Speed of conversion.
4) Interface method.
5) Total error allowance.
6) Full scale reading and the magnitude of least significant bit.
7) Required measurement window.
8) Desired input characteristics.

The ADC for the roadheader is interfaced to an 8-bit microprocessor. An 8-bit binary coded output conversion of the analogue signal would simplify the interface, but other factors must govern this decision.

The boom has a maximum slewing angle of 105.9 degrees, and an 8-bit binary code would give an absolute accuracy of 0.4153 degree per one bit. The maximum angle of movement on the vertical axis is 78.97 degrees, making for an absolute accuracy of 0.3097 degrees per one bit. The absolute accuracies represent a maximum linear distance, at the tip of the boom, on a plane at right-angles to the machine centre-line, of 21.82mm on the horizontal axis, and 16.67mm on the vertical axis. These linear measurements decrease at the limits of the axes, because of angular displacement feedback, to 13.54mm on the tunnel horizontal axis, and 11.87mm on the tunnel vertical axis. Profile cutting of the boom is normally carried out close to the boom angular limits. A profiling accuracy within plus or minus 50mm allows for some inaccuracy in the conversion. However, the time period, from the instance the boom is at a desired position to the closure of the valves, also has a bearing on the accuracy limits in a simple comparative type system.

This time delay results from several factors: the frequency of individual channel conversion; the control system response; the hydraulic valve response on closing.

Assuming a future requirement for conversion of 16 channels. Then, with each examined in turn, a conversion time of 100μs per channel and total software time allowance of 30ms for ADC control and other routines. The total time period for updating the converted information from each channel is 31.6ms. Note that 1.6ms is attributable to the actual conversion of 16 channels, the remaining 30ms is estimated as the worst case processing time for the associated control software.

The response of the control system to converted data which calls for the valves to be closed, until the moment of sending the valve closure signal, was a maximum of 30ms.

By far the largest time delay was the valve closure response to receipt of an electrical signal. This was measured as 350ms.

These times are additive and amount to a total of 411.6ms.

The speed of the boom, when cutting, is a maximum of 110s for a full movement on the slewing axis, that is, an angular velocity of 0.963 degrees/s or 2.32 bits/s.

The distance moved, measured on the plane at right-angles to the machine centre-line is:-

2.32bits/s x 411.6ms x 13.54mm/bit = 12.93mm

To this figure must be added the possibility of 1/2-bit error in actual measurement, and a total error in conversion of 1-bit. The total error in positional accuracy then becomes plus or minus 33.24mm at the extremes of the boom axes and plus or minus 53.57mm when the boom is pointing directly ahead.

The required accuracy of plus or minus 50mm is provided over the area where profiling normally takes place. It is quite likely, since the worst conditions have been assumed throughout, that the accuracy requirement will be met over the whole of the boom ripping plane.

The measurement window is defined as the time over which the analogue signal is sampled. If an averaged value of the input signal (over some milliseconds) was acceptable then the use of an integrating converter would have the advantage of smoothing out the effect of high frequency noise on the analogue lines. However, velocity calculations for the two displacement feedbacks from the boom axes, require instantaneous sampling of the signal. This, plus the requirement of multi-channel conversions, led to the selection of a single chip ADC working on the successive approximation principle. The two most popular conversion techniques are successive approximation and integrating ADC and their characteristics are described in Ref.35, 39 and 39. There are a great number of ADC types (Ref.40), and each has particular applications for which they are the best, but only a few are available in IC form.

The IC selected for this application was the National Semiconducor ADC0816. The data acquisition components are monolithic CMOS devices with an 8-bit analogue-to-digital converter, a 16 channel multiplexer and microprocessor compatible control logic. The features of the specificaton for this device, particularly relevant to this application, are :-

Total unadjusted error < + or - 1/2 LSB.

Linearity error < + or - 1/2 LSB.

No missing codes.

Conversion time of 100 µs.

Single +5V operation.

Low power consumption of 15 mW.

No offset or scale adjustment required.

Latched tri-state output for conversion data.

Latched address input for channel selection.

Operating temperature range of -40 °C to +85 °C.

Further features of the ADC0816 can be found in Ref.41.

The ADC0816 is designed for ratiometric conversion systems, where the physical variable being measured is

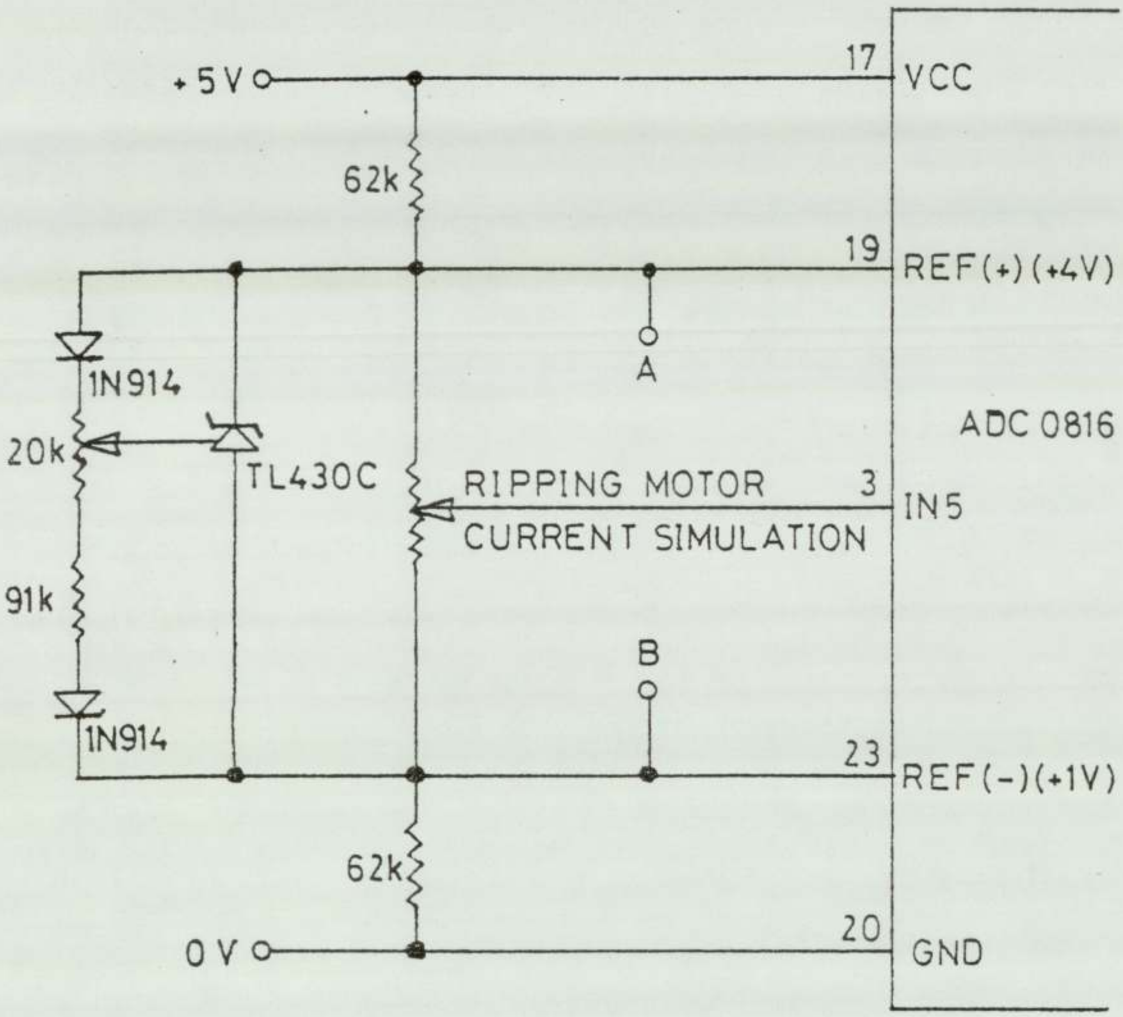


FIGURE 4.12 REGULATED SUPPLY FOR REF(+) & REF(-).

expressed as percentage of full-scale. Since all analogue signal inputs are obtained from linear potentiometers used as position sensors, the data is presented as a proportion of full-scale.

The transducers, analogue signal conditioning and ADC system are operated from a single +5V supply. The supply voltages to the amplifiers, used in the signal conditioning circuits, dictate that a full-scale analogue signal of less than +5v must be used. The ADC contains a resistor ladder network, and the centre of the ladder voltage must be near the centre of the supply. The supply voltage connections to the resistor ladder are labelled REF(-) and REF(+) and these are held at +1V and +4V respectively.

The analogue voltage range must also be +1V to +4V for a full 8-bit binary conversion. The signals from the boom angular positional feedback transducers, and driver operated joysticks have signal conditioning and the 1v to 4v range is set within these circuits.

A TL430C programmable Zener diode is used to regulate, within close limits, the REF(-) and REF(+) voltages. The circuit is shown in Figure 4.12. A load of upto 10mA could be connected across A and B without effecting the voltage levels. This would allow for all unused channels of the ADC to be fitted with potentiometers connected across A and B, in a similar way to the ripping motor absorbed current simulation input. This was done to allow for possible future simulation of the machine frame degrees of freedom.

The micprocessor system control of the ADC is by "memory mapped I/O". That is, seen from the microprocessor, each of the 16 analogue to digital channels appears to be at a particular address.

$\overline{CS7}$ is allocated for the memory mapping of the ADC0816 (Chapter 3). $\overline{CS7}$ is active low from address 3800H to 3FFFH. This is a 2K block exclusively allocated to the ADC. The low byte part of the address sets up the channel to be converted, as shown in Table 4.1.

```
Address 3800H selects channel 0.
Address 3801H selects channel 1.
   |      |        |        |    |
        Through to
   |      |        |        |    |
Address 380EH selects channel 14.
Address 380FH selects channel 15.
```

TABLE 4.1 ADC Channel Selection.

$\overline{CS7}$, together with IO/$\overline{M}$ and $\overline{WR}$ signals from the 8085A are used to send the address latch enable (ALE) and START signals to the ADC. These are active high, as shown in Table 4.2.

$\overline{CS7}$	IO/$\overline{M}$	$\overline{WR}$	ALE and START
0	0	0	1
Any Other Combination			0

TABLE 4.2 Truth Table for ALE and START for ADC.

The logic elements for obtaining this control are shown on Hardware Diagram 4 in Appendix A.

The timing specification for these signals is outlined in Ref.41, and was satisfied with the following simple software instructions :-

```
LXI H,  38X?H   ; LOAD CHANNEL SELECTION ADDRESS.
MOV M,A         ; ACTIVATE WR AND IO/M TO START CONVERSION.
```

where,

X indicates any Hex. quantity.

? indicates the Hex. code for the channel selection.

The ADC0816 sends an end of conversion (EOC) signal which is recognised by the microprocessor. It is important that recognition was by the rising edge of the EOC signal, since for a period of approximately 12 μs from the start of conversion, EOC is high. This is achieved by connecting the EOC signal direct to the RST7.5, rising edge sensitive, interrupt on the 8085A microprocessor. This interrupt is enabled and the microprocessor halted with the HLT instruction.

On receipt of the EOC signal the TRISTATE CONTROL to the ADC is taken high by pulling $\overline{CS}7$, IO/$\overline{M}$ and $\overline{RD}$ signals low. The logic elements for this control are shown on Hardware Diagram 4 in Appendix A. The software instruction, with the H and L registers already containing the address for $\overline{CS}7$ to go low, is :-

```
MOVE A,M        ; MOVE CONVERSION TO ACCUMULATOR.
```

This makes for an extremely efficient system, from a hardware and software aspect, for the ADC of sixteen channels.

CHAPTER FIVE

MICROPROCESSOR SYSTEM PROGRAMMING AND CONTROL ALGORITHMS FOR DATA RETRIEVAL SYSTEM

5.1 INTRODUCTION.

Having established the design of the microprocessor system hardware and the interface to the real world the operational programme must be developed for the necessary functions. As with the hardware system, there are various entry levels requiring weighted decisions for the writing of the programme (Ref.42). The implications of the various levels of programme writing are briefly discussed.

The task of information retrieval and data preparation for the roadheader is carried out by a dedicated processor system, the hardware of which is described in Chapters 3 and 4. The object of the system is to gather the input information and to carry out some preparation of the data, to enable the positional control of the ripping head of the roadheading machine. The flow charts for the programmed actions are contained in this chapter together with a description of several important aspects.

5.2 MICROPROCESSOR SYSTEM PROGRAMMING.

The lowest level for the programming of the microprocessor is the binary code on which the system operates. This is referred to as the machine code. Different microprocessors have varying architectures and modes of operation and an extremely good knowledge of these aspects for the processor being used is essential. Very few systems are programmed in this way because it is time consuming and debugging of the programme is very difficult. These aspects constitute a high economic cost in programme development(Ref.43).

Hexadecimal (Hex) notation can be used with a translator to convert the Hex instruction into the binary format. The translator offers little assistance other than that of transposition.

Symbolic assembly language programming, in which each instruction has a mnemonic with a binary equivalent, is the lowest practical level for the writing of complex programmes. Memory locations and variables can be given an alpha-numeric symbol. This, for example, allows the programming of a jump or call instruction without specifying the exact address. Programmes written in symbolic assembly language are converted to machine code by an "Assembler". There are many aspects of an assembler which are important to the user (Ref.33).

The writing of assembly language programmes requires a knowledge of the processor architecture and mode of operation equal to that for machine language programming. An assembly language programme is both application and processor orientated and offers the highest efficiency (equal to that of machine coding), in the use of memory locations and hence speed of operation in the system being developed. The programmes are not directly tranferable from one microprocessor to another of a different architecture.

Assembly language programming of mathematical routines can be difficult and hence time consuming. To help with this and other complex programming aspects there are available for most of the more popular microprocessors, libraries of software modules (Ref.44), which can be incorporated in the users programme.

High-level languages are application and not processor orientated and are therefore translatable to run on many different processor systems. The translating to machine code is carried out using a computer programme known as a "compiler". The compiler is dedicated to each processor type.

The writing of a suitable high-level language for an application is less time consuming than for an assembly language. However, unlike the assembly language, the high-level language does not have an equivalent machine code for each instruction. This, for a particular system, results in the use of an increased number of bytes of memory and hence slower speed.

Compiled high-level languages such as PL/M, RTL-2 and CORAL were written for the specific purpose of programming real-time process and machine control applications. Others such as Standard FORTRAN have poor input/output and real-time control facilities.

A further form of high-level language is the interpretive high-level language. Interpreters are used to translate the high-level statement to the machine code. The time required to execute an interpretive language is considerably higher than that to execute a compiled language programme. The advantage of an interpretive programme is that they are easy to use since only a few simple instructions are required to programme complex routines. The most popular interpretive language is BASIC. Interpretive languages for dedicated control systems pose a further problem in that the interpreter should be

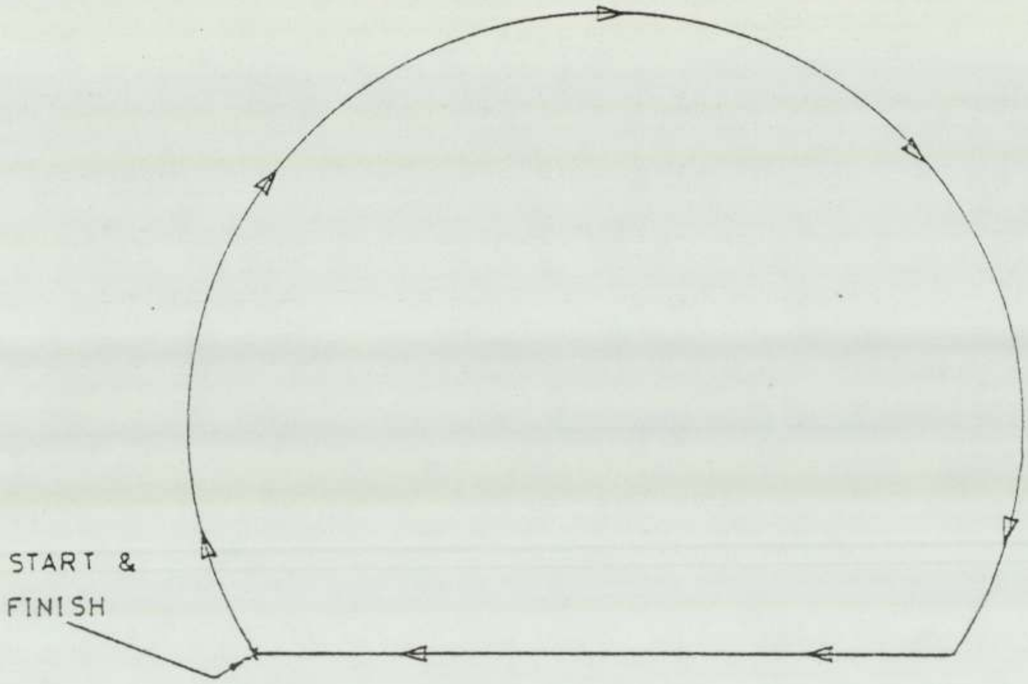


FIGURE 5.1 PROFILE MOVEMENT.

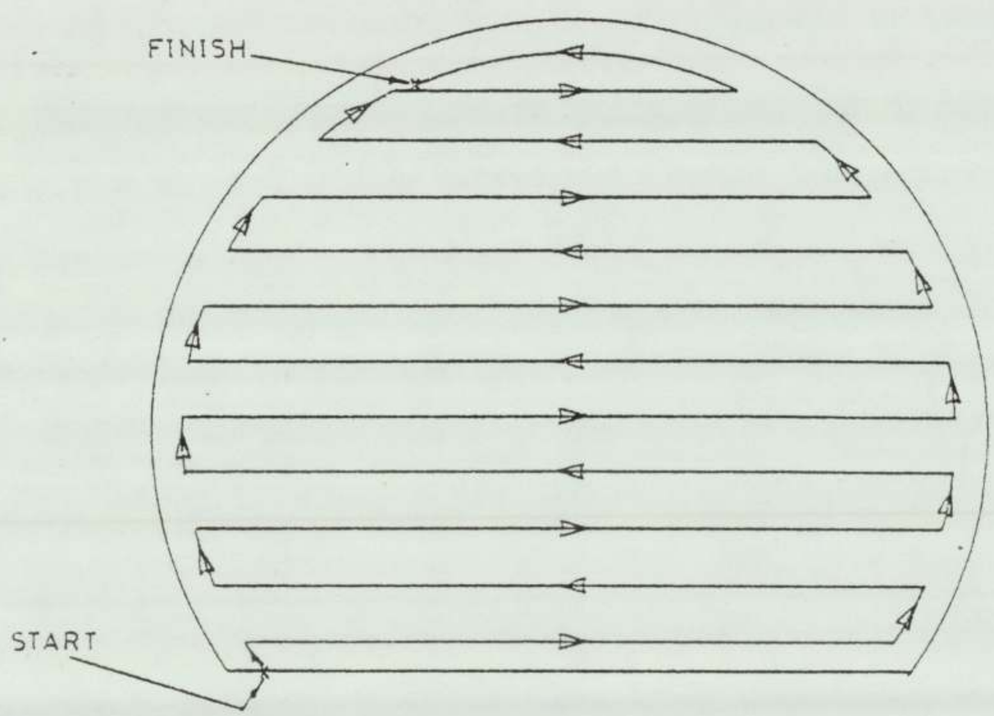


FIGURE 5.2 REMOVAL OF CAVITY MATERIAL MOVEMENT.

resident in memory.

The minimum system configuration requirement for the roadheader dictated the use of symbolic 8080/8085 assembly language programming (Ref.45), throughout. The high operating speed of this language enabled the real-time control requirements of the system to be implemented.

5.3 CONTROL ALGORITHMS FOR THE INFORMATION RETRIEVAL AND INPUT DATA PREPARATION SYSTEM.

The sequence of events from the moment of "power on" to the system, is as follows :-

1) "Power On" - all hydraulic valves are closed and the machine operator is not able to move the boom, other than by the direct manual operation of the main poppet valves.
2) The "profile definement" joystick must be in contact with the profile template and the "profile definement" push button pressed. The system is then waiting for data to be entered.
3) The joystick must then be moved around the template, which defines the tunnel profile to the control system.
4) On completion of the profile definement operation, the "cease profile definement" push button is pressed, which informs the system of the finish of profile data entry.
5) The system is now enabled and the operator has a choice of two automatic modes, or a manual movement of the boom with the "boom move" joystick. Pressing the "cut profile" push button causes the boom to move around the profile as shown in Figure 5.1. Pressing the "cut Cavity" push

****
* OVERALL FLOW CHART FOR DATA RETRIEVAL SYSTEM *
****

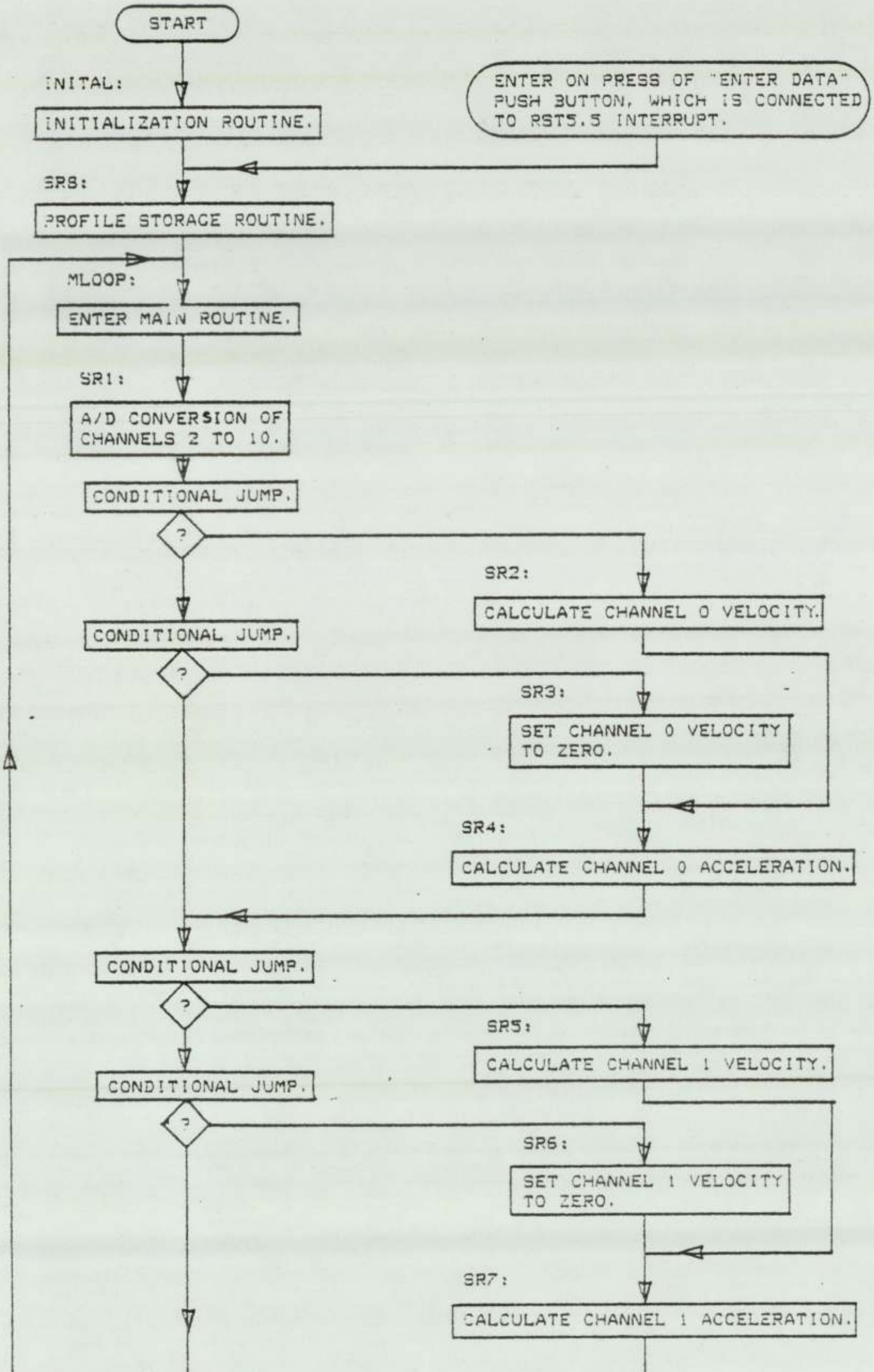


FIGURE 5.3 OVERALL FLOW CHART FOR DATA RETRIEVAL SYSTEM.

button, causes the boom to move as shown in Figure 5.2. If manually operated movement is chosen, the boom will move to the position defined by the "profile definement" joystick, which can be positioned at any point within the profile.

6) The operator can cease automatic operation at any time on press of the "stop current operation" push button. This returns the system back to stage 5 of the control cycle.

The boom will cease movement if the ripping motor absorbed current is above approximately 90% of full load current (FLC), whether under automatic or manual operation. If the absorbed current is above 10% of FLC, then the boom, manually input, "fast move" operation will automatically be reduced to "slow move" operation. All movement under automatic control is at slow speed.

In the event of the profile data storage area of memory being filled, the operator receives indication from a flashing, light-emitting diode (LED). The area of memory will accommodate a profile envelope, equivalent to the boom moving around the maximum profile limits on all sides, plus approximately 25%.

An overall simplistic flow chart of the data retrieval systems algorithm is shown in Figure 5.3. This is expanded with further flow charts for the following algorithms :-

Figure 5.4 Initialization Routine.

Figure 5.5 Main Routine.

Figure 5.6 Subroutine No. 1.

Figure 5.7 Subroutine No. 2.

FLOW CHART FOR INITIALIZATION ROUTINE.
INITAL:

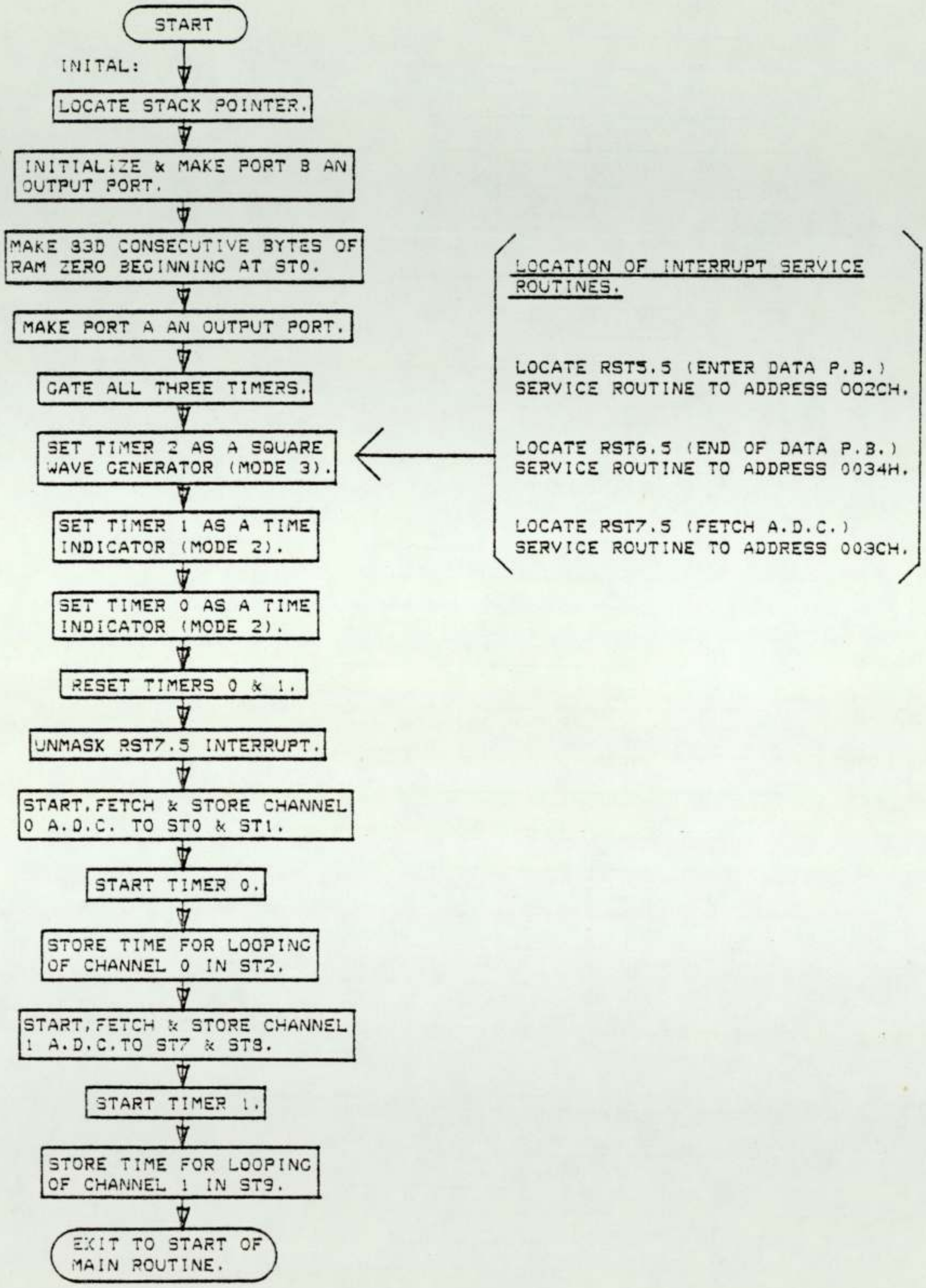


FIGURE 5.4 INITIALIZATION ROUTINE.

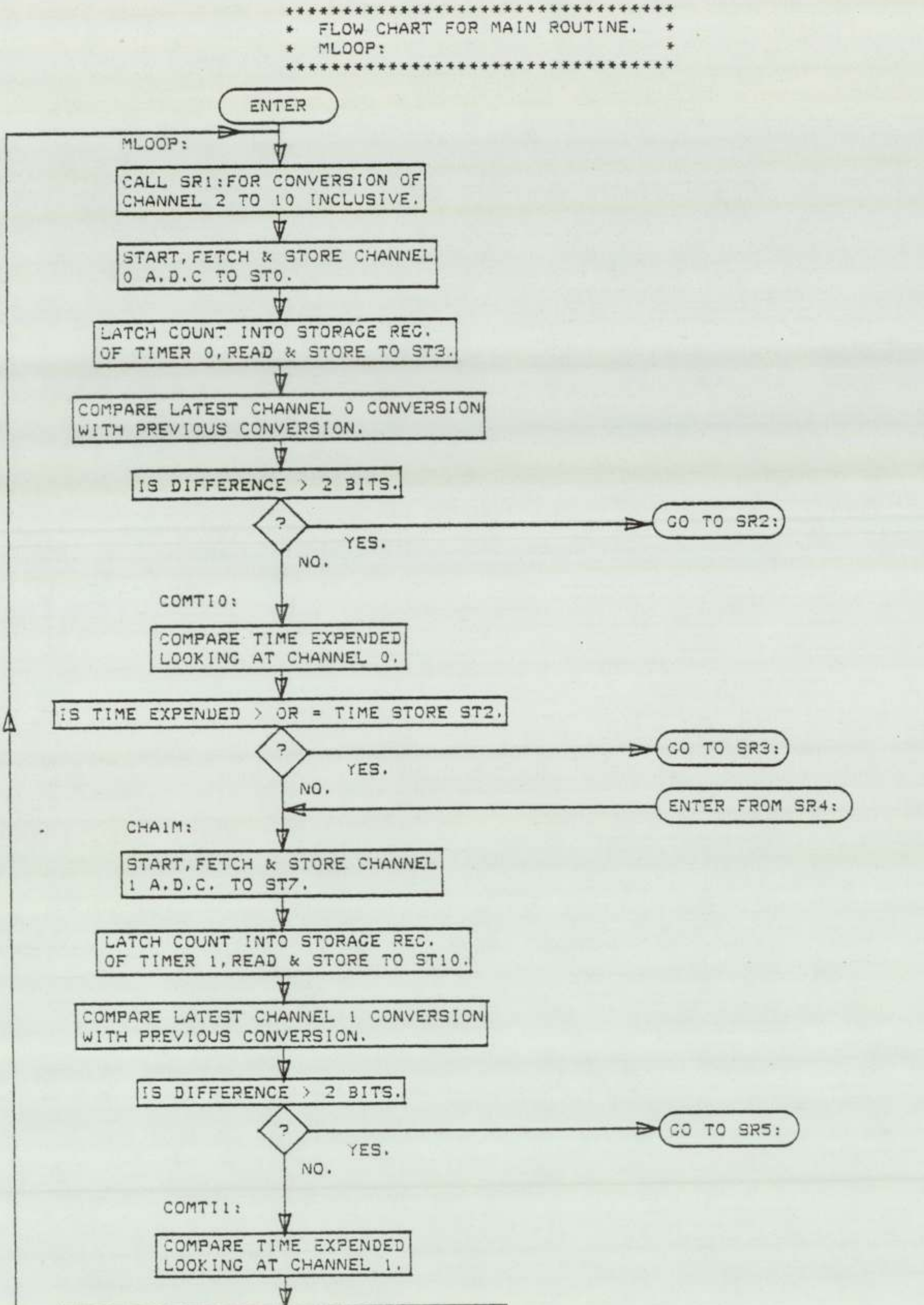


FIGURE 5.5 MAIN ROUTINE

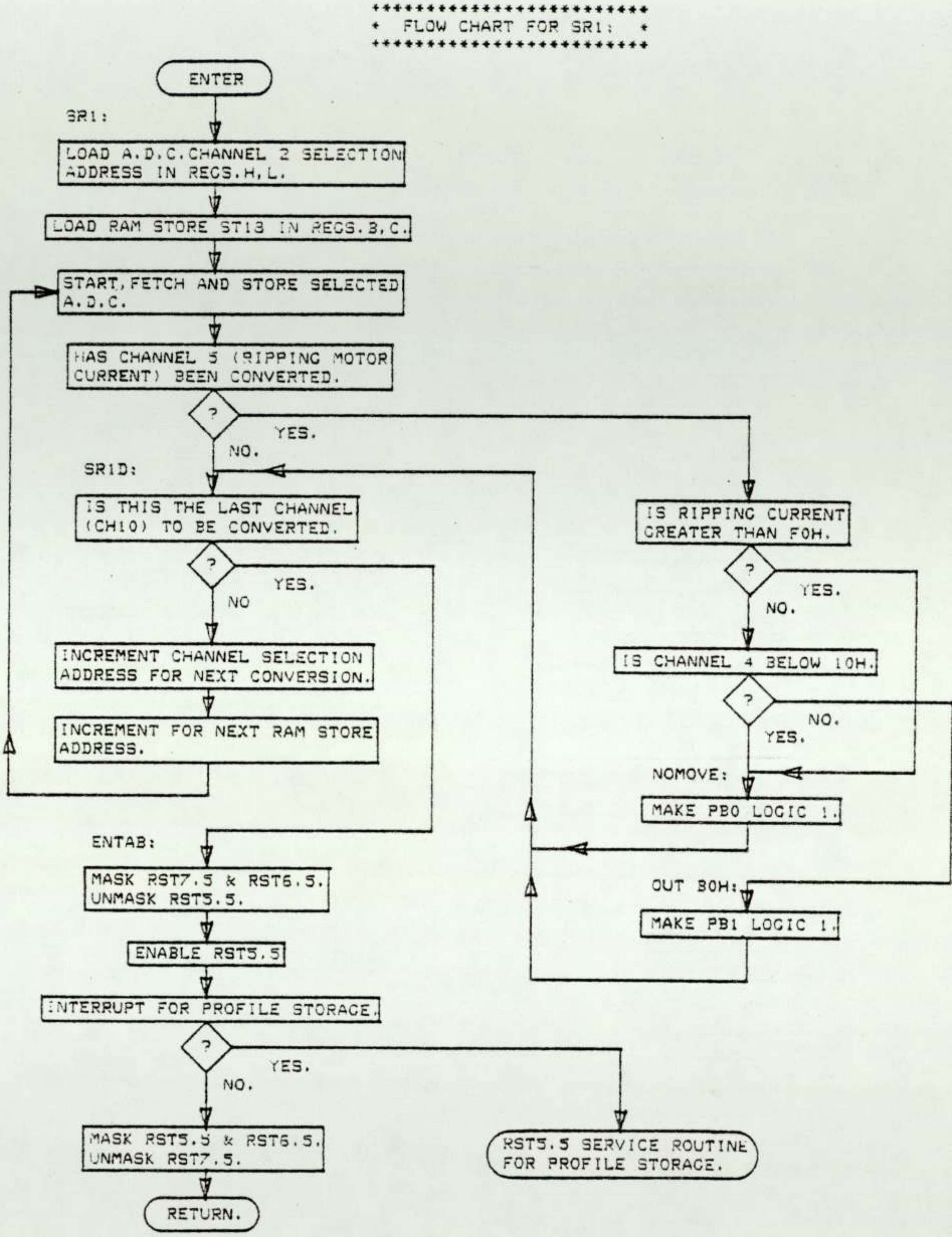


FIGURE 5.6 SUBROUTINE NO. 1.

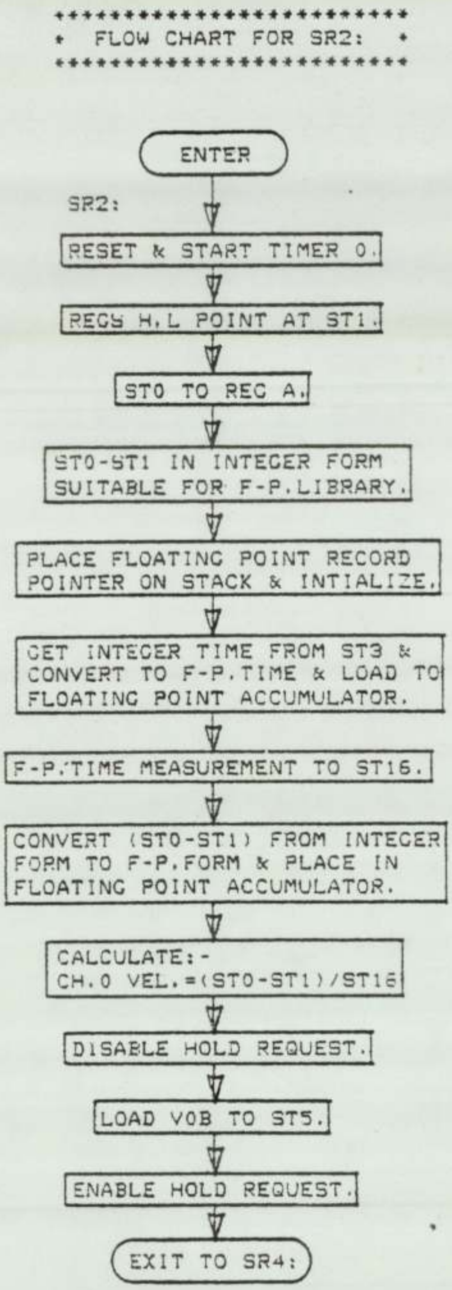


FIGURE 5.7 SUBROUTINE NO. 2.

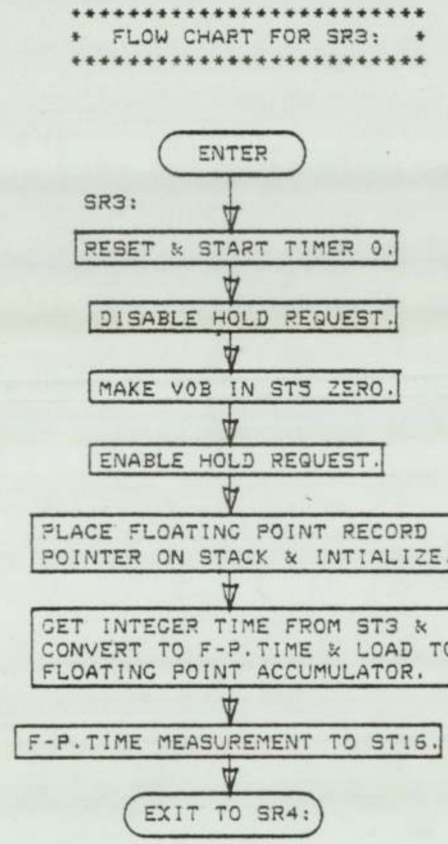


FIGURE 5.8 SUBROUTINE NO. 3.

```
**************************
*  FLOW CHART FOR SR4:   *
**************************
```

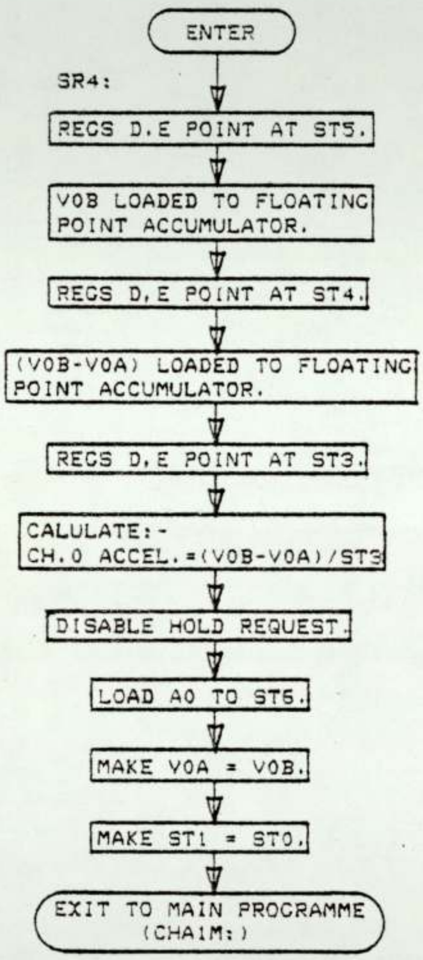


FIGURE 5.9 SUBROUTINE NO. 4.

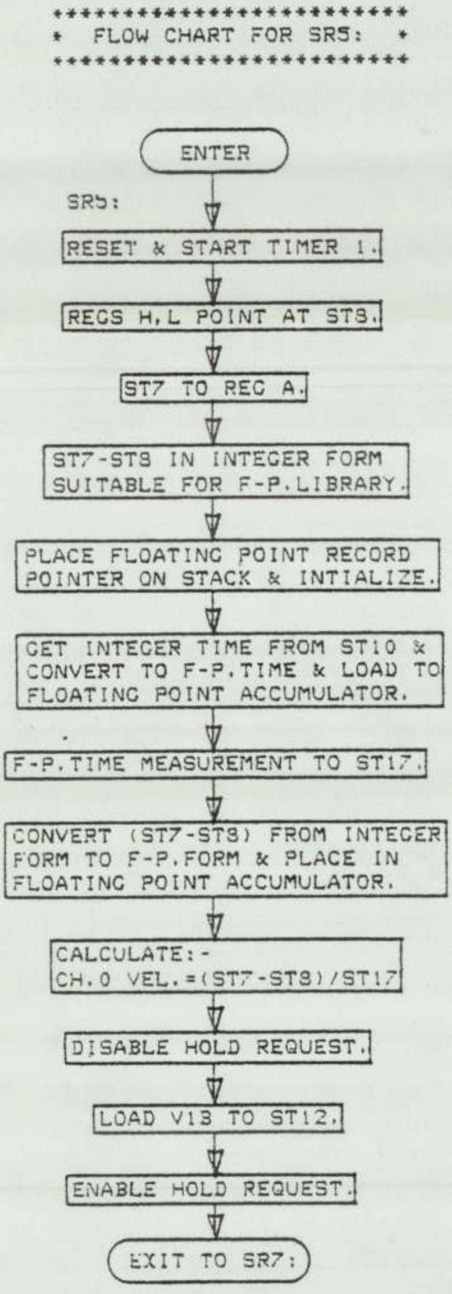


FIGURE 5.10 SUBROUTINE NO. 5.

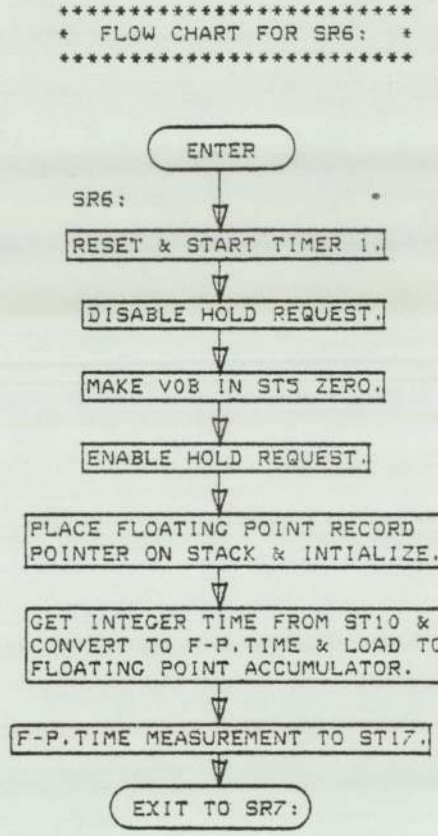


FIGURE 5.11 SUBROUTINE NO. 6.

* FLOW CHART FOR SR7: *

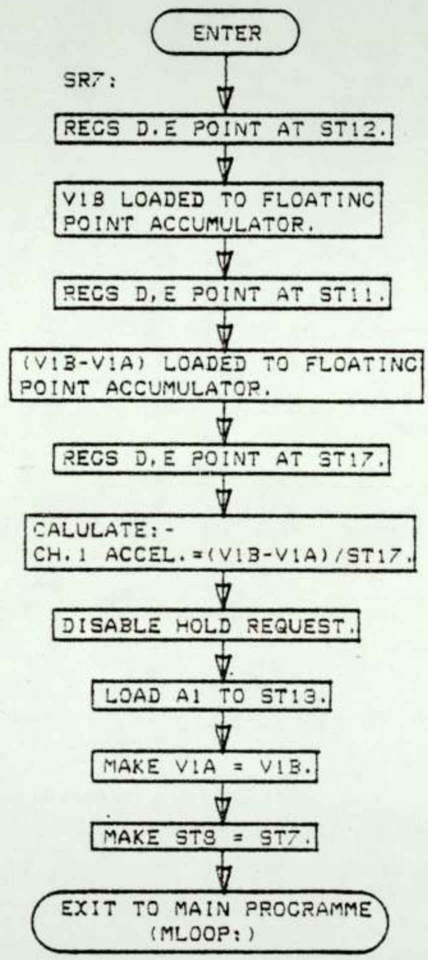


FIGURE 5.12 SUBROUTINE NO. 7.

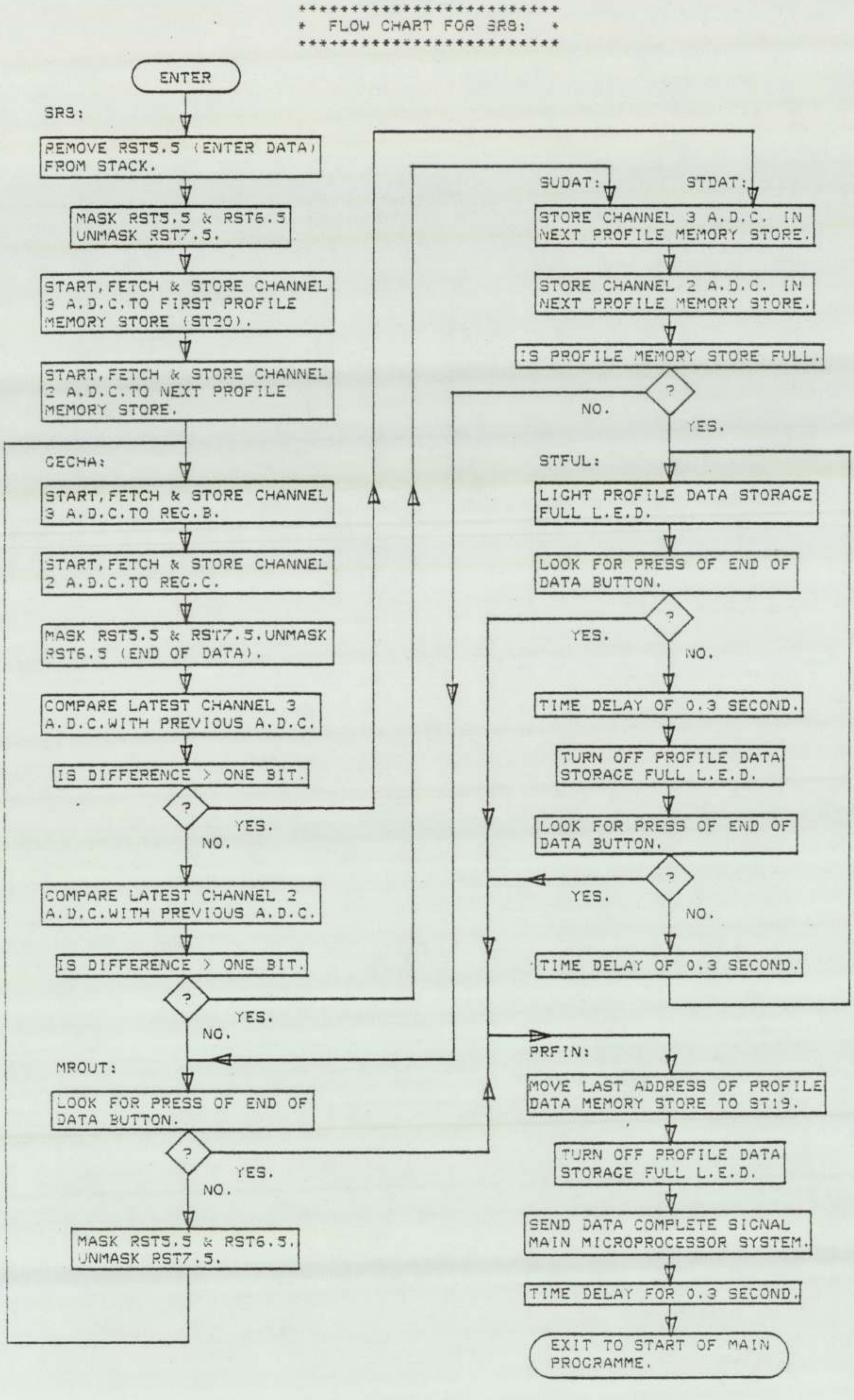


FIGURE 5.13 SUBROUTINE NO. 8.

Figure 5.8 Subroutine No. 3.

Figure 5.9 Subroutine No. 4.

Figure 5.10 Subroutine No. 5.

Figure 5.11 Subroutine No. 6.

Figure 5.12 Subroutine No. 7.

Figure 5.13 Subroutine No. 8.

The assembly language programmes, with mnemonic operation codes, labels and names, together with the corresponding machine language, for the flow charts, are contained in Appendix B. The itemised random access memory locations for the storage of temporary data are also contained in Appendix B.

It is the temporary data which is accessed by the main systems microprocessor to enable the correct switching of the hydraulic valves. Details of this system are contained in the thesis written by C. W. Chuen.

Verbal descriptions of the more salient features of the information retrieval and input data preparation system are contained in this Chapter.

5.4 INITIALIZATION.

When power is first applied to the system, or if the system is reset, once only initialization processes need to be carried out. These include locating the stack pointer to a suitable area in RAM, defining output ports, gating and setting up the modes of the three timers and setting all velocity and acceleration data locations to zero.

Also included in this algorithm are the service routines for the interrupts. Figure 5.4 details the interrupt allocations and the vector address for the service routines. All interrupts used in this system are maskable, that is, they can be disabled. If any of the vectored interrupts used in this system are unmasked, and an interrupt is received, then this causes the processor to save the old programme counter in the stack and branch to the respective service routine address. In this system, interrupts are unmasked and enabled individually and hence priority is controlled.

5.5 VELOCITY AND ACCELERATION CALCULATION.

The angular velocity of the boom movement on the two axes was required by the main processor system for determining the optimum positional control of the boom. The acceleration data was, ultimately, not required (Refer to the thesis by C. W. Chuen).

It was decided to obtain the velocity by using angular displacement transducers and a programmable timer IC (Refer to Chapters 3 and 4). By taking an angular displacement reading and starting the timer, and waiting for a specified change of angular displacement and reading the time, then,

$$\text{angular vel.} = \frac{\text{latest displacement - initial displacement}}{\text{time interval}}$$

In a similar manner, having calculated two angular velocities, at a measured time interval,

$$\text{angular accel.} = \frac{\text{latest velocity - initial velocity}}{\text{time interval}}$$

For an analogue to digital converter (ADC) with a total error of less than + or - 1/2 LSB, then the higher the number of bits change in angular displacement, over which time is measured, then the higher the accuracy of the angular velocity calculation, for a constant velocity. Extending the bits change in angular displacement over which time is measured, also extended the frequency of angular velocity update, and it was necessary to make an optimization. This was determined at > 2 bits, which gave a reasonably accurate angular velocity calculation (See Chapter 8), and an acceptable frequency of update.

The boom axes angular velocities and accelerations are calculated with the aid of the Intel 8080/8085 Floating-Point Arithmetic Library (FPAL) (Ref.44). This library contains basic floating-point subroutines and procedures. The operations used for this application include, subtraction, division and conversion between 32-bit signed integer formats and floating point. The 32-bit, binary floating-point format recognized by FPAL consists of three fields :-

sign	exponent	fraction
1-bit	8-bits	23-bits

For further explanation see Ref.44.

Both displacement and time readings require software operations to place them in a form suitable for use by the FPAL. The routine for the boom slewing axis, as an example, is as follows :-

1) Obtain the angular displacement from channel 0 of the

analogue to digital converter (ADC) and place in temporary stores ST0 and ST1.

2) Start timer 0.

3) Obtain the angular displacement from channel 0 of the ADC and place in ST0.

4) Latch count into storage register of timer 0, read and store to ST3 in integer form, suitable for the FPAL. The timer gives a 16-bit binary down count from FFFFH. This is complemented and placed in 32-bit binary integer form in ST3. That is 0000????H.

5) Compare latest channel 0 conversion with previous conversion and if the difference is > 2-bits, calculate angular velocity.

   Assuming that, ST0 - ST1 = > 2-bits difference, then,

6) Reset and start timer 0.

7) Place the difference between the two channel 0 displacement readings in integer form suitable for the FPAL in ST14. The subtraction of ST1 from ST0 is an 8-bit binary quantity. The FPAL requires this to be a 32-bit, either positive or negative (two´s complement), binary integer number. If positive the number will read 000000??H, and if negative FFFFFF??H.

8) Get integer time from ST3, and using the FLTDS procedure of the FPAL, convert to a floating-point number and place in ST16.

9) Convert the displacement difference (ST0-ST1) from integer form in ST14, to a floating-point number using the FLTDS procedure and place in floating-point accumulator (FAC).

10) Calculate,

$$\frac{(ST0-ST1)}{ST16} = \frac{ST14}{ST16} = V0B$$

V0B is placed in ST5.

V0B is the latest angular velocity of the boom on the slewing axis. Following the angular velocity calculation, the acceleration is calculated using the FPAL procedures. The latest velocity calculation then becomes the initial velocity calculation, ready for the next time a difference of > 2-bits in the displacement readings is detected. The velocity and acceleration subroutines are then re-entered for calculation, using new data.

A similar procedure is used for calculation of the boom velocity and acceleration on the raising/lowering axis.

The two axes have individual subroutines for the velocity and acceleration calculations, as shown in Figure 5.2. It would have been possible to use the same velocity calculation subroutine and the same acceleration calculation subroutine for the two axes. This would have considerably complicated the software for a small saving in read only memory. This saving would not have reduced the IC count.

The velocity is available to the main systems processor in units of :-

$$\frac{\text{bits change of angular displacement}}{\text{increments of count}}$$

where,

1-bit = 0.4153 degree, for the slewing axis.

1-bit = 0.3097 degree, for the vertical axis.

and,

1 increment of count = 1.66664 x 10 s

5.6 STORAGE OF PROFILE DATA.

The profile storage routine algorithm is labelled SR8, and is shown in Figure 5.13.

Channels 2 and 3 of the ADC, are connected respectively to the horizontal and vertical tunnel axes potentiometers, of the profile definement joystick.

The data is stored, beginning at ST20, in consecutive pairs of vertical and horizontal axis data. With the inaccuracy of the ADC, storage of data is only carried out if there is > 1-bit change on either channel. This ensures that movement of the joystick has to take place for data to be stored. The data is correctly stored (See Section 4.2.1), irrespective of the speed at which the joystick is moved around the template, providing the joystick is always in contact with the template.

On press of "cease profile definement" push button, the address of the last profile data entry is placed in ST19. The main systems processor is then able to ascertain the exact area of memory containing the profile data.

The control of the flashing LED, to indicate to the operator that the profile data storage area is full, is also included in this subroutine.

CHAPTER SIX

ACTUATOR DIRECTIONAL CONTROL WITH POPPET VALVES

6.1 INTRODUCTION.

The valves that control the directional switching of the booms hydraulic actuators are interface elements between the electronic and hydraulic systems.

The criteria for the design and selection of the valves together with resultant considerations for performance improvement are studied with the aid of computerised simulation. The effect of individual supply and exhaust poppet valve closure variations on cylinder pressures, actuator piston displacement error and the interaction of the fluid columns is presented as a theoretical study.

It was important to gain knowledge of the valve opening and closing response times prior to the construction and bench testing phase. A computerised simulation is presented with actual performance comparisons.

6.2 VALVE SELECTION CRITERIA AND CONSIDERATIONS.

There are important criteria that the valves must satisfy. They must be suitable for :-

1) A high level of contamination of the fluid by solid matter.
2) Operation in a hazardous environment such as is found in coal mines (Ref.9).
3) Operation on dilute (5/95 oil-in-water) emulsion (Ref.10).
4) Ease of maintenance with modular replacement in the event of a breakdown.

5) Direct hand operation in the event of a failure in the processor based control system.

These basic requirements led to the selection of soft seat poppet valves with servo pilot control from intrinsically safe, solenoid operated, ball valves.

The hydraulic actuators are connected to the boom and pedestal for movement of the boom on the vertical axis and between the pedestal and machine frame for movement on the horizontal axis. This constitutes a high inertia load and a mechanically stiff structure. The fundamental mode open-loop natural frequency of the hydraulic/mechanical system is primarily determined by the total inertia, and the compliance in the fluid columns between the actuator piston and valves and in hoses connecting the valves and actuators.

It was realised, at an early stage, that the separate control of the actuator supply and exhaust poppet valves could be put to advantage. The control of a symmetrical actuator under rapid breaking is considered.

In particular the pressure peaks and troughs within the cylinder, the hydraulic stiffness and the piston positional error will be examined. The error is defined as the distance the piston moves from a datum, taken at the point at which the servo pilot valve closure cycle begins, to the final rest position of the actuator.

Cavitation in valve controlled hydraulic actuator systems has previously been heavily researched, notably in Ref.46, 47 and 48. In the most recent of these studies (Ref.48) McCloy stated that, cavitation has been shown to occur, under certain conditions, on both sides of the actuator piston, but compressibility and leakage effects would make this unlikely in practice. However, with soft seat poppets and modern actuator seals, leakage is negligable. Also the vapour pressure of water is much higher than that of mineral oils and hence cavitation is expected to occur more readily with dilute emulsions.

The formation of cavities in a liquid involves rupturing of the liquid. At 21°C vapour cavities form in water at a pressure of 0.0247 bar and the assumption might be made that the liquid has ruptured at this pressure and hence its tensile strength is low. However, it has been shown experimentally (Ref.49) that the tensile strength of water can be as high as 1.034×10^8 N/m^2. Cavitation in a liquid is now generally recognised as being associated with a nucleation centre, such as a microscopic gas particle. If the liquid is subjected to a tensile stress, cavities do not form as a result of liquid rupture, but are caused by the rapid growth of these nuclei (Ref.50). It is entrained air and not dissolved air that causes problems. Cavitation, if it does occur, can lead to the damaging effect of collapsing bubbles.

The complete valve system for the actuator directional control is shown in Figure D1 in Appendix D. The overall system response time, measured from the receipt of a feedback, or operative input, signal to the main poppet opening or closing, is an important factor in the performance of the control system.

The main poppets are manufactured by Fletcher, Sutcliffe and Wilde Ltd., and the solenoid operated,

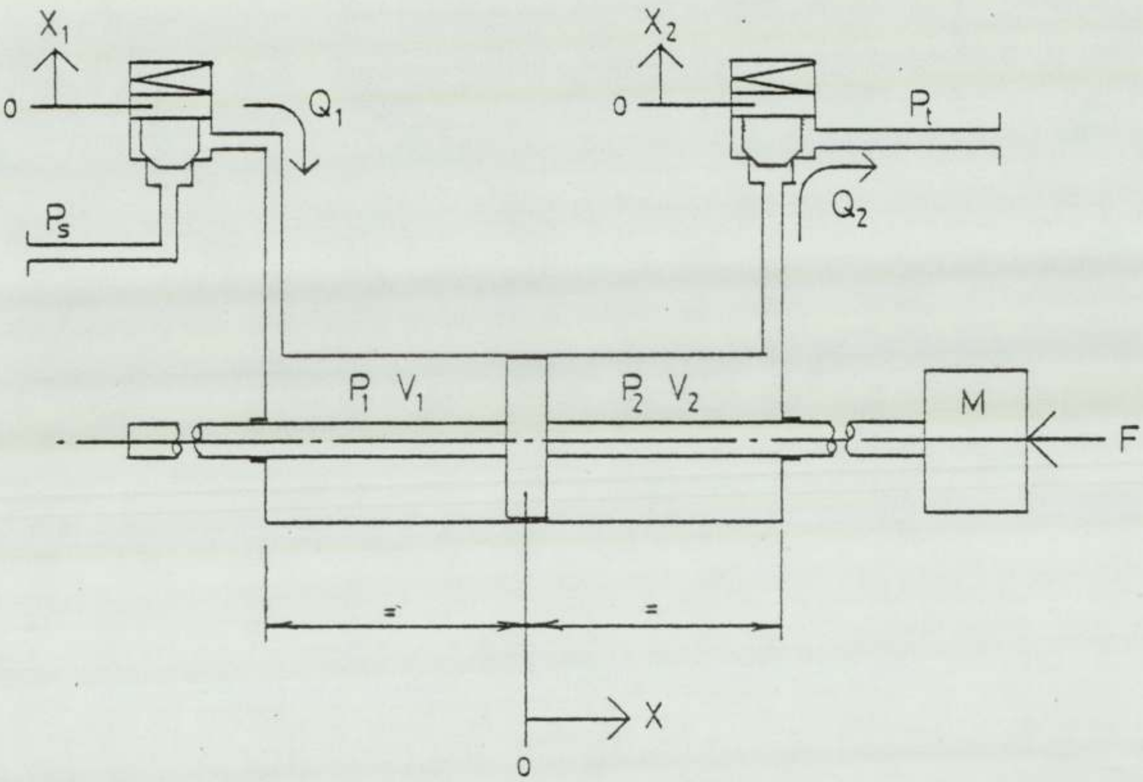


FIGURE 6.1 THE POPPET VALVES AND ACTUATOR.

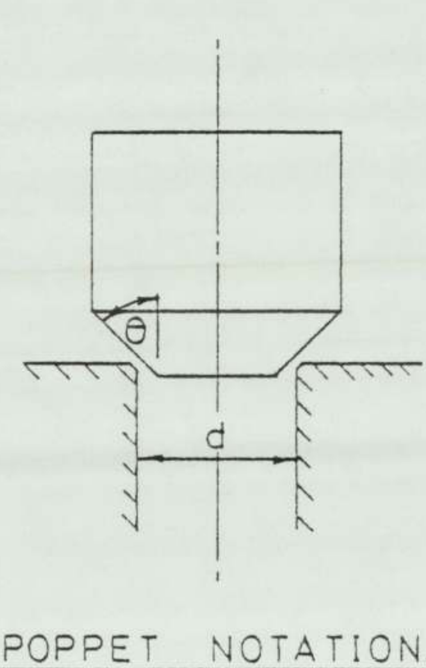


FIGURE 6.2 POPPET NOTATION.

intrinsically safe servo valves are model number 1410 122 34 of Dowty Hydraulic Units Ltd., manufacture. Both valves are used extensively in the mines for control of roof support systems. Roof support systems are relatively static, and response times are not such important criteria, as they are for this application.

6.3 CONTROL OF INERTIA LOAD WITH HYDRAULIC ACTUATOR AND POPPET VALVES.

The hydraulic actuator and poppet valves are shown in Figure 6.1, with the notations used in developing the mathematical model. The poppet valves have individual control and Figure 6.2 shows the poppet notation.

6.3.1 Mathematical Model.

Expressing the flow into the actuator as,

$$Q_1 = C_d \; a_1 \sqrt{2/\rho \left| Ps - P_1 \right|} \quad \text{Sign } (Ps - P_1) \qquad (6.1)$$

Similarly the flow out of the actuator,

$$Q_2 = C_d \; a_2 \sqrt{2/\rho \left| P_2 - Pt \right|} \quad \text{Sign } (P_2 - Pt) \qquad (6.2)$$

where C_d, the orifice discharge coefficient, assumes that the upstream area is much larger than the orifice area and approach velocity effects are zero.

The poppet orifice areas are expressed as,

$$a_1 = \pi \, d \, X_1 \, \text{Sin } \theta \qquad (6.3)$$

and

$$a_2 = \pi \, d \, X_2 \, \text{Sin } \theta \qquad (6.4)$$

where the jet angle is taken to be the same as the poppet angle, as shown in Figure 6.2.

Considering the flow relationship through the actuator, taking into account the fluid compressibility, defined by the bulk modulus of the fluid as,

$$\beta = -V \frac{dP}{dV} \qquad (6.5)$$

Then,

Q_1 = flow rate due to compressibilty + flow rate due to piston displacement.

$$Q_1 = \frac{V_1}{\beta} \frac{dP_1}{dt} + A \frac{dX}{dt} \qquad (6.6)$$

Similarly,

Q_2 = -flow rate due to compressibility + flow rate due to piston displacement.

$$Q_2 = - \frac{V_2}{\beta} \frac{dP_2}{dt} + A \frac{dX}{dt} \qquad (6.7)$$

From the equation of motion for the piston,

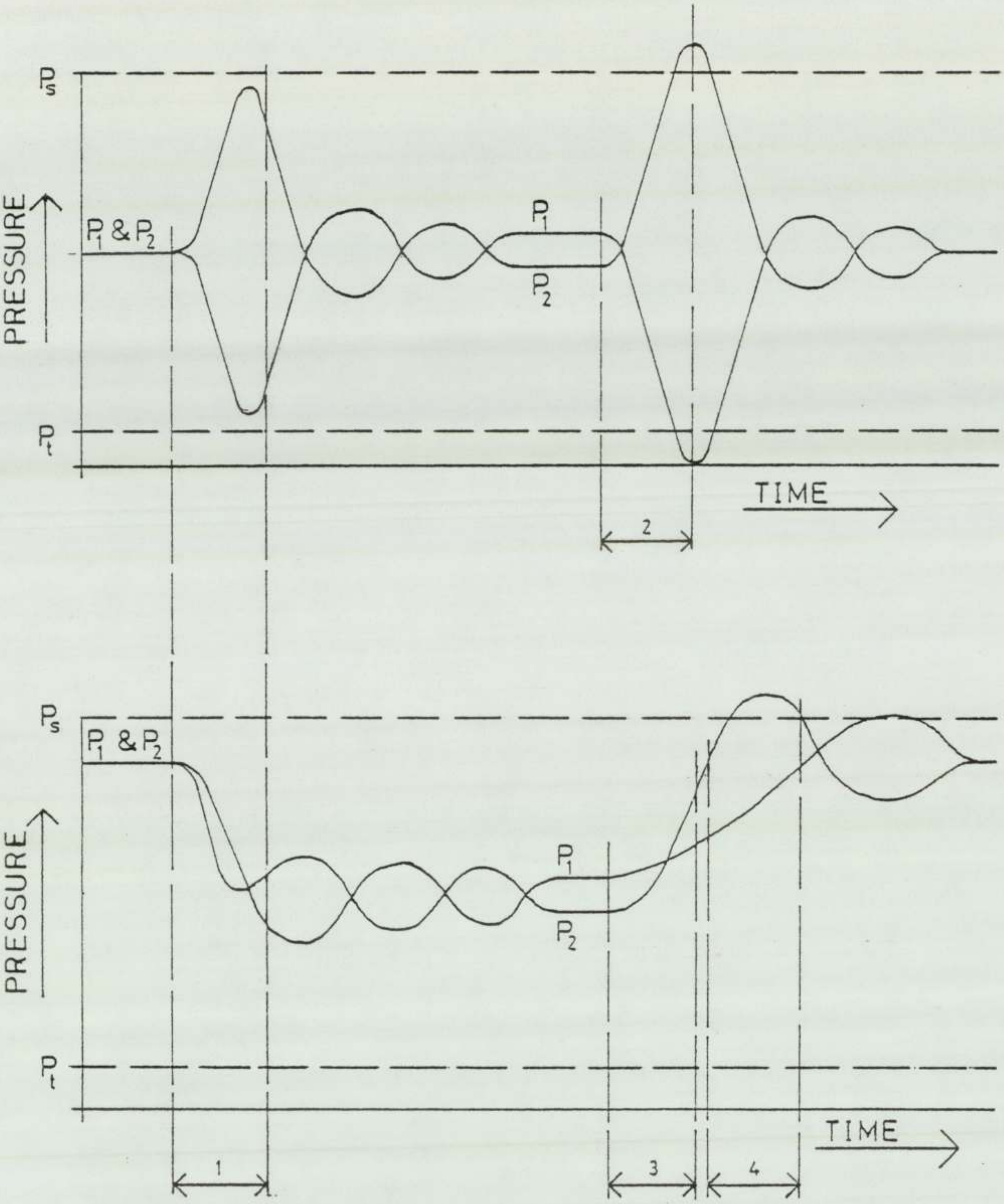
$$\frac{d^2X}{dt^2} = (P_1 - P_2) \frac{A}{M} - \frac{F}{M} \qquad (6.8)$$

Let V = total cylinder volume ($V_1 + V_2$) and assuming X = 0 when the piston is in mid stroke. Then,

$$V_1 = \frac{V}{2} + XA \qquad (6.9)$$

and,

$$V_2 = \frac{V}{2} - XA \qquad (6.10)$$



1 — VALVES OPEN IN UNISON.
2 — VALVES CLOSE IN UNISON.
3 — VALVE TO TANK CLOSES.
4 — SUPPLY VALVE CLOSES.

FIGURE 6.3. EFFECT OF VALVE CLOSURE VARIATIONS ON CYLINDER PRESSURES.

Combining equations 6.1, 6.3, 6.6 and 6.9 gives,

$$\frac{dP_1}{dt} = \frac{\beta}{V/2 + XA}\left[C_d \pi d X_1 \sin\theta \sqrt{2/\rho (P_s - P_1)} - A \frac{dX}{dt}\right] \quad (6.11)$$

Combining equations 6.2, 6.4, 6.7 and 6.10 gives,

$$\frac{dP_2}{dt} = \frac{\beta}{V/2 - XA}\left[C_d \pi d X_2 \sin\theta \sqrt{2/\rho (P_2 - P_t)} - A \frac{dX}{dt}\right] \quad (6.12)$$

6.3.2 Computerised Simulation.

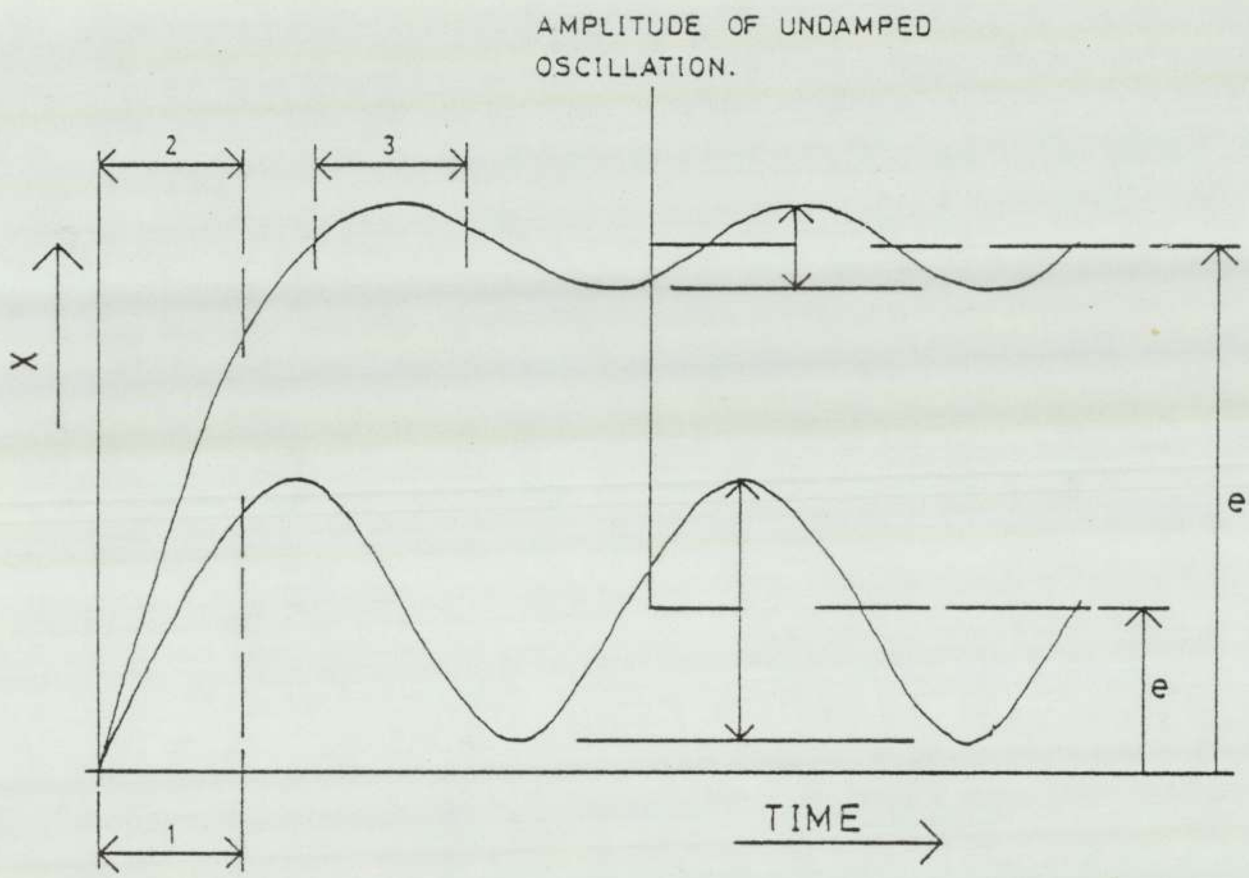
Equations 6.8, 6.11 and 6.12 describe the system. These equations were run on the main frame computer, HP 2000 Access System, using the interactive differential equation algorithm, IDEA, prepared by P. Cooley (Ref.51). The algorithm uses a third-order Runge-Kutta integration scheme to solve the equations. An example, for a given set of dimensional parameters, in the use of this programme, is shown in Appendix D.

Look-up tables are used for the poppet displacements, X_1 and X_2, with respect to time. Outputs for P_1, P_2, X, DX and D2X are obtained. Where,

$$D \equiv \frac{d}{dt} \quad \text{and} \quad D2 \equiv \frac{d}{dt}$$

6.3.3 Fluid Column Interaction.

The effect of valve closure variations on cylinder pressures are shown in Figure 6.3. With the supply and exhaust poppets closing in unison, then, with large inertia loading conditions, high transient pressures are developed in the cylinder. The outflow side of the ram piston has a



1 — SUPPLY VALVE & VALVE TO TANK CLOSE IN UNISON.
2 — VALVE TO TANK CLOSES.
3 — SUPPLY VALVE CLOSES.
e — ERROR (ASSUMING EQUAL DIRECTIONAL DAMPING COEFFICIENT).

FIGURE 6.4. EFFECT OF VALVE CLOSURE VARIATION ON PISTON DISPLACEMENT.

high peak pressure and the inflow side pressure can be reduced to the vapour pressure of the fluid, making for a possible fluid cavitation condition. The conditions that give rise to cavitation can be estimated by developing the linear equations for the actuator (Ref.52).

Delaying the supply poppet closure provides increased final steady state pressures in the actuator and the simulation results, shown in Figure 6.4, indicate that a reduced amplitude of undamped oscillation is also obtained.

The maximum pressure peaks would be produced when the boom is moving downwards at maximum velocity and then braked by the rapid closing of the valves, with the supply valve delayed behind the exhaust valve. The poppet valves selected for the system are able to withstand a back pressure of at least 700 bar and still form a tight seal when closed. This allows for a considerable margin of safety. The actuator and the hydraulic hoses between the valves and actuator should also be selected to handle the high transient pressures.

The combined stiffness of two equal fluid columns can be shown to be,

$$k = \frac{4 \beta A^2}{V} \qquad (6.13)$$

where, from equation 6.5, the bulk modulas of the fluid is the reciprical of the fractional reduction in volume of the fluid per unit increase of applied pressure. The curve for pressure plotted against percentage reduction in volume for water-in-oil emulsions at 20°C is shown in

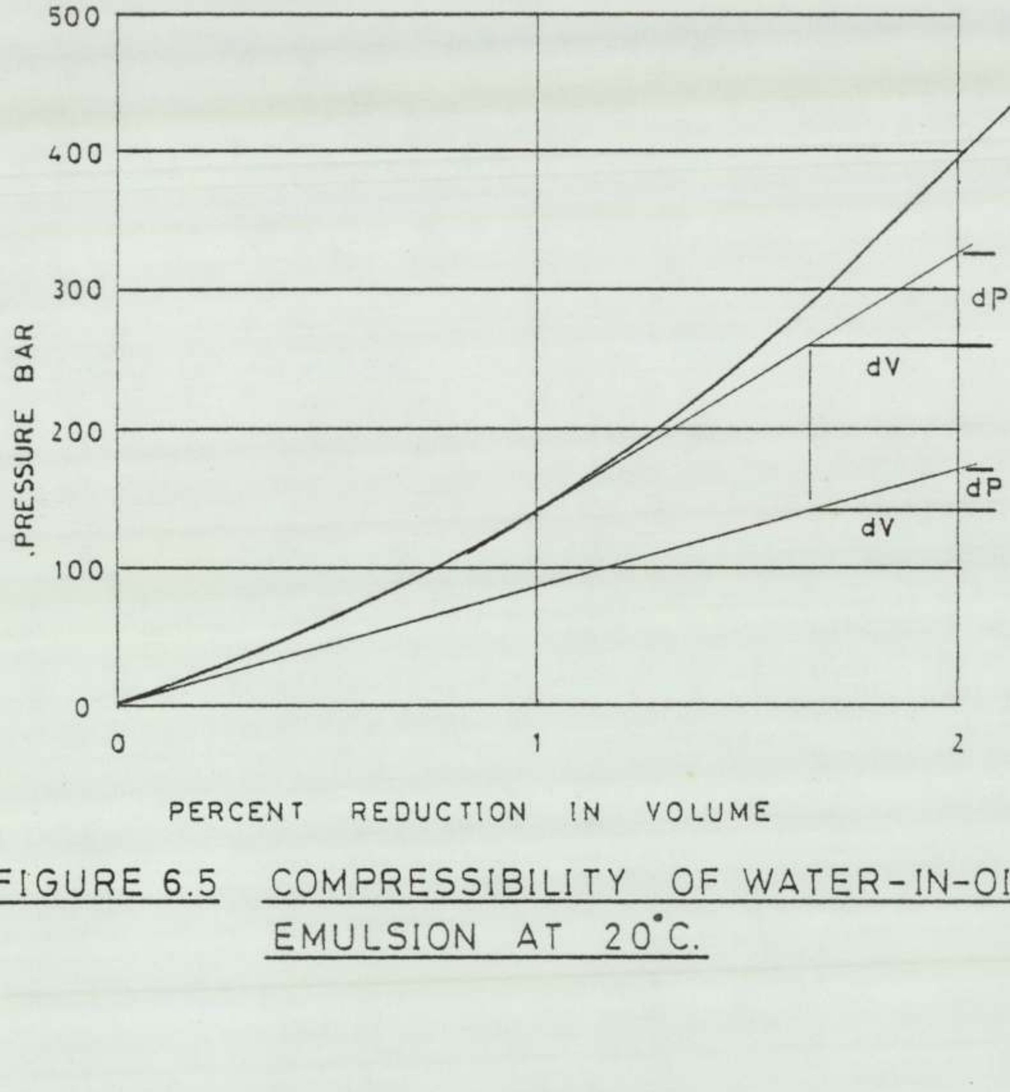


FIGURE 6.5 COMPRESSIBILITY OF WATER-IN-OIL EMULSION AT 20°C.

Figure 6.5 (Ref.53). Data is not given for compressibility of the fluid at other temperatures, however the compressibility of mineral hydraulic oils at 100°C is 25% to 30% more than at 20°C.

Refering to Figure 6.5, the slope of the line, that is $\frac{dP}{dV}$, at the system working pressure of 137 bar is over twice that at 0 bar. Combining equations 6.5 and 6.13,

$$k = 4A^2 \frac{dP}{dV} \qquad (6.14)$$

and hence, the increase in stiffness of the fluid columns is in direct proportion to the increase of $\frac{dP}{dV}$.

The valves on the roadheader machines are positioned approximately three metres from the boom actuators and connection between the two is entirely by hydraulic flexible hose. The contribution to the hydraulic system compliance by the hoses should therefore be considered.

The only reference to the compliance to be found in the standard specification for heavy duty, 6-spiral steel wire reinforced, rubber covered hydraulic hose (SAE 100R11), is the change in length test. This states that the change in length shall not exceed +2%, -4% change when pressurized to operating pressure. No reference is made to the change in diameter. The hose consists of a seamless inner tube of oil resistant synthetic rubber, 6-spiral plies of heavy wire wrapped in alternating directions and an oil and weather resistant synthetic rubber cover. It is reasonable to assume that initially the largest contribution to an increase in volume of the fluid within the hose for an increase in pressure would be the compressing of the inner rubber lining against the wire wrapping. There would also be a contribution from the stressing of the wire reinforcing. It is difficult to determine the relationship, fractional increase in volume of the hose per unit increase in pressure. It is quite possible that two hoses of the same size and to the same specification would produce different results. It can however be stated from the available evidence that maintaining high pressures between the actuator piston and valves would contribute to improved stiffness of the boom. This advantage would be more relevant to the drilling boom, where the boom must be held stable while a drill penetrates up to two metres into the rock face.

6.3.4 Derivation of the Switching Function.

It has been demonstrated in Figure 6.4 that a delay in the closure of the supply poppet leads to an increase in the final positional error of the actuator. This would have a bearing on the valve switching criteria, which were studied in depth for simultaneous supply and exhaust poppet closures in the parallel thesis carried out by C. W. Chuen.

A simplified analysis is presented for determining the optimum instance of independent closure for the exhaust and supply poppets in order to obtain accuracy in the positioning of the actuator, increased captive hydraulic pressures and minimun amplitude of undamped oscillation. Application of the analysis for the control of high inertial loads with solenoid operated poppet valves is also discussed.

Assumming the actuator piston has an initial steady

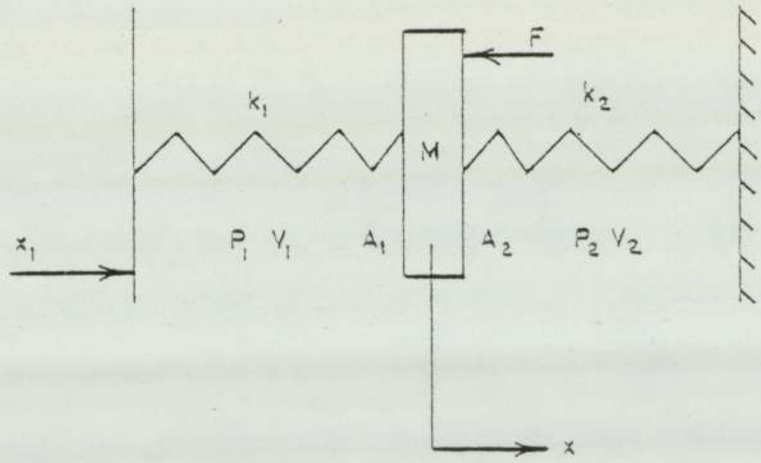


FIGURE 6.6 CONDITIONS FOR EXHAUST POPPET CLOSED.

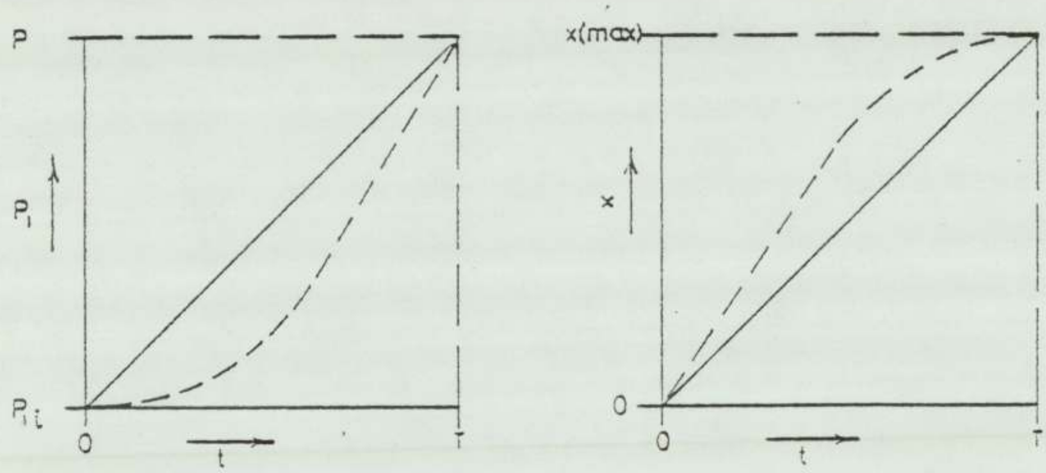


FIGURE 6.7 APPROXIMATION OF P_1 & x CHANGES WITH RESPECT TO t.

state velocity, that is $\ddot{x} = 0$, and neglecting any damping, then Figure 6.6 illustrates the conditions for instantaneous closure of the exhaust poppet.

The equation of motion for the system is :-

$$M\ddot{x} = -k_1(x - x_1) - k_2 x - F \tag{6.15}$$

where oil compressibility is considered as springs of stiffness k_1 and k_2 and x_1 is a displacement contribution due to the flow of fluid through the supply valve.

$$x_1 = \int \frac{Q}{A_1} dt \tag{6.16}$$

Where Q, the flow through the valve, is made up of a contribution due to piston movement and a contribution due to pressure change.

The pressure P_1 will approach P_s and the velocity $\dot{x}$ will approach zero as x approaches x(max). The changes are illustrated in Figure 6.7, where the actual changes, indicated by the computerised simulation, are represented by the broken lines. To simplify the analogy, $\frac{dP_1}{dt}$ and $\frac{dx}{dt}$ are assummed to be constant.

Letting, $\frac{dP_1}{dt} = \frac{P_s - P_{1i}}{T}$ and $\frac{dx}{dt} = \frac{x(max)}{T}$ and assumming $P_{1i} = \frac{P_s}{2}$

then,
$$\frac{dP_1}{dt} = \frac{P_s}{2\,x(max)} \frac{dx}{dt} \tag{6.17}$$

Combining equations 6.6, 6.16 and 6.17 gives,

$$x_1 = \left[1 + \frac{V_1 P_s}{2A_1\beta x(max)}\right] x \tag{6.18}$$

Combining equations 6.15 and 6.18 gives,

$$M\ddot{x} + \left[k_2 - \frac{k_1 V_1 P_s}{2A_1\beta x(max)}\right] x = -F \tag{6.19}$$

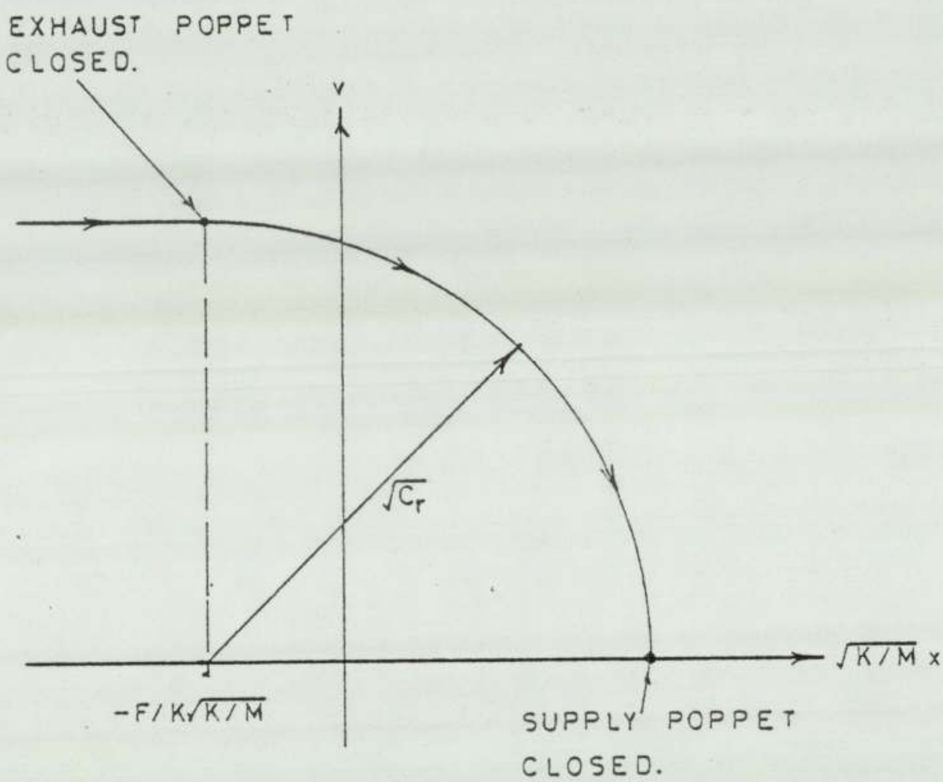


FIGURE 6.8 PHASE-PLANE TRAJECTORY.

Making the substitution: $x_T = x + \frac{F}{K}$

and $K = k_2 - \frac{k_1 V_1 P_s}{2A_1 \beta x(max)}$

then, $M\ddot{x}_T + Kx_T = 0$

Letting $\dot{x}_T = \dot{x} = v$ and $\ddot{x}_T = \ddot{x}$, then $\ddot{x}_T = v \frac{dv}{dx_T}$, and

$$Mv\frac{dv}{dx_T} = - Kx_T$$

Solving this first-order differential equation directly by integration,

$$\int v \, dv = - \frac{K}{M} \int x \, dx$$

therefore, $$v^2 + \frac{K}{M}\left[x + \frac{F}{K}\right]^2 = C_T \qquad (6.20)$$

The constant of integration is obtained by evaluating the result at t = 0, when $v = v_i$ and $x = x_i = 0$, and therefore,

$$C_T = v_i^2 + \frac{F^2}{MK} \qquad (6.21)$$

Eq 6.20 is for a family of ellipses in the x,v coordinate system. With v as the vertical axis and $\sqrt{K/M}\,x$ as the horizontal axis, the phase portraite for Eq 6.20 is a family of circles of radius $\sqrt{C_T}$. The centre, $x = - F/K$, is located at,

$$\sqrt{\frac{K}{M}}\, x = - \frac{F}{K}\sqrt{\frac{K}{M}}$$

The phase-plane trajectory is shown in Figure 6.8.

From equation 6.20, when v = 0,

$$\frac{K}{M}\left[x(max) + \frac{F}{K}\right]^2 = v_i^2 + \frac{F^2}{MK}$$

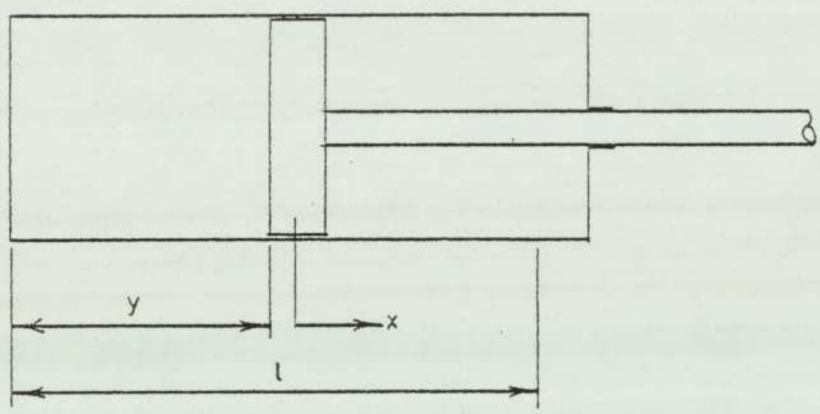


FIGURE 6.9 RELATING PISTON POSITION TO STROKE.

Substituting for K,

$$\frac{k_2}{M} x^2(\max) - \left[\frac{k_1 V_1 P_s}{2A_1 \beta M} - \frac{2F}{M}\right] x(\max) - v_i^2 = 0 \qquad (6.22)$$

The solution for x(max) is found by applying the formula for the quadratic equation, substituting for k_1 and k_2 and relating the piston position as shown in Figure 6.9.

For $k_1 = \frac{\beta A_1^2}{V_1}$ and $k_2 = \frac{\beta A_2^2}{V_2}$

$$x(\max) = \frac{\alpha_1(l-y)}{4} - \alpha_2(l-y) \pm \sqrt{\left[\frac{\alpha_1(l-y)}{4}\right]^2 - \frac{\alpha_1\alpha_2(l-y)^2}{2} + (\alpha_2(l-y))^2 + \alpha_3(l-y)v_i^2} \qquad (6.23)$$

where $\alpha_1 = \frac{P_s A_1}{\beta A_2}$, $\alpha_2 = \frac{F}{\beta A_2}$ and $\alpha_3 = \frac{M}{\beta A_2}$

For the hydraulic actuators braking about the central position, that is $y = l/2$, then applying Eq 6.23 to the boom:

For slewing, $\alpha_2 = 0$ since F= 0, and reasoning that an increase in v would make for an increase in x(max), then:

$$x(\max) = \frac{\alpha_1}{8} + \sqrt{\left[\frac{\alpha_1}{8}\right]^2 + \frac{\alpha_3}{2} v_i^2} \qquad (6.24)$$

For raising and lowering there is a force either opposing or aiding motion due to the weight of the boom, then:

$$x(\max) = \frac{\alpha_1}{8} - \frac{\alpha_2}{2} \pm \sqrt{\left[\frac{\alpha_1}{8}\right]^2 - \frac{\alpha_1\alpha_2}{8} + \frac{\alpha_2}{4} + \frac{\alpha_3}{2} v_i^2} \qquad (6.25)$$

The sign and value of α_2, which is the function containing the force on the ram, determines the sign of the square-root term.

The only variables in Eqs 6.24 and 6.25 for the boom operating in free space are displacement (y) and velocity (v_i) at the instance of closure of the exhaust poppet. Both of these values are available from the data retrieval system for the two axes of the boom.

If the supply poppet is closed at the instance of $x = x(max)$ and $v = 0$, two locked fluid columns then exist. P_2 will rise to a maximum during this period due to the braking of the inertial load and with a delay in the closure of the supply poppet, P_1 will also rise. If these pressures are equal when $v = 0$ then there would be zero undamped oscillation.

The total time from removal of the electrical signal to the solenoid to the actuator becoming stationary can be divided into three phases :-

Phase 1. Solenoid de-energising cycle measured from removal of the electrical signal to the servo pressure (P_{se}) beginning to decrease (This was measured for the normally closed servo valve in the same way as that described for the normally open valve discussed in Section 7.4.3).

350ms (This is an average value. Measurements indicated a variation of plus or minus 10%).

Phase 2. Hydraulic response of valve closure (Section 6.4.4).

41ms (Measured and confirmed to remain relatively constant irrespective of pressure drop across the main poppet).

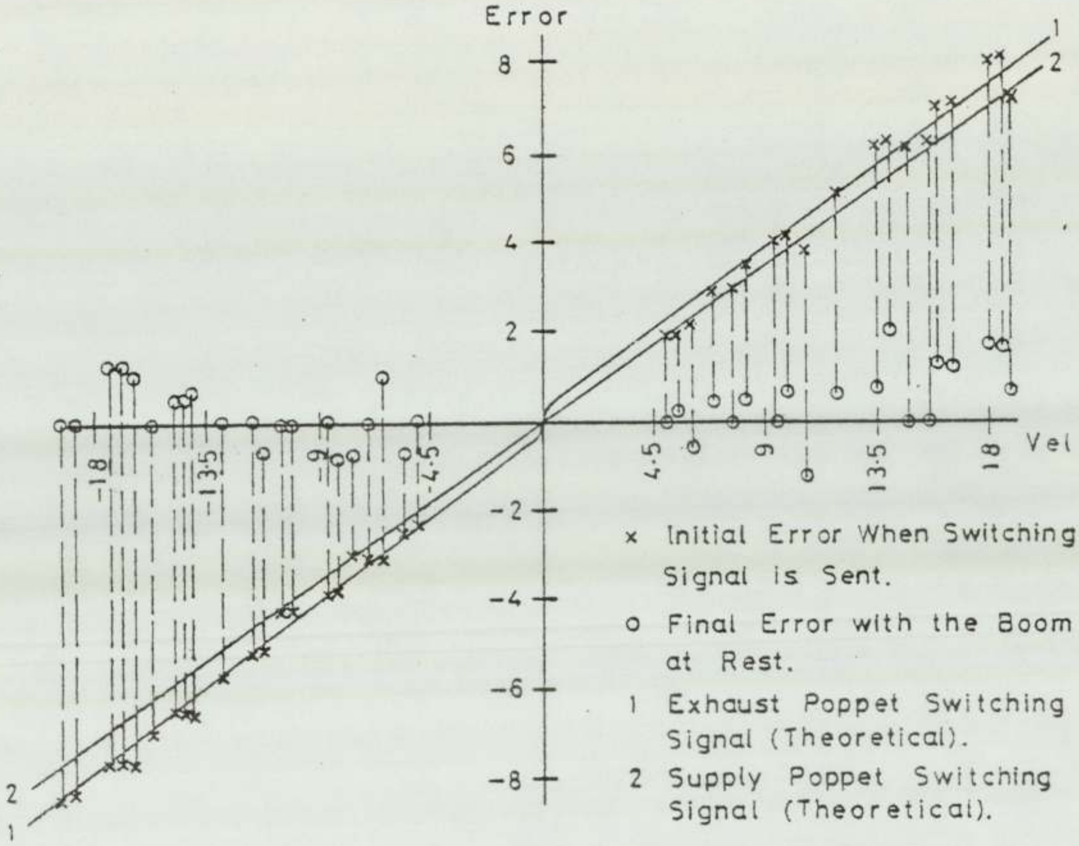


FIGURE 6.10 Error (bits) — Boom Slewing Vel. (bits/sec)

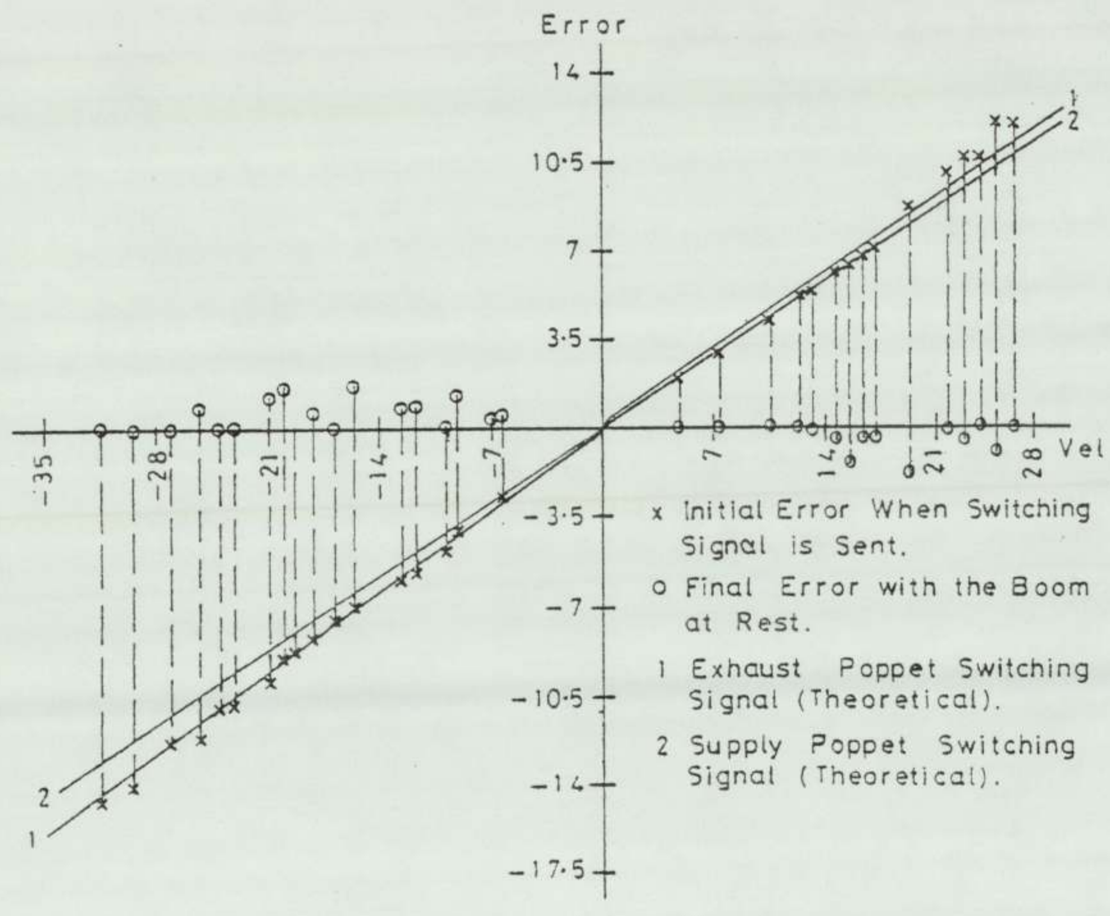


FIGURE 6.11 Error (bits) — Boom Vertical Vel. (bits/sec)

Phase 3. Overshoot of actuator from closure of exhaust poppet (x(max)).

Assuming constant velocity during phases 1 and 2:

$$\text{The total error} = x(max) + (v \times 0.391s) \qquad (6.26)$$

Using the following parameters the coefficients, α_1, α_2 and α_3, were calculated for the boom:

Mass of boom = 3070 kg (Calculated from the measured boom dimensions and assumed densities).

Mass of ram = 7 kg.

Effective External Force = 40 kN (due to the weight of the boom. This ranges from 37.65 to 43.67 kN depending on the boom elevation).

The coefficients for the boom slewing are:

$\alpha_1 = 0.00478$ and $\alpha_3 = 0.372 \times 10^{-4} s^2/m$

and for the boom moving on the vertical plane:

For raising,

$\alpha_1 = 0.00638$, $\alpha_2 = 0.505 \times 10^{-3}$ and $\alpha_3 = 0.515 \times 10^{-4} s^2/m$

For lowering,

$\alpha_1 = 0.00359$, $\alpha_2 = -0.379 \times 10^{-3}$ and $\alpha_3 = 0.386 \times 10^{-4} s^2/m$

These coefficients were used in applying Eqs 6.24, 6.25 and 6.26 for various velocities about the ram mid-stroke position. The lines for the calculated point of closure for the exhaust poppet and point of closure for the supply poppet to give zero final positional error, are shown in Figures 6.10 and 6.11 for the boom horizontal and vertical movement. The measured results were obtained by applying the theory developed by Chuen for simultaneous closure of the exhaust and supply poppets.

The time delay (t_d) in closing the supply poppet behind the exhaust poppet can be found by integrating the equation:

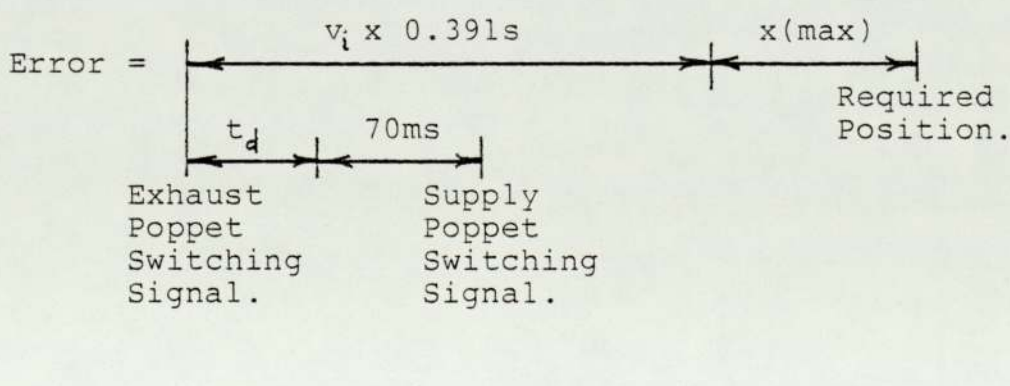
$dt = \frac{dx_T}{v}$, and substituting for $x_T(max) = x(max) + \frac{F}{K}$

This gives:

$$t = \sqrt{\frac{M}{K}} \left[\sin^{-1} \sqrt{\frac{K}{C\,M}} \left[x(max) + \frac{F}{K} \right] \right] \qquad (6.27)$$

The maximum time delay is for the condition where the boom is moving at maximum velocity on the vertical plane close to the beginning of the downwards stroke. This was calculated to be 13.474ms. By observation: $t(max) = \sqrt{M/K}\ (\pi/2)$

Applying the switching signal simultaneously to the exhaust and supply solenoids could result in the supply poppet closing prior to the exhaust poppet. This could lead to cavitating conditions on the supply side of the actuator piston and reduced captive pressures. To delay the supply poppet closure beyond the point of x(max) would not destroy the conditions sought in this analogy and would ensure that the exhaust poppet was always closed prior to the supply poppet. Taking into account the measured maximum variation in the response characteristics of seemingly identical solenoids (350ms ± 10%), the valve switching function should be:



The application of the valve switching functions generated by Chuen were implemented using software routines and an arithmetic processing unit (APU) IC. The relatively linear characteristics indicated by this simplified analogy correspond closely to those obtained by Chuen. The functions could be handled simply and at speed using look-up tables and interpolation software routines. The linear characteristics would mean that only a minimum of additional memory would be required. A single output signal could be used to switch both solenoids with a monostable device generating a delay of 84ms for the supply poppet. This would take account of the worse possible case.

Each axis of the boom is provided with four main poppet valves, with individual pilot operation from solenoid operated valves, as shown in Figure D1 in Appendix D. The delay for the supply poppet closure could be generated using software routines. Alternatively, a single output from the control system could be used for the supply and exhaust valves solenoids, with a monostable device generating the delay for the supply poppet closure.

If the supply and exhaust poppets were paired for operation from a single solenoid servo pilot valve, as shown in Figure D2 in Appendix D, then the delay could be produced in the hydraulic servo line to the supply poppet by a restricting orifice. This method of creating a delay would, on opening the valves, cause the exhaust valve to open prior to the supply valve. This could lead to possible cavitating conditions on the supply side of the actuator piston if an overhauling load is applied. This simpler system was not applied to the boom because of this aspect.

6.3.5 Fluid Power System Instability Considerations.

Instability in fluid power systems can arise in the servo loop as a whole or from an element of that loop such as the control valves:

1) Unstable flow.

The geometry and the on-off operation of poppet type valves reduce the incidence of unstable flow. The absolute closure of the poppets reduce any orifice metering effects.

2) Instability due to steady-state forces.

The on-off actuation of each poppet by full system servo pressure results in the poppets being held firmly against physical stops, whether open or closed. Static pressure unbalance and instability due to steady-state forces do not therefore arise within the valves.

3) Resonant instability.

The natural frequency of two equal fluid columns is:

$$\omega_n = \sqrt{\frac{k}{M}} = \sqrt{\frac{4\beta A^2}{VM}} \qquad (6.28)$$

The system natural frequency for the boom was calculated to be approximately 20.5×10^3 Hz.

The forcing excitation frequency for the boom, where the cutter with 24 radial picks revolves at 88 revs/min, is 35.2 Hz.

The boom is therefore operating at well below the resonant frequency. Doubling the hydraulic stiffness, discussed in Section 6.3.3, increases the resonant frequency by a factor of $\sqrt{2}$.

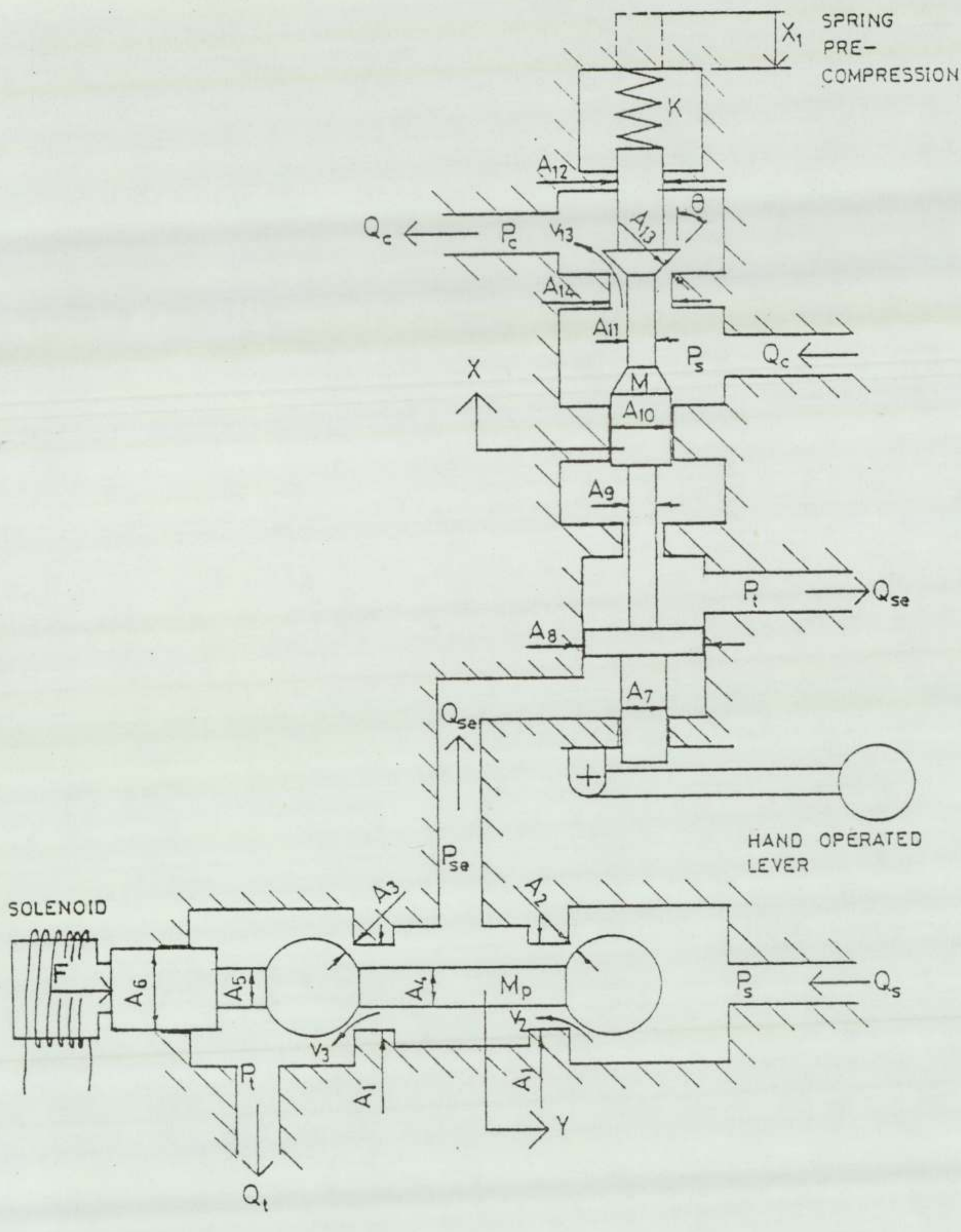


FIGURE 6.12 MAIN & SERVO POPPET VALVES FOR ACTUATOR DIRECTIONAL CONTROL.

6.4 RESPONSE TIME OF ACTUATOR DIRECTIONAL CONTROL POPPET VALVES.

The overall system response time, measured from the receipt of a feedback or operative input signal to the main poppet opening or closing, is an important factor in the performance of the control system. The computerised simulation of the poppet valve system operation enabled performance predictions to be made for the servo pilot hydraulic response. The performance predictions were made prior to obtaining the valves and carrying out bench tests. The simulation and the bench test results are contained in this section..

The solenoid response to an electrical signal is a major element in the overall response time of the valve and is discussed in Chapter 7.

6.4.1 Mathematical Model.

The main and servo poppets are shown in Figure 6.12, with valve system notations used in developing the mathematical model.

The equation of motion for the main poppet is,

$$M \frac{d^2 X}{dt^2} = P_{se} (A_8 - A_7) - P_c (A_{14} - A_{12}) - K(X + X_1) - \text{flow force} - \text{friction force} \qquad (6.29)$$

To simplify the mathematical model the tank pressure is assumed to be zero, that is, $P_t = 0$.

It has been demonstrated (Ref.54) that the magnitude of flow forces on poppet valves is dictated mainly by the poppet angle with lesser effects due to flow pattern and downstream chamber size. The flow force theoretical result based on simple momentum considerations has been applied in the mathematical modelling of poppet valves throughout the thesis. This is a reasonable approximation to make since flow forces are small compared with the operating pressure forces.

$$\text{Flow force (main poppet)} = \rho Q_c V_{13} \cos\theta \qquad (6.30)$$

where,
$$V_{13} = \frac{Q_c}{A_{13}}$$

and, assuming the approach velocity effects are zero,

$$Q_c = C_d A_{13}\sqrt{2/\rho\,|P_s - P_c|} \qquad \text{Sign}\,|P_s - P_c| \qquad (6.31)$$

Since $A_{10} = A_{14}$, the poppet is pressure balanced and all P_s terms disappear.

The force required to displace the main poppet would first have to overcome the static friction. Sliding friction would then take over. For the purpose of this simulation, static friction and sliding friction are assumed to be the same, and the friction force, which always opposes motion, is F_f.

From equations (6.29), (6.30) and (6.31),

$$M\frac{d^2X}{dt^2} = P_{se}(A_8 - A_7) - P_c(A_{14} - A_{12}) - K(X + X_1)$$

$$- C_d^2 A_{13} 2(P_s - P_c)\cos 45^\circ - (\text{Sign}\frac{dX}{dt})F_f \qquad (6.32)$$

where,

$$A_{13} = D_{13}\pi X \sin 45^\circ \qquad (6.33)$$

To simplify the analogy, the servo poppet is

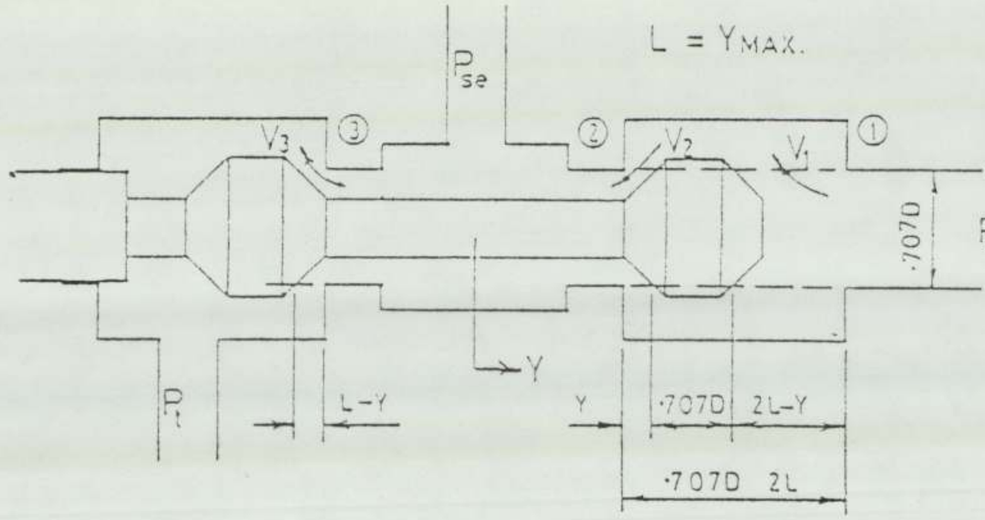


FIGURE 6.13 SERVO POPPET ANALOGY.

considered to be of the form shown in Figure 6.13. The servo poppet is physically small compared to the main poppet (Appendix D.3) and completes actuation over a short period of the overall valve operation.

$$\text{Flow force at } ① = \rho Q_s V_1 \cos 45^\circ \tag{6.34}$$

and,

$$\text{Flow force at } ③ = \rho Q_t V_3 \cos 45^\circ \tag{6.35}$$

where,

$$V_1 = \frac{Q_s}{.707 D\pi(2L-Y)\sin 45^\circ} = \frac{Q_s}{1.57D(2L-Y)} \tag{6.36}$$

and,

$$V_3 = \frac{Q_t}{.707 D\pi(L-Y)\sin 45^\circ} = \frac{Q_t}{1.57D(L-Y)} \tag{6.37}$$

Where D = Servo ball poppet diameter.

$$\text{Flow force at } ② = \rho Q_s V_2 \cos 45^\circ \tag{6.38}$$

where,

$$V_2 = \frac{Q_s}{.707 D\pi Y \sin 45^\circ} = \frac{Q_s}{1.57D\,Y} \tag{6.39}$$

The equation of motion for the servo poppet, referring to Eqs.(6.34), (6.35), (6.36), (6.37), (6.38) and (6.39),

$$M_p \frac{d^2Y}{dt^2} = -P_s A_1 - \frac{.4504\rho Q_s^2}{D\,Y} + \frac{.4504\rho Q_s^2}{D\,(2L-Y)} + \frac{.4504\rho Q_t^2}{D\,(L-Y)} + F \tag{6.40}$$

By continuity,

$$Q_{se} = Q_s - Q_t \tag{6.41}$$

Taking the approach velocity effects as zero,

$$Q_s = C_d\, A_2\sqrt{2/\rho\,|P_s - P_{se}|} \qquad \text{Sign}\,|P_s - P_{se}| \tag{6.42}$$

$$Q_t = C_d\, A_3\sqrt{2/\rho\,|P_{se} - P_t|} \qquad \text{Sign}\,|P_{se} - P_t| \tag{6.43}$$

and,

$$Q_{se} = (A_8 - A_7) \frac{dX}{dt} \tag{6.44}$$

Substituting Eqs.(6.42) and (6.43) in Eq.(6.40), the equation of motion for the servo poppet is,

$$M_p \frac{d^2Y}{dt^2} = - P_s A_1 - 2.22\, C_d^2 D\, Y\, (P_s - P_{se}) + \frac{2.22\, C_d^2 D\, Y^2 (P_s - P_{se})}{(2L - Y)} + 2.22\, C_d^2 D\, (L-Y)\, P_{se} + F \tag{6.45}$$

The two equations of motion are related by the servo pressure, P_{se}. From Eqs.(6.41), (6.42) and (6.43), assuming $P_s > P_{se}$ and letting $P_t = 0$,

$$\frac{Q_{se}}{C_d\, 2/\rho} = A_2 \sqrt{(P_s - P_{se})} - A_3 \sqrt{P_{se}} \tag{6.46}$$

Substituting Eq.(6.44) for Q_{se}, the solution for P_{se} is of a quadratic form, that is,

$$P_{se} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{6.47}$$

where,

$$a = 1 + \frac{A_2^2}{2A_3^2} + \frac{A_3^2}{2A_2^2} \tag{6.48}$$

$$b = \frac{1}{2} \left[- P_s \left[1 + \frac{A_2^2}{A_3^2}\right] - \frac{(A_8 - A_7)^2 \rho}{2C_d^2} \left[\frac{1}{A_2^2} - \frac{1}{A_3^2}\right] \left[\frac{dX}{dt}\right]^2 \right] \tag{6.49}$$

$$c = \frac{P_s^2 A_2^2}{2A_3^2} - \frac{P_s (A_8 - A_7)^2 \rho}{2C_d^2 A_3^2} \left[\frac{dX}{dt}\right]^2 + \frac{(A_8 - A_7)^4 \rho^2}{8C_d^4 A_2^2 A_3^2} \left[\frac{dX}{dt}\right]^4 \tag{6.50}$$

When Y=0, $A_2 = 0$ and $Q_s = 0$, the solution for P_{se} is,

$$P_{se} = \frac{(A_8 - A_7)^2 \rho}{2C_d A_3^2} \left[\frac{dX}{dt}\right]^2 \tag{6.51}$$

When $Y = Ymax = L$, $A_3=0$ and $Q_t=0$, the solution for P_{se} is,

$$P_{se} = P_s - \frac{(A_8-A_7)^2\rho}{2C_d A_2^2}\left[\frac{dX}{dt}\right] \qquad (6.52)$$

6.4.2 The Dimensionless Equations.

The analysis results are often more useful presented in dimensionless terms, besides being in a shortened form, and hence, simplifying the computerised simulation.

The following reference quantities are used,

Ref. length = Ymax = L Ref. pressure = P_s Ref. area = L^2

Ref. time = $t_t = \sqrt{\frac{M_p}{K}}$ Ref. mass = M_p Ref. force = KL

The non-dimensional variables are,

$$l = \frac{L}{L} = 1 \qquad y = \frac{Y}{L} \qquad x = \frac{X}{L} \qquad x_1 = \frac{X_1}{L}$$

$$(a_8-a_7) = \frac{(A_8-A_7)}{L^2} \qquad (a_{14}-a_{12}) = \frac{(A_{14}-A_{12})}{L^2} \qquad a_1 = \frac{A_1}{L^2}$$

$$a_2 = \frac{A_2}{L^2} \qquad a_3 = \frac{A_3}{L^2} \qquad a_{13} = \frac{A_{13}}{L^2} \qquad d = \frac{D}{L}$$

$$p_s = \frac{P_s}{P_s} = 1 \qquad p_{se} = \frac{P_{se}}{P_s} \qquad p_c = \frac{P_c}{P_s} \qquad m = \frac{M}{M_p}$$

$$m_p = \frac{M_p}{M_p} = 1 \qquad f = \frac{F}{KL} \qquad f_f = \frac{F_f}{KL} \qquad \tau = \frac{t}{t_t}$$

The equation of motion of the main poppet (Eq.6.32) becomes,

$$\frac{d^2x}{d\tau^2} = \frac{\lambda}{m}(p_{se}(a_8-a_7)-p_c(a_{14}-a_{12})-\pi C_d^2 d_{14} x(1-p_c))$$

$$- \frac{(x+x_1)}{m} - (\mathrm{Sign}\frac{dx}{d\tau})\frac{f_f}{m} \qquad (6.53)$$

where $\lambda = \dfrac{P_s L}{K}$ (A dimensionless quantity) (6.54)

The equation of motion of the servo poppet, Eq.(6.45), becomes,

$$\frac{d^2 y}{d\tau^2} = \lambda\, 2.22\, C_d^2 d\left(.873y(1-p_{se}) + y^2\frac{(1-p_{se})}{(2-y)} + (1-y)p_{se}\right) - \lambda a + f \qquad (6.55)$$

The elements of the quadratic equation for p_{se}, Eq.(6.47), become,

from Eq.(6.48),

$$a = 1 + \frac{y^2}{2\alpha} + \frac{\alpha}{2y} \qquad (6.56)$$

from Eq.(6.49),

$$b = -\frac{1}{2} - \frac{y^2}{2} - \frac{\delta}{2}\left[\frac{1}{y^2} - \frac{1}{\alpha}\right]\left[\frac{dx}{d\tau}\right]^2 \qquad (6.57)$$

from Eq.(6.50),

$$c = \frac{y^2}{2\alpha} - \frac{\delta}{\alpha}\left[\frac{dx}{d\tau}\right]^2 + \frac{\delta^2}{2}\left[\frac{dx}{d\tau}\right]^4 \qquad (6.58)$$

where,

$$\alpha = (1-y)^2 \qquad (6.59)$$

and,

$$\delta = \frac{(A_8 - A_7)^2 \rho K}{4.93\, M_p C_d^2 D^2 P_s} \quad \text{(A non-dimensional group)} \qquad (6.60)$$

When Y = 0, from Eq.(6.51),

$$p_{se} = \frac{\delta}{\alpha}\left[\frac{dx}{d\tau}\right]^2 \qquad (6.61)$$

When Y = L, from Eq.(6.52),

$$p_{se} = 1 - \frac{\delta}{y^2}\left[\frac{dx}{d\tau}\right]^2 \qquad (6.62)$$

6.4.3 Restraints.

The non-dimensional equations do not fully describe the behaviour of the valve. Before the equations can be computed, it is necessary to incorporate, in mathematical form, the physical restraints within the valve. Since we are only interested in the hydraulic response time for opening and closing of the valve, then separate computer runs can be carried out for each case. It is the discontinuities caused by the main and servo pilot poppets meeting the physical restraints within the valve, that have to be accomodated within the computer runs.

Considering the case when the main poppet is closing. Initially, X = Xmax, and Y = Ymax. Upon de-energising of the solenoid, Y will begin to reduce, since $P_s > P_t$. X will not begin to reduce, until the spring force of the main poppet is greater than all upward forces. Up to this stage a restraining force acts on the main poppet to hold X = Xmax.

Let the restraining force be FR and,

$$\frac{d^2x}{d\tau^2} = FS - FR \qquad (6.63)$$

where FS is the accelerating force given in Eq.(6.53).

For the valve closing case, initially,

X = Xmax and FS is -ve, then FR = FS and,

$$\frac{d^2x}{d\tau^2} = FS - FS = 0$$

When, 0 < X < Xmax and FS is -ve, then FR = 0, and,

$$\frac{d^2x}{d\tau^2} = (-FS)$$

When X = 0 and FS is -ve, then FR = -FS, and,

$$\frac{d^2x}{d\tau^2} = (-FS) - (-FS) = 0$$

For the valve opening case, the additional requirement is, that,

when 0 < X < Xmax and FS is +ve, then FR = 0, and,

$$\frac{d^2x}{d\tau^2} = FS$$

Expressing the restraints mathematically, for Eq.(6.63) to hold true,

$$FR = \frac{ST}{2}(Abs(FS)+FSxST)+(FSxInt\left[1-\frac{X}{Xmax}\right]xST1)$$

$$+(FSxInt\left[\frac{X}{Xmax}\right]xST2) \qquad (6.64)$$

where, for valve closing,

ST = 1 ST1 = 1 ST2 = 0

and, for valve opening,

ST = -1 ST1 = 0 ST2 = 1

The servo poppet also has physical restraints. Let the restraining force be FU, and,

$$\frac{d^2Y}{d\tau^2} = FT - FU \qquad (6.65)$$

where FT is the servo poppet accelerating force given in Eq(6.55).

To satisfy the restraining conditions, for Eq.(6.65) to hold true, then,

$$FU = (FTxInt\left[1-\frac{Y}{Ymax}\right]xST1)+(FTxInt\frac{Y}{Ymax} \text{ x } ST2) \qquad (6.66)$$

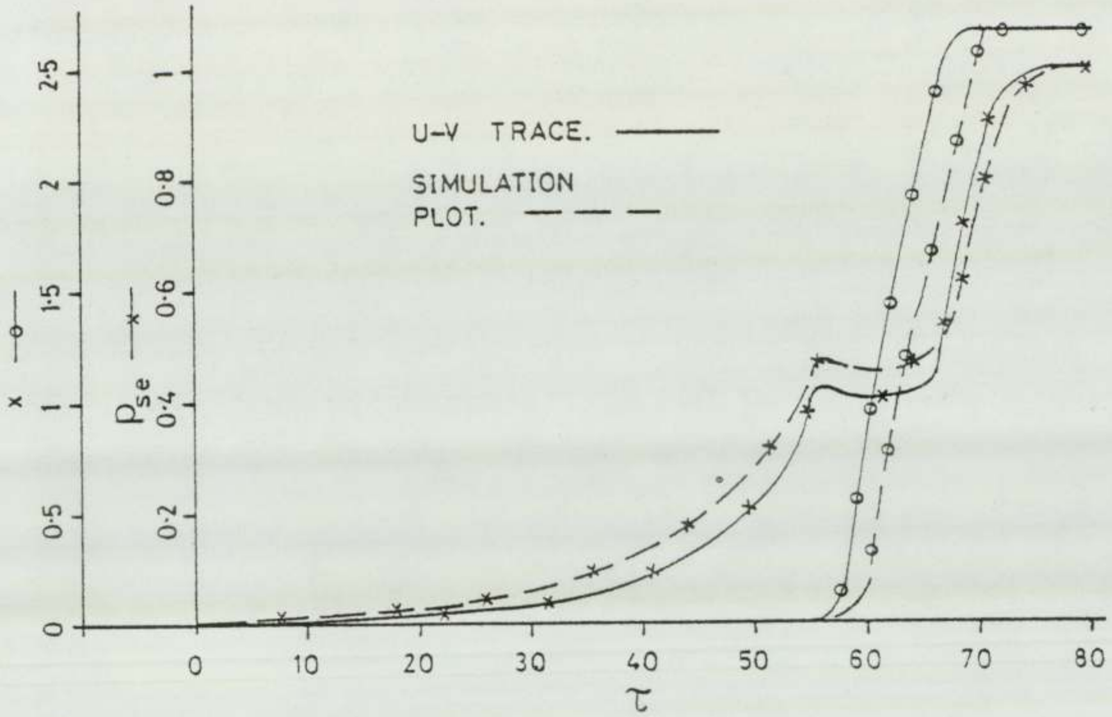


FIGURE 6.15 VALVE OPENING COMPARISON.

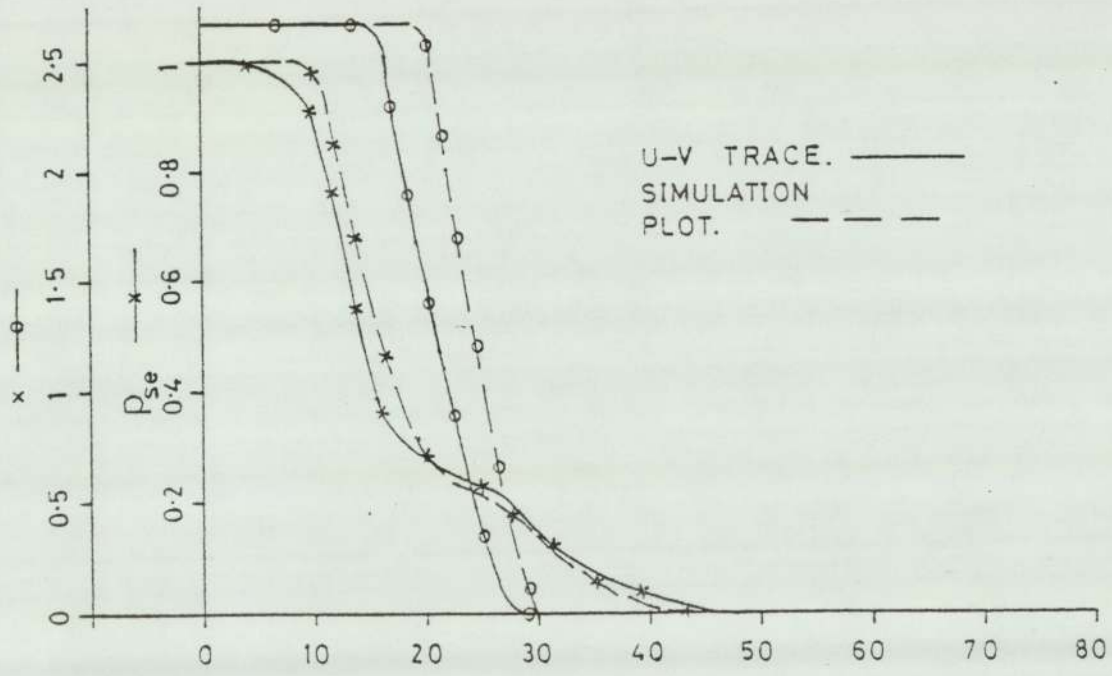


FIGURE 6.16 VALVE CLOSING COMPARISON.

6.4.4 Computerised Simulation.

The valve is described, in non-dimensional terms, by Eq.(6.47), (6.53), (6.54), (6.55), (6.56), (6.57), (6.58), (6.59), (6.60), (6.63), (6.64), (6.65) and (6.66). These equations are used, together with additional terms for handling the servo pressure quadratic equation, for the computerised simulation. The valve dimensions, calculation of non-dimensional constants, initial conditions and sample programme run are contained in section D3 of the Appendix.

The computer based simulation was carried out using the HP 9845, and a modified version of the interactive differential equation algorithm (IDEA), prepared by P. Cooley (Ref.51). The modifications were carried out to enable the handling of the high number of terms required in this simulation. The algorithm uses a third-order Runge-Kutta integration procedure to solve the equations.

Figure 6.15 shows the comparison between the simulation results and measured performance, for the valve opening case, and Figure 6.16 for the valve closing case. The performance was measured with the aid of a pressure transducer inserted in the servo pilot line, and a linear displacement transducer connected to the main poppet. The displacement transducer was of the LVDT type, capable of withstanding the full system hydraulic pressure. The transducer signals were fed into a U-V recorder and a trace obtained.

The comparison times for the hydraulic response, measured from the instance the servo pilot poppet begins to move, to the instance the main poppet was fully open, or closed, was:-

	Simulation Result	Measured Time
Valve opening	τ = 70.5	τ = 69.0
	t = 99.69 ms	t = 97.57 ms
Valve closing	τ = 30.0	τ = 29.0
	t = 42.42 ms	t = 41.0 ms

TABLE 6.1 Valve Hydraulic Response Comparisons.

These response times were used in applying the switching criteria, developed by C. W. Chuen, for accurate positioning of the boom. The response time of the solenoid actuation of the servo poppet should be added to these times for the overall valve response. The solenoid analysis is contained in Chapter 7.

CHAPTER SEVEN

VOLUME FLOW CONTROL AND SIMULATION OF A PULSE WIDTH MODULATED POPPET VALVE

7.1 INTRODUCTION.

Controlling the speed of a hydraulic actuator requires either flow restriction of the fluid by various methods or control of volumetric flow rate by a variable displacement pump (Ref.54). There are many aspects to be considered in the implementation of speed control for hydraulic actuation of complex loads.

The requirement for the roadheader boom led to the design of a simple poppet type valve giving two flow rates. The performance of this valve was studied with the aid of a computerised simulation programme. This programme is extended to simulate the pulse width modulation of the poppet valve. This simulation required a programme that would run with four sets of interactive discontinuities and a quadratic expression for the servo pressure.

The major portion of the hydraulic poppet valve time response to an electrical signal, whether opening or closing, was in the solenoid actuation of the pilot stage. An analysis of the solenoid operated motive section of the servo pilot valve, in order to determine whether it was possible to improve the response times, is contained in this Chapter.

7.2 ROADHEADER BOOM SPEED CONTROL REQUIREMENT.

A minimum of two speeds of boom angular velocity was required for this application. A slow speed, giving full movement on either axis in 110s, when cutting, and a fast speed for free space positioning of the boom.

Cutting forces, and the high inertia of the boom, can present an overhauling load, and for this reason a "meter-out" control of the hydraulic fluid was selected. Speed is less affected by load changes with this method of control (Ref.54).

Individual flow restricting poppet valves were installed in the hydraulic return paths, from the actuators for each of the two axes of the boom. The valves consisted of main soft seat poppets manufactured by Hemscheidt Ltd., with servo pilot operation from Dowty Hydraulic Units Ltd., intrinsically safe, solenoid valves, model number 4311 112 05.

A metering groove was cut in the seat of the main poppet to give the flow required for slow speed with the poppet on its seat. The fast speed was obtained by the main poppet opening fully. The groove has a self cleaning characteristic when the main poppet is opened, thus ensuring that the fluid contamination tolerance for the valve system was maintained.

It is possible to obtain several stages of flow rate using a "weighted system" of open/shut poppets. For example, four poppets on a binary flow rate weighting, that is, 1, 2, 4 and 8, would provide sixteen increments of flow rate, including no-flow. Dowty Hydraulic Units Ltd. have recently produced for the NCB a multi-stage intrinsically safe solenoid operated system of weighted poppets, which is at present awaiting tests (July 1983).

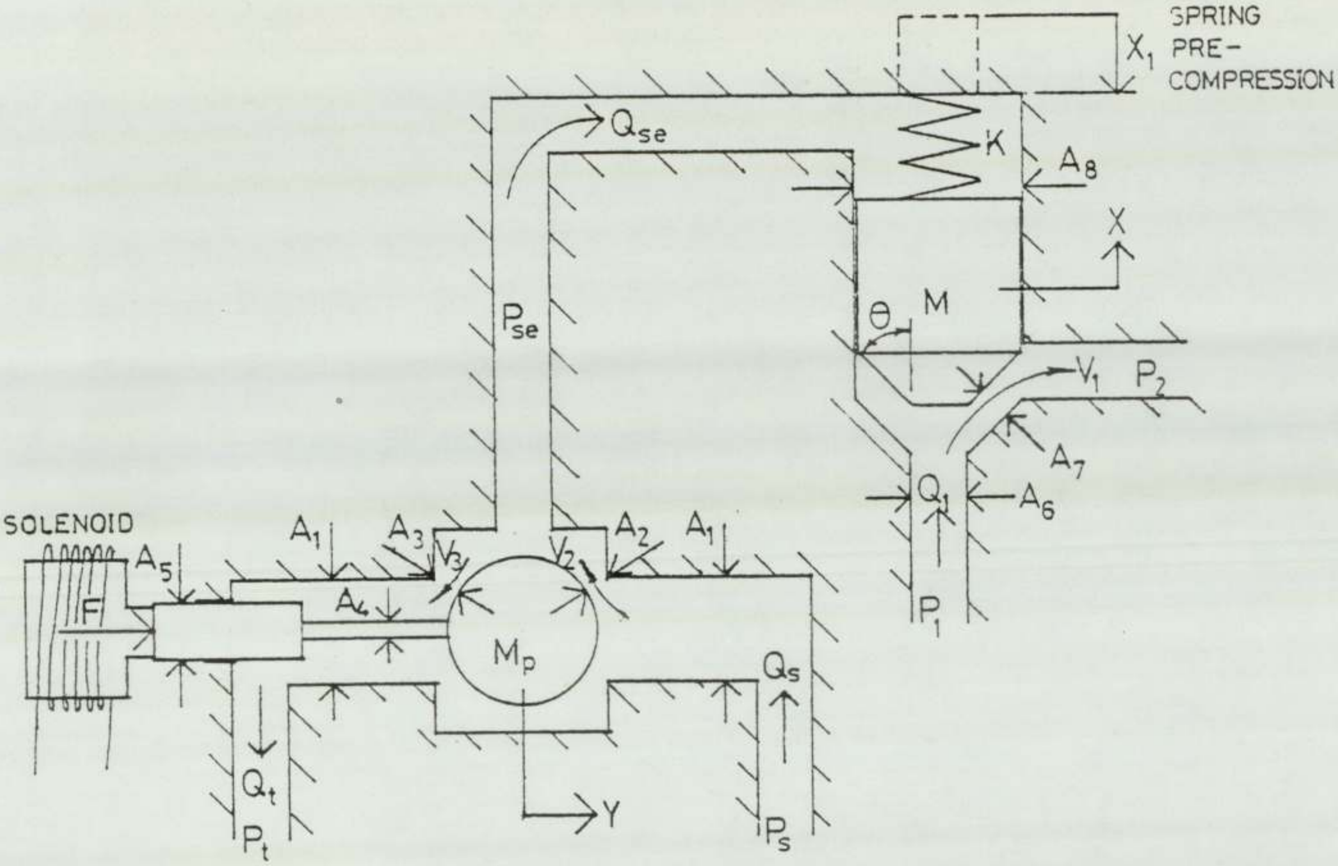


FIGURE 7.1. MAIN & SERVO POPPET VALVES FOR FLOW RATE CONTROL.

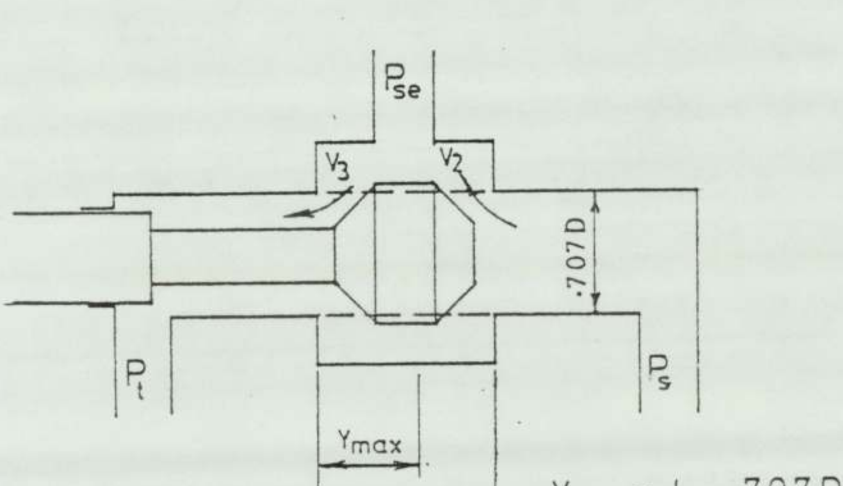


FIGURE 7.2. SERVO POPPET ANALOGY.

7.3 SIMULATION OF A PULSE WIDTH MODULATED POPPET VALVE.

The valve is shown with all notations used for the simulation, in Figure 7.1, and the servo poppet analogy is shown in Figure 7.2.

7.3.1 Mathematical Model.

The equations that describe the valve were developed in exactly the same way as those for the directional control poppet valves in Chapter 6, and are listed below in non-dimensional form.

The reference quantities are as for the simulation of the directional control poppets, except that,

Ref. length = Ymax = L - .707D = Lo

and,

Ref. area = Lo^2

The equation of motion for the main poppet is,

$$\frac{d^2x}{d\tau^2} = (\lambda p_1 a_6 - \lambda\pi C_d^2 d_6 (p_1 - p_2)x - \lambda p_{se} a_8 - x - x_1$$

$$- \text{Sign}\left[\frac{dx}{d\tau}\right] f_f)/m \tag{7.1}$$

where $$\lambda = \frac{P_s\ L_o}{K} \quad \text{(A dimensionless quantity)} \tag{7.2}$$

The equation of motion for the servo poppet is,

$$\frac{d^2y}{d\tau^2} = \delta d(y(p_{se} - p_t) + (1 - y)(1 - p_{se}))$$

$$+ \lambda(p_t(a_1 - a_5) - a_1) + f \tag{7.3}$$

where $$\delta = \frac{2.22\ C_d^2\ P_s\ L_o}{K} \quad \text{(A dimensionless quantity)} \tag{7.4}$$

The two equations of motion are related by the servo pressure p_{se} which is expressed in quadratic form, that is,

$$p_{se} = \frac{- b \pm \sqrt{b^2 - ac}}{a} \qquad (7.5)$$

where,

$$a = 1 + \frac{(1 - y)^2}{2y^2} + \frac{y^2}{2(1 - y)^2} \qquad (7.6)$$

$$b = \frac{\delta a_8^2}{9.86d^2 y^2} \left[\frac{dx}{d\tau}\right]^2 - \frac{\delta a_8^2}{9.86d^2 (1 - y)^2} \left[\frac{dx}{d\tau}\right]^2 - \frac{p_t}{2}$$

$$- \frac{1}{2} - \frac{(1 - y)^2}{2y^2} - \frac{p_t y^2}{2(1 - y)^2} \qquad (7.7)$$

where $\delta = \frac{\rho L_o^2 K}{C_d^2 P_t M_p}$ (A dimensionless quantity) (7.8)

$$c = \frac{p_t}{2} + \frac{(1 - y)^2}{2y^2} + \frac{p_t^2 y^2}{2(1 - y)^2} + \frac{\delta a_8 p_t}{4.93d^2 (1 - y)^2} \left[\frac{dx}{d\tau}\right]^2$$

$$- \frac{\delta a_8^2}{4.93d^2 y^2} \left[\frac{dx}{d\tau}\right]^2 + \frac{\delta a^4}{48.6\ d^4 y^2 (1-y)^2} \left[\frac{dx}{d\tau}\right]^4 \qquad (7.9)$$

When Y = 0, the solution for p_{se} is,

$$p_{se} = 1 - \frac{\delta a_8^2}{4.93d^2 (1 - y)^2} \left[\frac{dx}{d\tau}\right]^2 \qquad (7.10)$$

When Y = Ymax, the solution for p_{se} is,

$$p_{se} = \frac{\delta a_8^2}{4.93d^2 y^2} \left[\frac{dx}{d\tau}\right]^2 + p_t \qquad (7.11)$$

The rate of flow through the main poppet is expressed as,

$$q = \mathcal{L} x \qquad (7.12)$$

where $\mathcal{L} = \frac{2.22\ C_d D_6}{L_o^2} \sqrt{\frac{2M_p (P_1 - P_2)}{K}}$ [A dimensionless quantity] (7.13)

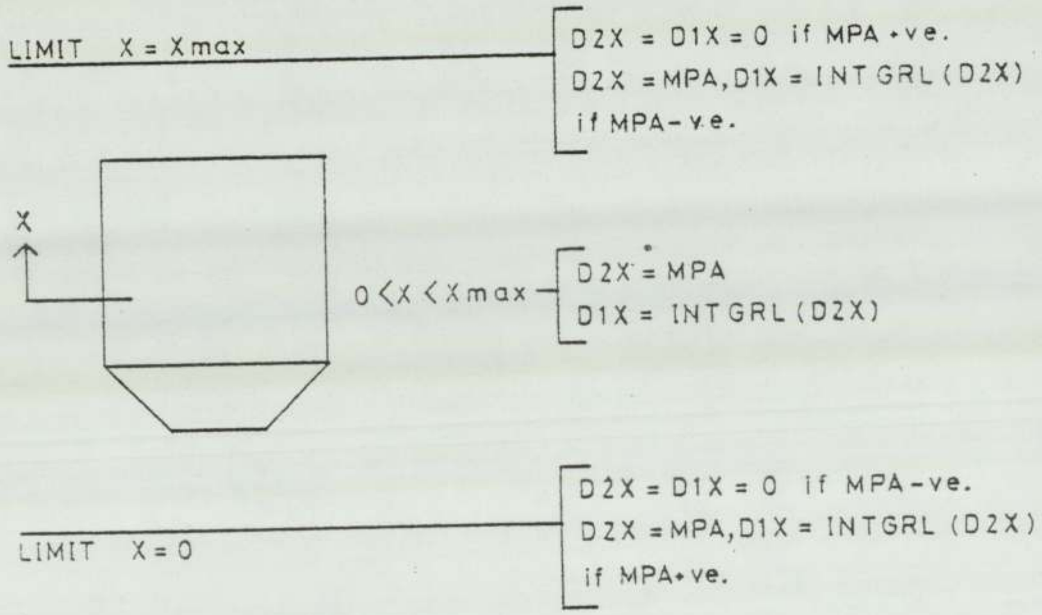


FIGURE 7.3 MAIN POPPET RESTRAINT CONDITIONS.

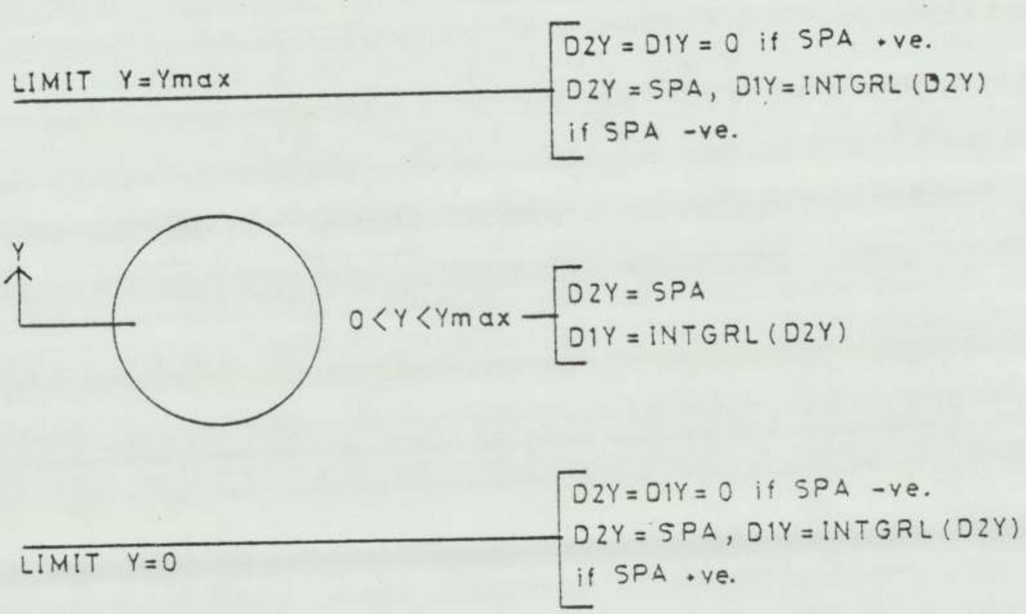


FIGURE 7.4 SERVO POPPET RESTRAINT CONDITIONS.

7.3.2 Restraints.

Physical restraints exist within the valve for both poppets. We require to examine the behaviour of the main poppet with the servo pilot poppet pulsing over it's full stroke. The full restraining conditions for both poppets need to be incorporated in the computed equations, to cope with the discontinuities and to provide a continuous output of the behaviour of the poppets, from a solenoid force input to the servo pilot poppet.

The restraint conditions for the main poppet are shown in Figure 7.3 and for the servo pilot poppet in Figure 7.4, where :-

$$MPA = \frac{\text{Main poppet accelerating force}}{m}$$

SPA = Servo pilot accelerating force.

(Note :- The mass of the servo pilot poppet is unity.)

$$D2X \equiv \frac{d^2x}{d\tau^2}, \quad D1X \equiv \frac{dx}{d\tau}, \quad D2Y \equiv \frac{d^2y}{d\tau^2}, \quad \text{and} \quad D1Y \equiv \frac{dy}{d\tau}$$

Immediately the poppets meet the physical restraints, the respective accelerations and velocities are required to be computed to zero. Assuming there is zero yield, at this instance there would be an infinite de-acceleration for zero velocity. Attempting to simulate this fact requires extremely small increments of the independent variable (time), to avoid the simulation process going unstable. This aspect is discussed further in the following section.

The required outputs are not affected by using this approach and an instability aspect is avoided.

7.3.3 Computerised Simulation.

Simulation has been used for many years to study, design and develop systems which can range from simple basic operations to complex systems requiring simultaneous solution to a number of interactive elements. These systems were originally modelled using analogue computers (Ref.54). However, the digital computer with its versatility, accuracy, and increasing speed has become a suitable tool for modelling . Numerical integration methods now fulfill the same function as the capacitive feedback amplifier of the analogue computer. Simulation languages now incorporate comprehensive interaction facilities, replacing the hardware defined function elements of the analogue computer with the software of the digital computer.

The system representative mathemetical equations are solved simultaneously by holding the independent variable, which is usually time, constant while other variables in the equation are calculated and updated ready for the next increment of the independent variable. There are inherent problems with this method, particularly at instances of high change with respect to the independent variable, when the simulation using digital computers can become unstable and produce obvious inaccuracies, or worse, misleading inaccuracies that are not always so obvious.

New simulation languages have become increasingly more powerful with facilities for modelling continuous systems on digital computers. One such language, which was used for the simulation of the pulse width modulation of the poppet

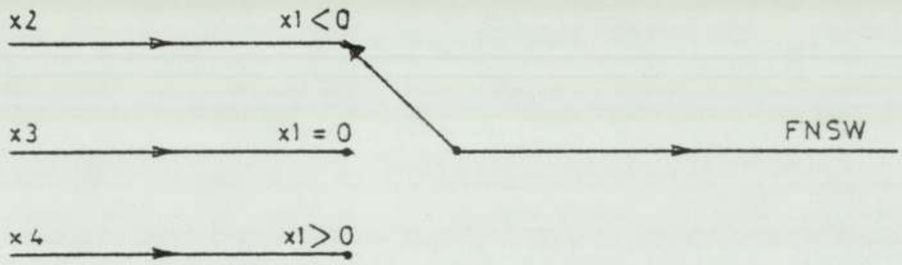


FIGURE 7.5 FUNCTION SWITCH (FNSW).

valve, is SLAM Mk.2 (Simulation Language for Analogue Modelling). This is a high-level language, based on FORTRAN and fully described in Ref.55.

Briefly SLAM offers the following facilities :-

1) Equation-based expressions and block-description formats.
2) Simple input/output.
3) Analogue block functions.
4) Choice of several integration methods.
5) Function generation.
6) Simple programming of differential equations and automatic sorting.
7) Macro facilities.
8) The full capabilities of the FORTRAN language. FORTRAN has an extensive scientific library and relevant user programmes.

The driving force to the servo poppet, derived from the solenoid, was input using the SPULSE function (Ref.55).

The conditions at the physical restraints, described in Section 7.3.1, were handled using different methods for each poppet.

The servo pilot poppet was modelled using the FNSW (Function Switch) and the SWIN (Input Switch) functions.

FNSW has the form of :-

FNSW(x1,x2,x3,x4)

where, x1, x2, x3 and x4 are arithmetic expressions of type REAL. The value is x2, x3 or x4 as x1 is less than zero, equal to zero or greater than zero respectively, as shown in Figure 7.5.

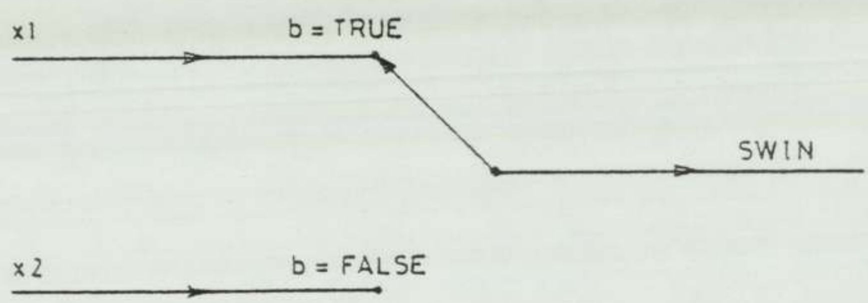


FIGURE 7.6 INPUT SWITCH (SWIN).

SWIN has the form :-

SWIN(x1,x2,b)

where x1 and x2 are arithmetic expressions of type REAL and b is a logical expression, as illustrated in Figure 7.6.

The computed equations to satisfy the restraint conditions for the acceleration of the servo pilot poppet are :-

```
D2YC=FNSW(AINT(Y)-AINT(1.0-Y),0.0,SPA,SPA)
D2YO=FNSW(AINT(Y)-AINT(1.0-Y),SPA,SPA,0.0)
D2Y=SWIN(D2YO,D2YC,ISTATE.EQ.1.0)
```

and for the velocity :-

```
SPV=INTGRL(D2Y,0.0)
DY1C=FNSW(AINT(Y)-AINT(1.0-Y),0.0,SPV,SPV)
D1YO=FNSW(AINT(Y)-AINT(1.0-Y),SPV,SPV,0.0)
D1Y=SWIN(D1YO,D1YC,ISTATE.EQ.1.0)
```

The computed equations to satisfy the restraint conditions for the acceleration of the main poppet, using standard FORTRAN, are :-

```
D2X=MPA
IF(X.LE.0.0.AND.MPA.LE.0.0) D2X=0.0
IF(X.GE.10.444.AND.MPA.GE.0.0) D2X=0.0
```

and for the velocity :-

```
MPV=INTGRL(D2X,0.0)
D1X=MPV
IF(X.GE.0.0.AND.MPV.LE.0.0) D1X=0.0
IF(X.GE.10.444.AND.MPV.GE.0.0) D1X=0.0
```

It was necessary to implement the two methods for incorporating the restraint conditions. If either method was used for both poppets, the equations would not SORT.

The equations that express the servo pressure, p_{se}, also required special consideration. Depending on the value of Y, either Eq.7.5, 7.10 or 7.11 provides the solution.

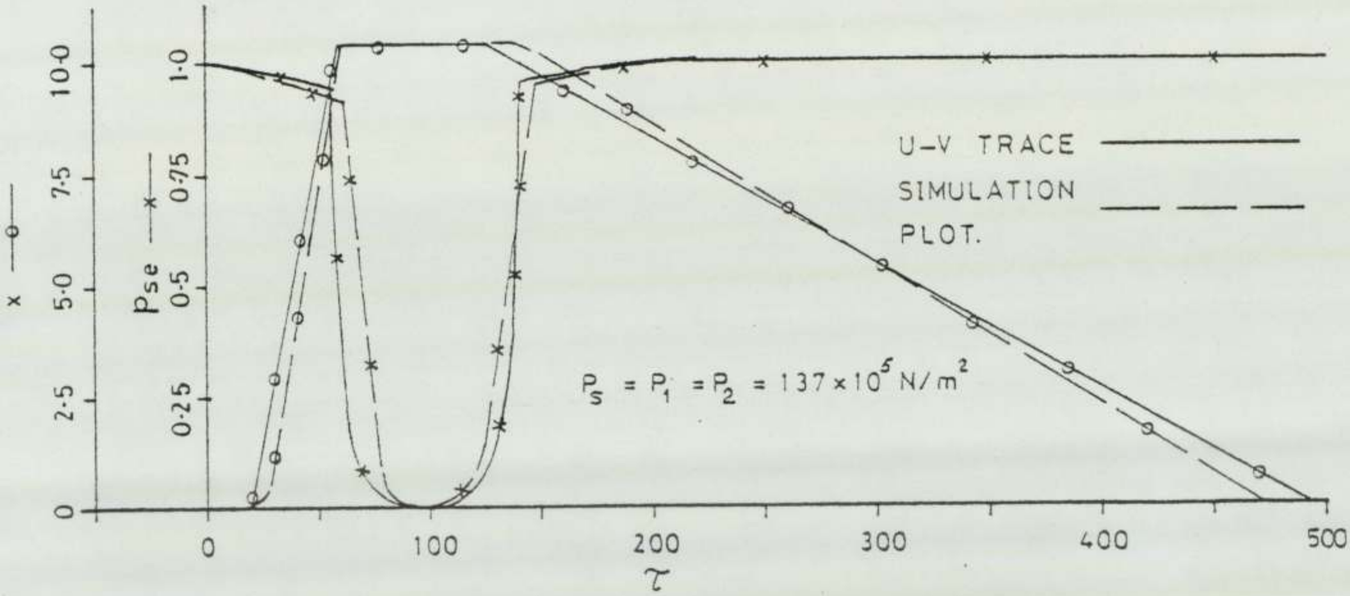


FIGURE 7.7 VALVE RESPONSE COMPARISONS.

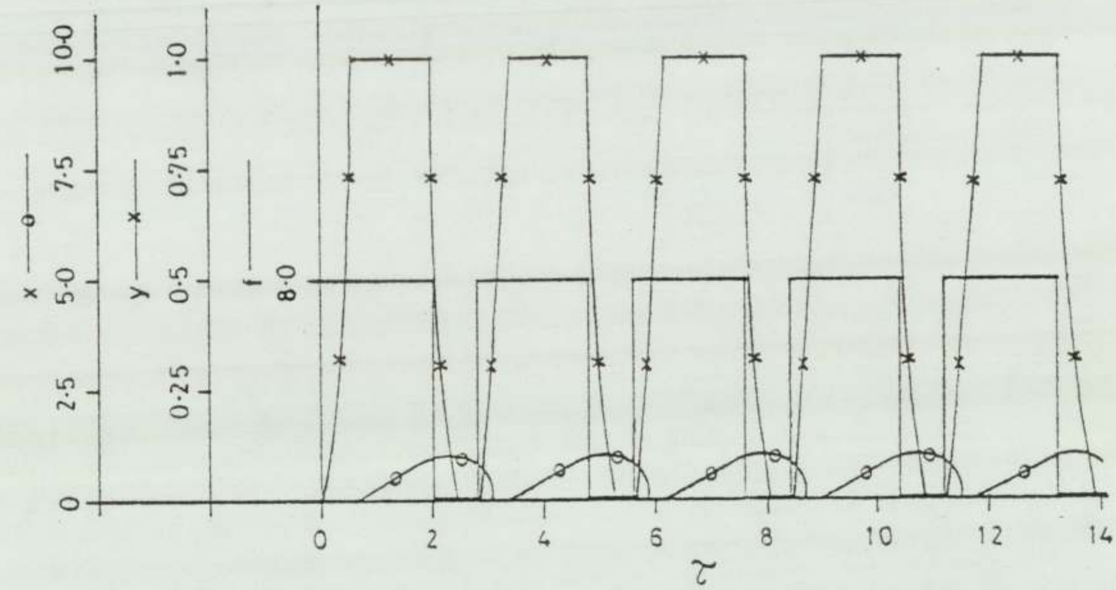


FIGURE 7.8 PULSING VALVE. (CONSTANT PULSE WAVE)

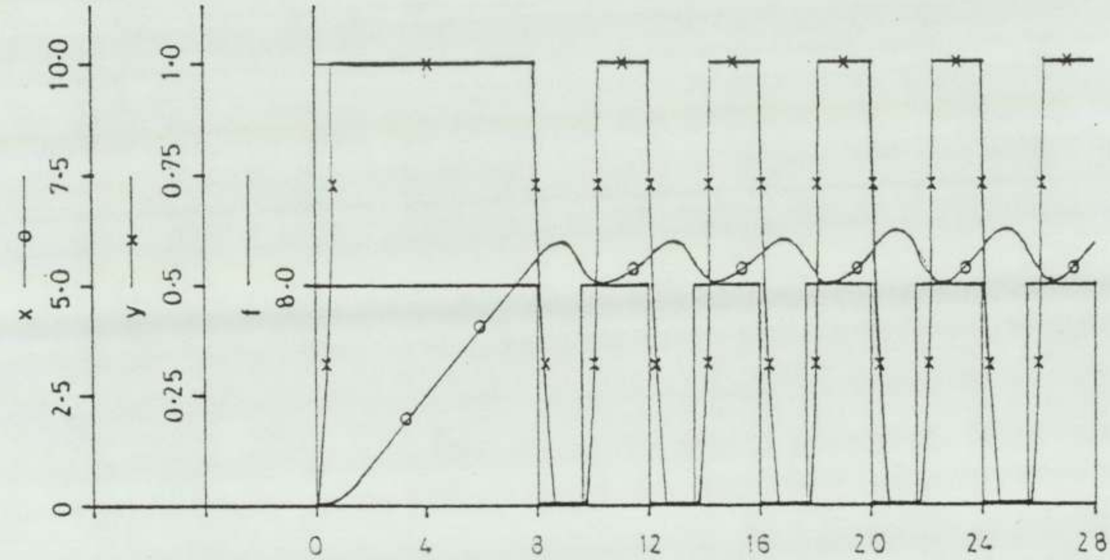


FIGURE 7.9 PULSING VALVE. (VARYING PULSE WAVE)

The computed equations for the servo pressure are :-

```
SIGNDX=FNSW(D1X,-1.0,0.0,1.0)
PSE=FNSW(AINT(Y)-AINT(1.0-Y),1-K,
&    (SIGNDX*SQRT(ABS(W))-B)/A,J+PT)
W=B**2-A*C
A=1+H+1/(4*H)
B=(J-K-PT-1)/2-1/(4*H)-PT*H
C=PR/2+1/(4*H)+PT**2*H+PT*K-J+J**2*H
H=Y**2/(2*L)+0.00001*INT(1-Y)
J=N*D1X::2/(Y::2+0.00001*INT(1-Y))
K=N*D1X**2/L
L=(1-Y**2+0.00001*INT(Y)
```

PT and N are non-dimensional constants and are defined, together with the valve dimensions, additional notations and the complete programme in Section D.4 of Appendix D.

The SLAM user can choose either to use any of the six integration methods provided by SLAM or to define his own method. By trial the Trapezoidal integration algorithm was adopted with the communication interval and integration steps per communication interval as defined in the Appendix. The integration system of SLAM makes it possible to change the integration algorithm, communication interval and step value at run time. The different techniques can therefore be used without the need to recompile the programme, by simply supplying different values for the variables. This enabled a relatively fast but less accurate integration method in the first stages of the study and then a more sophisticated method in the final stages without rewriting and recompiling the programme.

Figure 7.7 shows the comparison between the simulation results and measured performance for the valve opening and closing. To simplify the verification of the simulation, pressures P_3 , P_1 and P_2 were all held at 137×10^5 N/m^2 . This constituted a no-flow condition for the main poppet and is a condition that would not be met in a metering out application. Since the poppet is not pressure balanced, it also made for fast opening and slow closing response times.

The comparisons for the simulation and actual hydraulic response, from the instance the servo poppet begins to move to the instance the main poppet was fully open, or closed, are shown in Table 7.1.

	Simulation Result	Measured Time
Min. Flow Rate → Max. Flow Rate	τ = 60 t = 121.2 ms	τ = 58 t = 117.2 ms
Max. Flow Rate → Min. Flow Rate	τ = 370 t = 747.4 ms	τ = 390 t = 787.8 ms

TABLE 7.1 Valve Hydraulic Response Comparisons.

The results of the comparison tests lead to the expectation that the simulated results for the pulsing of the valve, shown in Figures 7.8 and 7.9, would be found in the actual testing of the valve. However, the maximum rate at which the intrinsically safe solenoid could be pulsed for movement of the servo pilot poppet to take place, would not permit the main poppet to oscillate within a mid-position. It was not possible to provide small increments of flow rate regulation with this valve. With only two rates of flow required for the boom, as mentioned in the introduction to this Chapter, the valve fulfilled all requirements. Separate valves were installed to give metering out control of the fluid from the actuators for the slewing and the actuators for the raising/lowering of the boom.

Besides the poor response time of the solenoid, the design of the main poppet could be improved for pulse width modulation. A proportion of pressure balancing would reduce the opening force on the poppet and a restricting orifice in the pilot line would slow down the response of the main poppet. In pressure relief poppet valves, where a measure of proportional control is required, poppets with a long engagement length and multiple grooves (Ref.12) have been found to give improved erosion rates. The high poppet lift characteristic of these valves would also be advantageous for pulse width modulation control of flow rate.

The programme developed for the simulation of the valve could be used for the simulation of valves with different poppet configurations with only small modifications being required. It has been demonstrated the discontinuities created by the physical restraints within the valve can be modelled and a simulation of performance obtained.

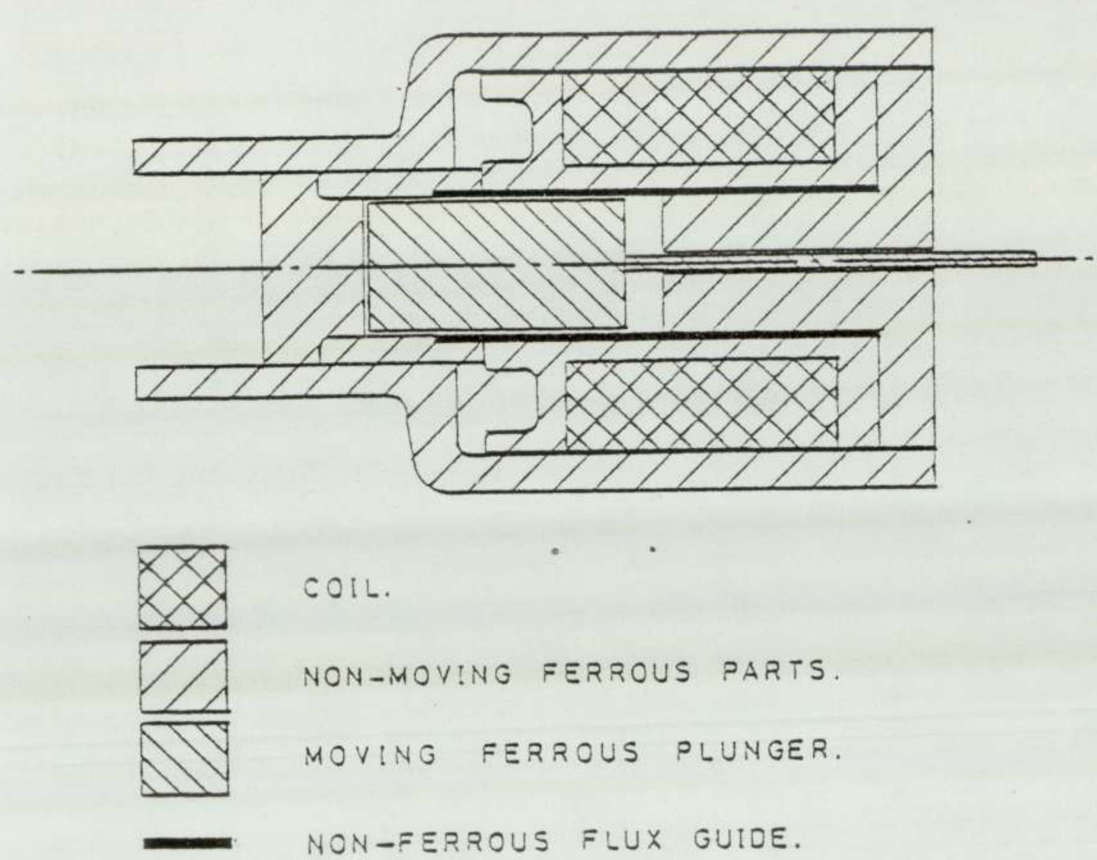
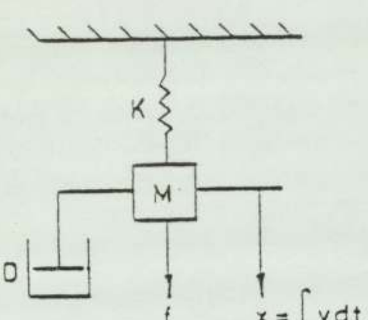
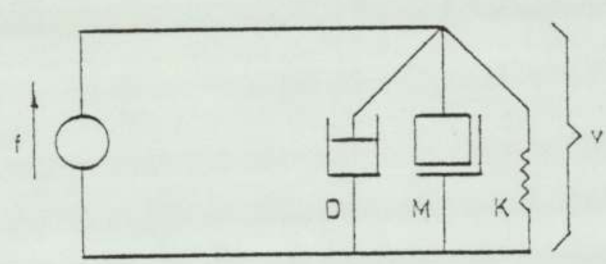


FIGURE 7.10 DOWTY I.S. SOLENOID.



PHYSICAL SYSTEM.

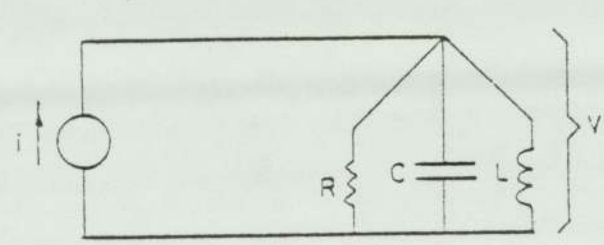


EQUIVALENT NETWORK.

$$M\frac{dv}{dt} + Dv + K\int v dt = f$$

REPRESENTATION OF MDK SYSTEM.

$$C\frac{dV}{dt} + \frac{V}{R} + \frac{1}{L}\int V dt = i$$



A PARALLEL RLC CIRCUIT.

FIGURE 7.11 ANALOGY BETWEEN MDK & RLC SYSTEMS.

7.4 SOLENOID MAGNETISM ANALYSIS

The major portion of the hydraulic valve overall time response to an electrical signal, whether opening or closing, was in the solenoid actuation of the pilot stage.

Both the directional (described in Chapter 6) and the flow rate control servo pilot valves are solenoid operated. Figure 7.10 illustrates the solenoid and the physical magnetic circuit common to both valves. An analysis is made of the solenoid operated motive section with the object of improving the response time.

Electromagnetism is a subject where elegant mathematical formulation often obscures the experimental bases. The subject is explained avoiding this approach in Ref.56 and it was decided to follow the same philosophy and deal with reality in carrying out the analysis.

7.4.1 Analysis of Magnetism Due To Current.

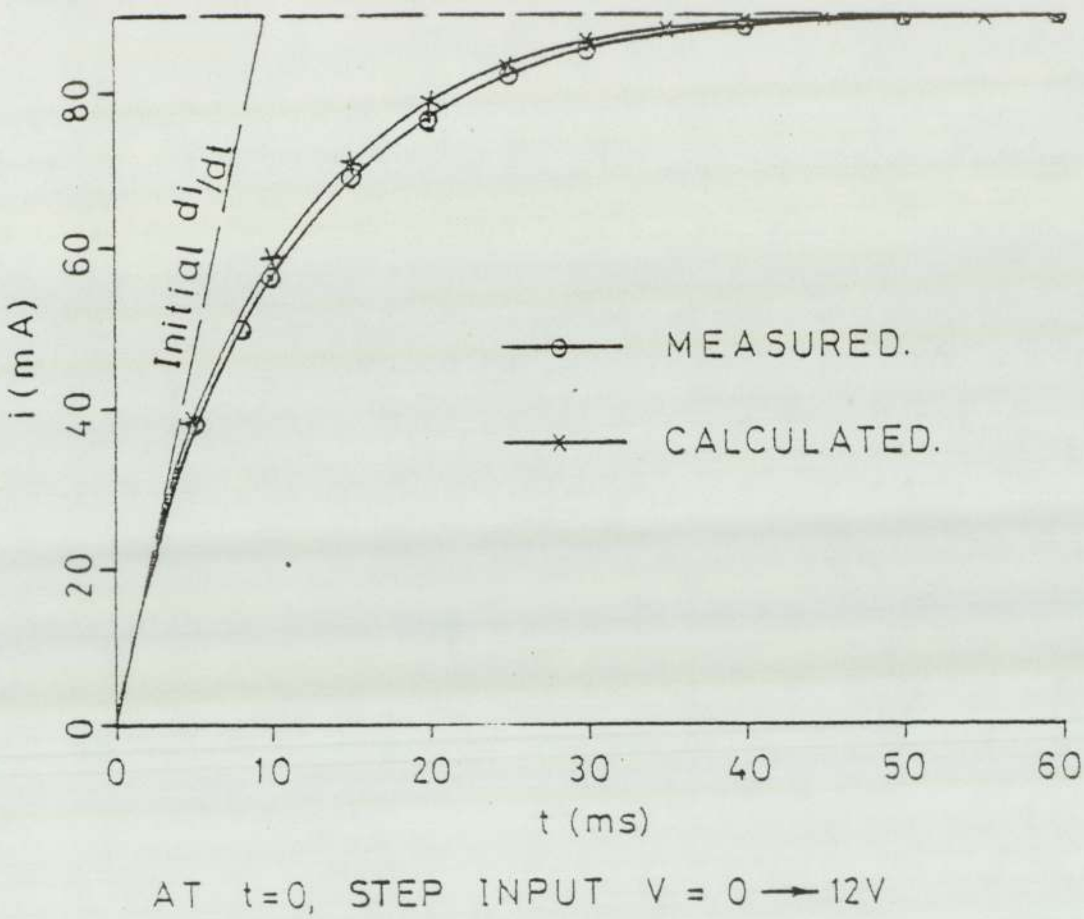
Figure 7.11 illustrates the analogy between the mechanical, mass, damper, spring (MDK) system and the electrical, resistance , inductance, capacitance (RLC) system.

Since electric charges possess inertia, not only on account of their gravitating mass, but also because of their electrical charge, magnetic energy is kinetic. The ratio of charge to mass of an electron is large,

$$1.76 \times 10^{11} \text{ coulomb/kg.}$$

The kinetic energy due to mass is therefore neglected.

Developing the equation for the RLC circuit, shown in Figure 7.11, neglecting any capacitance the circuit might



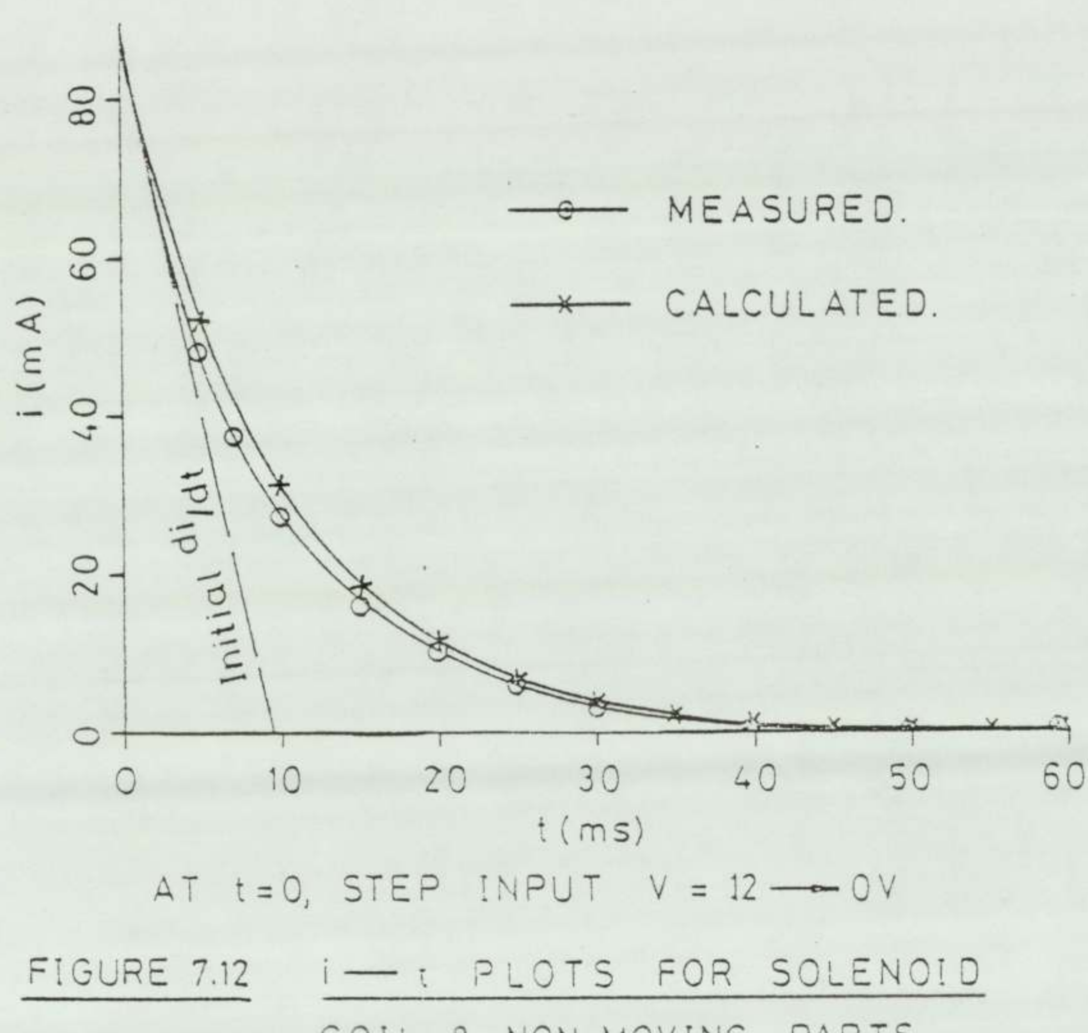


FIGURE 7.12 i — t PLOTS FOR SOLENOID COIL & NON MOVING PARTS.

have, and for a step input of V, increasing, gives,

$$i(s) = \frac{V}{R}\left(1 - e^{-(R/L)t}\right) \qquad (7.14)$$

and for a step input of V, decreasing, gives,

$$i(s) = \frac{V}{R}\left(e^{-(R/L)t}\right) \qquad (7.15)$$

where i is a polynomial in s, and,

$$s \equiv \frac{d}{dt}$$

The initial test was to measure the self inductance (L) of the coil and non-moving ferrous parts. Ultra-voilet (U-V) recorder traces were obtained for i and t for step inputs of V, of 0V to 12V, and 12V to 0V. These are shown in Figure 7.12.

The coil resistance was measured to be 133.33Ω and from Ohms law, $i(max) = 90mA$.

From the relationship,

$$V = L\frac{di}{dt} + Ri \qquad (7.16)$$

the initial rise, or fall, of i depends entirely on L,

that is, $$\text{initial } \frac{di}{dt} = \frac{V}{L} \qquad (7.17)$$

The self inductance for both cases was calculated to be,

$$L = 1.2667H$$

The values for V, R, L and t were substituted in Eqs.(7.14) and (7.15) and the calculated values for i, with respect to t, are shown plotted in Figure 7.12.

The current reaches 63.2% of its final value of V/R after a time of L/R, known as the time constant.

$$\text{Time constant } (t_c) = \frac{1.2667\text{H}}{133.33} = 9.5\text{ms}$$

The self inductance (L) of the circuit was shown to remain constant for V increasing, and V decreasing. With the armature removed, the iron magnetising circuit is incomplete, and there is no mutual inductance or hysteresis.

The book, "Solenoid Magnet Design", by D. B. Montgomery (Ref.57) deals in some detail in the design of magnets involving currents only, and not with magnets involving iron circuits.

7.4.2 Analysis of Magnetism Due to Current and an Iron Circuit.

If the armature is replaced, the iron circuit is complete, except for a small gap required for valve actuation. When the valve is in use this gap contains the hydraulic fluid.

The flux now linked with the coil is of two kinds :-

1) A self induced flux (ϕ_s).
2) A mutual flux (ϕ_m) provided by the changing magnetic field of the iron circuit, with the relationship,

$$V = \frac{d\phi_s}{dt} + \frac{d\phi_m}{dt} + Ri \qquad (7.18)$$

The magnetic field strength (H) for iron and water are expressed as,

$$H(\text{iron}) = \frac{B}{\mu r \mu o} \qquad (7.19)$$

$$H(water) = \frac{B}{\mu o} \qquad (7.20)$$

Where,

B = Flux density.

μr = Relative permativity.

μo = Absolute permativity.

Neglecting any leakage flux,

$$\mu r = \frac{B(iron)}{B(water)} = \text{Approx. } 3000$$

This illustrates why, in order to save magnetising current, it is important that the non-iron gap in magnetic circuits be kept as small as possible. In many electrical machines this is merely a mechanical clearance, but in a solenoid, where a linear actuating movement is required, the non-iron gap becomes an important consideration. With an iron magnet circuit length of 30 times the length of water gap, then only 1% of the magnetomotive force (m.m.f.) is absorbed by the iron path, and 99% in forcing the flux across the water gap. The term m.m.f. is unfortunate as it is not a force, but an energy divided by the pole strength.

There is an electromotive force (e.m.f.) induced in the stationary coil by the changing magnetic field as the armature becomes magnetically charged and discharged.

Faraday found that the electromotive force acting around the circuit is equal to the rate of change of flux (ϕ) linked with the circuit. That is,

$$e.m.f. = - \frac{d\phi}{dt} \qquad (7.21)$$

This equation applies generally, including the case of moving or stationary circuits of arbitary shape, in constant or moving magnetic fields. The law deals only with the total electromotive force and it would be convenient to write,

$$E(total) = E1 + E2 + E3 \qquad (7.22)$$

Where,

E(total) = Total electric field strength.

E1 = Electrostatic field strength.

E2 = Electric field strength due to electromotive force induced by relative motion between a conductor and a magnetic field.

E3 = Electric field strength due to a change of magnetic field with time.

Equation (8.21) is often used, but E3 is difficult to express in mathematical terms because of the complicated arrangement of a large number of magnetic domains (Ref.56).

We are primarily concerned with the time taken for the armature to begin movement during "power on" and "power off". E1 and E3 are relevant to this situation. Once the armature is moving then a further change of magnetic field with respect to time is induced. Since the armature motion is largly parallel to the lines of flux, the change of electric field strength due to movement of the armature is categorised by E3, with possibly a small proportion by E2.

The armature was placed within the solenoid and two further tests carried out.

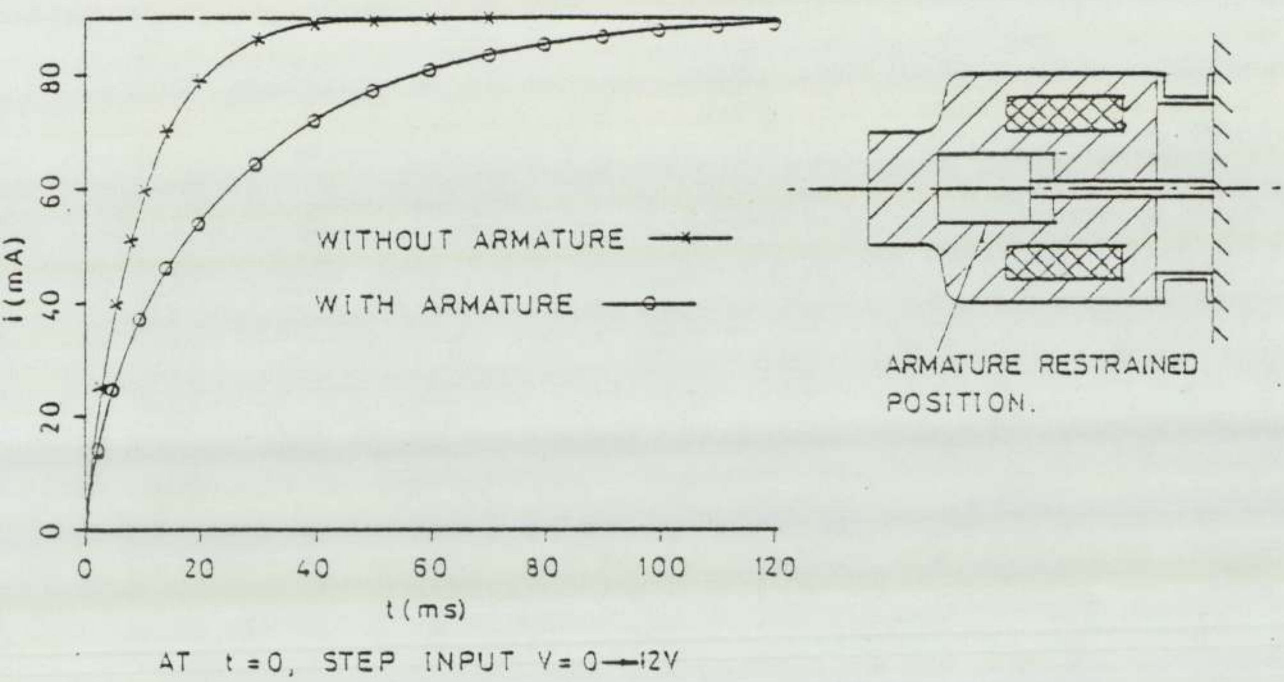


FIGURE 7.13 COMPARISON i—t PLOTS. "POWER ON".

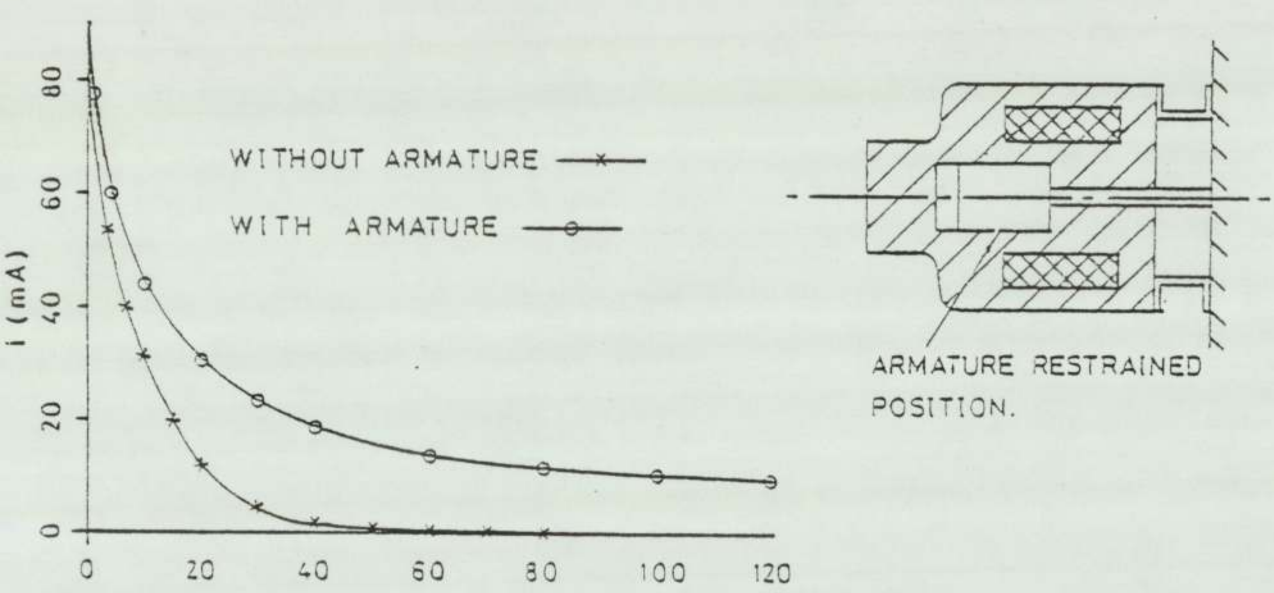


FIGURE 7.14 COMPARISON i—t PLOTS "POWER OFF"

The first test was with the armature held in the normal position at the instance of "power on". A U-V recording was obtained for i, with respect to t, for a step input of V of 0 to 12V. This is shown in Figure 7.13.

The second test was with the armature held in the normal position at the instance of "power off". A U-V recording was obtained for i, with respect to t, for a step change of 12 to 0V. This is shown in Figure 7.14.

Comparison U-V recorder plots were obtained for i-t, for, with, and without, the armature. The effect of the armature is greater for the "power off" condition due, in main, to the magnetic circuit consisting almost entirely of iron.

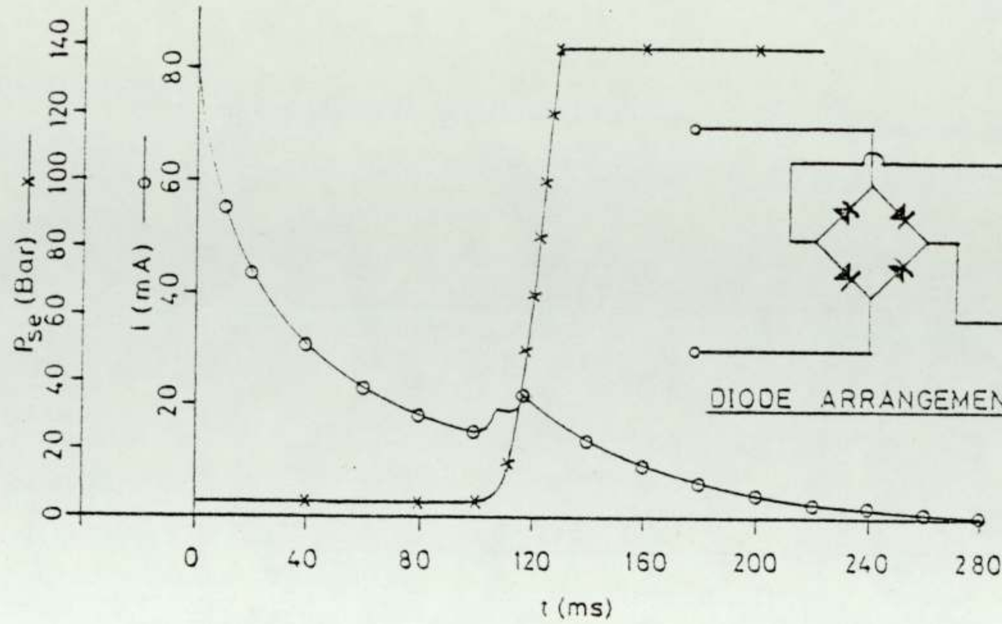
7.4.3 Solenoid Response Time Improvement.

From the results of the analytical tests on the solenoid it was reasoned that a reverse polarity pulse, prior to "power off", would have the effect of increasing the reduction rate of the magnetic flux.

The solenoid valve was placed within the hydraulic circuit and U-V recordings were made of the solenoid voltage and current, and the pilot servo hydraulic pressure. By recording this pressure change it was possible to get comparative readings indicative of the armature displacement.

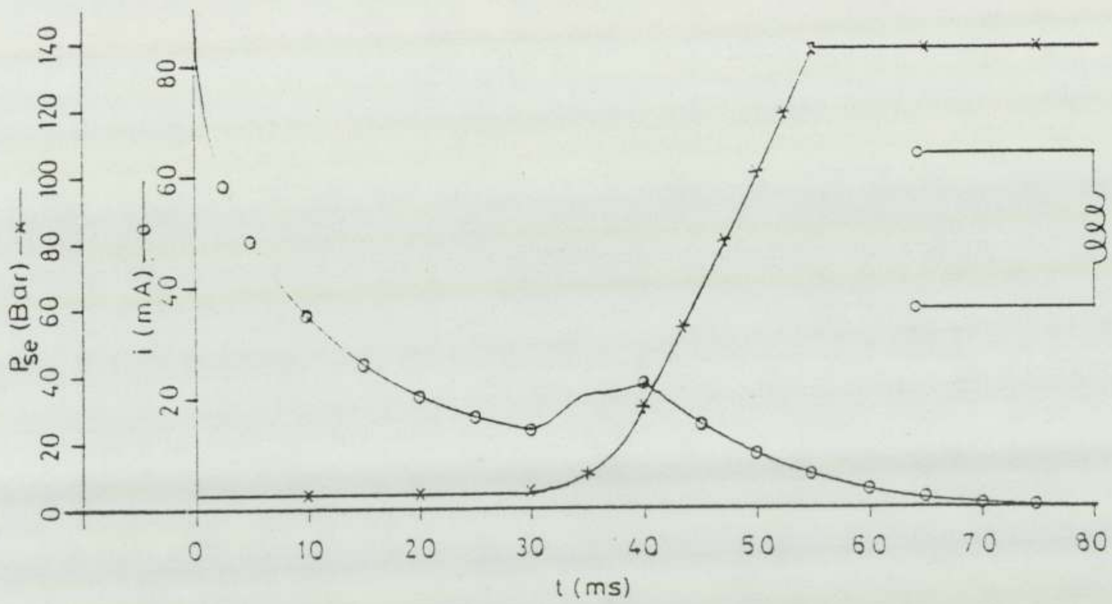
Three separate tests were carried out :-

1) For the standard valve, as received from Dowty, with the diode arrangement as shown in Figure 7.15, the valve closure response time was 130ms. That is, measuring the



AT t = 0, STEP INPUT V = 12—0V

FIGURE 7.15 i–t and Ps–t PLOTS for STANDARD VALVE. (U–V TRACES.)



AT t=0, STEP INPUT V = 12→0V

FIGURE 7.16 i–t and Ps–t PLOTS for VALVE with DIODES REMOVED. (U-V TRACES.)

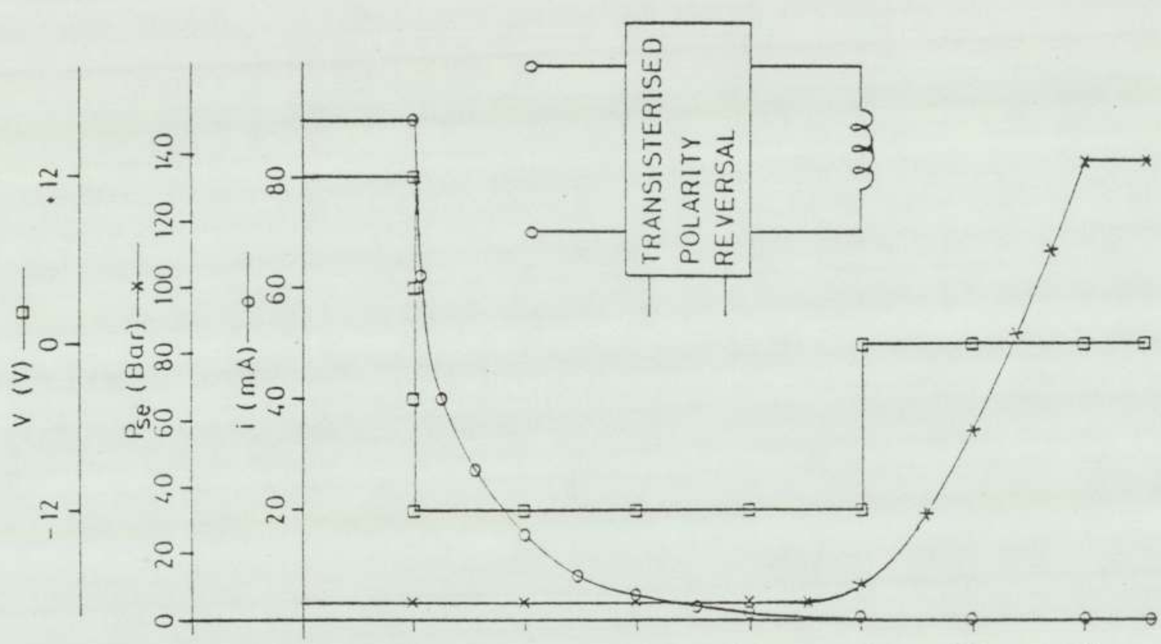


FIGURE 7.17 i–t, V–t and Ps–t PLOTS for VALVE with POLARITY REVERSAL. (U-V TRACES.)

time from the instance the voltage was taken to 0V, to the instance the servo pressure (P_{se}) reached a maximum. The current fell throughout the solenoid de-energising cycle, except between period of 100ms and 117ms. At the start of this period, P_{se} began to increase, indicating that this is the time over which the armature is moving. The increase of current over this period is due to the change of electric field strength by relative motion between the conductor and the armature magnetic field.

2) The diodes were removed and the power supply was connected direct to the solenoid. The results of the test are shown in Figure 7.16 and the valve closure response time was measured to be 55ms. However, at the instance of "power off" there was a reverse polarity inductive "spike" measured as -75V. This would render the valves non-intrinsically safe, besides being a possible hazard to the electronic circuits.

3) The improvement in response time for the previous test led to further investigation of the electromagnetic characteristics of solenoid and iron magnetic circuits and a number of tests were carried out using a reverse polarity pulse. The circuit, using TTL logic signals to control the polarity by switching transistors, is shown in Figure 8, in Appendix A. The optimum reverse polarity pulse length was found to be 40ms, and the test results are shown in Figure 7.17. The valve closure response time of 60ms was achieved, which is only marginally above the previous test, without any detection of an inductive voltage spike.

Because of the difficulty in removing the diodes, due to the whole of the electrical part of the valve being encased in a resin type substance, unmodified solenoid operated pilot valves were used for the system. Any modification to the electrical part of the valve would have required re-application for intrinsic safety approval.

An improvement in response time for the directional control valves would be beneficial to positional accuracy of the boom, as mentioned previously. For pulse width modulation of volume flow control poppet valves a solenoid response times of only a few milli-seconds would be required.

Inertia within the solenoid, both mechanical and electromagnetic, is the principal enemy preventing fast response from conventional solenoids. A recent interesting development by Alec Seilly (Ref.58), advanced product engineer at SGRD Ltd., Lucas CAV's R. and D. company, is the helical solenoid, called a helenoid, and the colenoid. These were developed for the automobile, for engine and gearbox management, operating on a modest voltage with response times of less than lms. Seilly and SGRC Ltd., claim to have done much of the groundwork and developed simple-to-make layouts.

The application of electronic control systems in the mines, and elsewhere, underlines the need for electro-mechanical actuators, capable of fast response to input signals. Further development work would be required to produce an intrinsically safe helenoid or colenoid for hydraulic servo control.

CHAPTER EIGHT

TESTS, RESULTS, CONCLUSIONS AND RECOMMENDATIONS

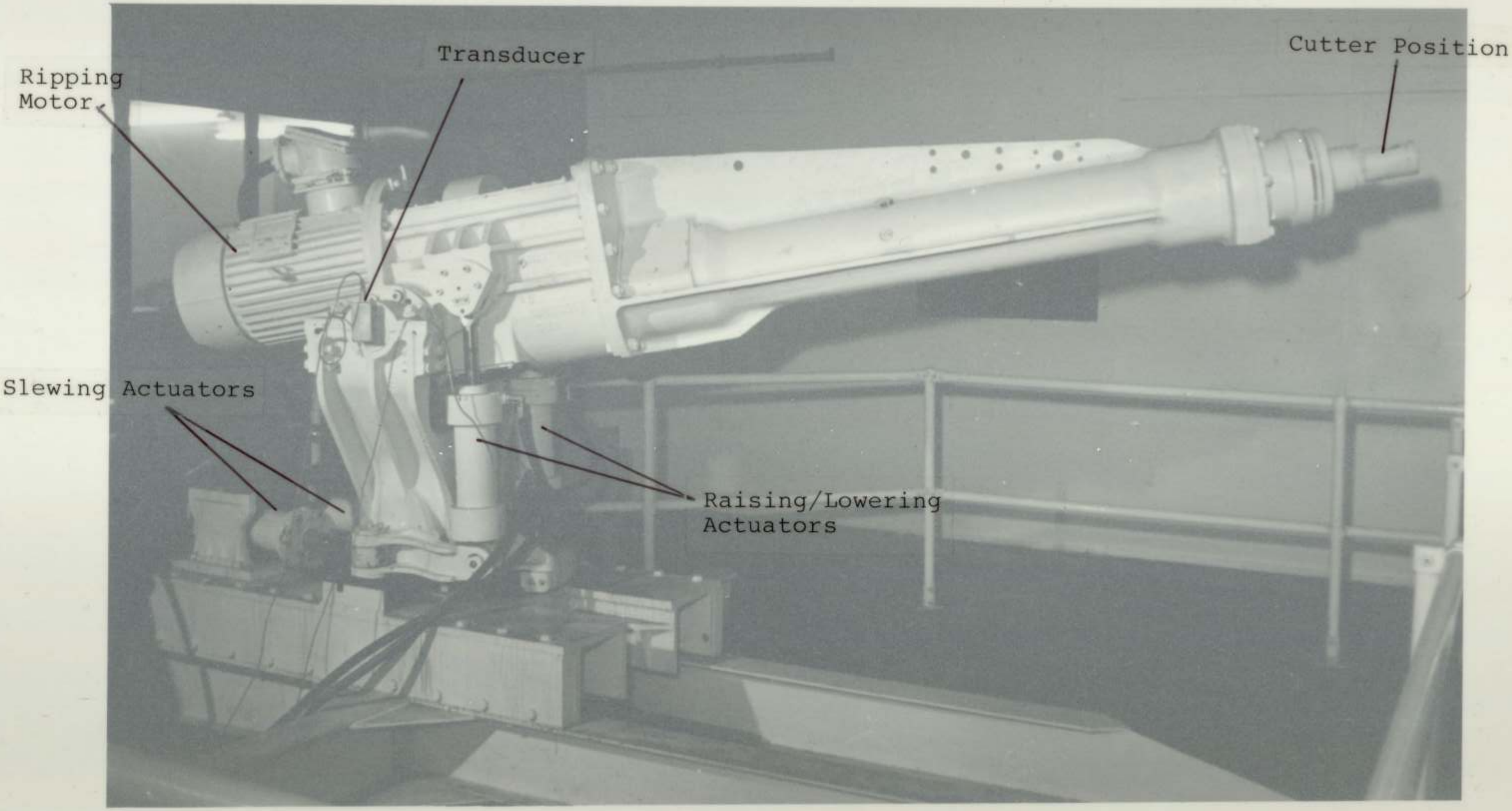


FIGURE 8.1 THE DOSCO MK.2 BOOM IN THE LABORATORY.

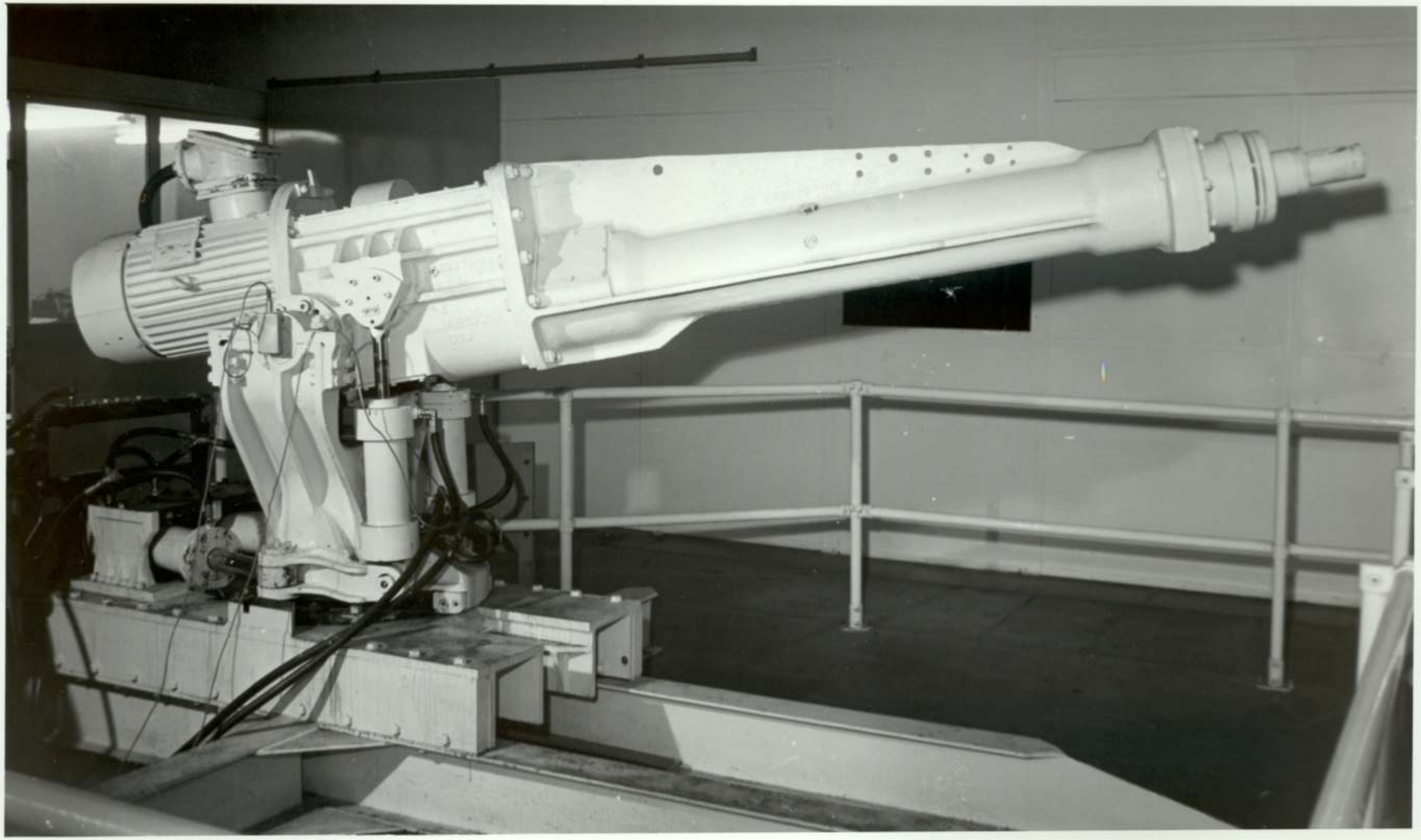


FIGURE 8.1 THE DOSCO MK.2 BOOM IN THE LABORATORY.

8.1 INTRODUCTION.

The micro-electronic and hydraulic circuits, described in this thesis, constitute a system providing continuous path and point-to-point control for a boom with large inertia and operating load forces. The system is unique in that on-off solenoid operated poppet valves are used throughout. This has been made possible by exploitation of the microprocessor, which has produced a system with automatic and manually operated modes of operation.

The control is for existing machines and a Dosco Mk. 2 roadheader boom was provided by the NCB to which the systems were applied for testing and verification purposes. The boom is shown installed in the laboratory at Aston University in Figure 8.1.

The microprocessor controlled information retrieval and input data preparation system, described in this thesis, operates in conjunction with a microprocessor system which controls the operation of the hydraulic valves from retrieved information. This system was developed by C. W. Chuen, in a parallel project. Together these two systems give control to the boom.

Many of the Chapters in this thesis contain test information and conclusions applicable to the individual aspects of the system. This Chapter describes the overall system performance and conclusions with recommendations for expansion to incorporate further control and monitoring functions. The microprocessor is versatile and its application for control systems is an ongoing operation.

8.2 MULTIPROCESSOR SYSTEM ADVANTAGES.

The advantages to be gained by using a dual processor system, for this control application, are discussed in Chapter 3. There are many different multiprocessor configurations and each application must be carefully considered. The benefits of dividing the control task between two processors became evident during the development and at the final stage of the project. The additional work involved in interfacing the two processors was justified by :-

1) The control strategies of the main processor system could be developed and changes made independent of the retrieval processor system, and vice versa. The simultaneous and independent development of the two systems simplified, and hence, reduced the development time.

2) Two processors operating for most of the time independently of each other, have almost twice the work rate of a single processor. It became evident that the degree of control obtained for the boom could not easily be done with a single 8-bit processor.

The decision as to the overall architecture of the system has to be made at an early stage in the design and development of a microprocessor system when all the possible control requirements might not have been identified. The future expansion of the system, requiring further processor controlled elements, would have been better facilitated if a multibus communication between the processors and a separate direct memory access (DMA) controller board, had been implemented, as discussed in Chapter 2. Any modification requiring re-structuring of the hardware is a complex task and the extra cost would have been marginal compared with the benefits gained. The interfacing and implementation of the liquid crystal display, as discussed in Appendix C, fell into this catorgory in this project.

8.3 CONTROL STRATEGY.

The control, ultimately adopted for the roadheader boom, was by simple comparison. That is, the unity feedback of the booms position on the two axes, is compared with what is required, and the valves switched to give corrective action. The booms positional requirement data is either contained within the control system, such as the tunnel profile data for automatic profile ripping, or is obtained from the boom "positional definement" joystick for hand control movement.

This method of control is only suitable for low velocity movement of the boom, such as the speed of ripping. For hand operated movement of the boom to a defined position at fast speed, the system automatically switches to slow speed at a set distance close to the final required position. Simple comparison switching then gives acceptable positional control accuracy for the ripping head within the specified limits of plus or minus 50mm.

Chuen demonstrated the use of an arithmetic processing unit (APU) IC for handling complex mathematical routines for simultaneous switching of the valves to give positional accuracy with high speed movement of the boom.

The equations for determining the moment of sending the signals to give independent closing of the exhaust and supply poppets for minimum positional error of the boom with optimum locked hydraulic column characteristics were developed and discussed in Chapter 6. The relatively linear relationship between velocity and error about a point in the stroke of the actuator indicated that a look-up table, with a minimum of points, and interpolation would provide a suitable means for handling the valve switching criteria. Points for the look-up table can be simply calculated for braking of the actuators for other positions in the stroke for raising, lowering or slewing left or right of the boom. A point in the table could represent the numerical data for more than one axis, velocity or position in stroke where there is duplication. Entry to a point in the table can be determined by software routines. The advantages of high speed, simple implementation and modification of look-up tables could be applied and thus rule out the requirement of an APU for applications requiring accurate hydraulic actuation of high inertia loads. However, the roadheading machine is free-ranging and the kinematic equations developed in Appendix E for referencing the machine frame to the tunnel plane would require the handling of complex arithmetic routines and the APU would best provide this means.

A Honeywell chart recorder, with analogue voltage inputs for the two axes, was connected to the signals from the two potentiometers fitted to the "define profile" joystick. A switch enabled changeover to the feedback

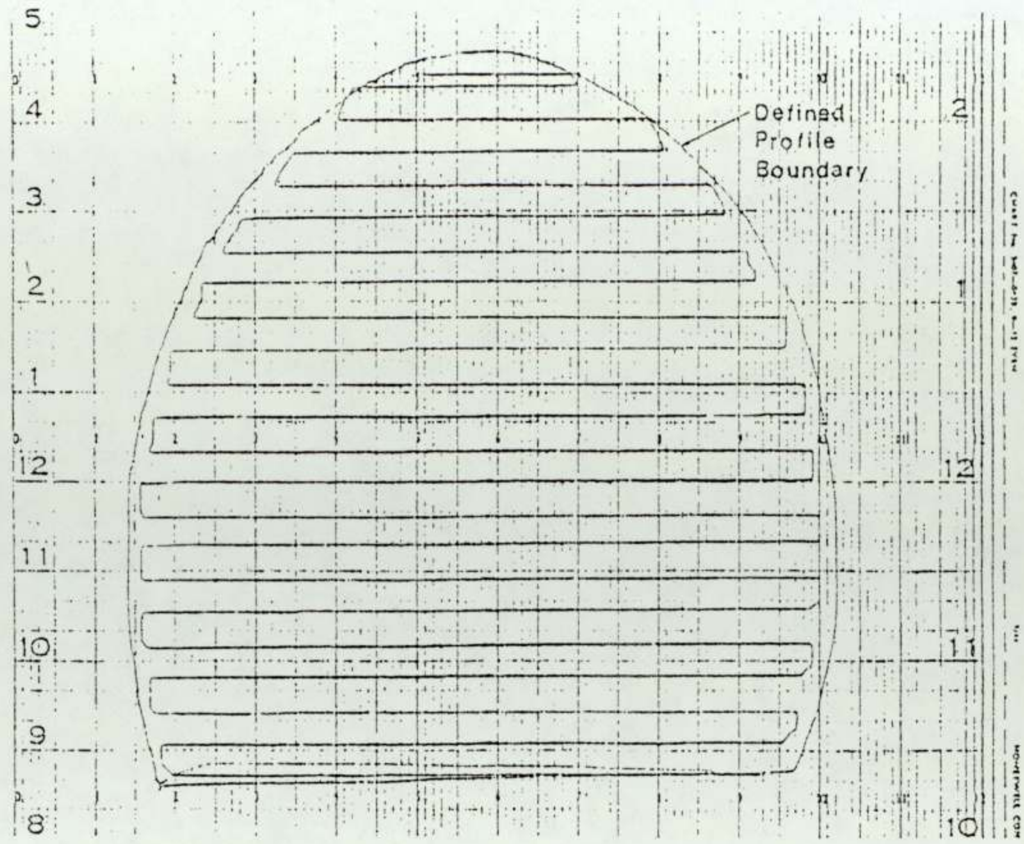


FIGURE 8.2 PROFILE DEFINITION & CAVITY RIP.

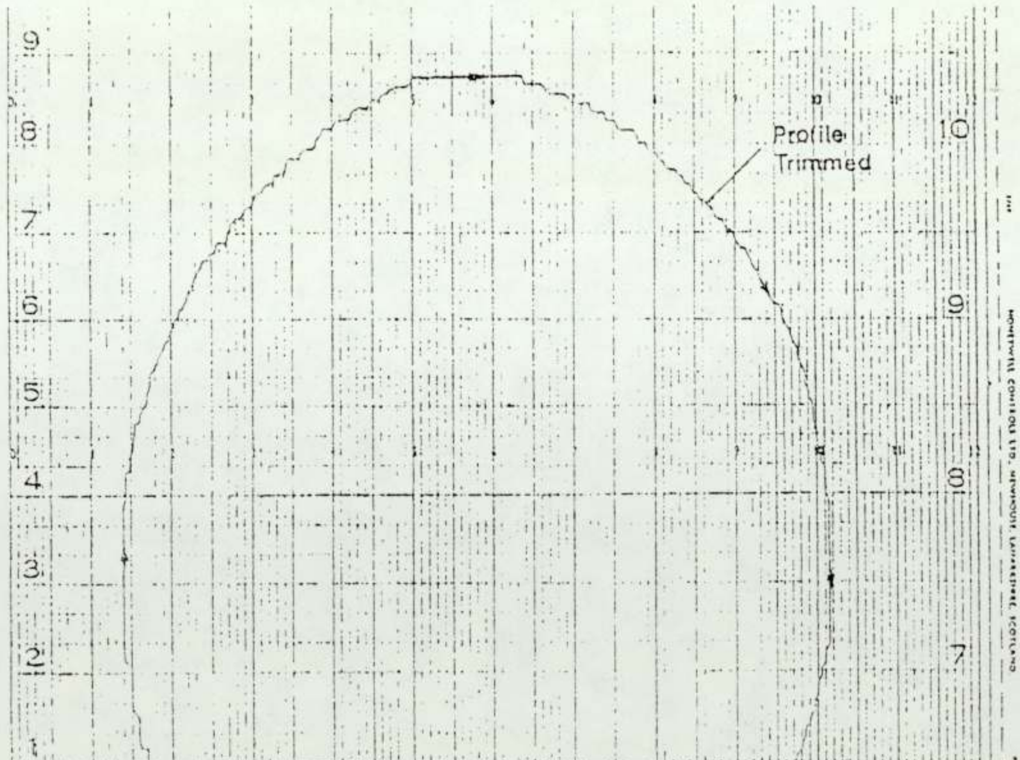


FIGURE 8.3 PROFILE RIP.

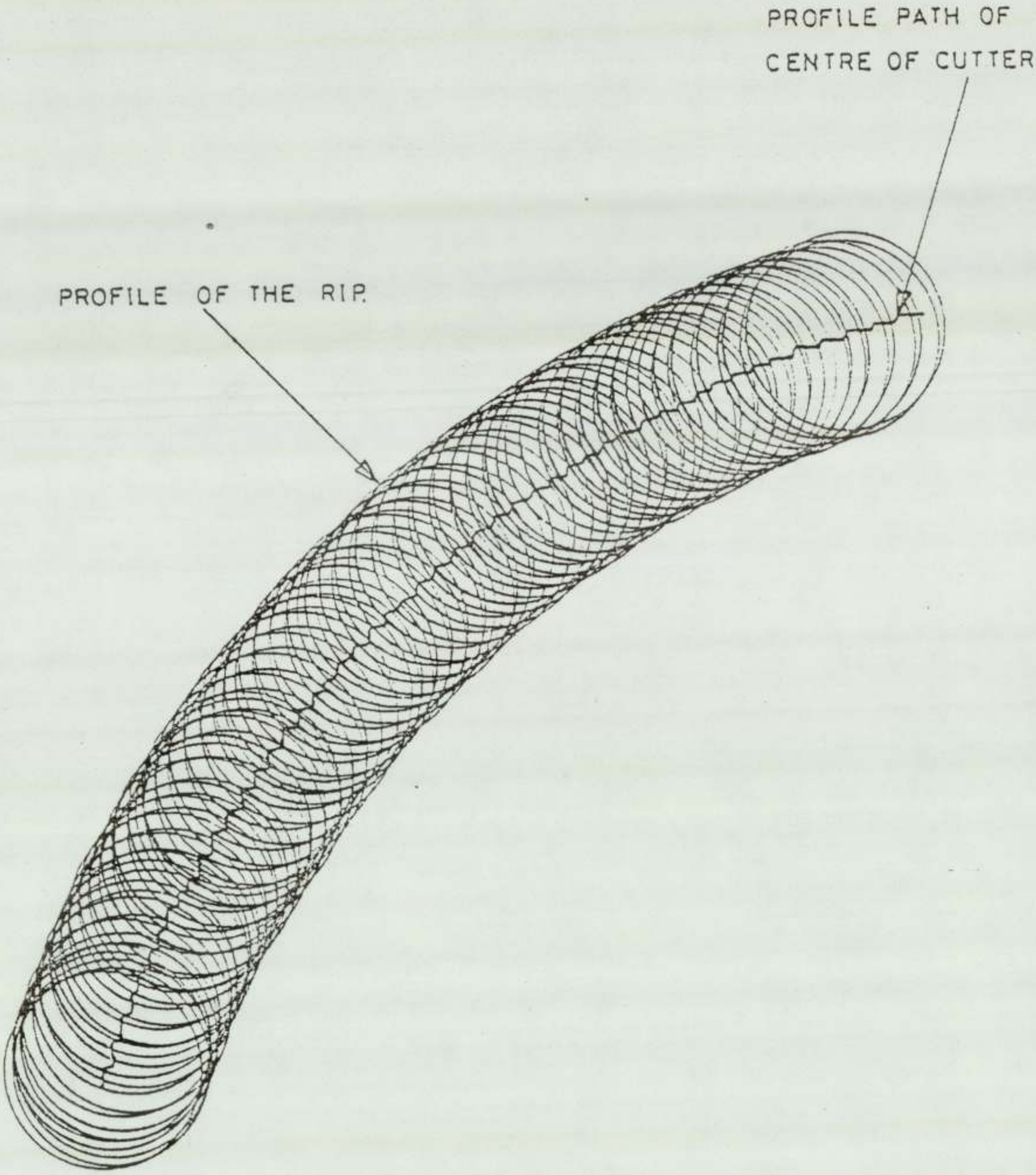


FIGURE 8.4 COMPARISON OF PROFILE PATH OF CENTRE OF CUTTER & PROFILE OF RIP.

signals from the the transducers fitted to the booms axes. A simple circuit was built to increase the input impedance of the chart recorder to reduce the effect on the analogue signals to the control system. The circuit also gave the required gain.

The profile was first defined to the system and the "cut cavity" routine carried out. The results are shown in Figure 8.2. The "cut profile" routine was then executed, and the results are shown in Figure 8.3. These two recordings demonstrate the control obtained with simple comparison switching of the valves.

The stepped movement around the profile is due to the bang-bang characteristic control requirement of the poppet valves. The plot is representative of the centre of the cutter and the profile path of the rip would be very much smoother, as is demonstrated by Figure 8.4. It is quite possible that this type of movement would have definite advantages when ripping hard brittle strata, where the impact ripping technique is often used.

Simple comparison switching of the valves does not in any way diminish the requirement of accurate, and repeatable, feed-in and feedback information.

The boom in the laboratory provided an excellent opportunity for the testing of various control strategies for the accurate positioning of large inertial loads using simple bang-bang (on/off) hydraulic poppet valves.

8.4 CONTROL SYSTEM INPUTS.

When carrying out the tests, mentioned in Section 5.2.1, for the profile definition accuracy from the template and joystick, repeatability was found to be always < or = 1-bit in the digital conversion of the analogue signals from the joystick potentiometers. The control algorithm, mentioned in Section 5.5, for the storage of profile data, ensured this was carried out correctly, irrespective of the speed the joystick was moved.

The boom's angular positional transducers, are small and compact and easily incorporated on existing machines. The same transducer can readily be adjusted to give a fixed full-scale voltage range for different ranges of angular displacement. We found no reason to doubt the potentiometer manufactures claims for life, linearity and repeatability, mentioned in Section 4.3.

All manual control system inputs operated as defined in Chapter 4.

8.5 BOOM VELOCITY CALCULATIONS.

The technique of obtaining boom angular displacement feedback and using a timer IC to generate information from which angular velocity could be calculated is described in Section 5.5.

Tests were carried out using hand regulated flow valves to give metering out speed control for the hydraulic actuators. The development system, with the in-circuit emulator connected to the retrieval systems processor, enabled recordings to be made of the calculated angular velocities. These were checked and verified, using a stop watch, and timing known displacements, to give a

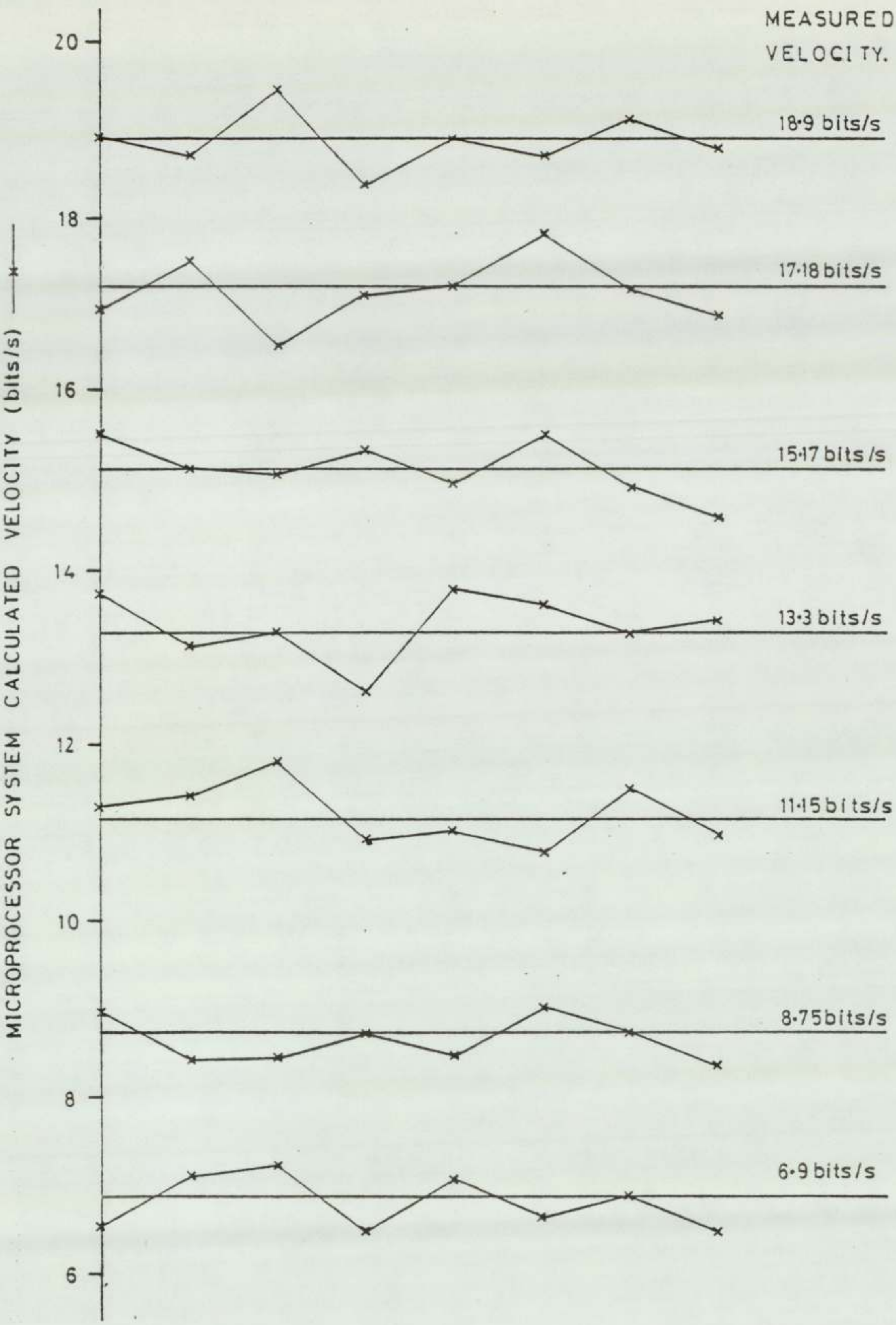


FIGURE 8.5 BOOM VELOCITY COMPARISON TESTS.
(SLEWING, +ve DIRECTION.)

measured angular velocity.

Figure 8.5 illustrates a set of comparison angular velocities for the boom slewing in a positive direction. Despite the inherent inaccuracy of the analogue to digital converter, discussed in Section 4.7, the results obtained were deemed to be sufficiently accurate for the calculation of valve closure operations to give optimum positional control for the boom, as verified by C. W. Chuen and shown in Figures 6.10 and 6.11. The accuracy of velocity calculation was measured to be within 10% at the low range, reducing to within 5% at the high range.

Similar results were obtained for the boom slewing in the negative direction, and for the boom rising and falling on the vertical axis.

The readings were recorded consecutively over a small arc near the centre of displacement, as the angular velocity of the boom would vary slightly for a constant hydraulic flow rate due to the geometry of the boom and actuators.

8.6 SAFETY ASPECTS OF THE SYSTEM.

Safety is of paramount importance in the operation of mining machinery. The safety aspects of the operational method described in this thesis for the roadheading machine are :-

1) On "power up" of the system, no movement of the boom takes place, and the operator is not able to move the boom until the profile has been fed into the system. This operation takes only a few seconds.

2) The feedback and overriding feature of the ripping motor absorbed current levels, prevents the automatic modes, or the operator using manually controlled movement, overloading the ripping motor. It might also be possible to use this characteristic to reduce movement of the machine frame due to high cutting forces.
3) In event of an electrical failure the boom stops dead, and can only then be moved by direct hand operation of the main poppets. Restoration of the power reproduces the "power on" state.
4) Pilot servo pressure failure would automatically cause the main poppets to close.
5) Because of the arrangement of the hydraulic circuit, a failure in the main pressure would not cause an immediate reduction in the pilot servo pressure. The boom would cease to move on the slewing axis or move vertically. It could fall under it's own weight, but only within the profile. It would be possible to detect the fall in main system pressure and implement complete automatic closure of all valves, if this was thought necessary.
6) The "no leak" characteristic of the soft seat poppet valves, ensure that the boom stays put when the system is "powered down". There was no detectable movement in the boom after a period of several weeks.

An additinal safety requirement is that of either intrinsic safety or flameproof enclosures, for all electrical equipment. The former is to be preferred. The electrical characteristics of the system are broadly as follows :-

1) The transducers, operator inputs, signal conditioning and analogue to digital conversion systems have a low, single voltage, power requirement of approximately 10 mA. All IC's used in this part of the system are CMOS and intrinsic safety approval should not present any problem.
2) The 8085A microprocessor, together with many of the family IC's, has recently become available using CMOS technology. This will considerably reduce the power requirement, lending to intrinsic safety approval.
3) The solenoids of the servo pilot valves have received intrinsic safety approval.
4) Except for the arithmetic processing unit (APU) IC, (incorporated in the main system, developed by C. W. Chuen) the whole of the electronic system operates from a single electrical supply of 5V. The results demonstrated in this thesis did not require the APU. The solenoid valves require a 12V supply. Opto-isolation is incorporated between the two power supply systems, as a system safety feature, and also as an intrinsic safety approval requirement.

8.7 HYDRAULIC SYSTEM.

The hydraulic system has many features desirable for a machine to be used in a mining environment. These features are, in main, gained by the application of poppet valves :-

1) The directional control and flow rate control poppets have soft seats. Should contaminant become trapped between the poppet and seat, a 100% seal should be

maintained. On the next opening the contaminant should be carried clear. This makes for a highly contaminant tolerant system, particularly compared with conventional spool valves.

The servo pilots are served from the main hydraulic system via a non-return valve and with an accumulator to maintain servo pressure in event of a fall in main system pressure. The complete hydraulic power circuit is shown in Appendix D, Figure D.4. The flow rates for the servo pilots are low with zero flow rate when the valves are not switching. The servo poppets are of ball type, with inherent self-cleaning characteristics and require filtration to 55 microns.

2) The complete hydraulic system, including the valves, is suitable for working with dilute (5/95, oil in water) emulsion.
3) The open/shut characteristic of solenoid operated poppet valves, simplifies the interface to the digital electronic control systems.
4) Poppet valves lend themselves to a modular form of construction. This simplifies in-service maintenance.
5) Sliding, close tolerant seals, are avoided with poppet valves, thus simplifying the manufacturing process.
6) With independent control for the supply and exhaust poppets, serving an actuator, closing of the valves can be timed to give optimum hydraulic stiffness and avoidance of cavitating conditions. This is particularly relevant in the positioning of large inertia loads, as was demonstrated in Chapter 6.

The response time of the hydraulic valves was studied using computerised simulation with verification by bench tests. These are contained in Chapters 6 and 7. The most interesting aspect of the simulation was that of the pulse width modulated poppet valve. With a solenoid operated poppet giving servo pilot control to a main poppet, there are two poppets which give four discontinuities in the simulation process. It was successfully demonstrated that this complication can be accommodated and reasonably accurate results obtained for a continuous simulation using digital computation.

The valves performed without trouble throughout the system test and development period. Despite constant pulsing no visible sign of wear or damage to the poppets or seats could be detected.

The valves used in this application had relatively slow response times, due in main to the electromagnetic inductance of the solenoid. Chapter 7 analysed this characteristic, and demonstrated that a reverse polarity pulse on closing could considerably improve the response.

8.8 SIGNAL CONDITIONING.

The conditioning of the analogue signals for this application employed the latest techniques. Any noise pick-up on these lines could interfere with the boom positioning accuracy or cause the boom to move when it should be stationary. Despite the transducer cables running close to the 37 kW ripping motor, at no time did noise pick-up interfere with the system. The conditioning circuits described in Chapter 4 should be suitable for other applications in the mining environment.

8.9 CONCLUSION.

The dual processor system has demonstrated that it is possible to give improved control to a roadheading machine of existing design using a hydraulic system with improved contaminant tolerance and suitable for dilute 5/95 (oil in water) emulsion.

The two automatic modes of "cavity removal" and "trim profile", and simplified hand operated boom positioning, considerably ease and de-skill the requirement of the operator. The choice of any mode of operation, and the termination at any time of one mode and selection of another, provides for flexible control.

The template and joystick method of inputing the profile data, and limiting the hand operated boom movement, has been shown to have sufficient repeatable accuracy for this application. This method of inputing the data is mine worthy. Change of tunnel profile is easily implemented and the operator is better able to relate the required boom position within the profile.

The simple comparison method of control, where the boom angle required is dictated by the angle of the joystick, would have many interesting applications for other machines employing multi-axis booms. This type of control is relatively easy to implement and uses a minimum of IC's.

The final cost of the electronic hardware for the roadheader application, though not of paramount importance, because it is low when compared to the total cost of the machine and the benefits gained, amounted to approximately £500. This cost includes both processor systems, sixteen channels of analogue to digital conversion, two displacement transducers, power amplification circuits, opto-isolation and £150 for power supplies and printed circuit boards. The cost of system development however amounted to many thousands of pounds. The manufacturers of the machines would have to balance these costs with the advantages to be gained, such as improved control and productivity, and the likely result in the improvement of sales and profits.

The tools required for developing a microprocessor based control system, should also be a consideration, as to purchase these would mean a capital investment of many thousands of pounds.

The development of a system, such as is described in this thesis, demands multi-discipline skills :-

1) Digital and analogue electronic techniques.
2) Microprocessor software development using assembly and possible high-level languages.
3) Digital computing using high-level languages.
4) Hydraulics.
5) Dynamics.
6) Kinematics.
7) Control engineering.
8) Ergonomics.
9) Conceptual and detail design.

10) Value analysis.

Few engineers can be considered as expert in all of these, and hence the development task would be carried out as a group activity. The overall coordination should be carried out by an engineer with at least an understanding of all aspects.

The requirement of the roadheader in performing it's task, the mining environment, the man-machine interface and safety have been fundamental considerations. This should result in an improved roadheading machine acceptable to the National Coal Board, the machine operator and the Unions.

8.10 RECOMMENDATIONS.

Design and development is an ongoing operation and like any project of this type, work is required to implement a marketable product from the research work.

The valves require a design study to package them initially in a common manifold. If the control system and valves are found to perform reliably in service, and the direct manual stand-by operation of the main poppets can be dispensed with, then it would be possible to mount the solenoid operated servo pilot valves and main poppets at the actuators. This would reduce the multiplicity of hydraulic hoses to be found on present machines, reduce the size of the fluid columns either side of the actuator piston and remove the hose compliance characteristic. This would result not only in a neater hydraulic system, but improved hydraulic stiffness and possibly a more maintenance free system.

Only two control speeds were required for the boom for this application and this was simple to implement with poppet valves. Multiple flow rate control using poppets can be carried out in a number of ways as discussed in Chapter 7. Also contained in Chapter 7 is the computerised simulation of a pulse width modulated solenoid operated poppet valve for volume flow regulation. Unfortunately, the available intrinsically safe solenoids will not operate at the pulse frequency required for the servo pilot to give positional control to the main poppet for fine metering control of flow. The frequency response of solenoids is discussed in Chapter 7 with recommendations for further work.

When controlling the boom for simultaneous slewing on the horizontal axis and falling on the vertical axis, movement on the vertical axis takes precedence due to gravity, because of the large falling mass of the boom. This problem was avoided by using small incremental movements of the boom on either axis, that is, never both axes at the same time. Figure 8.3 demonstrates this aspect. Improved movement of the boom would be achieved with a flow dividing valve, with care taken not to destroy the contaminant tolerance of the system.

Full provision has not been made for machine frame movement. In the present system it would be relatively easy to carry out the necessary corrective action if machine frame displacement relative to tunnel coordinates is known. This would require the system handling the kinematic equations developed in Appendix E. Spare channels of analogue to digital conversion and data storage locations are available. The high arithmetic requirement would be met by the APU in the main system.

The liquid crystal display (LCD), described in Appendix C, is likely to find many applications in the mining and other hazardous areas. Further development is required to produce a large fully programmable dot matrix display, and interface circuits and software control would have to be developed to apply this to the roadheader. There is no doubt that a display of information, as demonstrated in Appendix C, would be of benefit to the roadheader operator and could eventually lead to remote operation of the machine.

REFERENCES

Abbreviations used:

A/D	Analogue to Digital.
ADC	Analogue to Digital Conversion.
Appl.	Applied.
Assoc.	Association.
Conf.	Conference.
Dev.	Development.
Engrs.	Engineers.
Hyd.	Hydraulic.
IEEE	Institution of Electrical and Electronic Engineers.
I.Mech.E	Institution of Mechanical Engineers.
I.Min.E	Institution of Mining Engineers.
Inst.	Institution of.
Int.	International.
Mech.	Mechanical.
MINOS	Mine Operating System.
MRDE	Mining Research and Development Establishment.
NCB	National Coal Board.
OEM	Original Equipment Manufacturer.
Proc.	Proceedings of.
Res.	Research.
SLAM	Simulation Language for Analogue Modeling.
TTL	Transistor-Transistor Logic.

REFERENCES.

1. Ezra, Sir Derek: "Applying New Technology in a Traditional Industry-Coal Mining", Electronics and Power, Vol. 27 No 1, Jan. 1981, pp. 36-40.

2. Carter, T. W.: "Survey of the Activities of the London Hydraulic Power Company Since its Inception in 1871", London Hydraulic Power Co., 1966.

3. Homfray, S. G.: "The Machinery of the Tower Bridge", Mins. of the Proceedings of the Inst.of Civil Engrs., Part 1, 1886-87.

4. Kelly, S. M.: "MINOS: Overview", MRDE Computer Systems Paper No. 30, NCB, July 1980.

5. Wort, K. G.: "Tunneling Machinery for Coal Mines in the 1980's", Colliery Guardian (1982), Vol. 230, No.3, pp 120-124.

6. Morris, A. H.: "Boom Ripping", Proc. Conf. Fluid Power Equipment in Mining, Quarrying and Tunneling (1974), pp 57-66, I.Mech.E. and I.Min.E., London.

7. Morris, A. H.: "Roadheaders-Tough Cutting", Colliery Guardian (1982), Vol. 230.

8. Rodford, I. G.: "Experience with Impact Units", Proc. Conf. Fluid Power Equipment in Mining, Quarrying and Tunneling (1974), pp 57-66, I.Mech.E. and I.Min.E., London.

9. Leahy, J. C. and Shipley, G. A.: "Selector Valves for the Use in Underground Hydraulic Systems", MRDE Report No. 2267, April 1965.

10. Pike, t. and Grant, S.: "A Survey of Hydraulic Control Valves for Use with Dilute Emulsion Fluids", Int. Res. and Dev. Co. Ltd., Feb. 1977.

11. Kelly, E. S.: "Fire Resistant Fluids: Factors Effecting Equipment and Circuit Design", 3rd Int. Fluid Power Symposium, Paper Fl, May 1973.

12. Wymer, D. G.: "The Use of Water Hydraulics in Machines for Mechanised Gold Mining in South Africa", Int. Conf. on Mining and Machinery, Brisbane, July 1979, pp 320-328.

13. Brierley, F. H. P., Probert, M. J. and Robinson, A.: "Electro-Hydraulic Controls in Mining", 6th Int. Fluid Symposium, Paper G6, April 1981.

14. Card, G. A.: "Electro-Hydraulic Servo Valves and their Applications", OEM Design, Jan 1974, pp 57-59.

15. "Multibus OEM Product Configuration Guide", Intel Corporation, 1983.

16. "Systems Catalogue", Intel Corporation, 1983.

17. Nichols, N.: "8080/8080A Microcomputer Reliability Report", Intel Corporation, 1976.

18. "Microprocessor Selection Guide", Electron Design, pp 53-57, Oct. 11th 1978.

19. McCann, T. M. and Findley, D.: "Microprocessor Product Design - The Role of the Development System", Proceedings of the 2nd Int. Conf. on Microprocessors in Automation and Communications, London, pp 1-17, Jan 1981.

20. Leventhal, L. A. and Walsh, C.: "Microcomputer Experimentation with the Intel SDK-85", Prentice-Hall Inc., 1980.

21. Dijkstra, E. W.: "Cooperating Sequential Process in Programming Languages", Academic Press, pp 43-112, 1968.

22. Toong, Hoo-Min D.: "Microprocessors", Scientific American, Sept. 1977.

23. Sutherland, I. E. and Mead, C. A.: "Microelectronics and Computer Science", Scientific American, Sept. 1977.

24. "MCS-86 Users Manuel", Intel Corporation, 1982.

25. Maisey, D.: "Distributed Processing for Industry", New Electronics, pp 84-85, 9th Dec. 1980.

26. "Component Data Catalogue", Intel Corporation, 1980.

27. Zissos, D.: "System Design with Microprocessors", Academic Press, 1978.

28. Tucker, S. G.: "Multiprocessing with Single Board Computers-A Solution to Complex Control Problems", Sym. Application of Microprocessors in Devices for Instrumentation and Automatic Control, Inst. of Measurement and Control, Nov. 1980.

29. Allison, A.: "Standard Specifications for Proposed Microcomputer System Backplanes", Euromicro Journal, pp 363-368, Nov. 1980.

30. Hill, B.: "Electrical Equipment in Flammable Atmospheres - The Balance of Safety", Mining Technology, pp 361-367, Aug. 1979.

31. "Basic Requirements for the Design and Construction of Underground Machinery", 8th Draft of NCB Report Number Q244VHY, Aug. 1979.

32. Lancaster, D.: "TTL Cookbook", Howard W. Sams and Co. Inc., 1978.

33. Mc Glynn, D. R.: "Microprocessors - Technology, Architecture and Applications", John Wiley & Sons Inc., 1976.

34. Fano, R. M.: "Signal to Noise Ratio in Correlation Detectors", M. I. T. Technical Report, Feb. 19th 1951.

35. Garrett, Patrick H.: "Analog Systems for Microprocessors and Minicomputers," Reston Publishing Co. (a Prentice Hall Co.), 1978.

36. Reamer, H. R.: "Statistical Communications Theory and Applications," Prentice Hall Co., 1969.

37. Horowitz, P. and Hill, W.: "The Art of Electronics", Cambridge University Press, 1981.

38. "Intersil Data Book," Intersil Datel (UK) Ltd., 1981.

39. Evans, Lee: "The Integrating A/D Converter", Intersil, Inc., 1979.

40. Fullager, David: "Selecting A/D Converters", Intersil, Inc., 1979.

41. "Data Sheet for the ADC0816/ADC0817 Single Chip Data Acquisition System", National Semiconductor (UK) Ltd., Sept. 1977.

42. Rooney, M.: "Tradeoffs in the Development of Microprocessor Software", Electro/78 Conference Records, Boston, Mass., U.S.A., May 23rd-25th 1978, published by the IEEE, pages 2/5.1-2/5.9.

43. Lloyd, M.: "Costing Microprocessor Software", Microprocessors and Micro-Systems, Vol.3, No.1, pp 29-31, Jan-Feb, 1979.

44. "8080/8085 Floating-Point Arithmetic Library User's Manual", Intel Corporation, 1979.

45. "8080/8085 Assembly Language Programming Manual", Intel Corporation, 1978.

46. Wang, P. K. C. and Ma, J. T.: "Cavitation in Valve Controlled Hydraulic Actuators", J. Appl. Math., Vol.29, Trans. A.S.M.E. (1962), Vol.84, page 435.

47. McCloy, D. and Martin, H. R.: "Some Effects of Cavitation and Flow Forces in the Electro-Hydraulic Servomechanism", Proc. Inst. Mech. Engrs., London (1963-64), Vol.178.

48. McCloy, D.: "Cavity Formation in Valve Controlled Hydraulic Cylinders", Proc. Inst. Mech. Engrs., London (1969-70), Vol.184, Pt.1.

49. Harvey, E., Newton, W. D., McElroy, E. and Whiteley, A.: "On Cavity Formation in Water", J. of Applied Physics, No.18, 1947.

50. Knapp, R. T., Dailey, J. W. and Hammit, F. G.: "Cavitation", Mc Graw-Hill Book Co., 1970.

51. Cooley, P.: "IDEA: Interactive Differential Equation Algorithm", IPC Business Press, (Sept. 1978), Vol.10, No.5.

52. McCloy, D.: "Cavitation in Hydraulic Systems", Tech. J. Fluid Power Inst., (May, 1967), Vol.7, No.2, Milwaukee School of Engineering.

53. "Fire Resistant Fluids Data Sheets", Assoc. of Hydraulic Equipment Manufacturers Ltd., 1976.

54. McCloy, D. and Martin, H. R.: "The Control of Fluid Power", Longman Group Ltd., 1973.

55. "SLAM 1900 Series", International Computers Ltd., April, 1974, Publication Notice No. SLAM (1), 13th Nov. 1974, Publication Notice No. SLAM (2), 10th Dec. 1975 and Publication Notice No. SLAM (3), 5th Jan. 1977.

56. Hammond, P.: "Electromagnetism for Engineers", Pergamon Press Ltd., 1978.

58. Baker, Alan.: "Vital Twist Overcomes Solenoid Inertia Problems", Eureka Magazine, July 1982.

59. Deboo, G. J. and Burrous, C. N.: "Integrated Circuits and Semiconductor Devices," McGraw-Hill Kogakusha Ltd., 1977.

60. "Specifications for Liquid Crystal Displays EG-Y84320AT (Preliminary)," Epson Corporation, Oct 1982.

61. Duffy, J.: "Analysis of Mechanisms and Robot Manipulators", Edward Arnold (Publishers) Ltd., 1980.

62. Potkonjak, Vukobratovic: "Dynamics of Manipulation Robots", Springer-Verlag, 1982.

APPENDICES

APPENDIX A

ELECTRONIC HARDWARE DIAGRAMS

APPENDIX A.

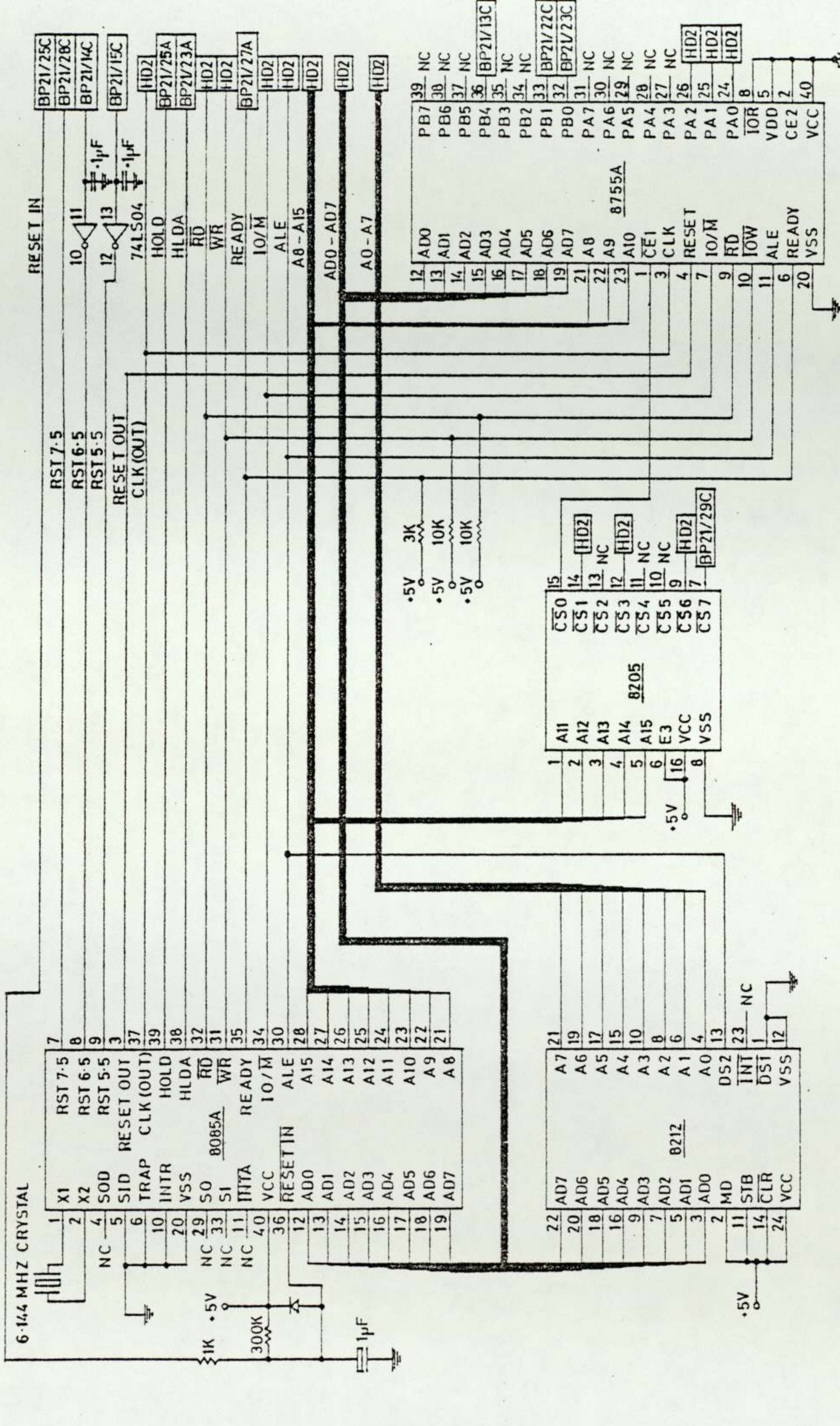
The electronic hardware connections for the information retrieval and input data preparation system are shown on Hardware Diagrams Nos. 1 to 6, inclusive. The system was assembled using Eurocards and wire wrapping techniques.

The cards are interconnected by plugging onto a microprocessor system backplane. The backplane serves both processor systems and is shown on Hardware Diagram No. 7, with connections to backplane tracks, and cut tracks, indicated.

The nomenclature for inter-card and card/backplane connections is as follows :-

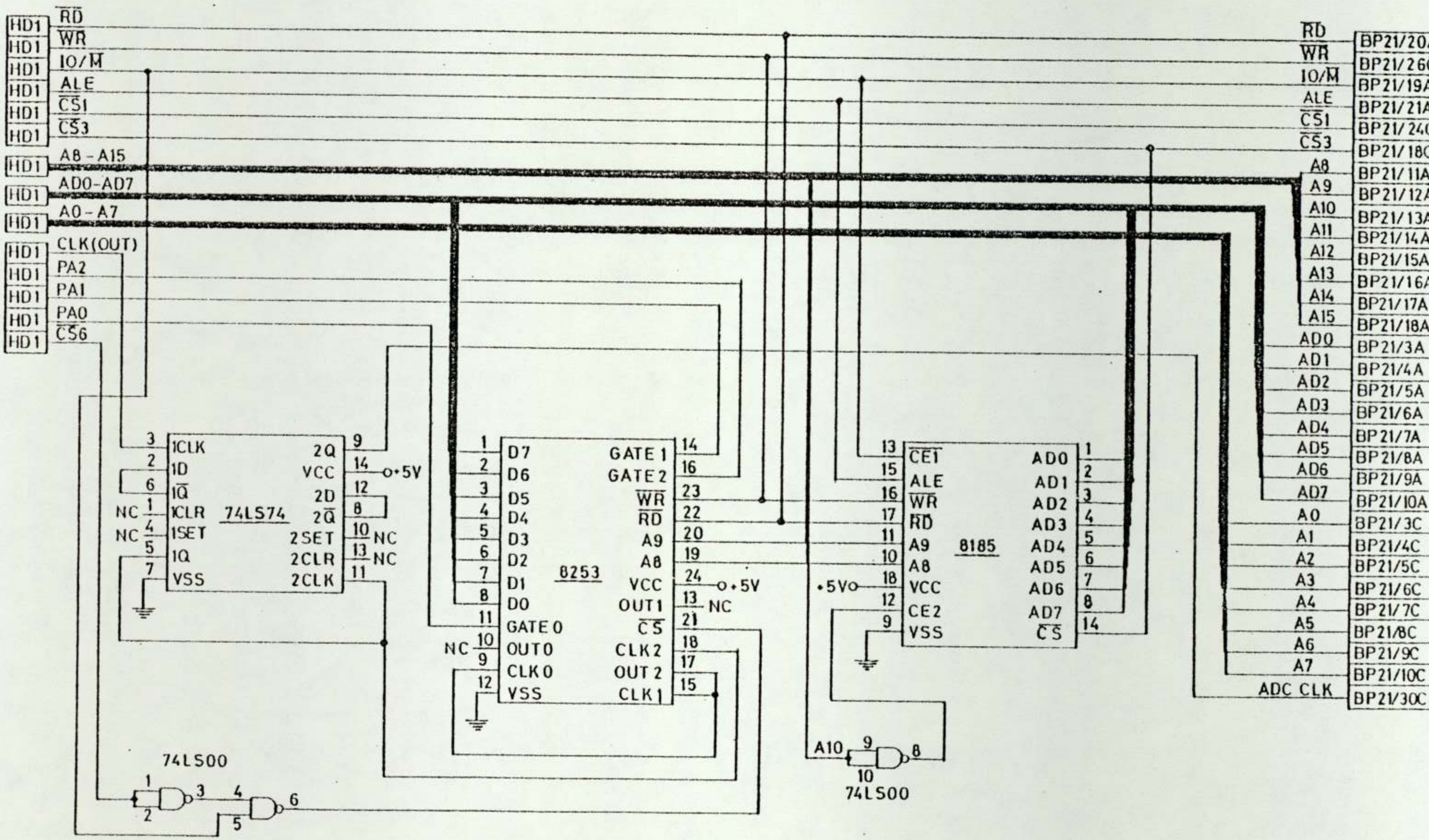
| HD2 | - Indicates that the connection is to be found on Hardware Diagram No. 2. To aid identification, the function of each connection is marked.

| BP21/25C | - This indicates that the connection is to the backplane, at card position number 21, and track position number 25C.



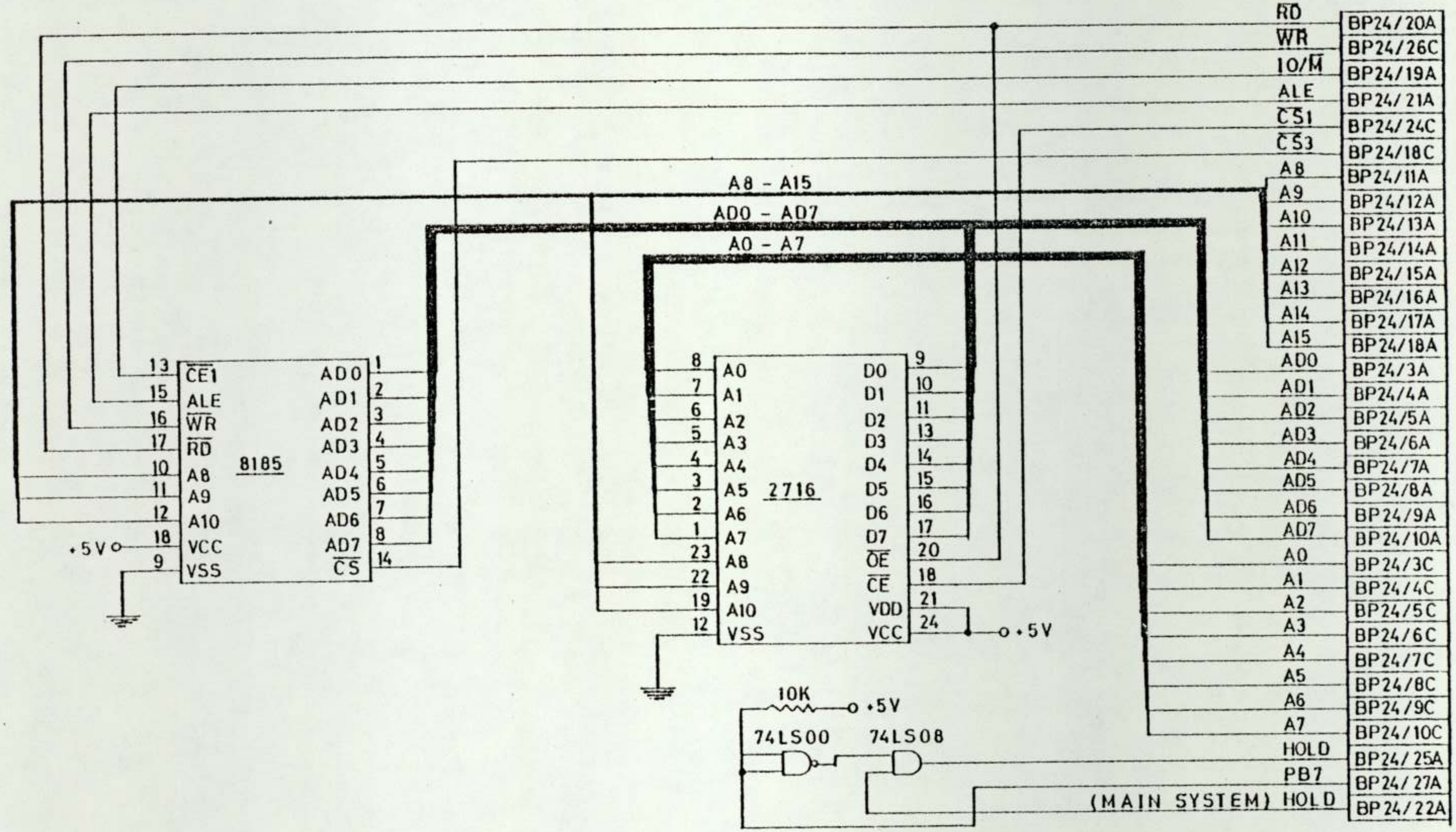
MAIN CARD (1 OF 2 DIAGRAMS)

HARDWARE DIAGRAM 1



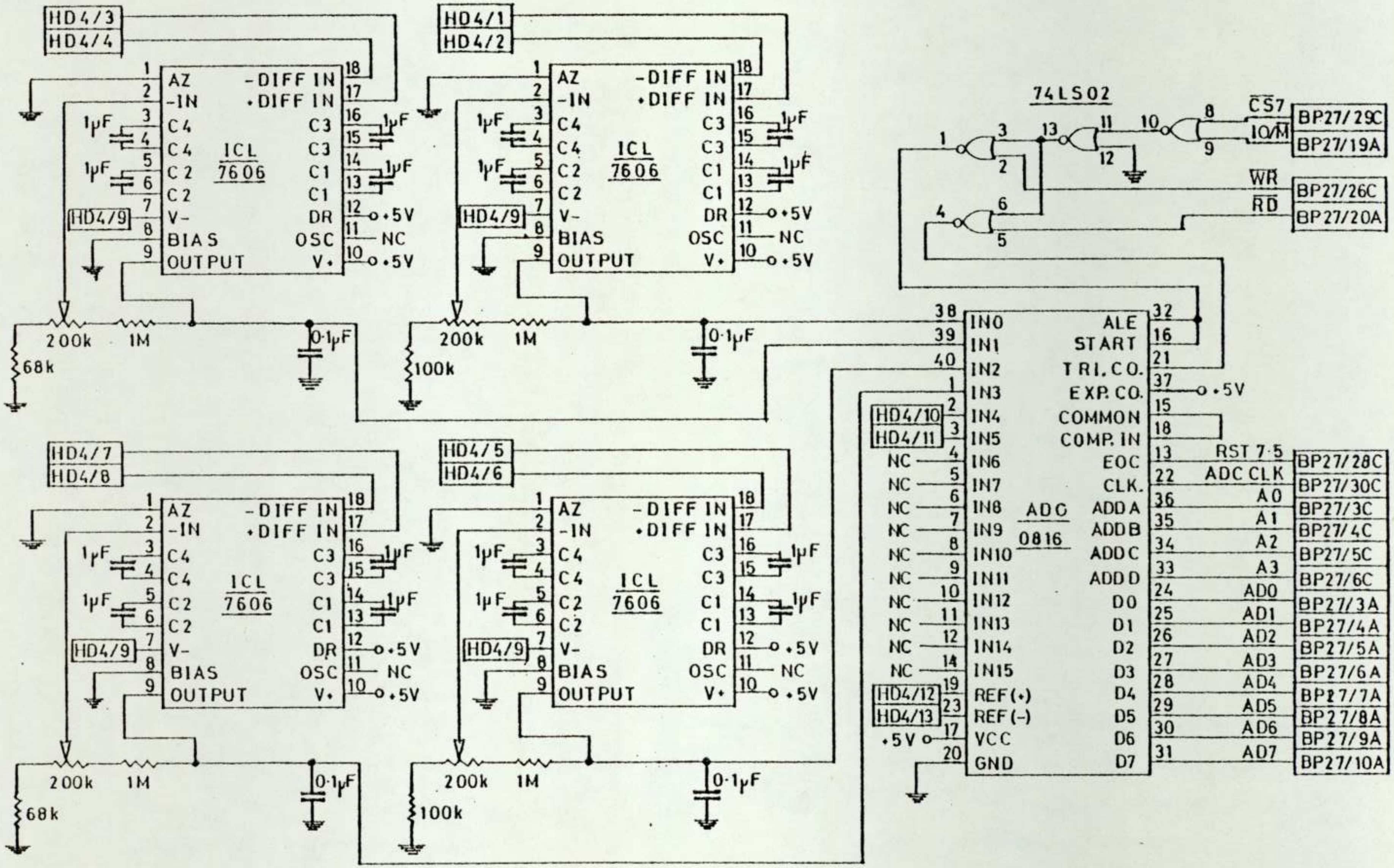
MAIN CARD (1 OF 2 DIAGRAMS)

HARDWARE DIAGRAM 2



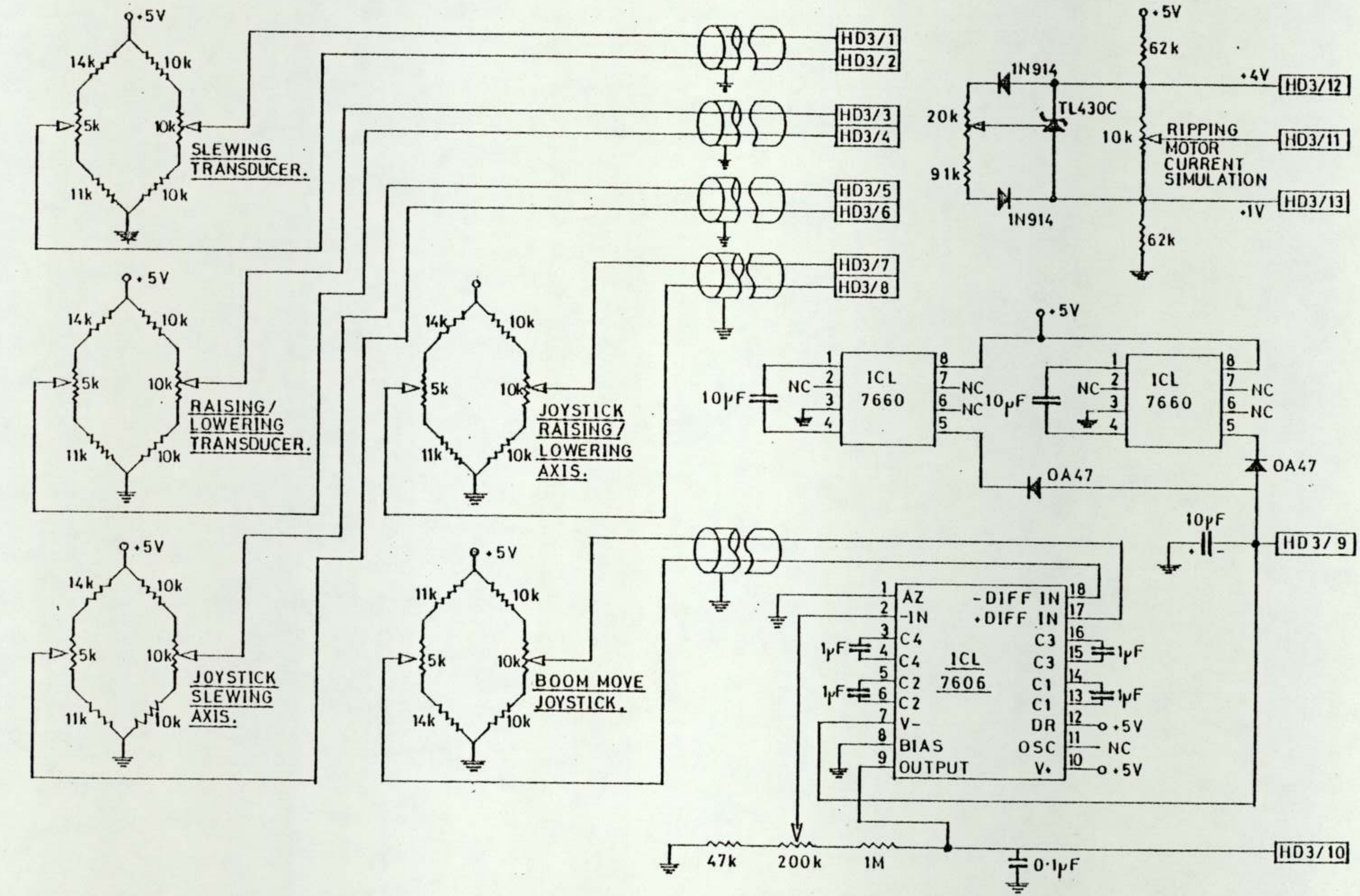
EXPANSION CARD

HARDWARE DIAGRAM 3

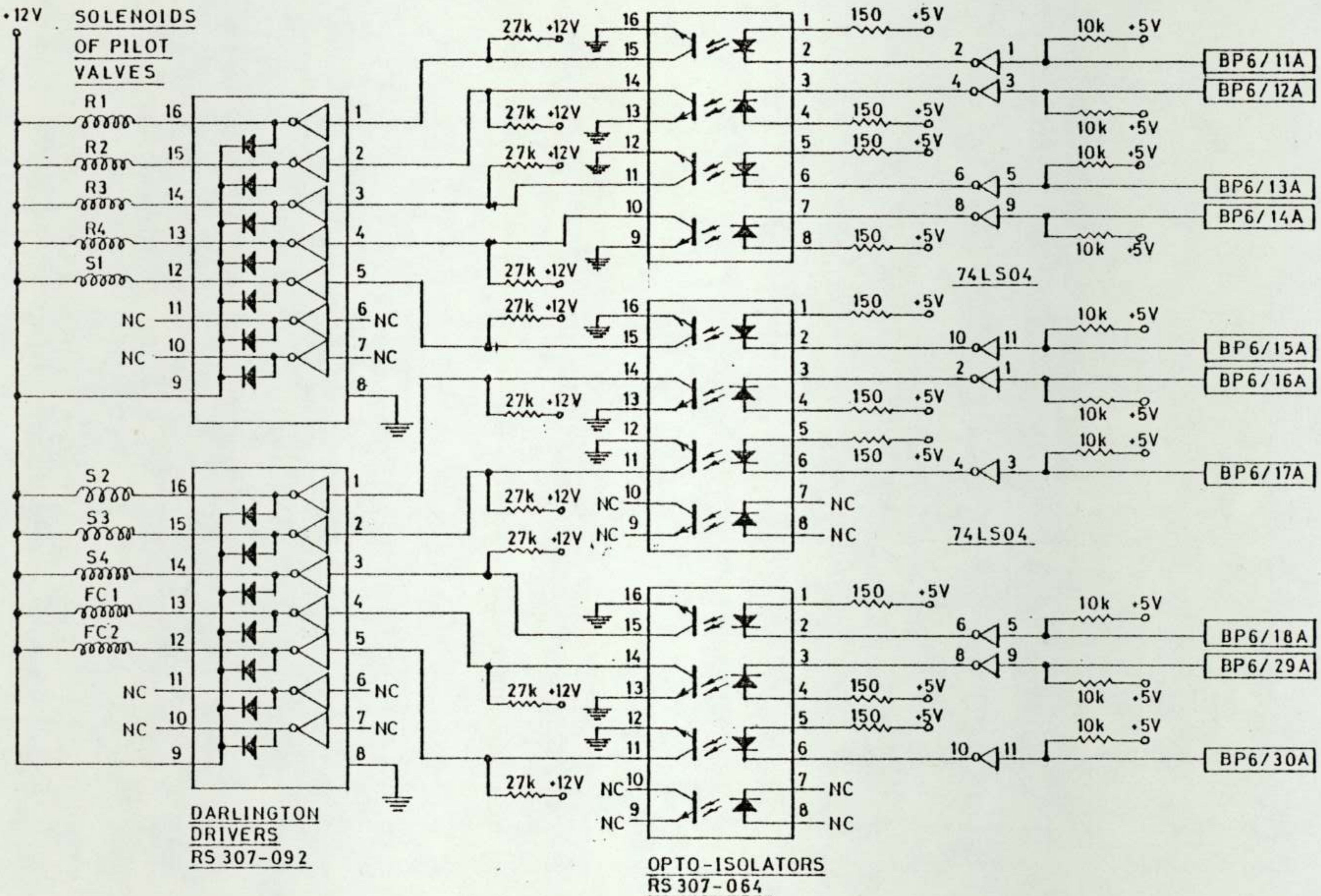


A.D.C. & SIGNAL CONDITIONING CARD (1 OF 2 DIAGRAMS)

HARDWARE DIAGRAM 4

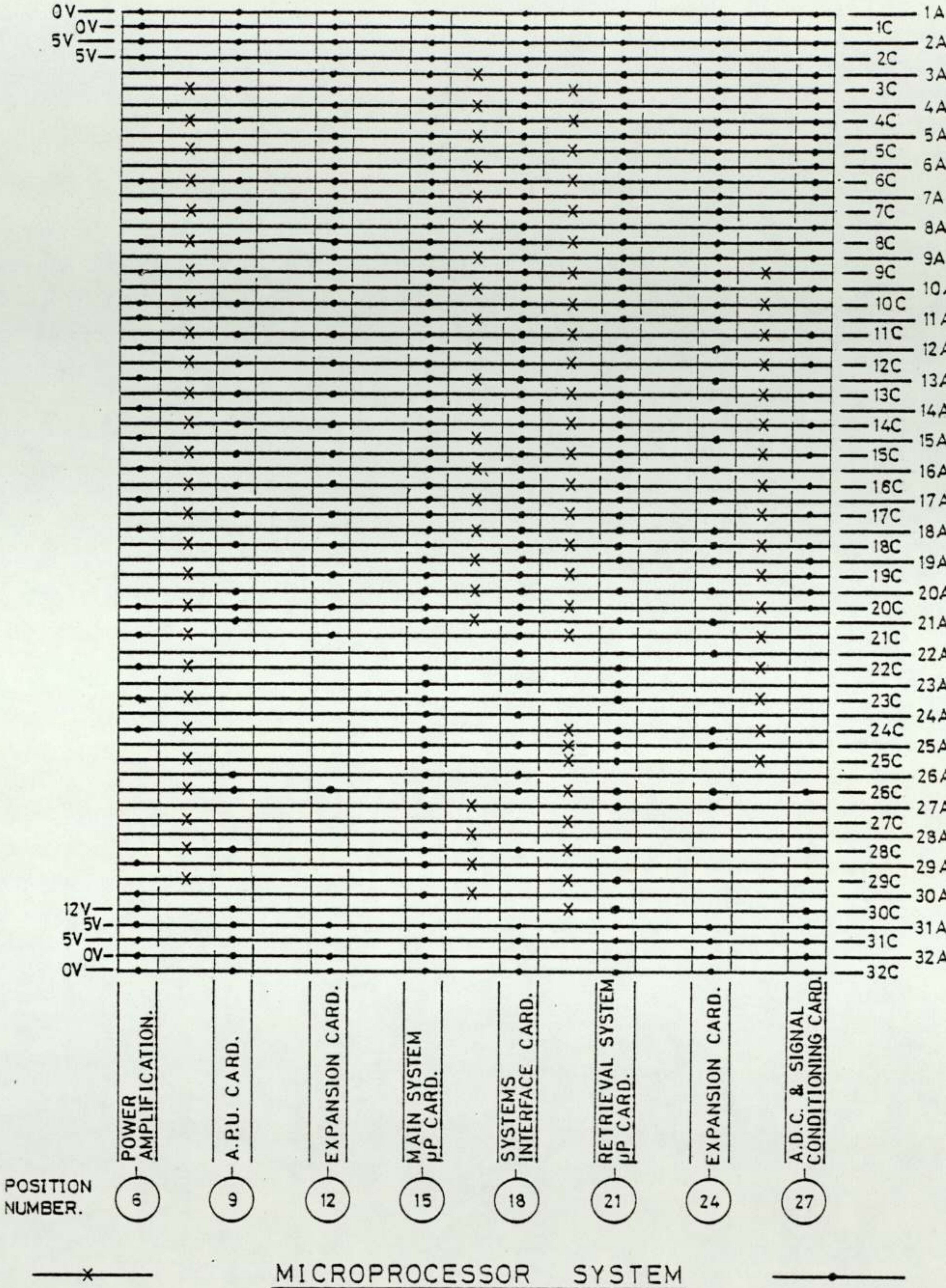


SIGNAL CONDITIONING CARD (1 OF 2 DIAGRAMS) & ANALOGUE INPUTS. HARDWARE DIAGRAM 5



POWER AMPLIFICATION CARD

HARDWARE DIAGRAM 6



MICROPROCESSOR SYSTEM

BACKPLANE

HARDWARE DIAGRAM 7

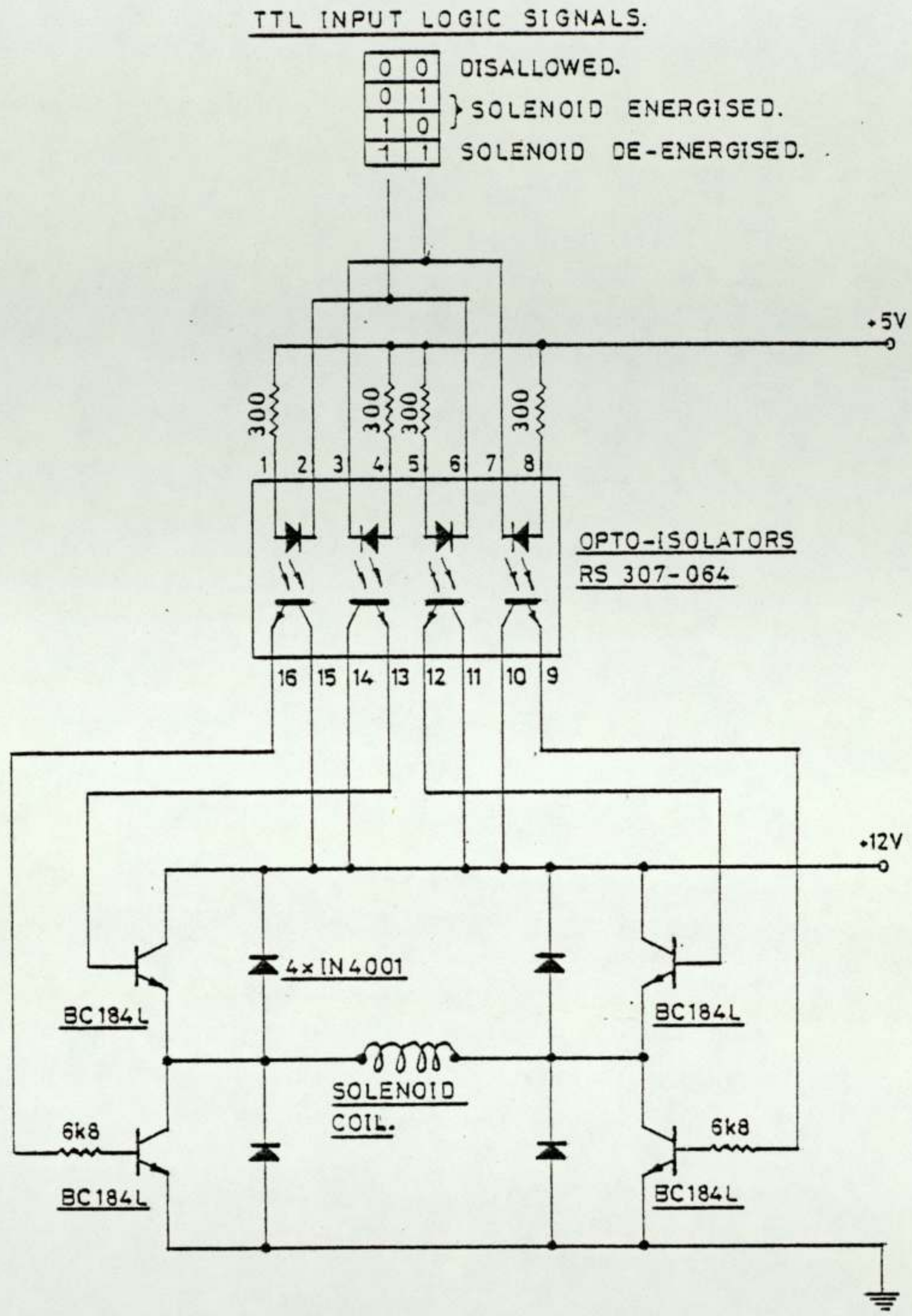


FIGURE A.8 CIRCUIT FOR SOLENOID POLARITY REVERSAL.

APPENDIX B

SYSTEM PROGRAMMES

APPENDIX B.

INFORMATION RETRIEVAL AND INPUT DATA PREPARATION SYSTEM PROGRAMMES.

This section contains the assembly language programmes for the control algorithms described in Chapter 8. The programmes are based on the 8085A microprocessor instruction set.

The RAM storage locations and description are shown on page 219.

```
                              ; ***********************************************************
                              ; *  INITIALIZATION ROUTINE FOR INFORMATION RETRIEVAL &      *
                              ; *  DATA PREPARATION SYSTEM.                                *
                              ; ***********************************************************
                              ; *  LABEL :- INITAL:                                        *
                              ; ***********************************************************
                              ; *  ENTERED BY SYSTEM "POWER UP" & RELEASE OF RESET         *
                              ; *  BUTTON.                                                 *
                              ; *  ON LEAVING :- RST5.5 & RST6.5 MASKED, RST7.5            *
                              ; *  UNMASKED & DISABLED, HOLD ENABLED & PORTS A & B         *
                              ; *  ASSIGNED AS OUTPUT PORTS.                               *
                              ; *  EXIT DIRECT INTO MAIN ROUTINE.                          *
                              ; ***********************************************************

                  CSEG
0000 31A01B         INITAL: LXI  SP,STSP    ; LOCATE STACK POINTER.
0003 3E12                   MVI  A,012H     ; INITIALIZE PORT B.
0005 D301                   OUT  001H       ;
0007 3EFF                   MVI  A,0FFH     ; MAKE ALL OF PORT B AN OUTPUT PORT.
0009 D303                   OUT  003H       ;
000B 0653                   MVI  B,053H     ; MAKE 83D CONSECUTIVE BYTES OF MEMORY ZERO BEGINNING
000D 21A21B                 LXI  H,STO      ; AT STO.
0010 3E00                   MVI  A,000H     ;
0012 77             ZERO0:  MOV  M,A        ;
0013 05                     DCR  B          ;
0014 23                     INX  H          ;
0015 C21200    C            JNZ  ZERO0      ;
0018 3EFF           GATIME: MVI  A,0FFH     ; MAKE ALL OF PORT A AN OUTPUT PORT.
001A D302                   OUT  002H       ;
001C 3E07                   MVI  A,007H     ; GATE ALL THREE TIMERS.
001E D300                   OUT  000H       ;
0020 3EB6           COUNT2: MVI  A,0B6H     ; SET TIMER 2 AS A SQUARE WAVE GEN.
0022 D333                   OUT  033H       ;
0024 3E1A                   MVI  A,01AH     ; COUNT REGISTER BYTE,LSB.
0026 D332                   OUT  032H       ;
0028 C33E00    C            JMP  CONTT2     ; JUMP TO CONTINUE TIMER 2 ROUTINE.
002C                        ORG  0002CH     ; LOCATE RST5.5 SERVICE ROUTINE TO ADDRESS 0002CH.
002C C32E03    C    SR55:   JMP  SR8        ; JUMP TO PROFILE STORAGE SUB-ROUTINE.
0034                        ORG  00034H     ; LOCATE RST6.5 SERVICE ROUTINE TO ADDRESS 00034H.
0034 C3A703    C    SR65:   JMP  PRFIN      ; JUMP TO LEAVE PROFILE STORAGE SUB-ROUTINE.
003C                        ORG  0003CH     ; LOCATE RST7.5 SERVICE ROUTINE TO ADDRESS 0003CH.
003C 7E             SR75:   MOV  A,M        ; MOVE CONVERSION TO ACCUMULATOR.
003D C9                     RET             ; RETURN.
003E 3E00           CONTT2: MVI  A,000H     ; COUNT REGISTER BYTE,MSB.
0040 D332                   OUT  032H       ;
0042 3E74           COUNT1: MVI  A,074H     ; SET TIMER 1 AS TIME INDICATOR.MODE 2.
0044 D333                   OUT  033H       ;
0046 3EFF                   MVI  A,0FFH     ; COUNT REGISTER BYTE.LSB.
0048 D331                   OUT  031H       ;
```

```
004A 3EFF             MVI  A,0FFH    ; COUNT REGISTER BYTE.MSB.
004C D331             OUT  031H      ;
004E 3E34    COUNT0:  MVI  A,034H    ; SET TIMER 0 AS TIME INDICATOR.MODE 2.
0050 D333             OUT  033H      ;
0052 3EFF             MVI  A,0FFH    ; COUNT REGISTER BYTE.LSB.
0054 D330             OUT  030H      ;
0056 3EFF             MVI  A,0FFH    ; COUNT REGISTER BYTE.MSB.
0058 D330             OUT  030H      ;
005A 3E04             MVI  A,004H    ; RESET TIMERS 0 AND 1.
005C D300             OUT  000H      ;
005E 3E0B             MVI  A,00BH    ; UNMASK RST 7.5 INTERRUPT.
0060 30               SIM            ;
0061 210038  CHA0:    LXI  H,03800H  ; LOAD CHANNEL 0 SELECTION ADDRESS.
0064 77               MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
0065 FB               EI             ; ENABLE INTERRUPT.
0066 76               HLT            ; WAIT FOR E.O.C.
0067 32A21B           STA  ST0       ; MOVE CONVERSION TO STORE 0.
006A 32E31B           STA  ST1       ; MOVE CONVERSION TO STORE 1.
006D 3E05             MVI  A,005H    ; START TIMER 0.
006F D300             OUT  000H      ;
0071 3E8C             MVI  A,08CH    ; STORE TIME FOR LOOPING OF CHANNEL 0 IN ST2M FOR
0073 32A41B           STA  ST2M      ; MSB AND ST2L FOR LSB.
0076 3EA0             MVI  A,0A0H    ;
0078 32A31B           STA  ST2L      ;
007B 210138  CHA1:    LXI  H,03801H  ; LOAD CHANNEL 1 SELECTION ADDRESS.
007E 77               MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
007F FB               EI             ; ENABLE INTERRUPT.
0080 76               HLT            ; WAIT FOR E.O.C.
0081 32AD1B           STA  ST7       ; MOVE CONVERSION TO STORE 7.
0084 32E41B           STA  ST8       ; MOVE CONVERSION TO STORE 8.
0087 3E07             MVI  A,007H    ; START TIMER 1.
0089 D300             OUT  000H      ;
008B 3E8C             MVI  A,08CH    ; STORE TIME FOR LOOPING OF CHANNEL 1 IN ST9M
008D 32AF1B           STA  ST9M      ; FOR MSB AND ST9L FOR LSB.
0090 3EA0             MVI  A,0A0H    ;
0092 32AE1B           STA  ST9L      ;
```

```
                                          ; **************************************************
                                          ; *  MAIN PROGRAMME FOR THE INFORMATION RETRIEVAL  *
                                          ; *  AND INPUT DATA PREPARATION SYSTEM.            *
                                          ; **************************************************
                                          ; *  LABEL :- MLOOP:                               *
                                          ; **************************************************
                                          ; *  ENTERED DIRECT FROM INITIALIZATION ROUTINE &  *
                                          ; *  FROM SR4:, SR7: & SR8:.                       *
                                          ; *  ON ENTERING :- RST5.5 & RST6.5 MASKED,        *
                                          ; *  RST7.5 UNMASKED & DISABLED , HOLD ENABLED &   *
                                          ; *  PORTS A & B ASSIGNED AS OUTPUT PORTS.         *
                                          ; *  ON LEAVING :- CONDITIONS AS ON ENTERING.      *
                                          ; *  EXIT ROUTINE ON COMPARISON OUTCOMES TO SR2:,  *
                                          ; *  SR3:, SR5:, & SR7:.                           *
                                          ; **************************************************
0095 CD2901   C  MLOOP:  CALL SR1         ; CALL SUB ROUTINE 1 FOR OTHER CONVERSIONS.
0098 210038      CHAOM:  LXI  H,03800H    ; LOAD CHANNEL 0 SELECTION ADDRESS.
009B 77                  MOV  M,A         ; ACTIVATE WR TO START CONVERSION.
009C FB                  EI               ; ENABLE INTERRUPT.
009D 76                  HLT              ; WAIT FOR E.O.C.
009E 32A21B              STA  ST0         ; STORE CONVERSION TO STORE 0.
00A1 3E00                MVI  A,000H      ; LATCH COUNT INTO STORAGE REGISTER OF TIMER 0.
00A3 D333                OUT  033H        ;
00A5 DB30                IN   030H        ; READ TIME LSB.
00A7 2F                  CMA              ; COMPLEMENT TIME LSB TO GIVE COUNT-UP.
00A8 32A51B              STA  ST3L        ; STORE TO ST3L TIME LSB.
00AB DB30                IN   030H        ; READ TIME MSB.
00AD 2F                  CMA              ; COMPLEMENT TIME MSB TO GIVE COUNT-UP.
00AE 32A61B              STA  ST3M        ; STORE TO ST3M TIME MSB.
00B1 21E31B      COMCON: LXI  H,ST1       ; LOCATION OF PREVIOUS CONVERSION.
00B4 3AA21B              LDA  ST0         ; NEW CONVERSION TO ACCUMULATOR.
00B7 96                  SUB  M           ; NEW CONVERSION MINUS PREVIOUS CONVERSION.
00B8 D2BD00   C          JNC  COMP0       ; JUMP IF PREVIOUS CONVERSION > NEW CONVERSION.
00BB 2F                  CMA              ; FIND 2'COMPLEMENT OF SUB M RESULT.
00BC 3C                  INR  A           ;
00BD FE03        COMP0:  CPI  003H        ; IS DIFFERENCE > OR = 3 RESOLUTIONS.
00BF D26801   C          JNC  SR2         ; TRUE,GO TO SUB ROUTINE 2.
00C2 21A41B      COMTIO: LXI  H,ST2M      ; LOCATION OF TIME STORE MSB.
00C5 3AA61B              LDA  ST3M        ; TIME MSB TO ACCUMULATOR.
00C8 BE                  CMP  M           ; COMPARE TIME MSB WITH TIME STORE MSB.
00C9 CAD200   C          JZ   LSBTO       ; TIME MSB = TIME STORE MSB.
00CC DADF00   C          JC   CHA1M       ; TIME MSB < TIME STORE MSB.
00CF C3CB01   C          JMP  SR3         ; TIME MSB > TIME STORE MSB.
00D2 21A31B      LSBTO:  LXI  H,ST2L      ; LOCATION OF TIME STORE LSB.
00D5 3AA51B              LDA  ST3L        ; TIME LSB TO ACCUMULATOR.
00D8 BE                  CMP  M           ; COMPARE TIME LSB WITH TIME STORE LSB.
00D9 CACB01   C          JZ   SR3         ; TIME LSB = TIME STORE LSB.
```

```
00DC D2CB01    C           JNC   SR3         ; TIME LSB > TIME STORE LSB.
00DF 210138          CHAIM: LXI   H,03801H    ; LOAD CHANNEL 1 SELECTION ADDRESS.
00E2 77                    MOV   M,A         ; ACTIVATE WR TO START CONVERSION.
00E3 FB                    EI                ; ENABLE INTERRUPT.
00E4 76                    HLT               ; WAIT FOR E.O.C.
00E5 32AD1B                STA   ST7         ; MOVE CONVERSION TO STORE 7.
00E8 3E40                  MVI   A,040H      ; LATCH COUNT INTO STORAGE REGISTER OF TIMER 1.
00EA D333                  OUT   033H        ;
00EC DB31                  IN    031H        ; READ TIME LSB.
00EE 2F                    CMA               ; COMPLEMENT TIME LSB TO GIVE COUNT-UP.
00EF 32B01B                STA   ST10L       ; STORE TO ST10L TIME LSB.
00F2 DB31                  IN    031H        ; READ TIME MSB.
00F4 2F                    CMA               ; COMPLEMENT TIME MSB TO GIVE COUNT-UP.
00F5 32B11B                STA   ST10M       ; STORE TIME MSB TO ST10M.
00F8 21E41B          COCHIC: LXI  H,ST8       ; LOCATION OF PREVIOUS CONVERSION.
00FB 3AAD1B                LDA   ST7         ; NEW CONVERSION TO ACCUMULATOR.
00FE 96                    SUB   M           ; NEW CONVERSION MINUS PREVIOUS CONVERSION.
00FF D20401    C           JNC   COMP1       ; JUMP IF PREVIOUS CONVERSION > NEW CONVERSION.
0102 2F                    CMA               ; FIND 2'COMPLEMENT OF SUB M RESULT.
0103 3C                    INR   A           ;
0104 FE03            COMP1: CPI   003H        ; IS DIFFERENCE > OR = 3 RESOLUTIONS.
0106 D24B02    C           JNC   SR5         ; TRUE,GO TO SUB ROUTINE 5.
0109 21AF1B          COMTI1: LXI  H,ST9M      ; LOCATION OF TIME STORE MSB.
010C 3AB11B                LDA   ST10M       ; TIME MSB TO ACCUMULATOR.
010F BE                    CMP   M           ; COMPARE TIME MSB WITH TIME STORE MSB.
0110 CA1901    C           JZ    LSBT1       ; TIME MSB = TIME STORE MSB.
0113 DA9500    C           JC    MLOOP       ; TIME MSB < TIME STORE MSB.
0116 C3AE02    C           JMP   SR6         ; TIME MSB > TIME STORE MSB.
0119 21AE1B          LSBT1: LXI   H,ST9L      ; LOCATION OF TIME STORE LSB.
011C 3AB01B                LDA   ST10L       ; TIME LSB TO ACCUMULATOR.
011F BE                    CMP   M           ; COMPARE TIME LSB WITH TIME STORE LSB.
0120 CAAE02    C           JZ    SR6         ; TIME LSB = TIME STORE LSB.
0123 D2AE02    C           JNC   SR6         ; TIME LSB > TIME STORE LSB.
0126 C39500    C           JMP   MLOOP       ;
```

```
                                    ; ***********************************************************
                                    ; *  CONVERSION OF ANALOGUE CHANNELS NOS. 2 TO 10 AND STORE. *
                                    ; *  GENERATION OF "NO MOVE" SIGNAL FROM DRIVER JOYSTICK.    *
                                    ; *  GENERATION OF "NO MOVE" SIGNAL FROM RIPPING MOTOR       *
                                    ; *  ABSORBED CURRENT SIMULATION.                            *
                                    ; ***********************************************************
                                    ; *  LABEL :- SR1.                                           *
                                    ; ***********************************************************
                                    ; *  ENTERED BY CALL INSTRUCTION IN MAIN PROGRAMME.          *
                                    ; *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5 UNMASKED  *
                                    ; *  & DISABLED, HOLD ENABLED & PORTS A & B ASSIGNED AS      *
                                    ; *  OUTPUT PORTS.                                           *
                                    ; *  ON LEAVING :- CONDITIONS AS ON ENTERING.                *
                                    ; *  EXIT ROUTINE ON RTN INSTRUCTION BACK TO MAIN PROGRAMME. *
                                    ; ***********************************************************

0129 210238       SR1:    LXI  H,03802H  ; LOAD CHANNEL 2 SELECTION ADDRESS.
012C 01DA1B               LXI  B,ST18    ; LOAD RAM ADDRESS FOR STORE 18.
012F 3E05         SR1C:   MVI  A,005H    ; CHECK IF CHANNEL 5 (RIPPING MOTOR CURRENT) IS TO BE
0131 95                   SUB  L         ; CONVERTED.
0132 77                   MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
0133 FB                   EI             ; ENABLE INTERRUPT.
0134 76                   HLT            ; WAIT FOR CONVERSION TO COMPLETE.
0135 02                   STAX B         ; STORE CONVERSION IN RAM.
0136 C25301    C          JNZ  SR1D      ; SKIP IF NOT CHANNEL 5.
0139 FEE5                 CPI  0E5H      ; CHECK IF CHANNEL 5 IS ABOVE 0E5H.
013B DB01                 IN   001H      ; GET THE CURRENT READING OF PORT B.
013D D24F01    C          JNC  NOMOVE    ; ASSUME NO MOVE IF CAPTURED DATA IS IN RANGE 0E6H TO
                                         ; 0FFH INCLUSIVE.
0140 0B                   DCX  B         ; POINT TO CHANNEL 4 (BOOM MOVE).
0141 0A                   LDAX B         ; LOAD CHANNEL 4 CONVERSION TO ACCUMULATOR.
0142 03                   INX  B         ; POINT TO CHANNEL 5 (RIPPING MOTOR CURRENT).
0143 FE10                 CPI  010H      ; CHECK IF BELOW 010H.
0145 DB01                 IN   001H      ; GET THE CURRENT READING OF PORT B.
0147 DA4F01    C          JC   NOMOVE    ; ASSUME `NO MOVE' IF THE CAPTURED DATA IS WITHIN THE
                                         ; RANGE 000H TO 00FH INCLUSIVE.
014A F601                 ORI  001H      ; OTHERWISE A `MOVE' SIGNAL IS GENERATED BY MAKING THE
                                         ; LSB OF THE ACCUMULATOR ONE.
014C C35101    C          JMP  OUTB0     ; JUMP TO OUTPUT THIS TO PORT B.
014F E6FE         NOMOVE: ANI  0FEH      ; A `NO MOVE' SIGNAL IS GENERATED BY MAKING THE LSB OF
                                         ; THE ACCUMULATOR ZERO.
0151 D301         OUTB0:  OUT  001H      ; OUTPUT THIS SIGNAL TO PORT B.
0153 3E0A         SR1D:   MVI  A,00AH    ; LOAD ACCUMULATOR WITH LAST CONVERSION ADDRESS BYTE.
0155 BD                   CMP  L         ; COMPARE REGISTER L WITH ACCUMULATOR.
0156 CA5E01    C          JZ   ENTAD     ; JUMP IF THEY COMPARE TO LOOK FOR RST5.5 INTERRUPT.
0159 2C                   INR  L         ; INCREMENT FOR NEXT CHANNEL SELECTION ADDRESS.
015A 03                   INX  B         ; INCREMENT FOR NEXT STORAGE ADDRESS.
015B C32F01    C          JMP  SR1C      ; GO TO START OF THIS SUB ROUTINE.
```

```
015E 3E0E       ENTAD:  MVI  A,00EH    ; MASK RST7.5 & RST6.5.UNMASK RST5.5.
0160 30                 SIM            ; SET INTERRUPT MASK
0161 FB                 EI             ; ENABLE RST5.5. INTERRUPT.
0162 00                 NOP            ;
0163 F3                 DI             ; DISABLE RST5.5 INTERRUPT.
0164 3E0B               MVI  A,00BH    ; MASK RST5.5 & RST6.5.UNMASK RST7.5.
0166 30                 SIM            ; SET INTERRUPT MASK.
0167 C9         ENDSR1: RET            ; RETURN.
```

```
                                    ;   ***********************************************************
                                    ;   *      CALCULATIOIN OF SLEWING VELOCITY (CHANNEL 0).      *
                                    ;   ***********************************************************
                                    ;   *  LABEL :- SR2.                                          *
                                    ;   ***********************************************************
                                    ;   *  ENTERED WHEN THERE ARE THREE OR MORE BITS DIFFERENCE   *
                                    ;   *  ON CHANNEL 0 CONVERSIONS.                              *
                                    ;   *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5          *
                                    ;   *  UNMASKED & DISABLED, HOLD ENABLED & PORTS A & B        *
                                    ;   *  ASSIGNED AS OUTPUT PORTS.                              *
                                    ;   *  ON LEAVING :- CONDITIONS AS ON ENTERING.               *
                                    ;   *  EXIT ROUTINE ON JMP INSTRUCTION TO SR4:.               *
                                    ;   ***********************************************************
0168 3E06           SR2:    MVI  A,006H  ; RESET TIMER 0.
016A D300                   OUT  000H    ;
016C 3E07                   MVI  A,007H  ; START TIMER 0.
016E D300                   OUT  000H    ;
0170 21E31B                 LXI  H,ST1   ; H,L POINT AT ST1 (SUBTRAHEND).
0173 3AA21B                 LDA  ST0     ; ST0 TO ACCUMULATOR (MINUEND).
0176 96                     SUB  M       ; (ST0-ST1).
0177 21B81B                 LXI  H,ST14  ; STORE RESULT IN ST14 IN INTEGER FORM
017A 77                     MOV  M,A     ; SUITABLE FOR F-P.LIBRARY.
017B DA8901     C           JC   NEG     ;
017E 3E00                   MVI  A,000H  ; IF POSITIVE:-
0180 2C                     INR  L       ;  MSB 000000?? LSB
0181 77                     MOV  M,A     ;
0182 2C                     INR  L       ;
0183 77                     MOV  M,A     ;
0184 2C                     INR  L       ;
0185 77                     MOV  M,A     ;
0186 C39101     C           JMP  VOBCAL  ; CALCULATE VELOCITY OF CHANNEL 0.
0189 3EFF           NEG:    MVI  A,0FFH  ; IF NEGATIVE:-
018B 2C                     INR  L       ;  MSB FFFFFF?? LSB
018C 77                     MOV  M,A     ;
018D 2C                     INR  L       ;
018E 77                     MOV  M,A     ;
018F 2C                     INR  L       ;
0190 77                     MOV  M,A     ;
0191 01C81B         VOBCAL: LXI  B,FPR   ; B,C POINT AT FPR.
0194 C5                     PUSH B       ; PLACE ON STACK.
0195 010000                 LXI  B,000H  ; DEFAULT ERROR HANDLER TO BE USED.
0198 CD0000     E           CALL FSET    ; FPR IS INITIALISED.
019B 01C81B                 LXI  B,FPR   ; B,C POINT AT FPR.
019E 11A51B                 LXI  D,ST3L  ; D,E POINT AT ST3L.
01A1 CD0000     E           CALL FLTDS   ; CONVERT INTEGER TIME INTO F-P.TIME AND LOAD INTO FAC.
01A4 11C01B                 LXI  D,ST16  ; D,E POINT AT ST16.
01A7 CD0000     E           CALL FSTOR   ; F-P.TIME MEASUREMENT TO ST16.
01AA 11B81B                 LXI  D,ST14  ; D,E POINT AT ST14.
```

```
01AD CD0000   E                CALL FLTDS     ; CONVERT(ST0-ST1)FROM INTEGER TO F-P.AND LOAD INTO FAC.
01B0 11C01B                    LXI  D,ST16    ; D,E POINT TO ST16.
01B3 CD0000   E                CALL FDIV      ; (ST0-ST1)/ST16=VELOCITY FOR CHANNEL 0.
01B6 DB01                      IN   001H      ; DISABLE HOLD REQUEST.
01B8 F680                      ORI  080H      ; MAKE PB7 LOGIC 1.
01BA D301                      OUT  001H      ;
01BC 11E51B                    LXI  D,ST5A    ; D,E POINT AT ST5A.
01BF CD0000   E                CALL FSTOR     ; VOB STORED AT ST5A,B,C AND D.
01C2 DB01                      IN   001H      ; ENABLE HOLD REQUEST.
01C4 E67F                      ANI  07FH      ; MAKE PB7 LOGIC 0.
01C6 D301                      OUT  001H      ;
01C8 C30602   C         ENDSR2: JMP  SR4       ; JUMP TO SUB-ROUTINE 4.
```

```
                                  ; *******************************************************
                                  ; *                SETTING SLEWING VELOCITY TO ZERO.    *
                                  ; *******************************************************
                                  ; *  LABEL :- SR3:                                      *
                                  ; *******************************************************
                                  ; *  ENTERED WHEN TIME IS EXPENDED WITHOUT CHANGE ON    *
                                  ; *  CHANNEL 0.                                         *
                                  ; *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5      *
                                  ; *  UNMASKED & DISABLED, HOLD ENABLED & PORTS A & B    *
                                  ; *  ASSIGNED AS OUTPUT PORTS.                          *
                                  ; *  ON LEAVING :- CONDITIONS AS ON ENTERING.           *
                                  ; *  EXIT ROUTINE DIRECT INTO SR4:.                     *
                                  ; *******************************************************
01CB 3E06         SR3:     MVI  A,006H   ; RESET TIMER 0.
01CD D300                  OUT  000H     ;
01CF 3E07                  MVI  A,007H   ; START TIMER 0
01D1 D300                  OUT  000H     ;
01D3 DB01                  IN   001H     ; DISABLE HOLD REQUEST.
01D5 F680                  ORI  080H     ; MAKE PB7 LOGIC 1.
01D7 D301                  OUT  001H     ;
01D9 3E00                  MVI  A,000H   ; MAKE VOB IN STORE 5 ZERO.
01DB 32E51B                STA  ST5A     ;
01DE 32E61B                STA  ST5B     ;
01E1 32E71B                STA  ST5C     ;
01E4 32E81B                STA  ST5D     ;
01E7 DB01                  IN   001H     ; ENABLE HOLD REQUEST.
01E9 E67F                  ANI  07FH     ; MAKE PB7 LOGIC 0.
01EB D301                  OUT  001H     ;
01ED 01C81B                LXI  B,FPR    ; B,C POINT AT FPR.
01F0 C5                    PUSH B        ; PLACE ON STACK.
01F1 010000                LXI  B,000H   ; DEFAULT ERROR HANDLER TO BE USED.
01F4 CD0000   E            CALL FSET     ; FPR IS INTIALISED.
01F7 01C81B                LXI  B,FPR    ; B,C POINT AT FPR.
01FA 11A51B                LXI  D,ST3L   ; D,E POINT AT ST3L.
01FD CD0000   E            CALL FLTDS    ; CONVERT INTEGER TIME INTO F-P TIME AND LOAD INTO FAC.
0200 11C01B                LXI  D,ST16   ; D,E POINT AT ST16.
0203 CD0000   E   ENDSR3:  CALL FSTOR    ; F-P TIME MEASURMENT TO ST16.
```

```
                                ;   **************************************************************
                                ;   *       CALCULATION OF SLEWING ACCELERATION (CHANNEL 0).      *
                                ;   **************************************************************
                                ;   *  LABEL :- SR4:                                              *
                                ;   **************************************************************
                                ;   *  ENTERED ON JMP INSTRUCTION FROM SR2: & DIRECT FROM SR3:.  *
                                ;   *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5 UNMASKED    *
                                ;   *  & DISABLED, HOLD ENABLED & PORTS A & B ASSIGNED AS        *
                                ;   *  OUTPUT PORTS.                                              *
                                ;   *  ON LEAVING :- CONDITIONS AS ON ENTERING.                   *
                                ;   *  EXIT ROUTINE ON JMP INSTRUCTION TO MAIN PROGRAMME.         *
                                ;   **************************************************************
0206 11E51B        SR4:     LXI  D,ST5A     ; D,E POINT AT ST5A. (MINUEND)
0209 CD0000   E             CALL FLOAD      ; V0B IS LOADED INTO FAC.
020C 11A91B                 LXI  D,ST4A     ; D,E POINT AT ST4A. (SUBTRAHEND)
020F CD0000   E             CALL FSUB       ; (V0B-V0A) IS LOADED INTO FAC.
0212 11C01B                 LXI  D,ST16     ; D,E POINT AT ST3L.
0215 CD0000   E             CALL FDIV       ; (V0B-V0A)/TIME IS LOADED INTO FAC.
0218 DB01                   IN   001H       ; DISABLE HOLD REQUEST.
021A F680                   ORI  080H       ; MAKE PB7 LOGIC 1.
021C D301                   OUT  001H       ;
021E 11E91B                 LXI  D,ST6      ; D,E POINT AT ST6.
0221 CD0000   E             CALL FSTOR      ; A0 STORED AT ST6.
0224 DB01                   IN   001H       ; ENABLE HOLD REQUEST.
0226 E67F                   ANI  07FH       ; MAKE PB7 LOGIC 0.
0228 D301                   OUT  001H       ;
022A 3AE51B                 LDA  ST5A       ; MAKE V0A =V0B.
022D 32A91B                 STA  ST4A       ;
0230 3AE61B                 LDA  ST5B       ;
0233 32AA1B                 STA  ST4B       ;
0236 3AE71B                 LDA  ST5C       ;
0239 32AB1B                 STA  ST4C       ;
023C 3AE81B                 LDA  ST5D       ;
023F 32AC1B                 STA  ST4D       ;
0242 3AA21B                 LDA  ST0        ; MOVE CONVERSION AT STORE 0 TO ACCUMULATOR.
0245 32E31B                 STA  ST1        ; MOVE ACCUMULATOR TO STORE 1.
0248 C3DF00   C    ENDSR4:  JMP  CHA1M      ; RETURN TO MAIN PROGRAMME.
```

```
                                ; *********************************************************
                                ; *  CALCULATION OF RAISING/LOWERING VELOCITY (CHANNEL 1). *
                                ; *********************************************************
                                ; *  LABEL SR5:                                           *
                                ; *********************************************************
                                ; *  ENTERED WHEN THERE ARE THREE OR MORE BITS DIFFERENCE  *
                                ; *  ON CHANNEL 1 CONVERSIONS.                            *
                                ; *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5        *
                                ; *  UNMASKED & DISABLED, HOLD ENABLED & PORTS A & B      *
                                ; *  ASSIGNED AS OUTPUT PORTS.                            *
                                ; *  ON LEAVING :- CONDITIONS AS ON ENTERING.             *
                                ; *  EXIT ROUTINE ON JMP INSTRUCTION TO SR7:              *
                                ; *********************************************************
024B 3E05        SR5:    MVI  A,005H   ; RESET TIMER 1.
024D D300                OUT  000H     ;
024F 3E07                MVI  A,007H   ; START TIMER 1.
0251 D300                OUT  000H     ;
0253 21E41B              LXI  H,ST8    ; H,L POINT AT ST8 (SUBTRAHEND).
0256 3AAD1B              LDA  ST7      ; ST7 TO ACCUMULATOR (MINUEND).
0259 96                  SUB  M        ; (ST7-ST8)
025A 21BC1B              LXI  H,ST15   ; STORE RESULT IN ST15 IN INTEGER FORM
025D 77                  MOV  M,A      ; SUITABLE FOR F-P.LIBRARY.
025E DA6C02   C          JC   NEG1     ;
0261 3E00                MVI  A,000H   ; IF POSITVE:-
0263 2C                  INR  L        ;  MSB 000000?? LSB
0264 77                  MOV  M,A      ;
0265 2C                  INR  L        ;
0266 77                  MOV  M,A      ;
0267 2C                  INR  L        ;
0268 77                  MOV  M,A      ;
0269 C37402   C          JMP  V1BCAL   ; CALCULATE VELOCITY OF CHANNEL 1.
026C 3EFF        NEG1:   MVI  A,0FFH   ; IF NEGATIVE:-
026E 2C                  INR  L        ;  MSB FFFFFF?? LSB
026F 77                  MOV  M,A      ;
0270 2C                  INR  L        ;
0271 77                  MOV  M,A      ;
0272 2C                  INR  L        ;
0273 77                  MOV  M,A      ;
0274 01C81B      V1BCAL: LXI  B,FPR    ; B,C POINT AT FPR.
0277 C5                  PUSH B        ; PLACE ON STACK.
0278 010000              LXI  B,000H   ; DEFAULT ERROR HANDLER TO BE USED.
027B CD0000   E          CALL FSET     ; FPR IS INITIALISED.
027E 01C81B              LXI  B,FPR    ; B,C POINT AT FPR.
0281 11B01B              LXI  D,ST10L  ; D,E POINT AT ST10L.
0284 CD0000   E          CALL FLTDS    ; CONVERT INTEGER TIME INTO F-P.TIME AND LOAD INTO FAC.
0287 11C41B              LXI  D,ST17   ; D,E POINT AT ST17.
028A CD0000   E          CALL FSTOR    ; F-P.TIME MEASUREMENT TO ST17.
028D 11BC1B              LXI  D,ST15   ; D,E POINT AT ST15.
```

```
0290 CD0000    E          CALL FLTDS     ; CONVERT(ST7-ST8)FROM INTEGER TO F-P.AND LOAD INTO FAC.
0293 11C41B               LXI  D,ST17    ; D.E POINT TO ST17.
0296 CD0000    E          CALL FDIV      ; (ST7-ST8)/ST17=VELOCITY FOR CHANNEL 1.
0299 DB01                 IN   001H      ; DISABLE HOLD REQUEST.
029B F680                 ORI  080H      ; MAKE PB7 LOGIC 1.
029D D301                 OUT  001H      ;
029F 11ED1B               LXI  D,ST12A   ; D,E POINT AT ST12A.
02A2 CD0000    E          CALL FSTOR     ; V1B STORED AT ST12A,B,C AND D.
02A5 DB01                 IN   001H      ; ENABLE HOLD REQUEST.
02A7 E67F                 ANI  07FH      ; MAKE PB7 LOGIC 0.
02A9 D301                 OUT  001H      ;
02AB C3E902    C  ENDSR5: JMP  SR7       ; JUMP TO SUB-ROUTINE 7.
```

```
                                    ;  *****************************************************
                                    ;  *      SETTING RAISING/LOWERING VELOCITY TO ZERO.   *
                                    ;  *****************************************************
                                    ;  *  LABEL :- SR6:                                    *
                                    ;  *****************************************************
                                    ;  *  ENTERED WHEN TIME IS EXPENDED WITHOUT CHANGE ON  *
                                    ;  *  CHANNEL 1.                                       *
                                    ;  *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5    *
                                    ;  *  UNMASKED & DISABLED, HOLD ENABLED & PORTS A & B  *
                                    ;  *  ASSIGNED AS OUTPUT PORTS.                        *
                                    ;  * ON LEAVING :- CONDITONS AS ON ENTERING.           *
                                    ;  * EXIT ROUTINE DIRECT INTO SR7:.                    *
                                    ;  *****************************************************
02AE 3E05          SR6:     MVI  A,005H   ; RESET TIMER 1.
02B0 D300                   OUT  000H     ;
02B2 3E07                   MVI  A,007H   ; START TIMER 1.
02B4 D300                   OUT  000H     ;
02B6 DB01                   IN   001H     ; DISABLE HOLD REQUEST.
02B8 F680                   ORI  080H     ; MAKE PB7 LOGIC 1.
02BA D301                   OUT  001H     ;
02BC 3E00                   MVI  A,000H   ; MAKE V1B IN STORE 12 ZERO.
02BE 32ED1B                 STA  ST12A    ;
02C1 32EE1B                 STA  ST12B    ;
02C4 32EF1B                 STA  ST12C    ;
02C7 32F01B                 STA  ST12D    ;
02CA DB01                   IN   001H     ; ENABLE HOLD REQUEST.
02CC E67F                   ANI  07FH     ; MAKE PB7 LOGIC 0.
02CE D301                   OUT  001H     ;
02D0 01C81B                 LXI  B,FPR    ; B,C POINT AT FPR.
02D3 C5                     PUSH B        ; PLACE ON STACK.
02D4 010000                 LXI  B,000H   ; DEFAULT ERROR HANDLER TOI BE USED.
02D7 CD0000    E            CALL FSET     ; FPR IS INTIALISED.
02DA 01C81B                 LXI  B,FPR    ; B,C POINT AT FPR.
02DD 11B01B                 LXI  D,ST10L  ; D,E POINT AT ST10L.
02E0 CD0000    E            CALL FLTDS    ; CONVERT INTEGER TIME INTO F-P TIME AND LOAD INTO FAC.
02E3 11C41B                 LXI  D,ST17   ; D,E POINT AT ST17.
02E6 CD0000    E   ENDSR6:  CALL FSTOR    ; F-P TIME MEASUREMENT TO ST17.
```

```
                                      ;  ****************************************************************
                                      ;  *  CALCULATION OF RAISING/LOWERING ACCELERATION (CHANNEL 1).  *
                                      ;  ****************************************************************
                                      ;  *  LABEL :- SR7:                                               *
                                      ;  ****************************************************************
                                      ;  *  ENTERED ON JMP INSTRUCTION FROM SR5: & DIRECT FROM SR6:.   *
                                      ;  *  ON ENTERING :- RST5.5 & RST6.5 MASKED, RST7.5 UNMASKED     *
                                      ;  *  & DISABLED, HOLD ENABLED & PORTS A & B ASSIGNED AS         *
                                      ;  *  OUTPUT PORTS.                                               *
                                      ;  *  ON LEAVING :- CONDITIONS AS ON ENTERING.                   *
                                      ;  *  EXIT ROUTINE ON JMP INSTRUCTION TO MAIN PROGRAMME.         *
                                      ;  ****************************************************************
02E9 11ED1B      SR7:    LXI  D,ST12A  ; D,E POINT AT ST12A. (MINUEND)
02EC CD0000   E          CALL FLOAD    ; V1B IS LOADED INTO FAC.
02EF 11B41B              LXI  D,ST11A  ; D,E POINT AT ST11A. (SUBTRAHEND)
02F2 CD0000   E          CALL FSUB     ; (V1B-V1A) IS LOADED INTO FAC.
02F5 11C41B              LXI  D,ST17   ; D,E POINT AT ST17.
02F8 CD0000   E          CALL FDIV     ; (V1B-V1A)/TIME IS LOADED INTO FAC.
02FB DB01                IN   001H     ; DISABLE HOLD REQUEST.
02FD F680                ORI  080H     ; MAKE PB7 LOGIC 1.
02FF D301                OUT  001H     ;
0301 11F11B              LXI  D,ST13   ; D,E POINT AT ST13.
0304 CD0000   E          CALL FSTOR    ; A1 STORED AT ST13.
0307 DB01                IN   001H     ; ENABLE HOLD REQUEST.
0309 E67F                ANI  07FH     ; MAKE PB7 LOGIC 0.
030B D301                OUT  001H     ;
030D 3AED1B              LDA  ST12A    ; MAKE V1A = V1B.
0310 32B41B              STA  ST11A    ;
0313 3AEE1B              LDA  ST12B    ;
0316 32B51B              STA  ST11B    ;
0319 3AEF1B              LDA  ST12C    ;
031C 32B61B              STA  ST11C    ;
031F 3AF01B              LDA  ST12D    ;
0322 32B71B              STA  ST11D    ;
0325 3AAD1B              LDA  ST7      ; MOVE CONVERSION AT STORE 7 TO ACCUMULATOR.
0328 32E41B              STA  ST8      ; MOVE ACCUMULATOR TO STORE 8.
032B C39500   C  ENDSR7: JMP  MLOOP    ; RETURN TO MAIN PROGRAMME.
```

```
                              ; ***************************************************
                              ; *              PROFILE STORAGE ROUTINE.           *
                              ; ***************************************************
                              ; *  LABEL :- SR8:                                  *
                              ; ***************************************************
                              ; *  ENTERED ON PRESS OF "ENTER DATA" BUTTON WHICH  *
                              ; *  ACTIVATES RST5.5.                              *
                              ; *  ON ENTERING :- RST5.5 UNMASKED & DISABLED,     *
                              ; *  RST6.5 & RST7.5 MASKED, HOLD ENABLED & PORTS   *
                              ; *  A & B ASSIGNED AS OUTPUT PORTS.                *
                              ; *  ON LEAVING :- RST5.5 & RST7.5 MASKED, RST6.5   *
                              ; *  UNMASKED & DISABLED & HOLD ENABLED.            *
                              ; *  EXIT ROUTINE ON PRESS OF "END OF DATA" BUTTON  *
                              ; *  WHICH ACTIVATES RST6.5.                        *
                              ; ***************************************************
032E C1      SR8:   POP  B         ; REMOVE RST5.5 RETURN ADDRESS OF STACK.
032F 3E12           MVI  A,012H    ; DISABLE BOOM MOVE SIGNAL.
0331 D301           OUT  001H      ;
0333 3E0B           MVI  A,00BH    ; MASK RST5.5 & RST6.5.UNMASK RST7.5.
0335 30             SIM            ; SET INTERRUPT MASK.
0336 210338         LXI  H,03803H  ; LOAD CHANNEL 3 SELECTION ADDRESS.
0339 77             MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
033A FB             EI             ; ENABLE RST7.5 INTERRUPT.
033B 76             HLT            ; WAIT FOR CONVERSION TO COMPLETE.
033C 21001C         LXI  H,ST20    ; LOCATE FIRST MEMORY STORE.
033F 77             MOV  M,A       ; STORE CONVERSION.
0340 EB             XCHG           ; SAVE MEMORY STORE IN REGS. D & E.
0341 210238         LXI  H,03802H  ; LOAD CHANNEL 2 SELECTION ADDRESS.
0344 77             MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
0345 FB             EI             ; ENABLE RST7.5 INTERRUPT.
0346 76             HLT            ; WAIT FOR CONVERSION TO COMPLETE.
0347 EB             XCHG           ; RESTORE MEMORY STORE.
0348 23             INX  H         ; INCREMENT MEMORY STORE.
0349 77             MOV  M,A       ; STORE CONVERSION.
034A EB      GECHA: XCHG           ; SAVE MEMORY STORE.
034B 210338         LXI  H,03803H  ; LOAD CHANNEL 3 SELECTION ADDRESS.
034E 77             MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
034F FB             EI             ; ENABLE RST7.5 INTERRUPT.
0350 76             HLT            ; WAIT FOR CONVERSION TO COMPLETE.
0351 47             MOV  B,A       ; STORE CONVERSION TO REG.B.
0352 2B             DCX  H         ; LOAD CHANNEL 2 SELECTION ADDRESS.
0353 77             MOV  M,A       ; ACTIVATE WR TO START CONVERSION.
0354 FB             EI             ; ENABLE RST7.5 INTERRUPT.
0355 76             HLT            ; WAIT FOR CONVERSION TO COMPLETE.
0356 4F             MOV  C,A       ; STORE CONVERSION TO REG.C
0357 3E0D           MVI  A,00DH    ; MASK RST5.5 & RST7.5.UNMASK RST6.5.
```

```
0359 30                       SIM               ; SET INTERRUPT MASK.
035A EB                       XCHG              ; FETCH MEMORY STORE.
035B 2B                       DCX   H           ; POINT TO PREVIOUS CHANNEL 3 CONVERSION.
035C 78                       MOV   A,B         ; LATEST CHANNEL 3 CONVERSION TO ACCUMULATOR.
035D 96                       SUB   M           ; LATEST CONVERSION - PREVIOUS CONVERSION.
035E D26303   C               JNC   COMPA       ; JUMP IF PREVIOUS CONVERSION > NEW CONVERSION.
0361 2F                       CMA               ; FIND 2'COMPLEMENT OF SUB M RESULT.
0362 3C                       INR   A           ;
0363 FE02         COMPA:      CPI   002H        ; IS DIFFERENCE > OR = 2 RESOLUTIONS.
0365 D27E03   C               JNC   STDAT       ; TRUE,STORE CONVERSIONS.
0368 23                       INX   H           ; POINT TO PREVIOUS CHANNEL 2 CONVERSION.
0369 79                       MOV   A,C         ; LATEST CHANNEL 2 CONVERSION TO ACCUMULATOR.
036A 96                       SUB   M           ; LATEST CONVERSION - PREVIOUS CONVERSION.
036B D27003   C               JNC   COMPB       ; JUMP IF PREVIOUS CONVERSION > NEW CONVERSION.
036E 2F                       CMA               ; FIND 2' COMPLEMENT OF SUB M RESULT.
036F 3C                       INR   A           ;
0370 FE02         COMPB:      CPI   002H        ; IS DIFFERENCE > OR = 2 RESOLUTIONS.
0372 D27F03   C               JNC   SUDAT       ; TRUE,STORE CONVERSIONS.
0375 FB           MROUT:      EI                ; ENABLE RST6.5 INTERRUPT.
0376 00                       NOP               ;
0377 F3                       DI                ; DISABLE INTERRUPT.
0378 3E0B                     MVI   A,00BH      ; MASK RST5.5 & RST6.5.UNMASK RST7.5.
037A 30                       SIM               ; SET INTERRUPT MASK.
037B C34A03   C               JMP   GECHA       ; STAY IN SUB-ROUTINE.
037E 23           STDAT:      INX   H           ; INCREMENT MEMORY STORE.
037F 23           SUDAT:      INX   H           ; INCREMENT MEMORY STORE.
0380 70                       MOV   M,B         ; STORE CHANNEL 3 CONVERSION.
0381 23                       INX   H           ; INCREMENT MEMORY STORE.
0382 71                       MOV   M,C         ; STORE CHANNEL 2 CONVERSION.
0383 3E1F                     MVI   A,01FH      ; MOVE MSB OF FINAL STORE TO ACCUMULATOR.
0385 BC                       CMP   H           ; COMPARE WITH MSB OF MEMORY STORE.
0386 CA8C03   C               JZ    COLSB       ; MEMORY STORE MSB = FINAL STORE MSB.
0389 C37503   C               JMP   MROUT       ; MEMORY STORE MSB < FINAL STORE MSB.
038C 3EFF         COLSB:      MVI   A,0FFH      ; MOVE LSB OF FINAL STORE TO ACCUMULATOR.
038E BD                       CMP   L           ; COMPARE WITH LSB OF MEMORY STORE.
038F CA9503   C               JZ    STFUL       ; MEMORY STORE LSB = FINAL STORE LSB.
0392 C37503   C               JMP   MROUT       ; MEMORY STORE LSB < FINAL STORE LSB.
0395 3E02         STFUL:      MVI   A,002H      ; LIGHT "DATA STORAGE FULL" LED.
0397 D301                     OUT   001H        ;
0399 FB                       EI                ; ENABLE RST6.5 INTERRUPT.
039A CDB403   C               CALL  DELAY       ; CALL DELAY ROUTINE.
039D 3E12                     MVI   A,012H      ; SWITCH OFF "DATA STORAGE FULL" LED.
039F D301                     OUT   001H        ;
03A1 CDB403   C               CALL  DELAY       ; CALL DELAY ROUTINE.
03A4 C39503   C               JMP   STFUL       ; STAY IN LIGHT FLASHING ROUTINE.
```

```
03A7 22FE1B        446 PRFIN:  SHLD ST19      ; LAST STORAGE ADDRESS TO ST19.
03AA 3E10          447         MVI  A,010H    ; SWITCH OFF "DATA STORAGE FULL" LED & SEND
03AC D301          448         OUT  001H      ; "DATA COMPLETE" SIGNAL.
03AE CDB403   C    449         CALL DELAY     ; CALL DELAY ROUTINE.
03B1 C30000   C    450         JMP  INITAL    ; JUMP TO START OF MAIN PROGRAMME.
03B4 010096        451 DELAY:  LXI  B,09600H  ; DELAY INPUT ARGUMENT.
03B7 0B            452 DCRBC:  DCX  B         ; DECREMENT INPUT ARGUMENT.
03B8 78            453         MOV  A,B       ;
03B9 B1            454         ORA  C         ; IS ARGUMENT ZERO?
03BA C2B703   C    455         JNZ  DCRBC     ; NO,CONTINUE.
03BD C9            456         RET            ; YES,RETURN.
```

```
                              ;  ***********************************************
                              ;  *  RAM STORAGE LOCATIONS AND DESCRIPTION.     *
                              ;  ***********************************************
1BA2     ST0     EQU  01BA2H  ; CHANNEL 0.LATEST DISPLACEMENT.
1BE3     ST1     EQU  01BE3H  ; CHANNEL 0.PEVIOUS DISPLACEMENT.
1BA3     ST2L    EQU  01BA3H  ; CHANNEL 0.TIME FOR LOOPING.LSB.
1BA4     ST2M    EQU  01BA4H  ; CHANNEL 0.TIME FOR LOOPING.MSB.
1BA5     ST3L    EQU  01BA5H  ; CHANNEL 0.TIME MEASUREMENT.LSB.
1BA6     ST3M    EQU  01BA6H  ; CHANNEL 0.TIME MEASUREMENT.MSB.
1BA7     ST3G    EQU  01BA7H  ;
1BA9     ST4A    EQU  01BA9H  ; CHANNEL 0.VELOCITY V0A.  LSB.
1BAA     ST4B    EQU  01BAAH  ;                            :
1BAB     ST4C    EQU  01BABH  ;                            :
1BAC     ST4D    EQU  01BACH  ;                          MSB.
1BE5     ST5A    EQU  01BE5H  ; CHANNEL 0.VELOCITY V0B.  LSB.
1BE6     ST5B    EQU  01BE6H  ;                            :
1BE7     ST5C    EQU  01BE7H  ;                            :
1BE8     ST5D    EQU  01BE8H  ;                          MSB.
1BE9     ST6     EQU  01BE9H  ; CHANNEL 0.ACCELERATION.  LSB.
1BAD     ST7     EQU  01BADH  ; CHANNEL 1.LATEST DISPLACEMENT.
1BE4     ST8     EQU  01BE4H  ; CHANNEL 1.PREVIOUS DISPLACEMENT.
1BAE     ST9L    EQU  01BAEH  ; CHANNEL 1.TIME FOR LOOPING.LSB.
1BAF     ST9M    EQU  01BAFH  ; CHANNEL 1.TIME FOR LOOPING.MSB.
1BB0     ST10L   EQU  01BB0H  ; CHANNEL 1.TIME MEASUREMENT.LSB.
1BB1     ST10M   EQU  01BB1H  ; CHANNEL 1.TIME MEASUREMENT.MSB.
1BB2     ST10G   EQU  01BB2H  ;
1BB4     ST11A   EQU  01BB4H  ; CHANNEL 1.VELOCITY V1A.  LSB.
1BB5     ST11B   EQU  01BB5H  ;                            :
1BB6     ST11C   EQU  01BB6H  ;                            :
1BB7     ST11D   EQU  01BB7H  ;                          MSB.
1BED     ST12A   EQU  01BEDH  ; CHANNEL 1.VELOCITY V1B.  LSB.
1BEE     ST12B   EQU  01BEEH  ;                            :
1BEF     ST12C   EQU  01BEFH  ;                            :
1BF0     ST12D   EQU  01BF0H  ;                          MSB.
1BF1     ST13    EQU  01BF1H  ; CHANNEL 1.ACCELERATION.  LSB.
1BB8     ST14    EQU  01BB8H  ; CHANNEL 0.(ST0-ST1)INTEGER FORM.
1BBC     ST15    EQU  01BBCH  ; CHANNEL 1.(ST7-ST8)INTEGER FORM.
1BC0     ST16    EQU  01BC0H  ; CHANNEL 0.TIME MEASUREMENT. F-P FORM.  LSB.
1BC4     ST17    EQU  01BC4H  ; CHANNEL 1.TIME MEASUREMENT. F-P.FORM.  LSB.
1BC8     FPR     EQU  01BC8H  ; FLOATING-POINT RECORD.
1BDA     ST18    EQU  01BDAH  ; CHANNEL 2 DISPLACEMENT.
1BFE     ST19    EQU  01BFEH  ; PROFILE DATA LAST STORAGE ADDRESS.
1C00     ST20    EQU  01C00H  ; FIRST PROFILE DATA MEMORY STORE.
1BA0     STSP    EQU  01BA0H  ; STACK POINTER LOCATION.
                              ;
                              ;
                 EXTRN  FSTOR,FSET,FLOAD,FSUB,FDIV,FLTDS,FCLR,FNEG
         END
```

APPENDIX C

OPERATOR'S VISUAL DISPLAY

	LED	NIXIE	GAS DISCHARGE	FLUORESCENT	INCANDESCENT	DYNAMIC SCATTERING LCD	FIELD EFFECT LCD
POWER/DIGIT	10 to 140 mW depending on colour & size	350 mW	30 to 100 mW	100 mW	250 mW to 1 W	100 μW	1 to 10 μW
VOLTAGE	2v to 18v	175v	180v	15v to 25v	5v	18v	3v to 7v
TEMPERATURE RANGE (°C)	- 55 to 125	0 to 70	0 to 55	- 55 to 100	- 55 to 100	0 to 80	0 to 70
SWITCHING SPEED	1 μs	150 μs	1 ms	1 ms	150 μs	300 ms	100 to 300 ms
LIFE IN HOURS	100,000 +	200,000	30,000	100,000	10,000 to 100,000	10,000 to 50,000	10,000 to 50,000
BRIGHTNESS	Good to Excellent	Excellent	Good	Good	Excellent	Not Applicable	Not Applicable
CONTRAST RATIO	10 : 1	8 : 1	20 : 1	10 : 1	20 : 1	10 : 1	10 : 1
VIEWING ANGLE	150°	100°	120°	150°	150°	10° to 150°	10° to 120°
FONT	7 & 6 segment Dot matrix	Individual characters	7 segment	7 segment	7 & 16 segment & shaped characters	7 & 16 segment	7 & 16 segment Dot matrix
RUGGEDNESS	Excellent	Poor	Fair	Poor	Fair	Good	Good
MOS COMPATIBILITY	Small - yes Large - No	No	Yes	Yes	No	Yes	Yes

TABLE C.1 DIGITAL DISPLAY COMPARISONS

C.1 INTRODUCTION.

It is not always possible for the machine operator to observe the position of the ripping head directly. The chart recordings obtained for studying the boom positional performance, on and within the profile envelope, led the NCB to request a display of similar information for the operator. This could eventually lead to increased remote operation of the roadheader, and similar machines, besides providing information not readily available at the present time.

Dramatic changes have occured in electronic displays over the last few years. Analogue displays are being replaced by digital readouts in many products for the following reasons:- The cost competitiveness and compact nature of digital displays; the change from analogue to digital circuit techniques thus making circuit/display interface simpler; the ruggedness, ease of reading and increased versatility of digital displays.

C.2 DIGITAL DISPLAY TECHNOLOGY.

Table C.1 (Ref.59) compares the most prominant digital display characteristics with particular reference to the requirements of the mining environment.

Most of the terms in the table are easily understood but some are peculiar to display terminology and are briefly defined below.

C.2.1 Brightness.

This is what the eye perceives. No industrial standard exists for measuring brightness. Point source luminous intensity is used by some manufacturers and others use area source luminance which takes into account the displays area and distance to observer. The best means of evaluating the display brightness is to view samples under the conditions anticipated.

C.2.2 Contrast Ratio.

This is defined as the difference in appearance between two parts of the field viewed.

C.2.3 Viewing Angle.

This refers to the off-axis angle at which the display is viewed. There is no industrial standard and spectral-radiation polar plots seem to be the most meaningful means of describing viewing angle.

C.2.4 Life.

Again, this is not standardised but generally refers to the time at which the the display brightness falls to 50% of its original value.

C.2.5 Font.

This refers to the arrangment of the display elements.

C.3 A DISPLAY FOR MINING APPLICATIONS.

The low power requirement, full dot graphic display capability, MOS compatibile signal level, easy installation and lightweight, compact construction makes the field effect LCD an obvious choice for applications in mines. There are however disadvantages with this type of display, namely the LCD has a slow response time, a low operating temperature range and a relatively short life.

The LCD's are passive displays, that is, they are not light sources and require some means of illumination in low ambient lighting levels, such as are found in mines. The temperature range, life and passive nature of LCD's are not considered to be serious disadvantages for this application.

A new development in LCD technology was the availability of the Epson dot matrix display module, part number EG-Y84320AT, with built-in graphic display data RAM. The specifications for this display are :-

Supply Voltage	: 5V + or - 0.25V D.C.
Power Consumption	: 1.2 mA.
Operating Temperature	: 0 to 50°C.
Switching Speed (turn on/off)	: 150 ms.
Contrast Ratio	: 10 : 1.
Expected Life	: 50,000 hours.

To obtain a simulation of what could be expected it was decided to interface this display to the de-multiplexed expansion bus of the SDK-85. The SDK-85 contains an 8085A microprocessor, clocked by a 6.144 MHz crystal, as does the boom control system. The timing problems between the display and control system would be similar in both cases.

The display is received complete with control IC's having built-in display data RAM, which considerably reduces the burden of interfacing to a microprocessor system. The display RAM can be interfaced by 4-bits or 8-bits, multiplexed or de-multiplexed, bus transmit modes. For the purpose of this simulation, the latter was the most suitable. It was not possible to interface the display RAM

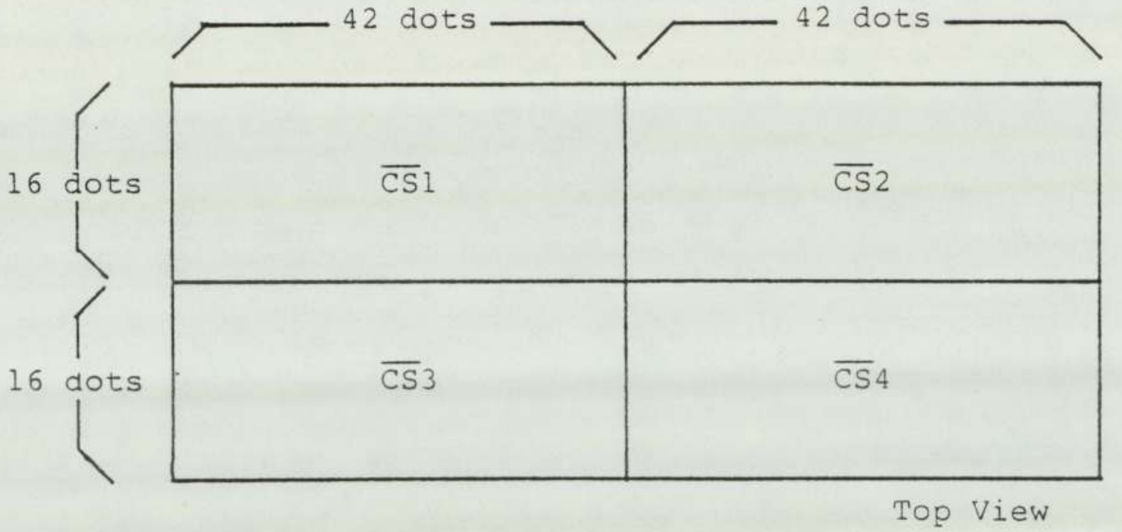


FIGURE C.1 DIVISION OF DISPLAY AREA CONTROL.

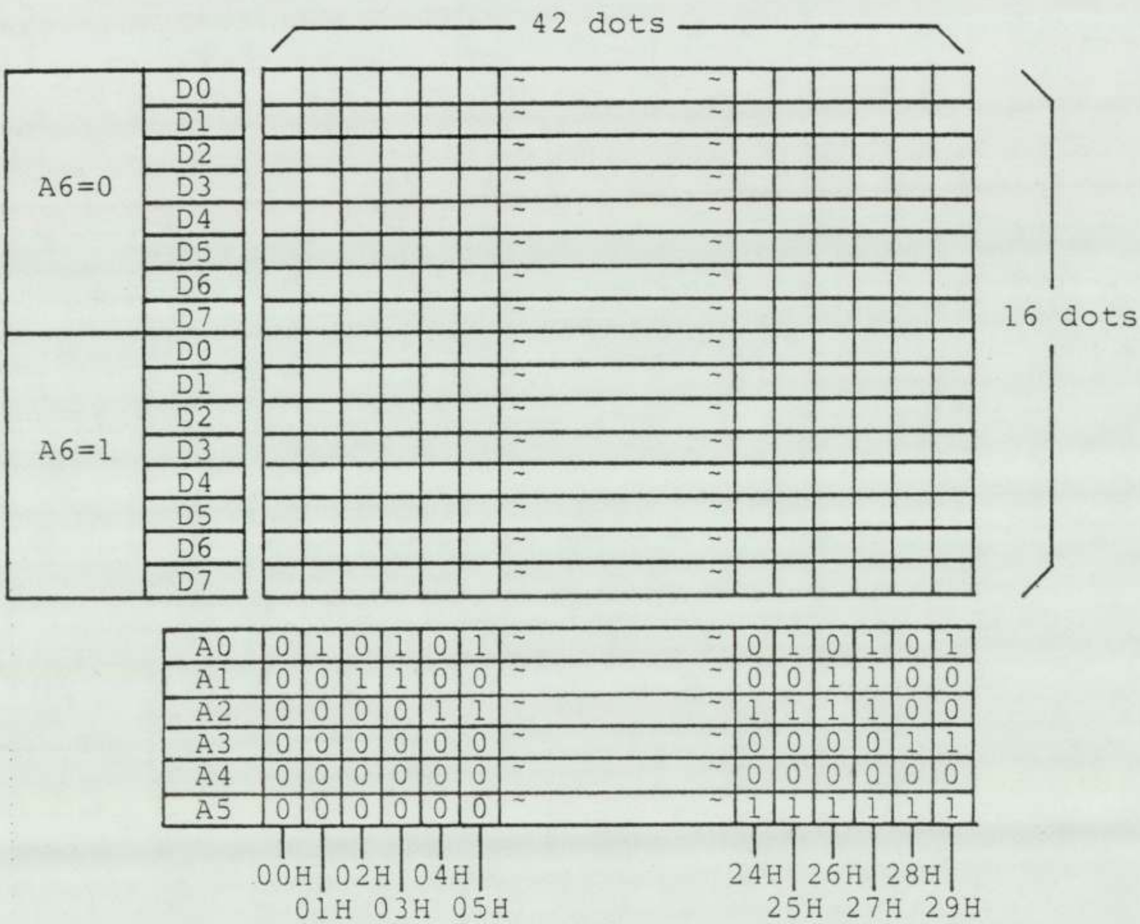


FIGURE C.2 DISPLAY DATA RAM ADDRESS/DATA CODE.

direct onto the 8-bit multiplexed bus of the 8085 CPU without slowing down the clocking rate with, for certainty, no greater than a 2 MHz crystal.

The display is constructed with four discrete areas, each with its own control and RAM IC, as shown in Figure C.1.

The display data RAM address/data code, for each of the discrete areas, is shown in Figure C.2. Further details of the display can be found in Ref.60.

The interface circuit, between the expansion bus of the SDK-85 and the display IC's, consisted of three Intel 8212 input/output ports. The 8212's are connected direct to the address lines A0 to A7 on the SDK-85 de-multiplexed bus, and to A8, A9, A10, A12, A13, A14, A15 and WR via interface logic. The code on the low address byte is gated to the 8212 outputs. Each 8212 has a discrete high address byte and WR gating code. One 8212 is used for the display address, one for the display data and one for the display control. The outputs of the 8212's are latched when gated, thus enabling

SDK-85 ADDRESS	DISPLAY SELECT.
F1XXH	$\overline{CS}1$, $\overline{CS}2$, $\overline{CS}3$, $\overline{CS}4$ and $\overline{WR}$ SELECT. The low address byte determines which one, or any combination, is taken low.
F2XXH	ADDRESS SELECT. The low byte defines the display address.
F3XXH	CONTROL and ADDRESS SELECT.
F4XXH	DATA SELECT. The low byte defines the display data.
F7XXH	CONTROL, ADDRESS and DATA SELECT.

TABLE C.2. Decoded SDK-85 Addresses for Display Programming.

software control of the sequence and timing of the display address, data and control. The display select codes are as set out in Table C.2.

For the purpose of this simulation it is only necessary to write to the display. It would be possible, with the correct interface circuit, not only to write, but also to read the display data RAM. This would be required for the display to be controlled by the boom control system.

The condition of the display command register is unknown when first "powered up" and it is necessary to initialize for the desired bus transmitt mode. The timing sequence to initialize for 8-bits, de-multiplexed data and address bus, transmit mode is shown in Figure C.3.

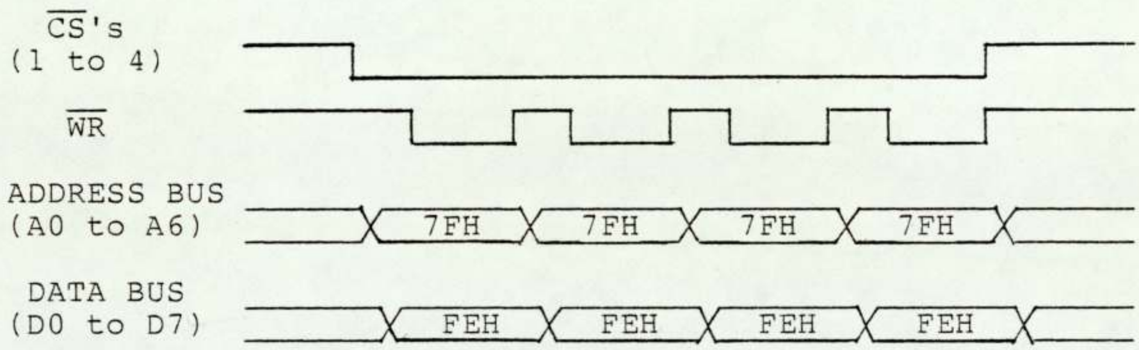


FIGURE C.3. Timing Sequence for 8-Bit, De-Multiplexed Data and Address Bus, Transmit Mode.

The display output is random at "power up". It was necessary to clear the display following initialization. This is carried out by writing 00H, to address 00H through to 29H (A6 = 0), and address 40H through to 69H (A6 = 1), for each of the display areas, in turn. The timing sequence for this is shown in Figure C.4. The same timing sequence is also used for writing any desired pattern to the display, taking care to define the required pixel, correctly.

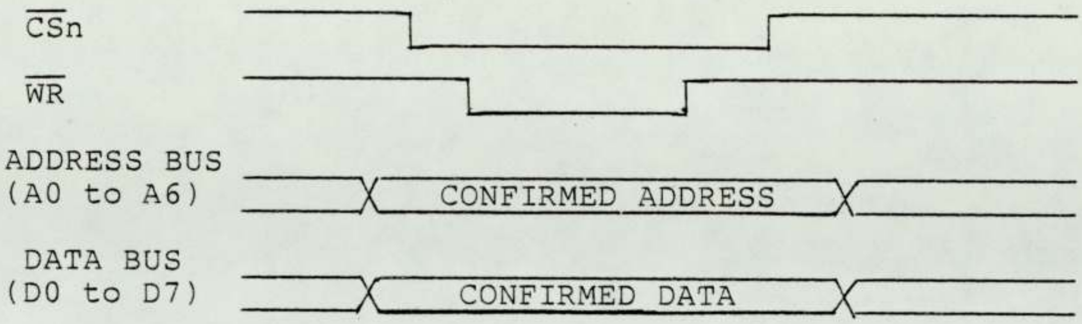


FIGURE C.4. Timing Sequence for Writing to Display.

Through out all sequences described the $\overline{RD}$ line to the display must be held at logic 1. Further details of the display, including the write timing, can be found in Ref.60.

A knob adjustment is provided for the contrast adjusting potentiometer across display connections VR1 and VR2. This requires adjustment to give the optimum contrast ratio, depending on the viewing angle and ambient temperature.

The results of the simulation are shown in Figures C.5, C.6 and C.7.

"Moving picture" effects are obtained by building time delays into the software.

Figure C.7 illustrates that messages can be displayed, This aspect could be used for displaying monitored information of the performance, or total running time, etc., of various parts of the workings of the roadheading machine.

A larger display with increased resolution would ideally be required for the roadheader. This would improve

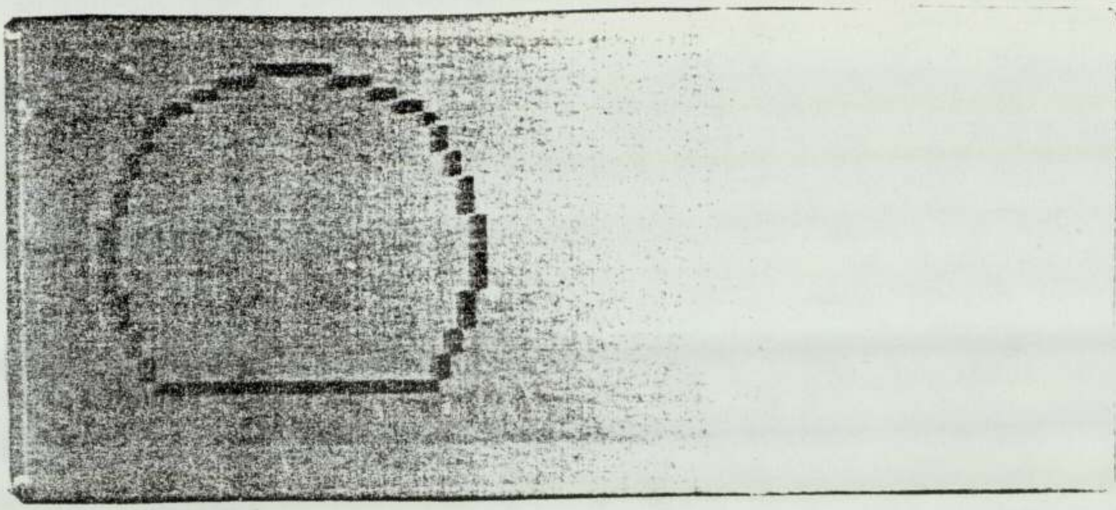


FIGURE C.5 DISPLAY OF TUNNEL PROFILE ENVELOPE.

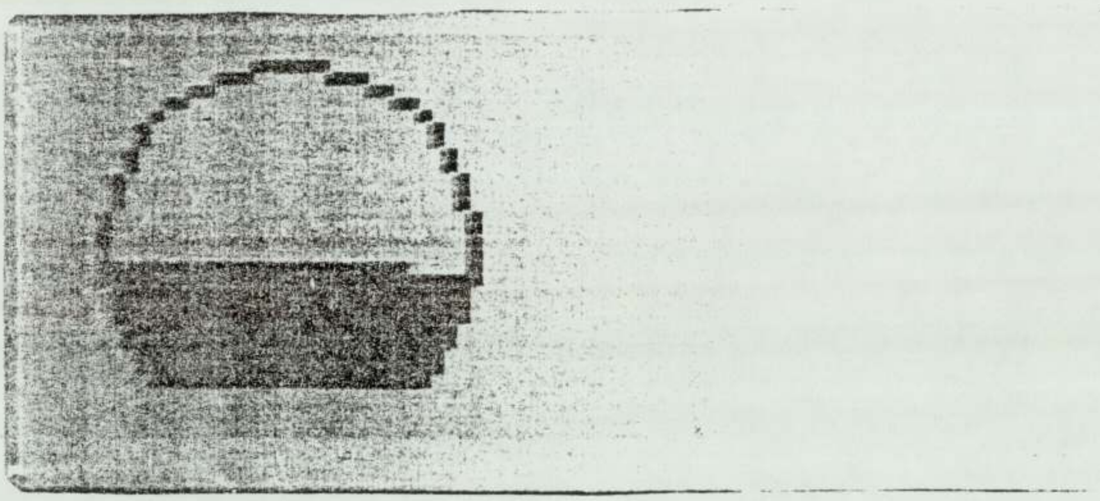


FIGURE C.6 DISPLAY OF CAVITY REMOVAL IN OPERATION.

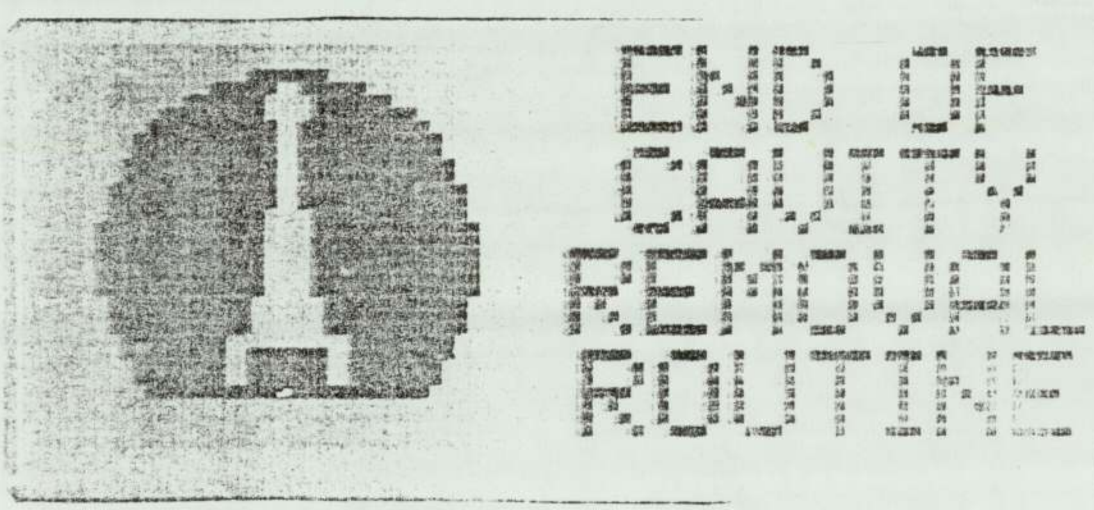


FIGURE C.7 DISPLAY OF CAVITY REMOVAL COMPLETED.

the display of profile and cavity ripping data.

The LCD would have many other applications in the mining, and other hazardous, environments.

APPENDIX D

HYDRAULIC SYSTEM AND COMPUTERISED SIMULATION OF HYDRAULIC VALVES PERFORMANCE

APPENDIX D.

D.1 Hydraulic System Details.

The valve sets for directional control of the slewing and raising/lowering boom actuators, are shown in Figure D.1. An alternative, simplified arrangement, using only two solenoid operated servo pilot valves, is shown in Figure D.2. The simplified arrangement was not applied to the boom for the reasons stated in Chapter 6.

Figure D.3 shows the detail of the main flow control poppet valve, and details of the solenoid operated pilot valve, are shown in Figure 1.5, in Chapter 1.

The hydraulic power pack, built for the boom in the laboratory, is shown in Figure D.4. The same pump is used for the pilot and main pressure supply. The pilot pressure must be maintained for a drop in main pressure. This can occur, particularly, when the boom is moving in free space at fast speed. A seperate accumulator and non-return valve are incorporated in the pilot pressure line for this purpose.

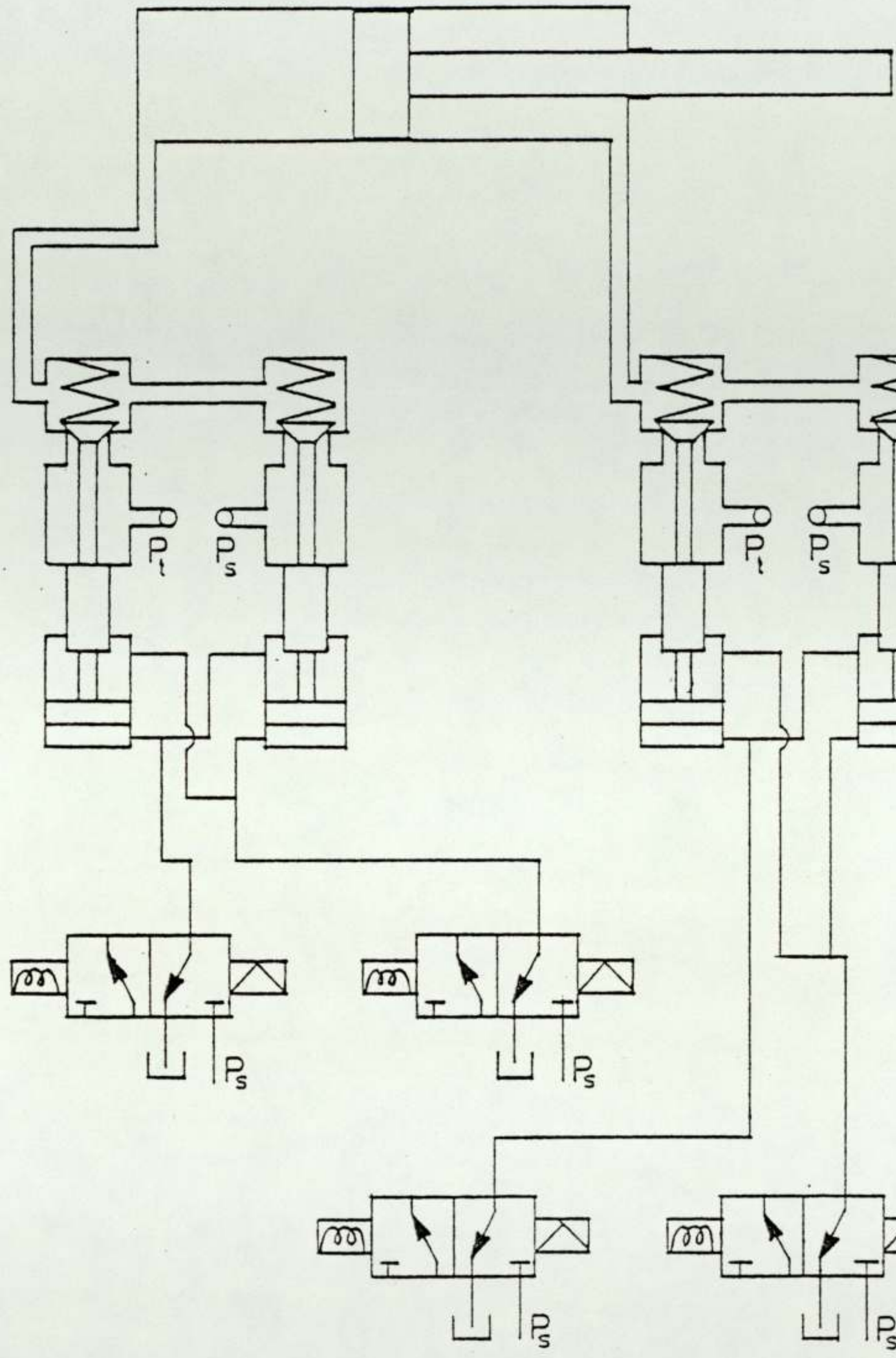


FIGURE D.1 HYDRAULIC ACTUATOR POPPET VALVE OPERATION WITH 4 SOLENOID OPERATED SERVO VALVES.

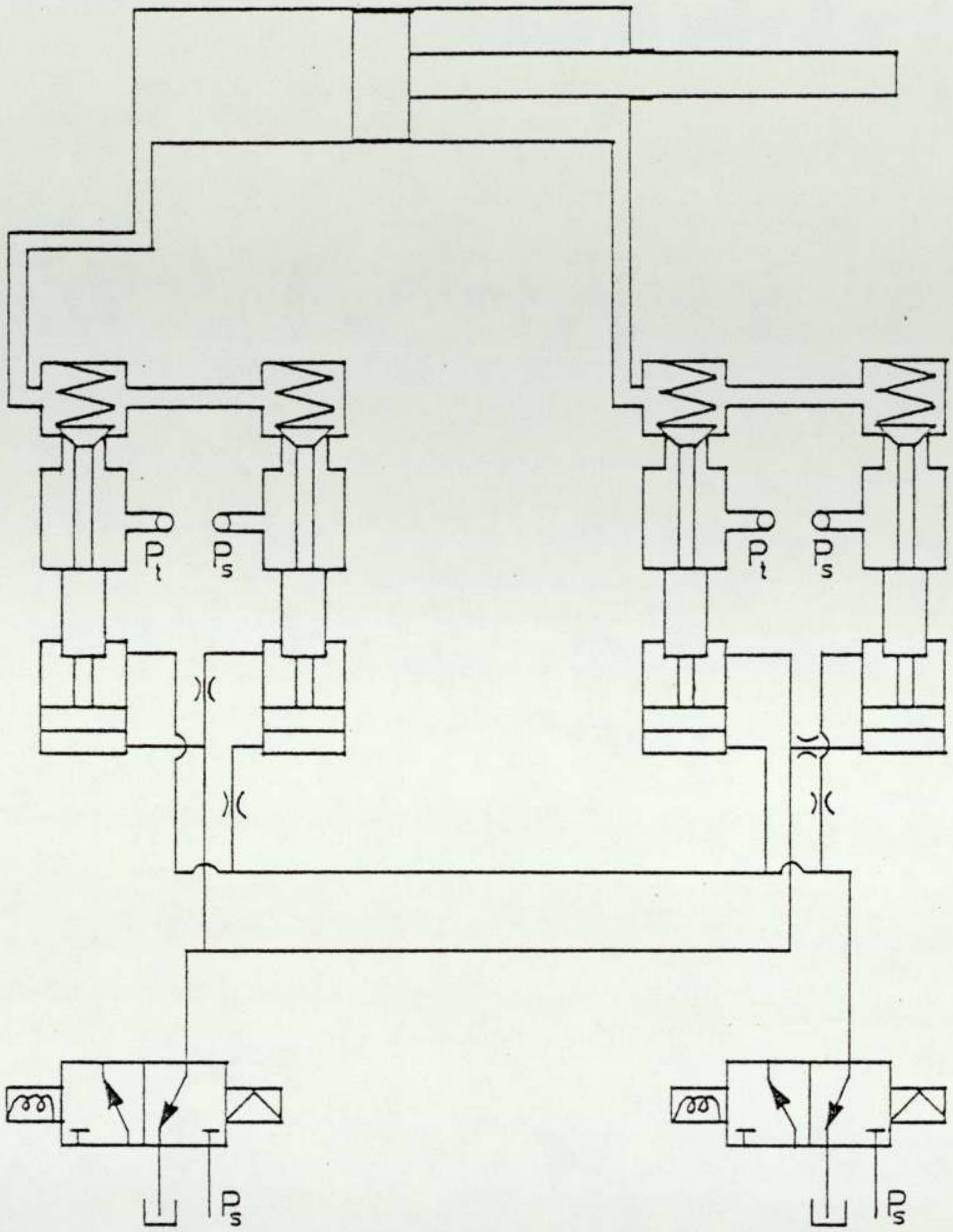


FIGURE D.2 HYDRAULIC ACTUATOR POPPET VALVE OPERATION WITH 2 SOLENOID OPERATED SERVO VALVES.

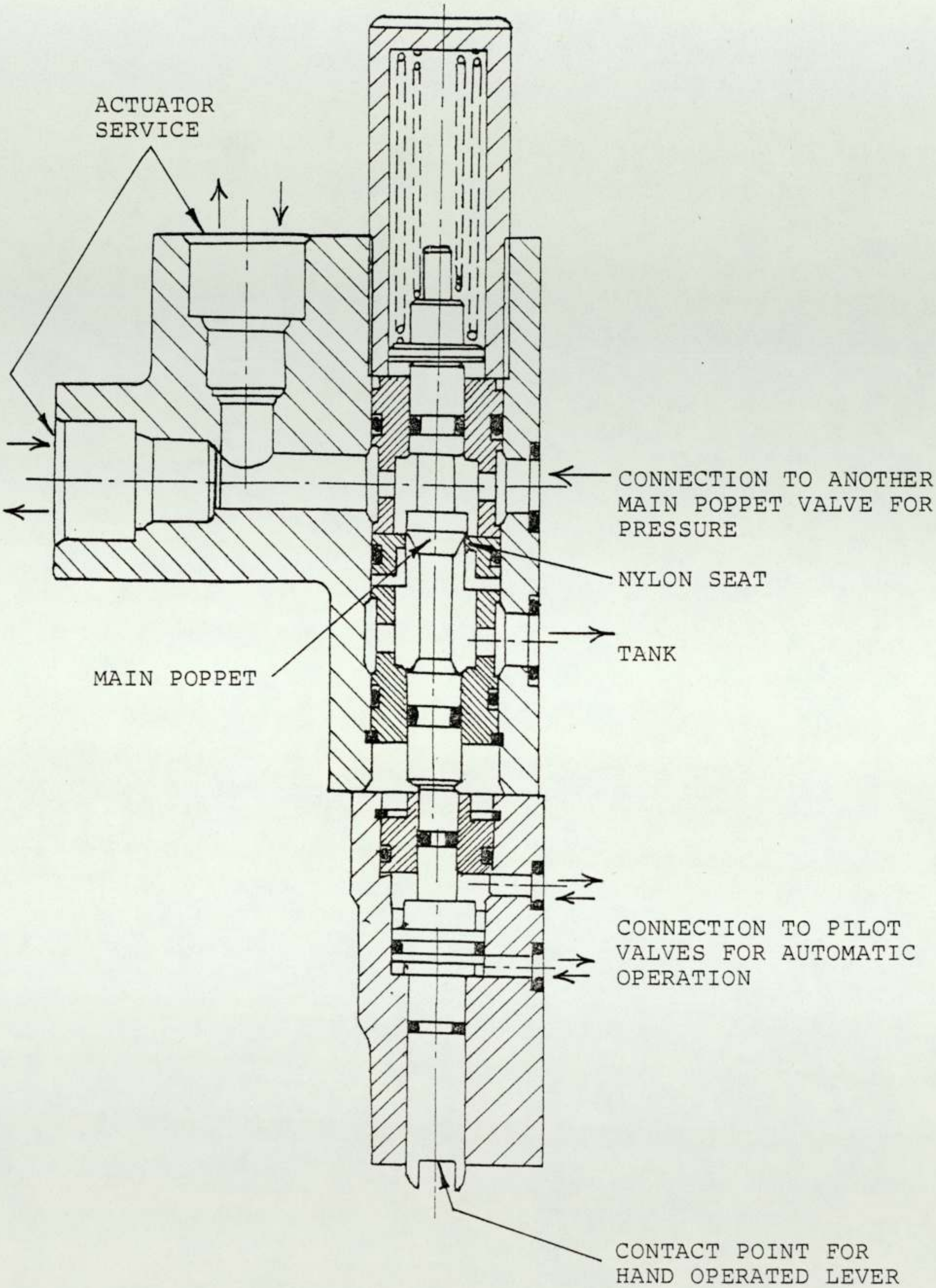


FIGURE D.3 ACTUATOR DIRECTIONAL CONTROL POPPET VALVE.

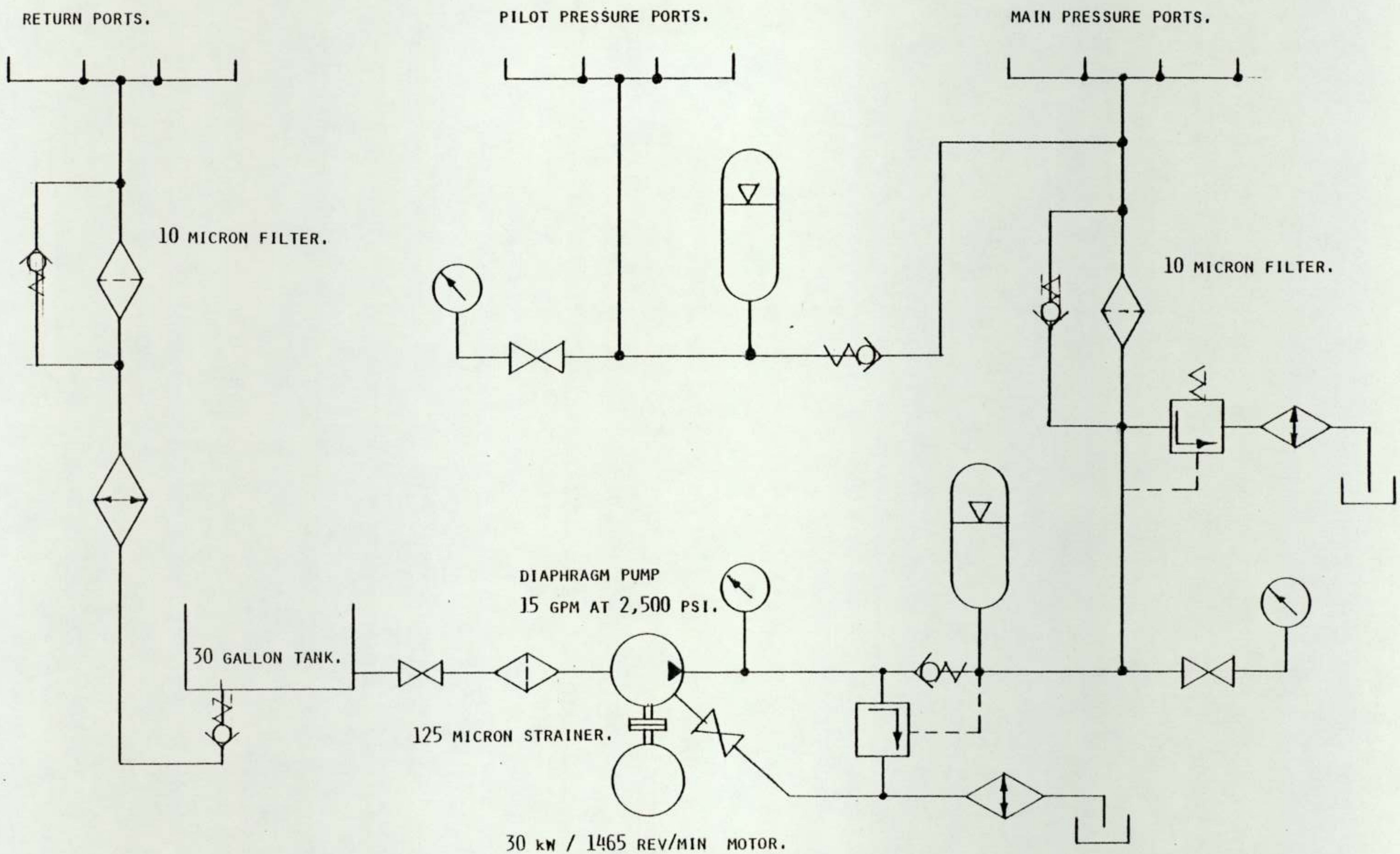


FIGURE D.4 HYDRAULIC POWER PACK.

D.2 SIMULATION OF POPPET VALVE CONTROL OF HYDRAULIC ACTUATOR. (MAIN TEXT CHAPTER 6)

The example is for one particular set of system dimensions and for valve closure cycle with the valve to tank delayed 6ms behind supply valve.

D.2.1 Dimensions.

A (effective area of piston) = $.01m^2$
B (bulk modulas of fluid) = 2.09×10^9 N/m^2
M (effective mass of piston) = 200kg
F (force on piston) = 1962N
V (total fluid volume in cylinder) = $.01m^3$
Ps (system supply pressure) = 137 x 10 N/m^2
Pt (system tank pressure) = 15 x 10 N/m^2
Cd (poppet discharge coefficient) = .75
d (poppet valve inlet diameter) = .01m
ϕ (poppet angle) = 45°
ρ (fluid density) = $1000kg/m^3$

$$R \text{ (constant)} = \frac{B\ Cd\ \pi\ d\ \sin\phi\ \sqrt{2}}{\sqrt{\rho}} = 1557246.71 N/m \sqrt{kg/m^3}$$

D.2.2 Initial Conditions.

D(X) = .7315m/s
X = 0
P1 = 76.9 x 10 N/m^2
P2 = 75.0 x 10 N/m^2

D.2.3 Computer Programme.

```
THE UNIVERSITY OF ASTON HP 2000 ACCESS SYSTEM

IDEA

DO YOU REQUIRE INSTRUCTIONS (YES/NO)? N
NAME OF INDEPENDENT VARIABLE (UP TO SIX CHARACTERS)? TIME
NUMBER OF EQUATIONS TO BE INPUT? 5
EQUATION NO.  1  ? D2(X)=(P1-P2)*A/M-F/M
EQUATION NO.  2  ? D(P1)=SGN(PS-P1)*R*X1/(V/2+X*A)*
SQR(ABS(PS-P1))-A*B/(V/2+X*A)*D(X)
EQUATION NO.  3  ? D(P2)=A*B//(V/2-X*A)*D(X)-SGN(P2-PT)*
R*X2/(V/2-X*A)*SQR(ABS(P2-PT))
EQUATION NO.  4  ? X1=TAB(TIME)
EQUATION NO.  5  ? X2=TAB(TIME)
THE EQUATIONS HAVE BEEN ANALYSED AND SORTED. PRINT OUT
(YES/NO)? N
VALUE OF CONSTANT A?  .01
VALUE OF CONSTANT F?  1962
VALUE OF CONSTANT B?  2090000000
```

```
VALUE OF CONSTANT M?  200
VALUE OF CONSTANT PS? 13700000
VALUE OF CONSTANT R?  1557246.71
VALUE OF CONSTANT V?  .01
VALUE OF CONSTANT PT? 1500000
INITIAL VALUE OF D(X)? .7315
INITIAL VALUE OF X?    0
INITIAL VALUE OF P1?   7690000
INITIAL VALUE OF P2?   7500000
NUMBER OF DATA POINTS FOR X1?  10
POINT NO.   VALUE OF TIME   VALUE OF X1
   1? 0,.004
   2? .006,.004
   3? .0065,.0035
   4? .007,.003
   5? .0075,.0025
   6? .008,.002
   7? .0085,.0015
   8? .009,.001
   9? .0095,.0005
   10? .01,0
NUMBER OF DATA POINTS FOR X2?  9
POINT NO.   VALUE OF TIME   VALUE OF X2
   1? 0,.004
   2? .0005,.0035
   3? .001,.003
   4? .0015,.0025
   5? .002,.002
   6? .0025,.0015
   7? .003,.001
   8? .0035,.0005
   9? .004,0
DO YOU WISH TO SPECIFY THE INCREMENT OF TIME? Y
VALUE OF INCREMENT FOR NUMERICAL SOLUTION? .0001
NUMERICAL (N) OR GRAPHICAL (G) OUTPUT? N
HOW MANY PARAMETERS ARE TO BE OUTPUT (UP TO 6)? 6
NAME OF PARAMETER NO. 1? TIME
NAME OF PARAMETER NO. 2? X
NAME OF PARAMETER NO. 3? D(X)
NAME OF PARAMETER NO. 4? D2(X)
NAME OF PARAMETER NO. 5? P1
NAME OF PARAMETER NO. 6? P2
AT WHAT INTERVALS OF TIME IS THIS OUTPUT REQUIRED? .0005
NAME OF PARAMETER THAT WILL TERMINATE RUN? TIME
MAXIMUM VALUE OF TIME? .024
```

D.3 SIMULATION OF PERFORMANCE OF HYDRAULIC ACTUATOR DIRECTIONAL CONTROL VALVES. (MAIN TEXT CHAPTER 6)

The valves are shown in Figure 6.12 and the equations for the simulation of the valve are developed in main text (Chapter 6).

D.3.1 Dimensions.

P_s (system supply pressure) = 137×10^5 N/m^2
P_c (pressure to cylinder) = 130×10^5 N/m^2
C_d (poppet discharge coefficient (both poppets)) = .75
A_8 (main poppet gross piston area) = 0.201×10^{-3} m^2
A_7 (non-effective main poppet piston area) = 0.785×10^{-4}m^2
A_{14} (main poppet seat area) = 0.785×10^{-4}m^2
A_{12} (area of top stem of main poppet) = 0.282×10^{-4}m^2
K (spring stiffness) = 2.0 x 10 N/m
M (total mass of main poppet) = .092 kg
M_p (total mass of servo poppet) = .04 kg
L (stroke of servo poppet = Ymax) = 0.15×10^{-2}m
D (servo poppet ball diameter) = 0.158×10^{-2}m
ρ (fluid density) = 1000 kg/m^3
X_1 (spring pre-compression) = .01 m
Xmax (stroke of main poppet) = 0.4×10^{-2}m
A (servo poppet seat area) = 0.98×10^{-7}m^2
F_f (friction force) = 100 N
F (solenoid force on servo poppet) = 14 N to open valve.
0 N to close valve.
D (main poppet seat diameter) = 0.5×10^{-2}m

D.3.2 Non-dimensional Constants.

The equations developed in the main text have non-dimensional constants. These have values, calculated from the above parameters, as defined below.

$$\text{Let } U = \frac{\lambda}{m}(a_8 - a_7) = \frac{P_s(A_8 - A_7)M_p}{KML} = 24.3225$$

$$\text{Let } V = \frac{\lambda}{m} p_c(a_{14} - a_{12}) = \frac{P_c M_p (A_{14} - A_{12})}{KML} = 9.477$$

$$\text{Let } Z = \frac{\lambda \pi C_d^2 d_{14}(1 - p_c)}{m} = \frac{P_s \pi C_d^2 D_{14} M_p (1 - P_c/P_s)}{KM} = .71083$$

$$\text{Let } Q = \frac{x_1}{m} = \frac{X_1 M_p}{LM} = 2.9$$

Let M = $m = \frac{M}{M_p} = 2.3$

Let FF = $\frac{f_f}{m} = \frac{F_f M_p}{KLM} = 1.449$

Let XM = $x\ max = \frac{Xmax}{L} = 2.6667$

Let R = $\lambda 2.22 C_d^2 d = \frac{P_s\, 2.22 C_d^2 D}{K} = 1.358$

Let S = $\lambda a_1 = \frac{P_s A_1}{KL} = 0.4473$

Let F = $f = \frac{F}{KL} = 0.4667$ valve opening (0 for valve closing)

Let YM = $y\ max = \frac{Ymax}{L} = 1$

Let N = $\delta = \frac{(A_8 - A_7)^2 \rho K}{4.93 M_p C_d^2 D^2 P_s} = 0.0791$

D.3.3 Initial Conditions.

Valve opening
D(X) = 0
X = 0
D(Y) = 0
Y = 0
PSE = 0

Valve closing
D(X) = 0
X = 2.6667
D(Y) = 0
Y = 0
PSE = 1

D.3.4 Sample Programme Run.

```
THE UNIVERSITY OF ASTON HP 9845 SYSTEM.

IDEAM1

DO YOU REQUIRE INSTRUCTIONS (YES/NO)? N
NAME OF INDEPENDENT VARIABLE (UP TO SIX CHARACTERS)? TAU
NUMBER OF EQUATIONS TO BE INPUT? 23
EQUATION NO.  1  ? D2(X)=FS-FR
EQUATION NO.  2  ? FS=U*PSE-V-Z*X1-Q-X1/M-(SGN(D(X))*FF)
EQUATION NO.  3  ? FR=0.5*ST*(ABS(FS)+FS*ST)+FS*E1*ST1+
FS*E2*ST2
EQUATION NO.  4  ? E1=INT(1-X1/XM)
EQUATION NO.  5  ? E2=INT(X1/XM)
```

```
EQUATION NO.   6  ? X1=0.5*(ABS(X)+X)
EQUATION NO.   7  ? D2(Y)=FT-FU
EQUATION NO.   8  ? FT=R*(1-PSE)*(     -Y1+Y1^2/(2-Y1))+
R*(1-Y1)*PSE-S+F
EQUATION NO.   9  ? FU=FS*E3*ST1+FT*E4*ST2
EQUATION NO.   10 ? E3=INT(1-Y1)
EQUATION NO.   11 ? E4=INT(Y1)
EQUATION NO.   12 ? Y1=0.5*(ABS(Y)+Y)
EQUATION NO.   13 ? PSE=E3*K+E5*(SGN(B)*SQR(ABS(W))-B)/A+
E4*(1-J)
EQUATION NO.   14 ? E5=INT(1-E3)*INT(1-E4)
EQUATION NO.   15 ? W=B^2-A*C
EQUATION NO.   16 ? A=1+H+1/(4*H)
EQUATION NO.   17 ? B=K/2-H-J/2-0.5
EQUATION NO.   18 ? C=H-K+L*K^2/2
EQUATION NO.   19 ? H=Y1^2/(2*L)+.00001*E3
EQUATION NO.   20 ? J=N*D(X)^2/(Y1^2+.00001*E3
EQUATION NO.   21 ? K=N*D(X)^2/L
EQUATION NO.   22 ? L=(1-Y1)^2+.00001*E4
EQUATION NO.   23 ? X2=XM-X1
THE EQUATIONS HAVE BEEN ANALYSED AND SORTED. PRINT OUT
(YES/NO)? N
VALUE OF CONSTANT U?  24.3225
VALUE OF CONSTANT V?  9.477
VALUE OF CONSTANT Z?  .71083
VALUE OF CONSTANT Q?  2.9
VALUE OF CONSTANT M?  2.3
VALUE OF CONSTANT FF?  1.449
VALUE OF CONSTANT ST?  1(for closing) -1(for opening)
VALUE OF CONSTANT ST1?  1(for closing) 0(for opening)
VALUE OF CONSTANT ST2?  0(for closing) 1(for opening)
VALUE OF CONSTANT XM?  2.6667
VALUE OF CONSTANT R?  1.3518
VALUE OF CONSTANT S?  .4473
VALUE OF CONSTANT F?  0(for closing) .4667(for opening)
VALUE OF CONSTANT N?  .0791
INITIAL VALUE OF D(X)?    0
INITIAL VALUE OF X?    2.6667(for closing) 0(for opening)
INITIAL VALUE OF D(Y)?    0
INITIAL VALUE OF Y?   1(for closing) 0(for opening)
DO YOU WISH TO SPECIFY THE INCREMENT OF TAU? Y
VALUE OF INCREMENT FOR NUMERICAL SOLUTION?  .01
NUMERICAL (N) OR GRAPHICAL (G) OUTPUT? N
HOW MANY PARAMETERS ARE TO BE OUTPUT (UP TO 6)? 4
NAME OF PARAMETER NO. 1? TAU
NAME OF PARAMETER NO. 2? X1
NAME OF PARAMETER NO. 3? Y1
NAME OF PARAMETER NO. 4? PSE
AT WHAT INTERVAL OF TAU IS THIS OUTPUT REQUIRED? .05
NAME OF PARAMETER THAT WILL TERMINATE RUN? X2(for closing)
X1(for opening)
MAXIMUM VALUE OF X2? 2.6667   MAXIMUM VALUE OF X1? 2.6667
```

D.4 SIMULATION OF A PULSE WIDTH MODULATED, FLOW RATE CONTROL, POPPET VALVE. (MAIN TEXT CHAPTER 7)

The valve is shown in Figure 7.1 and the equations for the simulation are to be found in Chapter 7, of the main text.

D.4.1 Dimensions.

P_s (system supply pressure) = 137 x 10^5 N/m^2
P_t (tank pressure) = 15 x 10^5 N/m^2
P_1 (main poppet inlet pressure) = 100 x 10^5 N/m^2
P_2 (main poppet outlet pressure) = 15 x 10^5 N/m^2
C_d (poppet discharge coeffficient (both poppets) = .75
D (servo poppet ball diameter) = 0.158 x 10 m
D_6 (main poppet seat diameter) = .01 m
A_1 (servo poppet seat area) = 0.98 x 10^{-6} m
A_5 (servo poppet piston area) = 0.31416 x 10^{-5} m^2
A_6 (main poppet seat area) = 0.7854 x 10^{-4} m^2
A_8 (main poppet piston area) = 0.31416 x 10^{-3} m^2
K (spring stiffness) = 8000 N/m
Lo (servo poppet stroke) = 0.383 x 10^{-3} m
X_1 (spring pre-compression) = .015 m
F_f (friction force) = 10 N
Xmax (stroke of main poppet) = 0.4 x 10 m
ρ (fluid density) = 1000 kg/m^3
Mp (total mass of servo poppet moving parts) = .03262 kg
M (total mass of main poppet) = .063 kg

D.4.2 Non-dimensional Constants.

The equations contained in the main text have non-dimensional constants. These have values, calculated from the above parameters, as defined below.

$$\text{Let } PT = p_t = \frac{P_t}{P_s} = .1095$$

$$\text{Let } R = \lambda(p_t(a_1 - a_5) - a_1) = \frac{P_s}{KL_o}\left(A_1 - \frac{P_t}{P_s}(A_1 - A_5)\right) = 5.44$$

$$\text{Let } S = \delta d = \frac{P_s L_o^2 2.22 C_d^2}{K} = .8190$$

$$\text{Let } V = \lambda p_1 a_6 = \frac{P_1 A_6}{KL_o} = 351.173$$

Let $Z = \lambda \pi C_d^2 d_b (p_1 - p_2) = \dfrac{\pi C_d^2 D_b (P_1 - P_2)}{K} = 26.9489$

Let $U = \lambda a_B = \dfrac{P_S A_B}{KL} = 1404.69$

Let $Q = x_1 = \dfrac{X_1}{L_o} = 39.164$

Let $FF = f_f = \dfrac{F_f}{KL_o} = 3.2637$

Let $M = m = \dfrac{M}{M_p} = 1.9313$

Let $N = \dfrac{\delta a_B^2}{4.93 d^2} = \dfrac{\rho K A_B^2}{4.93 C_d^2 P_S M_p D^2} = .2552$

Let $G = \; = \dfrac{2.22 \, C_d D_B}{L} \quad \dfrac{2M_p (P_1 - P_2)}{K} = 19729.28$

D.4.3 Additional Notations.

Let $AF = \dfrac{\text{main poppet accelerating force}}{m}$

Let ACC = servo poppet accelerating force

Let $D2X = \dfrac{d^2 x}{d \tau^2}$ and $D2Y = \dfrac{d^2 y}{d \tau^2}$

D.4.4 Representation of Poppet Restraints.

The continuous digital computerised simulation of the pulsing of the servo and main poppets required the representation of poppet restraints. This is discussed in Section 7.3.2 in the main text.

Figure 7.3 shows the restraints for the main poppet, and Figure 7.4 the restraints for the servo poppet. The restraints are incorporated in the computed equations using the function switch (FNSW) and input switch (SWIN) instructions. Further details explaining these functions can be found in the SLAM manual (Ref. 55).

D.4.5 Sample Programme Run.

THE UNIVERSITY OF ASTON 1CL 1900 SYSTEM.

MOPSLAM2

SOURCE
INPUT
LISTING

```
  FORTRAN (CP)
  OPTIONS ERRMSG,DEBUG 1
  PROGDESC
  SHORTLIST (LP)
  PROGRAM (SLAM)
  INPUT  1 = CRO
  INPUT  3 = TRO
  INPUT  5 = CR1
  OUTPUT 2 = LPO
  OUTPUT 6 = LP1
  COMPRESS INTERGER AND LOGICAL
  COMPACT
  END
  GETFROM (CR)
  MASTER SPS
     REAL J,K,L,M,N,MPA,MPV
     TITLE `PULSED SERVO POPPET SIMULATION´,1L,
     &     `------------------------------´,1L,
C--INITIALISATION
          V=351.173
          Z=18.11298
          U=1404.69
          Q=39.164
          FF=3.2637
          M=1.9313
          S=0.8190
          PT=0.1095
          R=5.44
          N=0.2552
          G=19729.28
          OUTHD `   TAU    ´,`   D2X    ´,`   D1X    ´,
  &       `    X     ´,`   D2Y    ´,`   D1Y    ´,
  &       `    Y     ´,`   Q1     ´,`    F     ´
C--DYNAMIC EQUATIONS SERVO POPPET
  F=F1+F2+F3+F4+F5
  F1=SPULSE(TIME,0.0,2.0,0.0,8.0)
  F2=SPULSE(TIME,2.8,4.8,0.0,8.0)
  F3=SPULSE(TIME,5.6,7.6,0.0,8.0)
  F4=SPULSE(TIME,8.4,10.4,0.0,8.0,)
  F5=SPULSE(TIME,11.2,13.2,0.0,8.0,)
  ISTATE=INT(F/8.0)
  SPA=S*(Y*(PSE-PT)+(1-PSE))-R+F
  D2YC=FNSW(AINT(Y)-AINT(1.0-Y),0.0,SPA,SPA)
  D2YO=FNSW(AINT(Y)-AINT(1.0-Y),SPA,SPA,0.0)
```

```
 D2Y=SWIN(D2YO,D2YC,ISTATE.EQ.1.0)
 SPV=INTGRL(D2Y,0.0)
 D1YC=FNSW(AINT(Y)-AINT(1.0-Y),0.0,SPV,SPV)
 D1YO=FNSW(AINT(Y)-AINT(1.0-Y),SPV,SPV,0.0)
 D1Y=SWIN(D1YO,D1YC,ISTATE.EQ.1.0)
 Y=INTGRL(D1Y,0.0,0.0,+1.0)
C--DYNAMIC EQUATIONS MAIN POPPET
 MPA=(V-Z*X-U*PSE-X-Q-SIGNDX*FF)/M
 NOSORT(D2X=X,MPA)
 D2X=MPA
 IF(X.LE.0.0.AND.MPA.LE.0.0) DSX=0.0
 IF(X.GE.10.444.AND.MPA.GE.0.0) D2X=0.0
 END
 MPV=INTGRL(D2X,0.0)
 NOSORT(D1X=X,MPV)
 D1X=MPV
 IF(X.LE.0.0.AND.MPV.LE.0.0) D1X=0.0
 IF(X.GE.10.444.AND.MPV.GE.0.0) D1X=0.0
 END
 X=INTGRL(D1X,0.0,0.0,10.444)
C--SERVO PRESSURE EQUATIONS
 SIGNDX=FNSW(D1X,-1.0,0.0,1.0)
 PSE=FNSW(AINT(Y)-AINT(1.0-Y),1-K,
&  (SIGNDX*SQRT(ABS(W))-B)/A,J+PT)
 W=B**2-A*C
 A=1+H+1/(4*H)
 B=(J-K-PT-1)/2-1/(4*H)-PT*H
 C=PR/2+1/(4*H)+PT**2*H+PT*K-J+J**2*H
 H=Y**2/(2*L)+0.00001*INT(1-Y)
 J=N*D1X**2/(Y**2+0.00001*INT(1-Y))
 K=N*D1X**2/L
 L=(1-Y)**2+0.00001*INT(Y)

 Q1=G*X
        INTINF
        ALG:TRPZ
        CI:CI=0.099
        ABSERR:ABR=.001
        STEPS:MINS=100
        MAXSTEPS:MAXS=1000
        MONITOR:IMON=0
        END
 OUTECI TIME,D2X,D1X,X,D2Y,D1Y,Y,Q1,F
 TERMINATE (TIME.GE.13.5)
 END
 FINISH
**** - END OF INPUT
```

APPENDIX E

ROADHEADER KINEMATICS

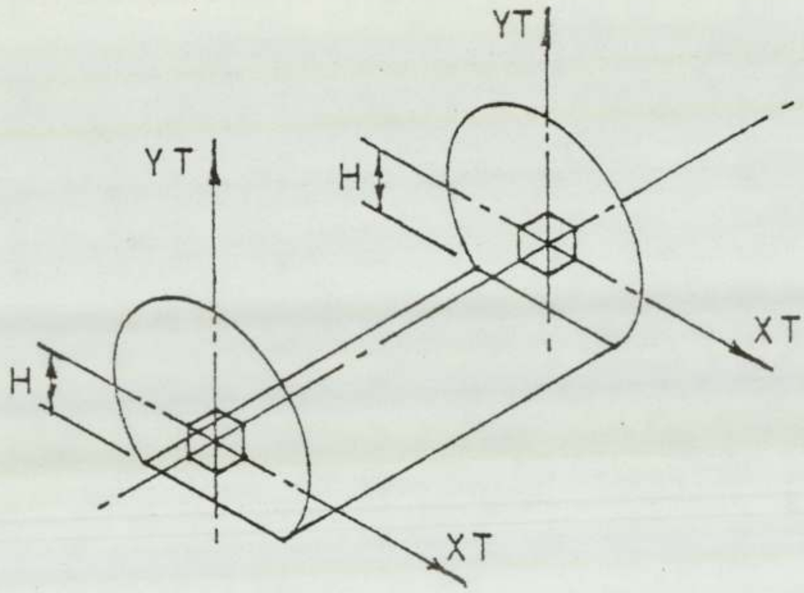


FIGURE E.1 TUNNEL COORDINATES.

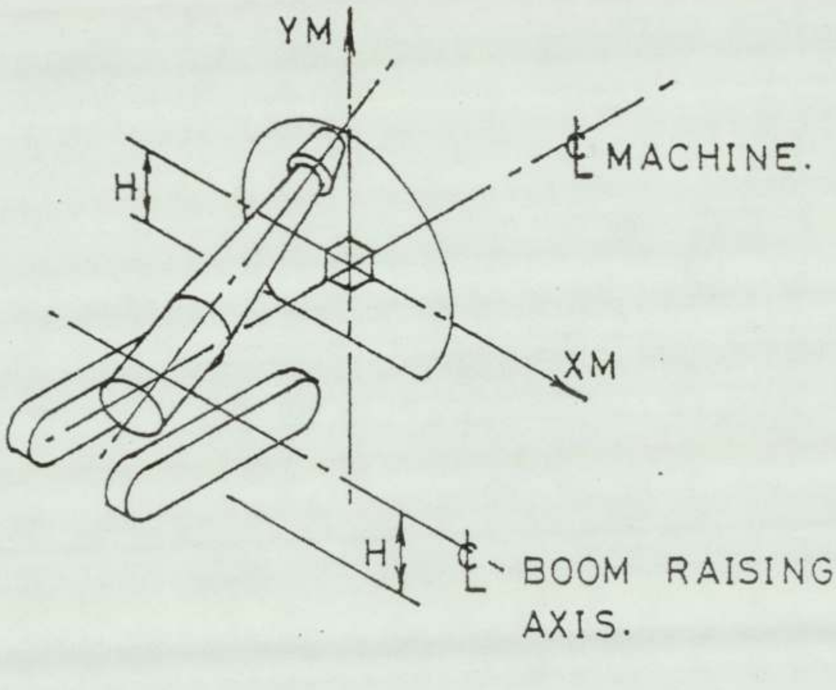


FIGURE E.2 MACHINE PLANE COORDINATES.

E.1 INTRODUCTION.

The processor system developed for the roadheader controls the boom position with respect to the machine frame. For accurate tunnel profiling the machine must remain in the same position with respect to the cross-section of the tunnel. This is recognised as an undesirable requirement.

To implement the control of all free ranging aspects of the roadheader it is necessary to reference the machine frame to the tunnel centre-line. This aspect of control can be implemented with present day technology, except for detecting the machine frame degrees of freedom in a mine worthy manner. Work is progressing at the MRDE, and elseware, on the development of suitable detectors.

This Chapter describes the kinematic exercise for the roadheader in relating the boom position to the tunnel cross-section, taking into account the machine frame degrees of freedom.

E.2 RELATING THE RIPPING HEAD TO THE MACHINE FRAME.

The profile cutting requirement for the ripping boom dictated continuous positional control of the ripping head on a predetermined path. This path is the profile of the tunnel being cut and can be defined using XT and YT coordinates on the tunnel cross-sectional plane as shown in Figure E.1. This plane can lie at any point along the length of the tunnel.

XT = 0, is fixed by the horizontal centre-line of the tunnel. The profile is usually symetrical about this point,

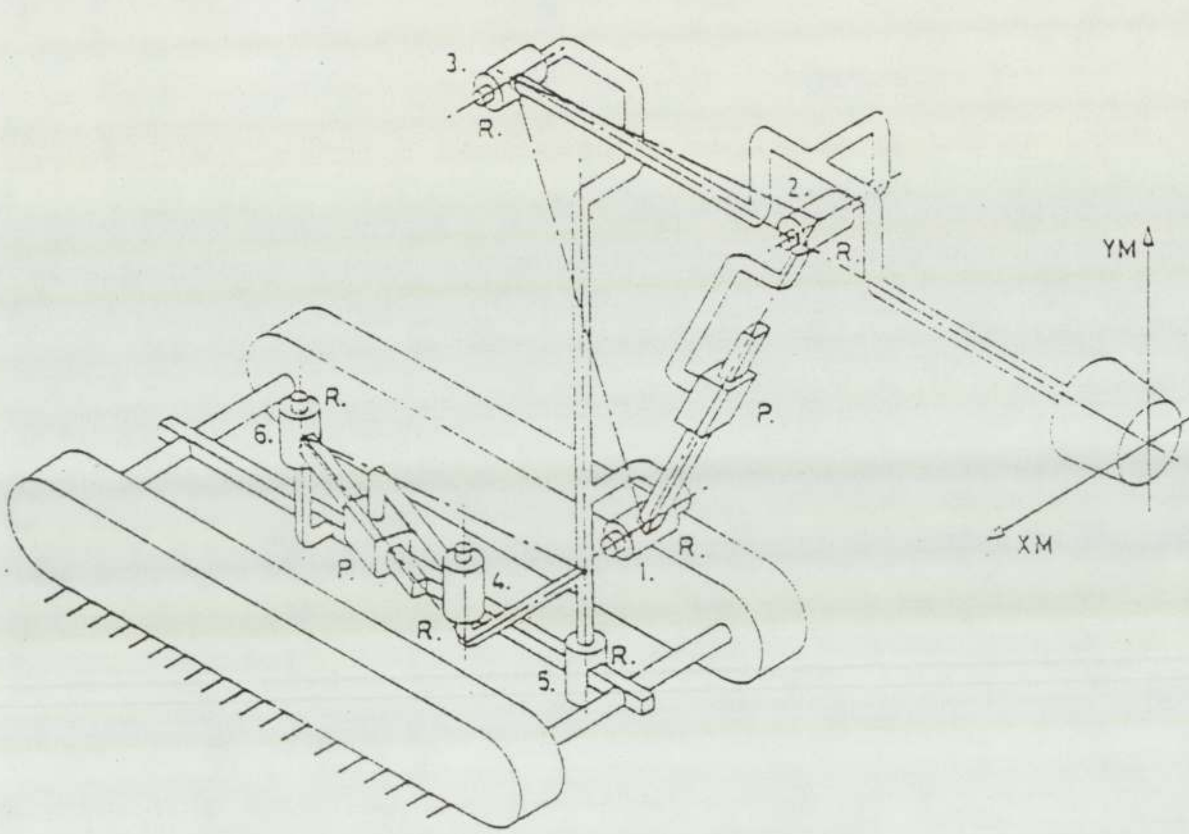


FIGURE E.3 BOOM LINKAGE.

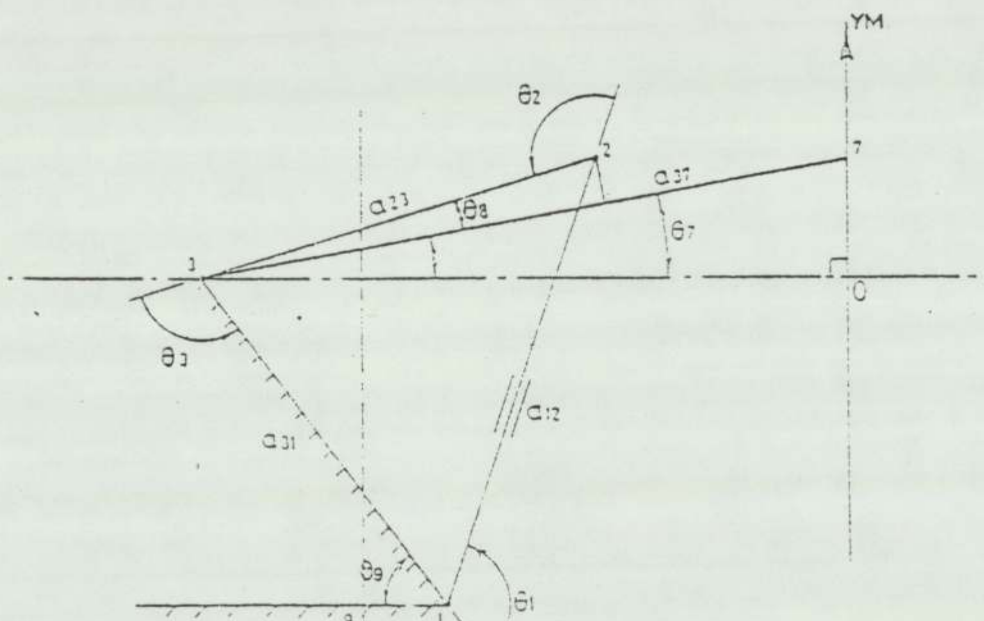


FIGURE E.4 BOOM VERTICAL PLANE LINKAGE.

on the XT axis.

YT = 0, is at a distance H from the tunnel floor and coincides with XT = 0.

To aid the kinematic analysis, a separate plane was used to relate the displacement in the degrees of freedom of the boom. This plane is shown in Figure E.2, and is taken as lying at right-angles to the machine centre-line. The machine centre-line is parallel with the tracks and passes through the boom raising pivot. The plane is positioned along this centre-line, at a point where it is in contact with the end of the ripping head.

XM = YM = 0, at the machine centre-line at height H from the bottom of the tracks.

XM = XT and YM = YT, when the machine centre-line and tunnel centre-line coincide.

The linkage arrangement of the Dosco Mk.2 roadheader boom is shown represented in Figure E.3.

Movement of the ripping head, in relation to the machine plane, is obtained using six revolute (R) pairs and two prismatic (P) pairs. The prismatic pairs represent the hydraulic actuators. Revolute pairs numbered 1, 2 and 3, and a prismatic pair form a planer triangle which effects the raising and lowering of the ripping head on the YM axis Revolute pairs numbered 4, 5 and 6, and a prismatic pair form a planar triangle which effects the the slewing of the ripping head on the XM axis.

The boom vertical plane linkage is shown in Figure E.4, where :-

$$YM = a37 \sin(\theta 9 + \theta 3 + \theta 8) \qquad (E.1)$$

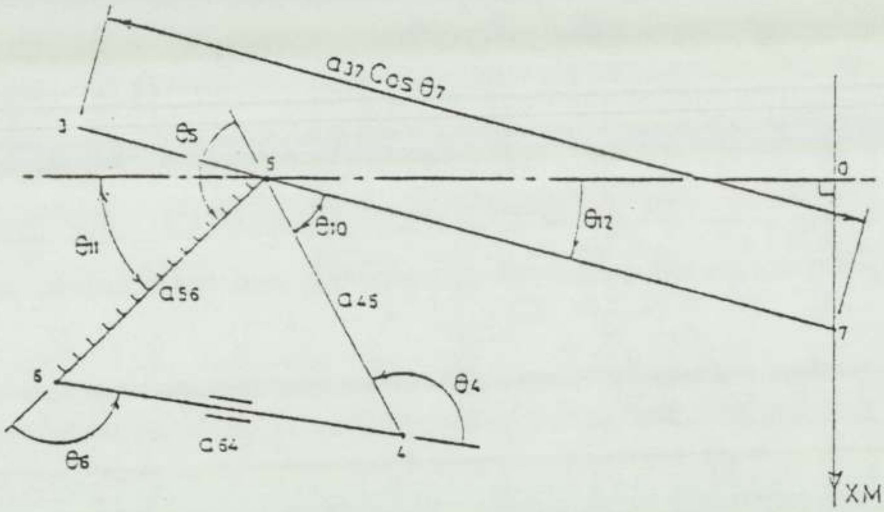


FIGURE E.5 BOOM HORIZONTAL PLANE LINKAGE.

All quantities in this equation are fixed dimensional parameters of the machine, except for θ3.

$$\text{Cos } \theta 3 = \frac{a12 - a23 - a31}{2\ a23\ a31} \qquad (E.2.)$$

The boom horizontal plane linkage is shown in Figure E.5, where :-

$$XM = (-a37\ \text{Cos}(\theta 9 + \theta 3 + \theta 8)) -$$

$$(a31\ \text{Cos}\theta 9 - a19)\ \text{Sin}(\theta 5 - \theta 10 - \theta 11) \qquad (E.3)$$

All quantities in this equation are fixed dimensionsal parameters of the machine, except for θ5.

$$\text{Cos } \theta 5 = \frac{a64 - a45 - a56}{2\ a45\ a56} \qquad (E.4)$$

These expressions relate the hydraulic actuator displacements to the ripping head displacements on the XM and YM axes on the machine plane. If displacement feedback was obtained from transducers, placed within the actuators (Chapter 4), then these equations would form part of the control kinematics.

The equations which relate the boom angular displacements to the ripping head displacements on the XM and YM axes on the machine plane are :-

$$YM = a37\ \text{Sin}\theta 7 \qquad (E.5)$$

and

$$XM = a37\ \text{Cos}\theta 7\ \text{Sin}\theta 12 \qquad (E.6)$$

Boom angular feedback considerably simplifies the machine kinematic equations.

E.3 RELATING THE MACHINE FRAME TO THE TUNNEL CENTRE-LINE.

When the roadheader is placed centrally, on a level floor, in a straight tunnel, the machine and tunnel

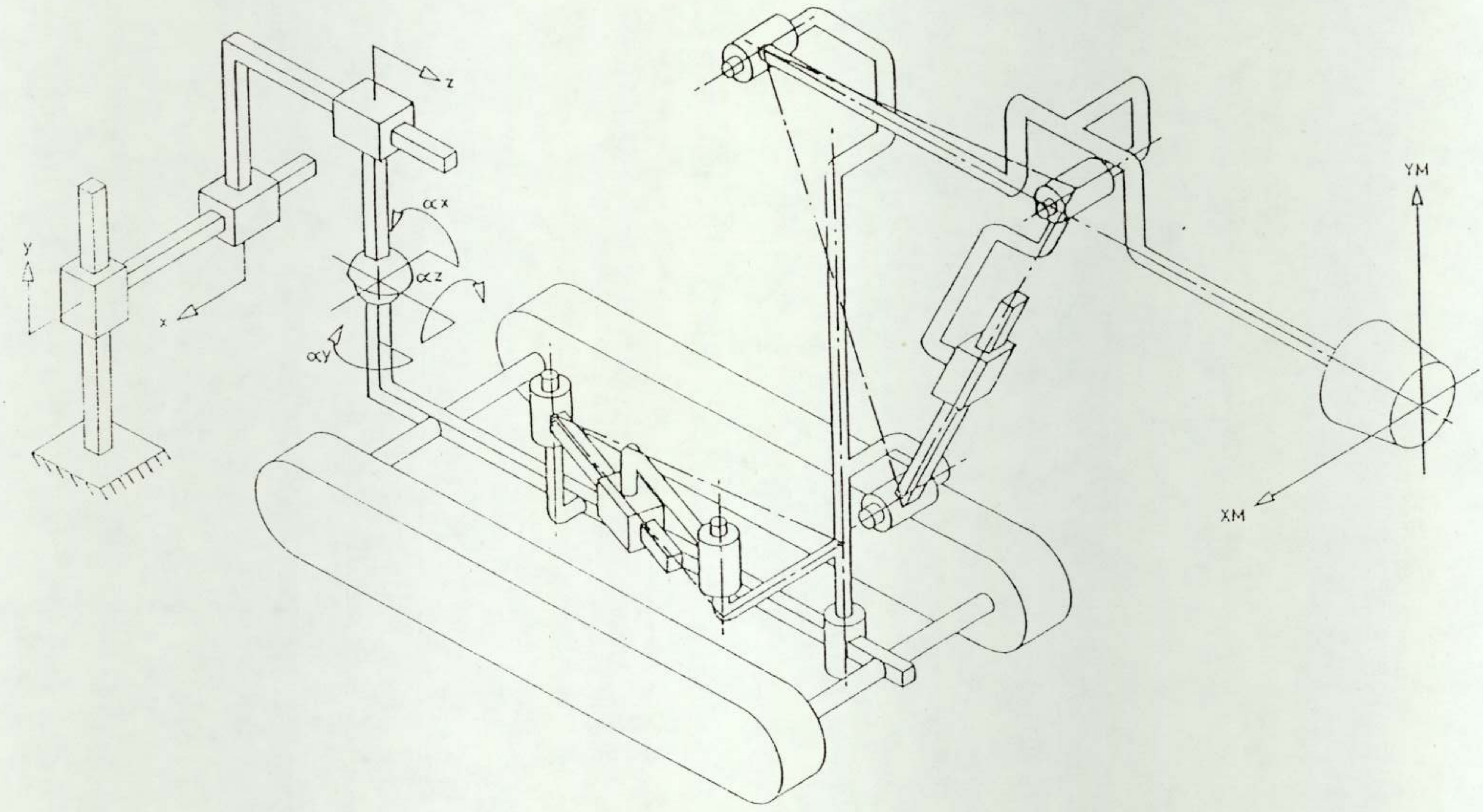


FIGURE E.6 BOOM SPATIAL LINKAGE DIAGRAM.

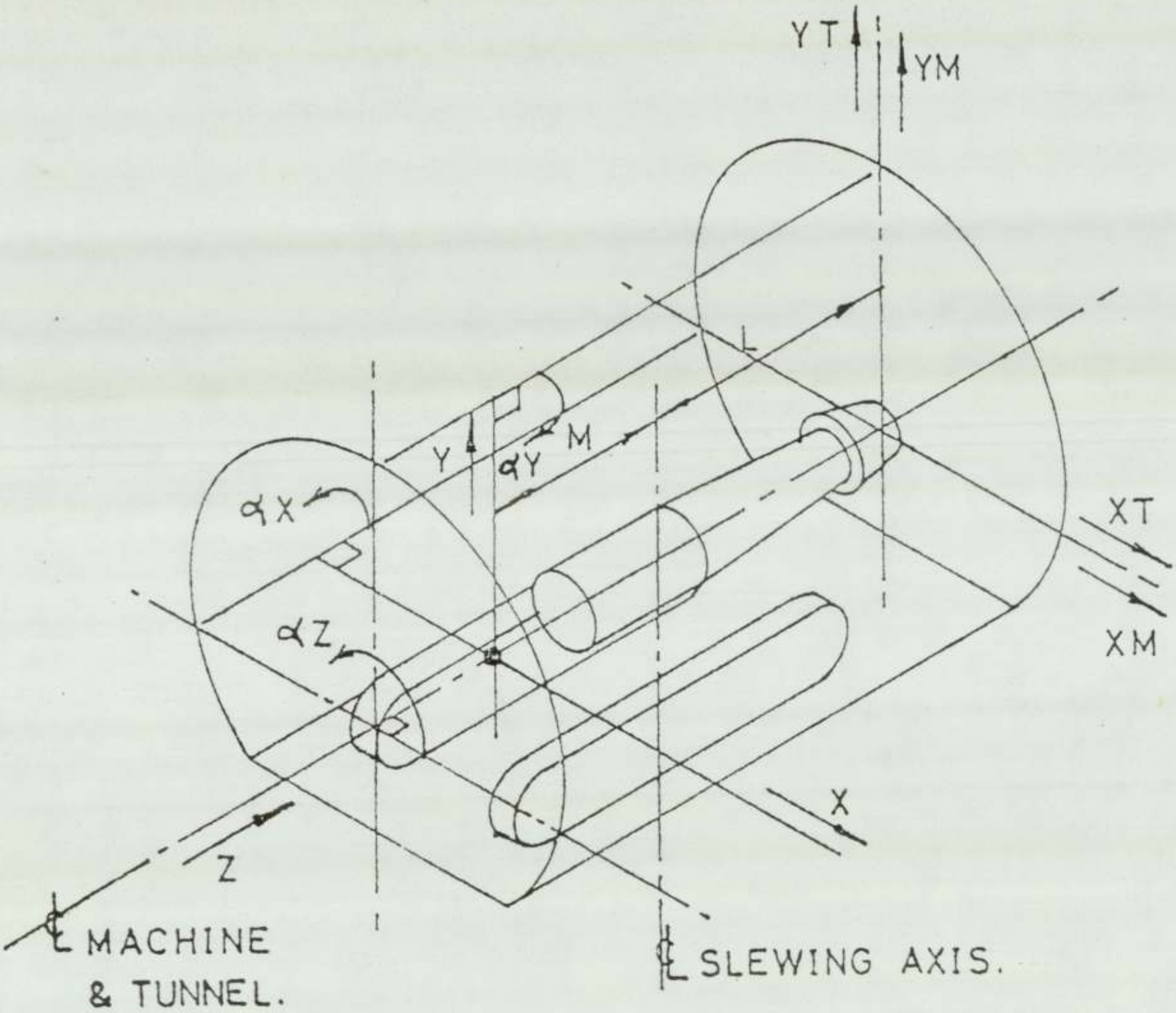


FIGURE E.7 MACHINE DEGREES-OF-FREEDOM.

(MACHINE AND TUNNEL PLANES COINCIDE.)

centre-lines coincide, as do the machine and tunnel planes. The roadheader is free-ranging and the ripping operation causes displacement of the machine frame with respect to the tunnel. It is necessary, therefore, to relate the two planes using machine frame degrees of freedom.

The complete kinematic linkage diagram is shown in Figure E.6. The three linear degrees of freedom are depicted with prismatic pairs, with directional notations X, Y and Z, and the three angular degrees of freedom, $\measuredangle X$, $\measuredangle Y$ and $\measuredangle Z$ are represented with a spherical pair.

A point on the roadheader, about which machine displacements are measured, is positioned on the machine centre-line, at a distance M from the slewing axis centre-line. This is shown in Figure E.7, where the machine and tunnel centre-lines coincide and all machine displacements are considered to be zero.

The machine displacement axes, X and Y, are considered always to lie at right-angles to the tunnel centre-line. Displacement Z is measured along the tunnel centre-line from a fixed datum point. All roadheader angular displacements are measured about the linear displacement axes.

The distance between the boom slewing axis and the machine plane, measured along the machine centre-line, is defined by dimension L, where :-

$$L = (-a37 \cos(\theta 9 + \theta 3 + \theta 8) - a31 \cos \theta 9 + a19) \times \cos(\theta 5 - \theta 10 - \theta 11) \qquad (E.7)$$

The machine is shown displaced from the tunnel centre-line in Figure E.8. The machine and tunnel planes no

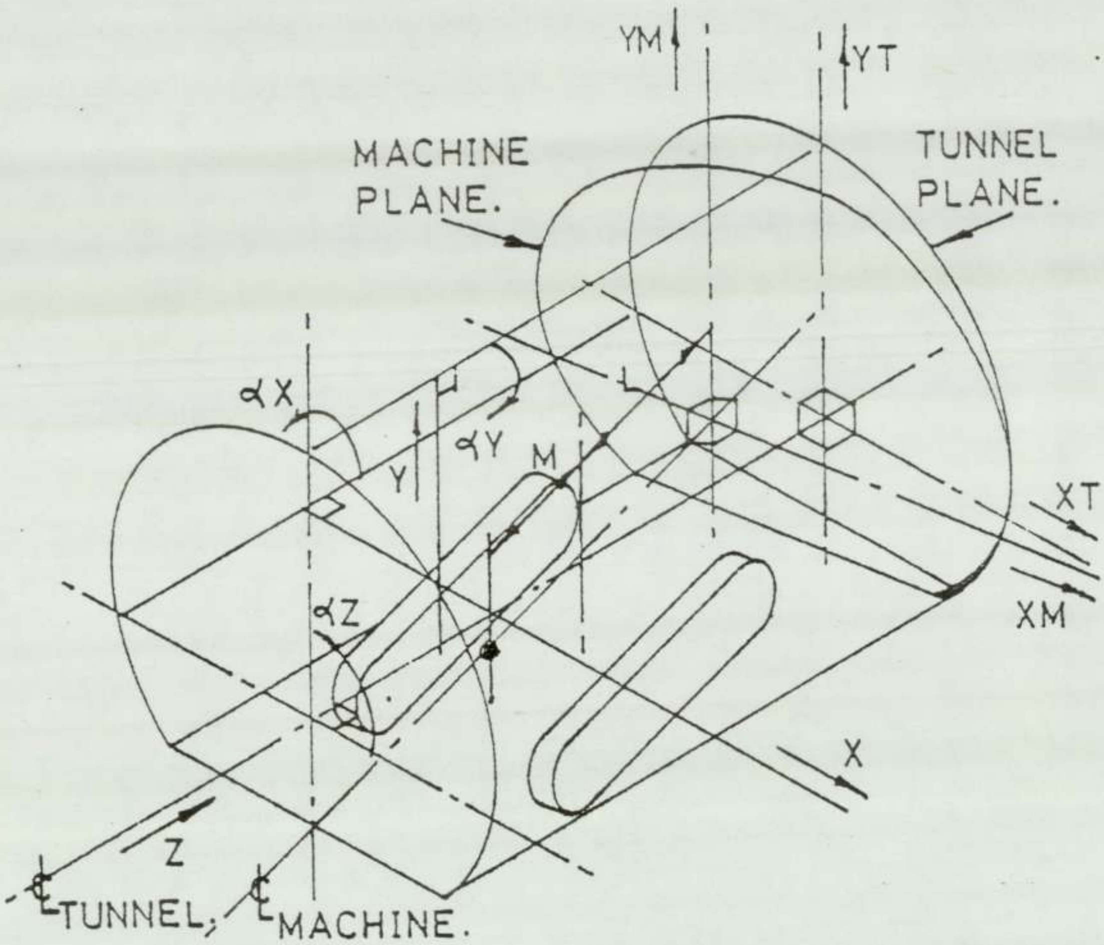


FIGURE E.8 MACHINE DEGREES-OF-FREEDOM.

(MACHINE AND TUNNEL PLANES OFFSET.)

longer coincide, and it is necessary to relate the machine plane displacements to the tunnel plane displacements :-

$$XT = (X + (M + L)\ Sin\ \alpha Y + XM\ Cos\ \alpha Y)\ Cos\ \alpha Z \qquad (E.8)$$

$$YT = (Y + (M + L)\ Sin\ \alpha X + YM\ Cos\ \alpha X)\ Cos\ \alpha Z \qquad (E.9)$$

Note, linear displacement Z is not incorporated in these equations since displacement along the tunnel centre-line does not constitute any offset between the two planes.

The equations are relavant only to a straight tunnel. Roadheaders are often required to rip tunnels with a curving centre-line. One possible method of incorporating this feature would be to input "false" displacements, on the linear degrees-of-freedom, representative of the curve required.

E.4 CONTROL OF FREE RANGING ASPECT OF ROADHEADER.

The control of the free ranging aspect of the machine has not been implemented at this stage, although the future requirement has been allowed for in various parts of the control system.

There are spare analogue to digital conversion channels and data storage locations for the six degrees-of-freedom. These could be used when transducers for detecting the machine frame displacements are available.

The handling of the arithmetic operations, for the kinematic equations, within the control system could be carried out using software operations, or an Arithmetic Processing Unit (APU), or a combination of software operations and lookup tables.

Software operations are relatively slow and demand memory, particularly for trigonometrical functions.

Using look-up tables is a simple way to perform arithmetic operations quickly, but at the cost of extra memory. Such tables simply contain all the possible answers organised in a convenient manner. All that is required is to access the desired answer which can make for high speed operations.

The mathematical capability of a wide variety of processor orientated systems has been enhanced by the APU.

The Intel 8231A APU, implemented in the main control system by C. W. Chuen, for handling valve switching criteria equations, would be an obvious choice for the kinematic equations. Accuracy, speed and simple interface are its advantages. It takes, for example, approximately 40 times longer to do a floating point, single precision, 32-bit, Sine operation using software. The only real disadvantage of the APU for this application, where intrinsic safety is a requirement, is that dual supplies of 5V and 12V are required. It is an expensive I.C. (£120), which is not particularly relevant in this case, with the high cost of roadheading machines.

Further details of the 8231A APU can be found in Ref.26, and comparison details of arithmetic operation methods can be found in the thesis carried out by C. W. Chuen.

The roadheading machine is a simple mechanism for kinematic considerations. The boom mounted drilling machine, with multiple linkages, would be more complex to analyse. A great deal has been written in recent years on the analysis of mechanisms, and Ref.61 and 62 were found particularly useful.

APPENDIX F

PHOTOGRAPHS

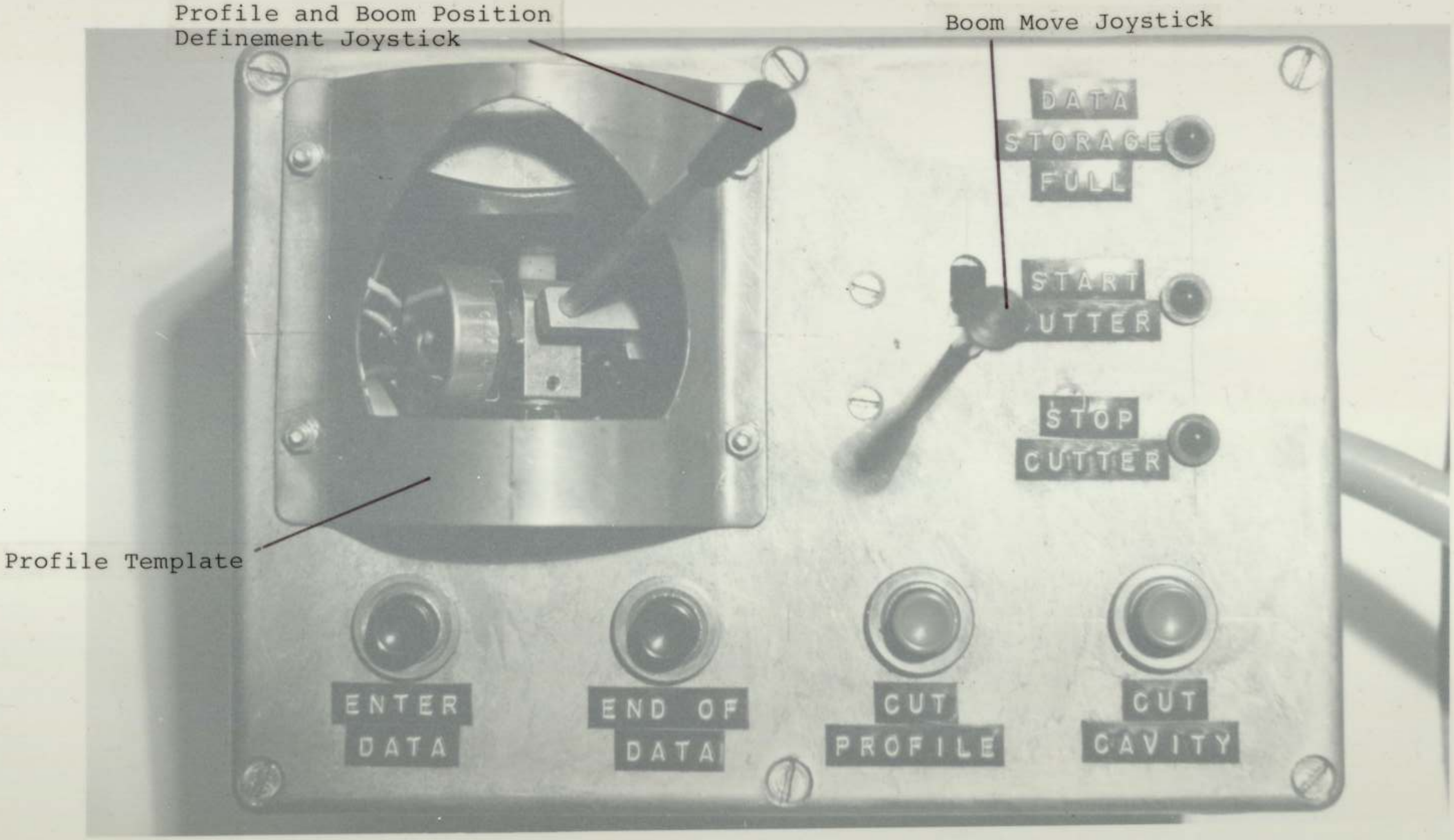


FIGURE F.1 , OPERATOR CONTROLS.

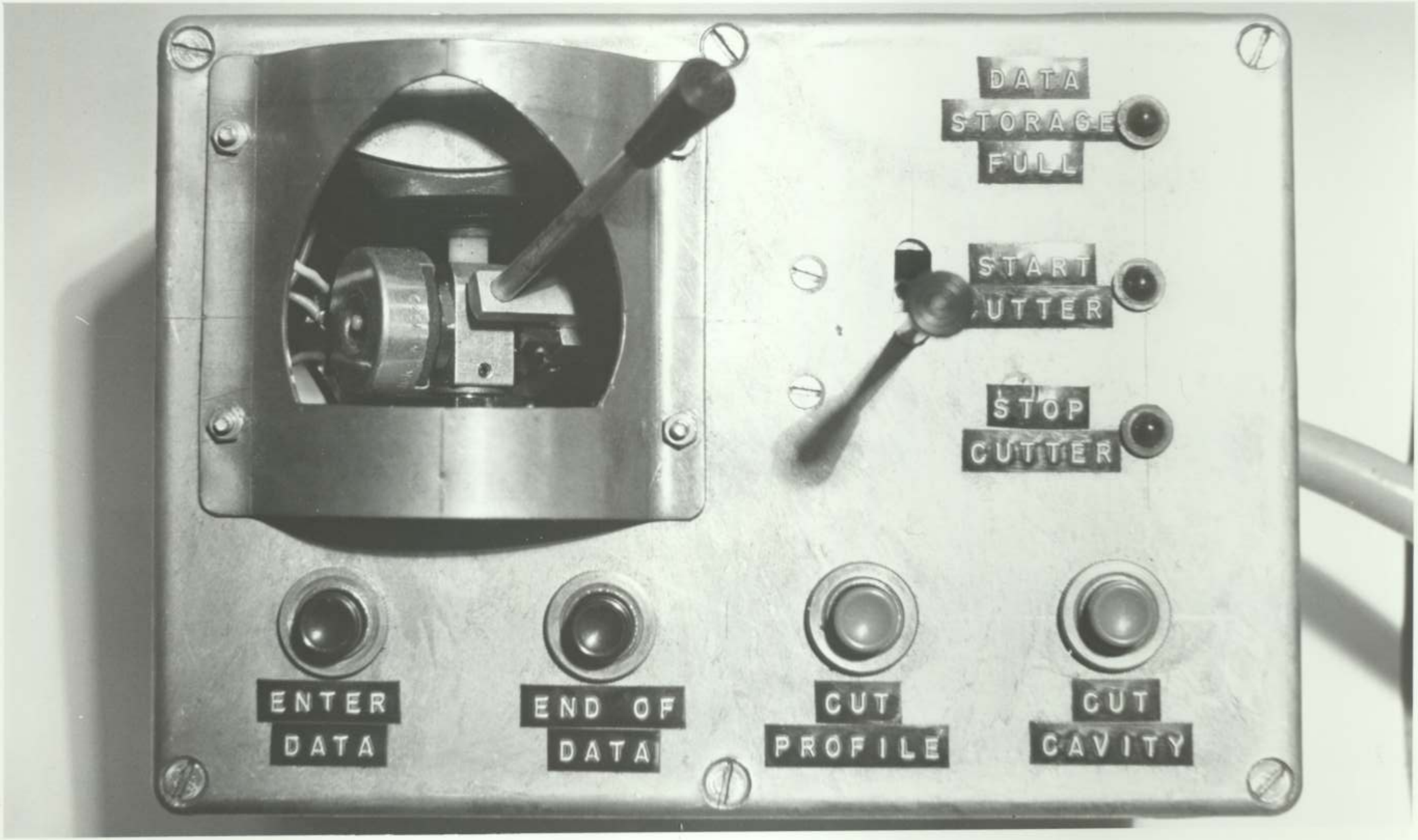


FIGURE F.1 OPERATOR CONTROLS.

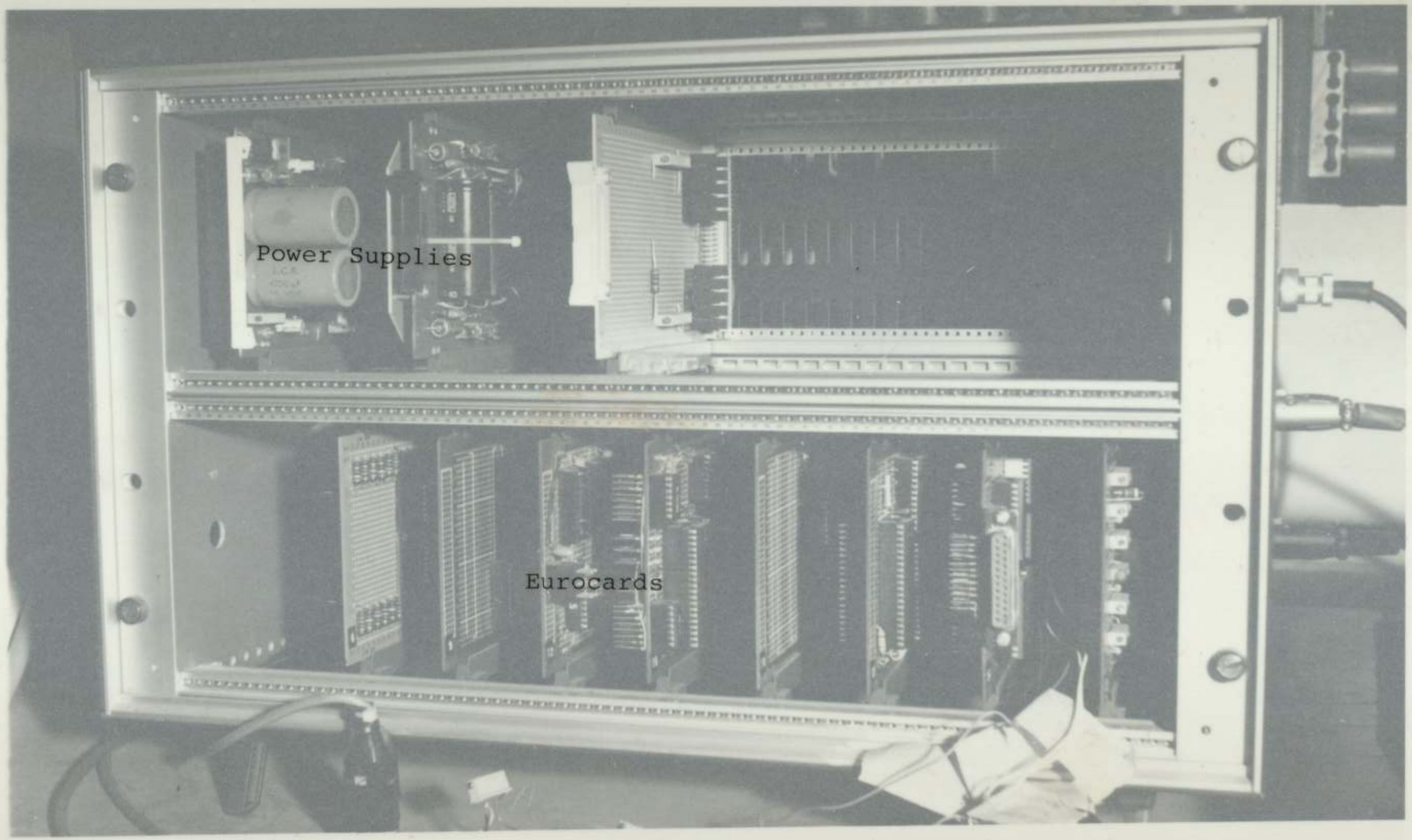


FIGURE F.2 DUAL MICROPROCESSOR CONTROL SYSTEM.

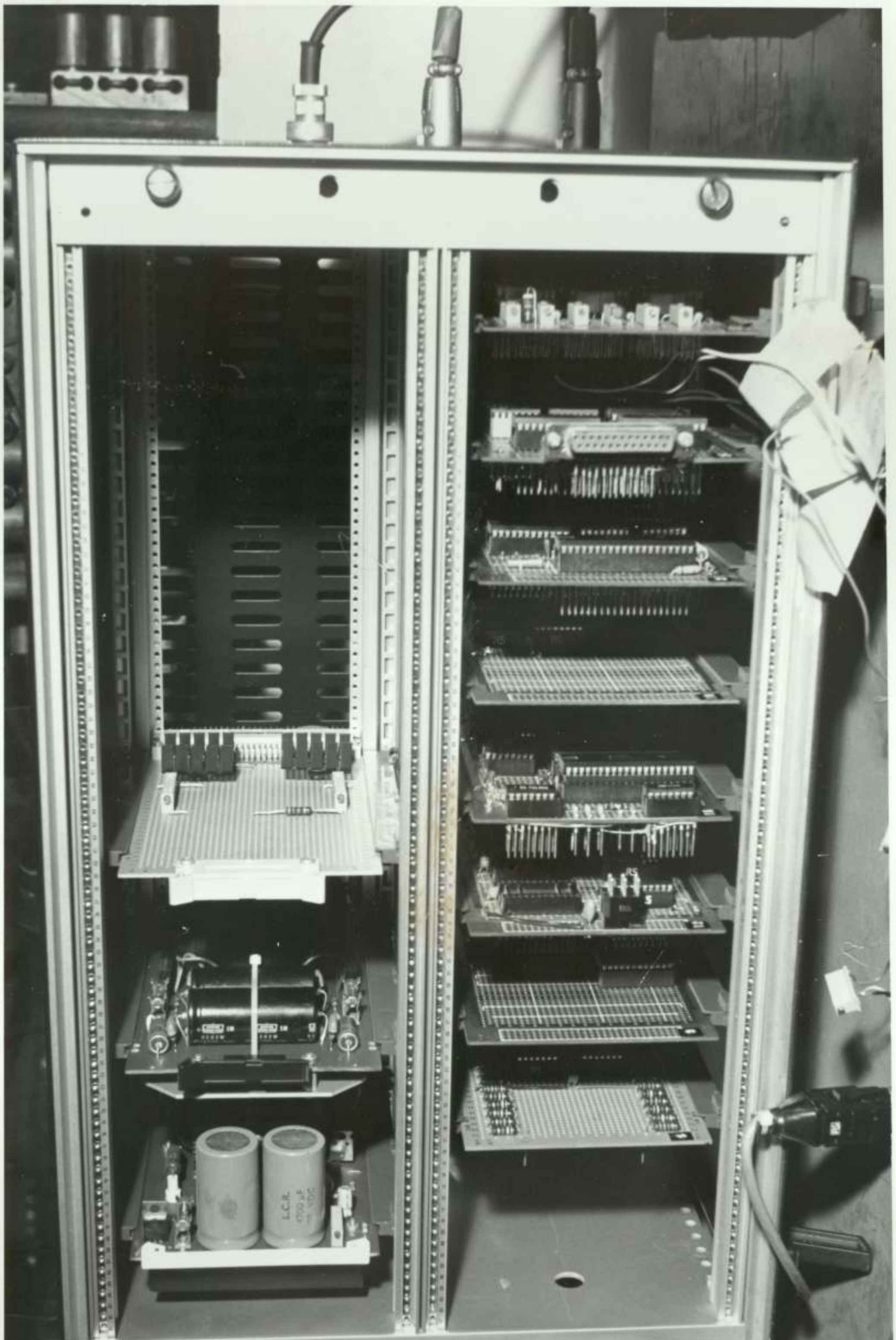


FIGURE F.2 DUAL MICROPROCESSOR CONTROL SYSTEM.

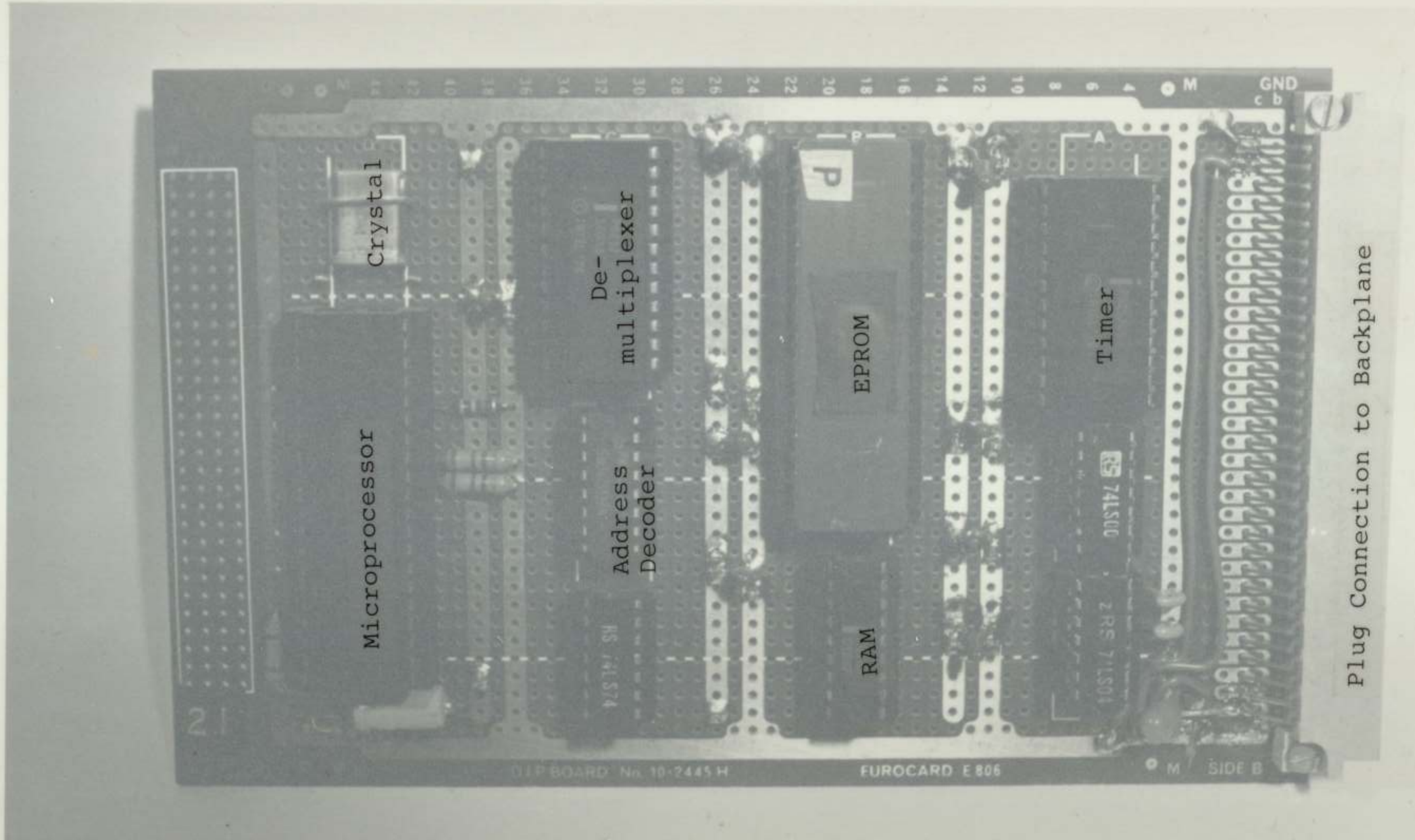


FIGURE F.3 RETRIEVAL SYSTEMS MAIN CARD.

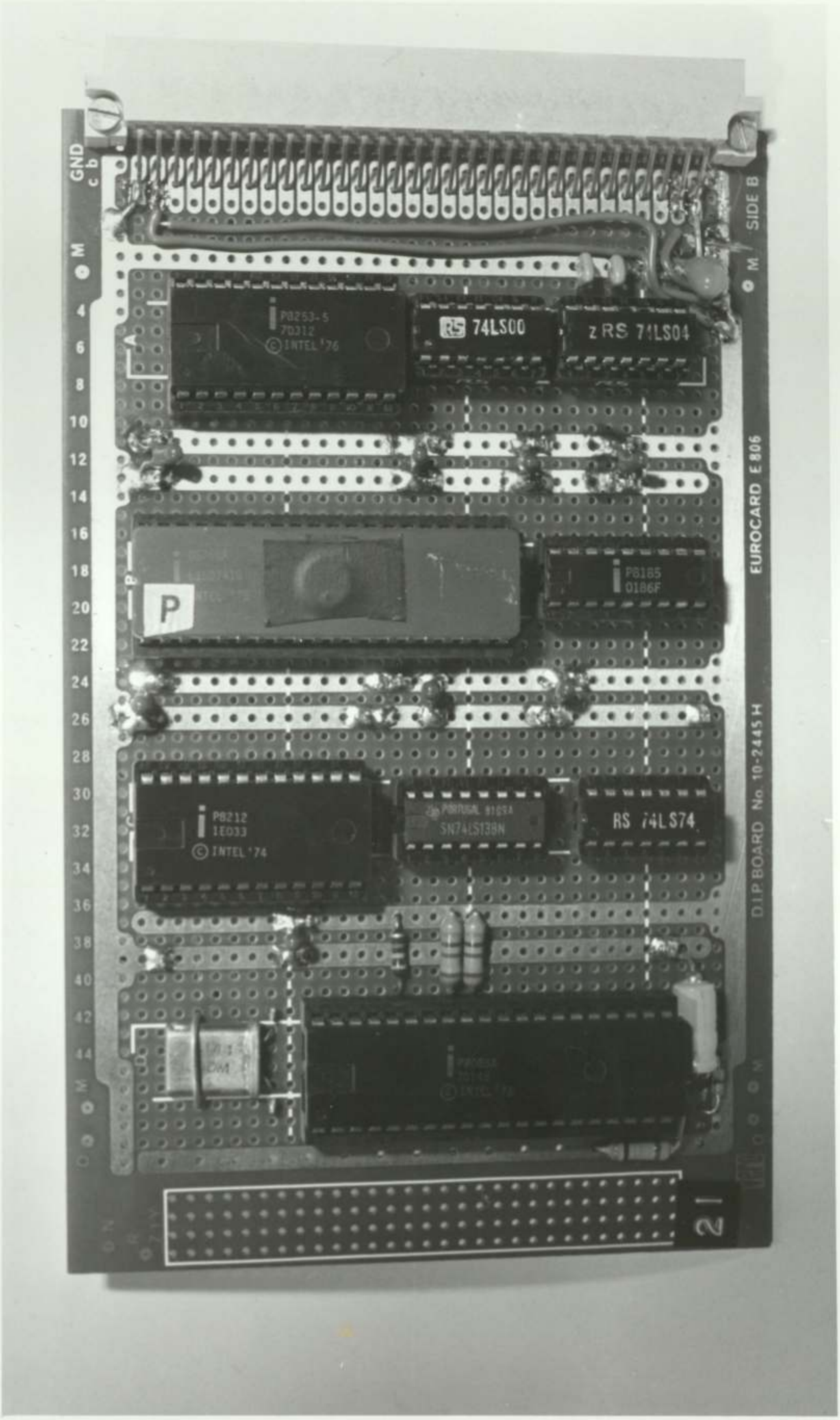


FIGURE F.3 RETRIEVAL SYSTEMS MAIN CARD.

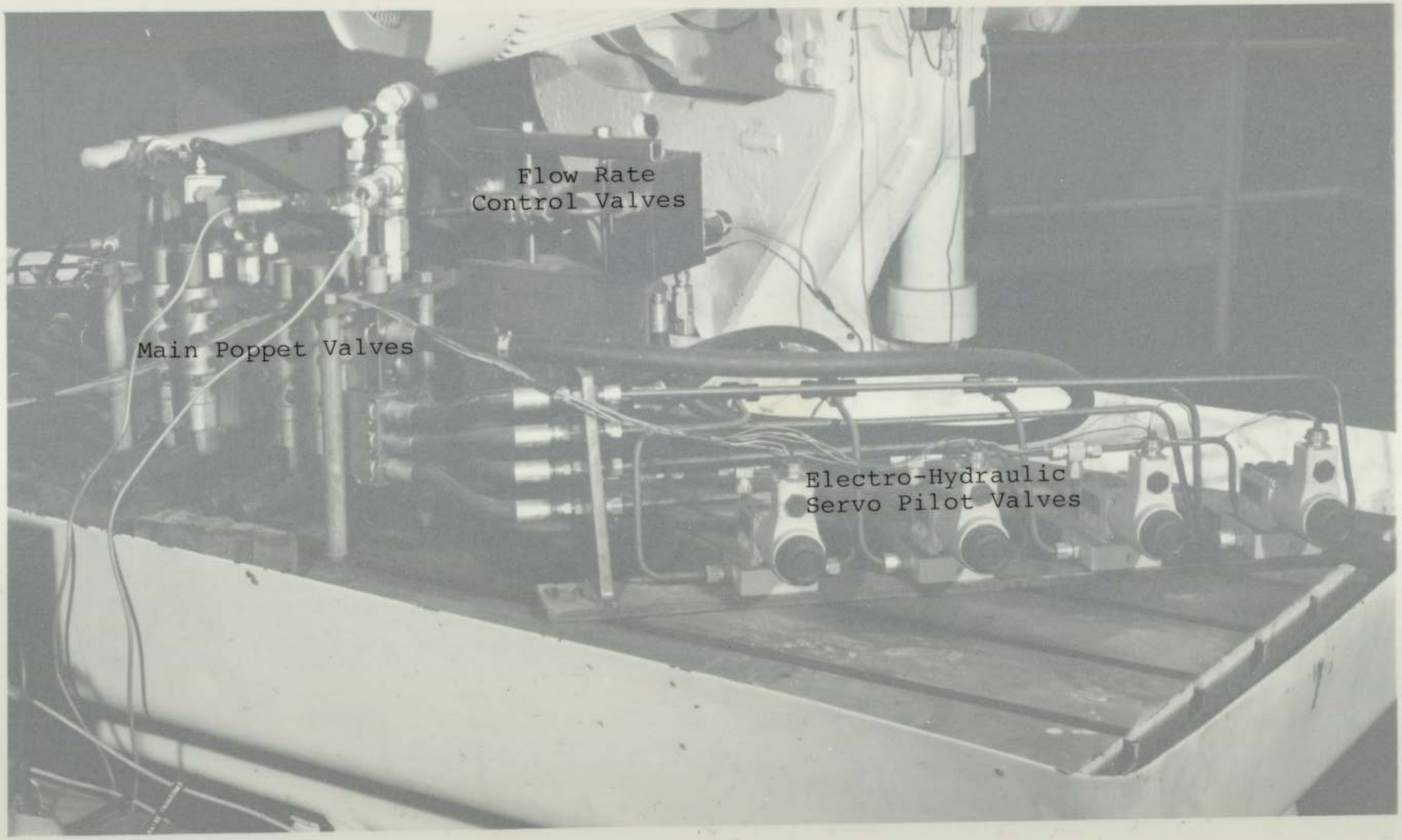


FIGURE F.4 VALVES MOUNTED ON HYDRAULIC BENCH.

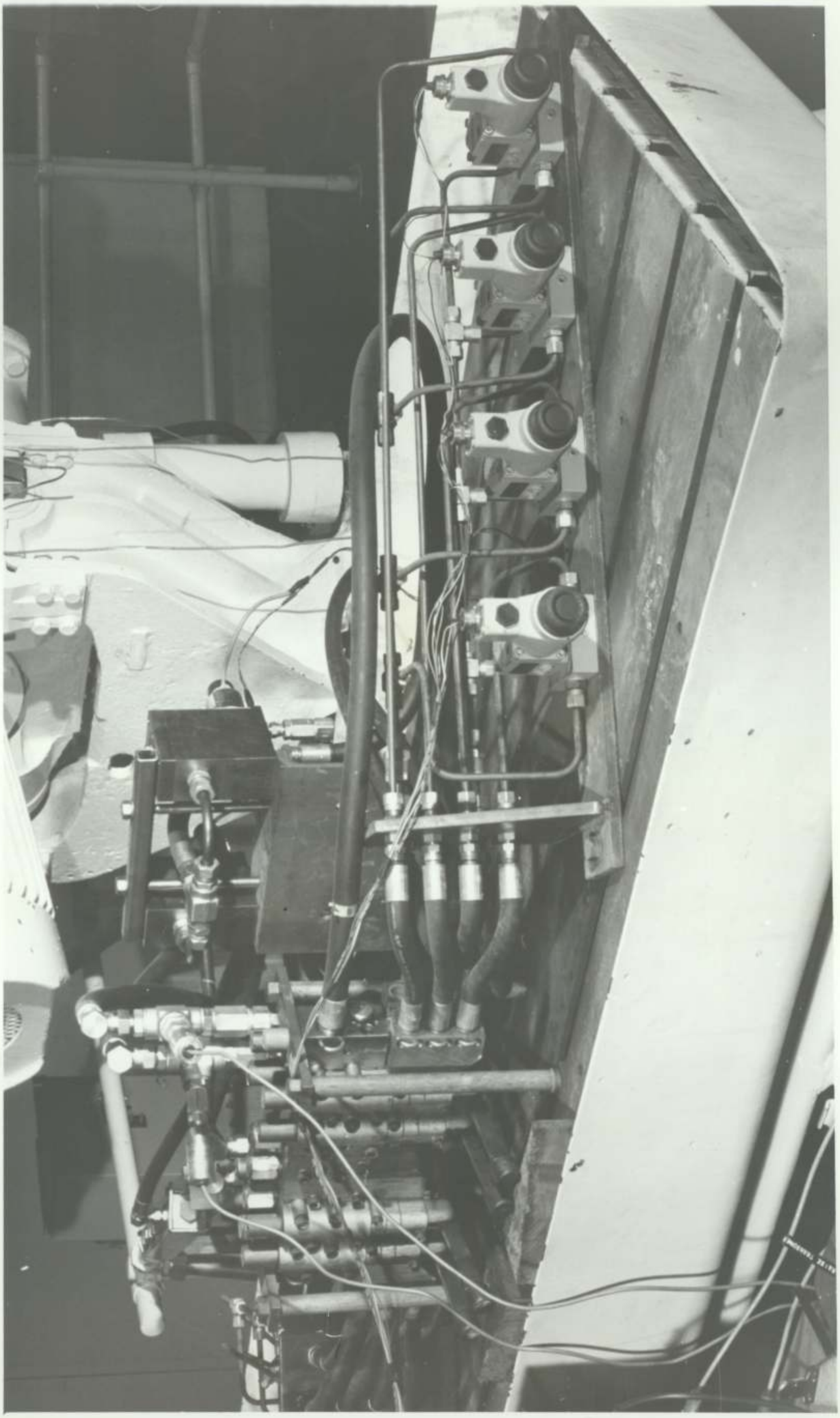


FIGURE F.4 VALVES MOUNTED ON HYDRAULIC BENCH.

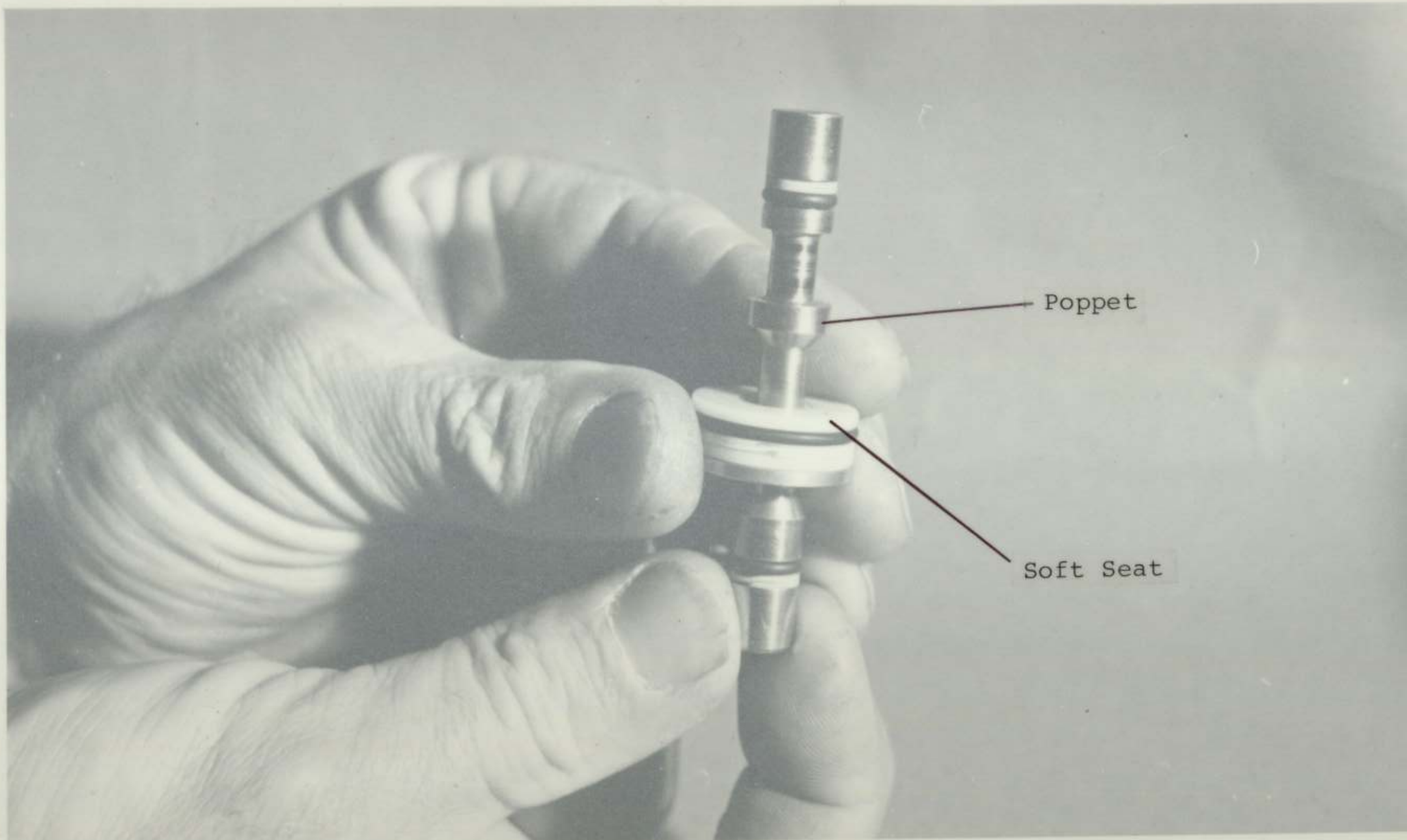


FIGURE F.5 MAIN POPPET AND SEAT.

FIGURE F.5 MAIN POPPET AND SEAT.