MICROPROCESSOR-BASED AGRICULTURAL

DIGGER CONTROL

Thesis submitted in accordance with the requirements
of the University of Liverpool for the degree of
Doctor in Philosophy

by

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SUMMARY

This thesis describes the design, construction, and evaluation of a closed loop microprocessor based control system for a tractor mounted type PA6 agricultural digger as manufactured by F.W. McConnel, Ltd., Ludlow. After a description and analysis of the principal operations for which the digger is used a set of functional objectives is defined. As agricultural diggers are used intermittently and mainly for annual maintenance it was decided to develop a system to reduce the level of skill to be maintained or acquired to use the machine efficiently and effectively.

To reduce the degree of coordination required of the operator the microprocessor system was designed to make straight cuts at any specified pitch by the deflection of a single control lever. To facilitate repetitive difficult cuts a learn and repeat facility was included to repeat a learned path from any given starting point.

To minimise the cost of the system single stage proportional electrohydraulic valves were used and were evaluated in a simple proportional controller built to operate in a fashion similar to the conventional mechanical control system. Having demonstrated that satisfactory manual control may be achieved using these valves the microprocessor system was built, based on an Intel 8085 with an AMD 9511 Arithmetic Processor Unit.

For closed loop control mechanically robust and water resistant transducers were designed to mount on the machine pivots and measure arm positions. The valves were interfaced to the computer by an eight bit pulse width modulator circuit and an eight bit multiplexed analogue to digital converter was used to input transducer signals and control inputs from the portable control unit. The computer is based on an Intel SDK-85 development kit and power for the system is derived from the tractor battery.

The system software was written in assembly language for speed of execution and stored in EPROM. The program reads the control inputs and machine outputs, inverts the machine geometry to calculate the required output positions and assigns the valve settings according to the positional errors. The sampling and execution frequency of the control software is 30 Hz.

Evaluation trials were carried out with both skilled and novice users. The principal results were that the system assisted with levelling and trench cutting, but overall did not provide any significant consistent increases in work rate for either group of users. Finally, further areas for research are discussed, with reference to both diggers and electrohydraulic hedge cutters.

Acknowledgements

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CHAPTER ONE

INTRODUCTION

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1.1 Microprocessors in Agriculture

Over the past few years microprocessors have been used in an increasing number of applications in agriculture to help make optimal use of the resources of energy, materials, money, and manpower. The first area in which they were applied is that of record keeping; subsequently they have been used in modelling, instrumentation, and the control of farm equipment and field machinery. The subject of this work is the application of microprocessors to the control of a tractor mounted hydraulic digger. It is useful, however, to start by putting the work in context and examining how the potential of microcomputers has so far been exploited by the agricultural industry, and what the future developments are likely to be.

1.2 Record Keeping

In 1982 it was estimated that about four hundred microcomputers were being used in farm offices is the UK for accounting, handling payrolls, livestock ration formulation and performance monitoring[1]. This number will have greatly increased with decreasing system cost and availability. One particular area for which a number of systems have been developed is that of dairy herd monitoring. In discussing this application Speicher[2] states

> "The ultimate goal is for the computerised data acquisition system to be fully informed on the production, nutrition, reproduction, health, and economic status of all animals at all times and to notify the manager of any appropriate action to be taken."

In some installations this goal is effectively attained, and in addition the monitoring system is used in conjunction with automatic feeding machinery. The data acquisition is automated by the use of cow identifiers, either implanted or worn around the neck, which allow detectors at the milking parlour and feeding points to recognise individual animals[3].

The US Department of Agriculture (USDA) is developing a minicomputer system for maintaining record of feed consumption, milk production, temperature, and condition on individual animals to improve the performance of the livestock producer[4]. The computer system facilitates the management of larger herds and enables changes in performance and health problems to be more easily detected by giving data on both the herd and individual animals. It will be a short time before such systems are implemented on microcomputers and come into more widespread use. In a scheme run in Scotland a number of farms use microcomputers to monitor health and, by linking individual micros to a mainframe, large scale statistical studies may be carried out for disease control and studies on optimum herd management strategies[5].

Another area where microcomputers are used for record keeping is that of plant breeding where conventionally card index systems are used. The USDA have produced a program to be run on a desk microcomputer for use by plant breeders and horticulturalists for maintaining records on plant pedigrees[6]. The program stores, searches, lists, corrects, appends, and duplicates plant pedigree records using magnetic tape for backing store.

1.3 Modelling

A number of programs have been developed for modelling and evaluation of the efficacy of different farming strategies. With for example arable farming, given data on the cropping history of the fields involved, soil analysis, and fertiliser input, the gross profit margin and cash flow for different crops may be calculated. The Ministry of Agriculture, in conjunction with the National Institute for Agricultural Engineering have developed a program for glass house crops and field vegetables where soil analysis data is used to provide information on the fertiliser requirements of each crop. Work has also been done on the optimisation of grassland usage. A number of detailed modelling programs have been written to run on mainframes, not directly accessible to the farmer[7]. With the low cost and versatility of desk top machines such programs should become increasingly available for use on microcomputers.

1.4 Instrumentation

Certain diseases affecting fruit and vegetables may be accurately predicted, and preventive action taken, by close monitoring of such environmental factors as temperature and humidity. Microcomputer systems may be used to continuously monitor these variables and alert the grower when dangerous conditions arise. One such system is being developed for the prediction of apple scab fungus which affects orchards; the processor monitors temperature, leaf wetness, and relative humidity in the orchard, checking for dangerous conditions[8]. The system gives on the spot warning as well as keeping record of the variables monitored for later reference.

Another system for predicting potato blight (the fungus Phytophthora infestans) is now commercially available and collects data every ten minutes on temperature, relative humidity, and rainfall[9]. When "blight weather" is detected a display indicates that preventive spraying is required.

An ingenious system has been made for the weighing of poultry whereby a perch is fitted with a load cell and linked to a microcomputer[10]. The mean flock weight is thus monitored as random birds alight on the perch. This saves time otherwise spent weighing manually, enables future weight prediction to be made, allows feed conversion measurement, avoids stress to the birds, and facilitates diet control to maximise the number of fertile eggs for breeding flocks.

An automatic system for weighing the different defect categories of fruits and vegetables has been made to facilitate grading operations[11]. The micro controls the weighing of the contents of each compartment of a mechanical grading table and records the data for the batch on a grade certificate. Microcomputer technology is also used for measuring grain moisture[12], which must be carefully monitored when drying and storing grain, and the quantity of grain harvested on a combine harvester[13]. On the combine harvester it is grain volume that is measured and the system must be first calibrated with the appropriate mass/volume setting. Acreage harvested, average yield, work rate, ground speed, and running yield are also measured and displayed.

1.5 Control of Machinery and Equipment

A major growth area in computerised farming equipment is that of automated animal feeding systems. As early as 1976 a microprocessor based system was developed for cattle recognition and feeding as well as for recording milk production[3]. It is also possible to mix rations automatically to suit individual animals. A pig feeding system described by Fuller[14] weighs and mixes skim milk and meal and pumps a controlled amount to each pen. Feed can be programmed to be given several times a day using up to four solid and two liquid feed ingredients. In principle each animal may be identified, weighed at the feeding point, have high and low density feeds mixed, and be fed in relation to cost and appetite. The ventilation and heating may also be kept under computer control and an adaptive model used to increase feeding when temperature drops[15].

In the Netherlands micros are used extensively for greenhouse climate control and sophisticated adaptive control schemes are employed using on-line identification[16]. Potato sorting has been automated using a microcomputer and a TV camera to sort the potatoes according to size[17]. Systems also exist for the control and monitoring of the drying and storage conditions of grain[18].

In the area of field machinery the use of microprocessor for control and monitoring functions is now well established. On combine harvesters the grain loss varies with the harvesting speed. As the machine is driven faster the grain loss increases, however to reduce the loss almost to nil the speed is prohibitively low so a compromise must be found. On a commercially available system produced by RDS Farm Electronics Ltd. an acceptable level of grain loss is selected and the grain loss monitor is used to control the forward speed of the machine, using another sensor at the front to give advance information about cropping levels[19].

When spraying crops the amount of chemical applied per unit area must be very closely controlled; if too little is applied the spraying may be ineffective and the cost of the chemicals wasted, if too much is applied the crop may be damaged. On the sprayer produced by RDS the operator keys in data on the number of nozzles in use, target speed, flow rate, pressure limits, etc. and by measuring forward speed and nozzle pressure the flow is closely controlled. The system compensates for the square law relation between speed and pressure. The unit displays speed, application rate, pressure, area, trip area as well as the preprogrammed target values. Also, commercially available from Evrard, is a microcomputer based spray system using sonic sensors to measure boom height and keep it constant by controlling the tractor hydraulics[20].

A tractor safety system has been developed using a microprocessor to sense p.t.o. engagement, throttle setting, brakes, hydraulics, operator's seat and brake. If, for example the driver leaves his seat with the p.t.o. engaged it will automatically be stopped. The equipment may also be connected up to equipment such as harvesters drawn by the tractor[21].

These examples show that the use of microprocessors is well established in the agricultural industry and that there is a growing number of applications both in the farm office and in the harsher environment of equipment and field machinery. In view of the rapid growth in the use of these devices in agriculture generally, and their low cost and flexibility, it was decided to investigate their applicability to tractor mounted diggers.

Considerable skill is required to operate these machines efficiently and effectively and a computer assisted control system presents the possibility of facilitating their use. The availability of proportional solenoid valves makes it possible to interface a computer to the machine without the high cost of two stage servo valves. The scope of this work is the development and evaluation, both functional and economic, of a computer based control system for a tractor mounted hydraulic digger. To the knowledge of the author there is not any other computer assisted digger in operation.

CHAPTER TWO

OBJECTIVES

2.1 Description of Conventional Machine

The machine used in this study was a "Power Arm 6" tractor mounted digger manufactured by F.W. McConnel Ltd., Ludlow. A side view of the machine is shown in Fig. 2-1; the main features are two arms and a bucket pivoted as shown and the machine may also slew about a vertical axis. The movement about each of the pivots is effected by double-acting hydraulic rams, shown shaded; for slewing there are two rams, one on each side of the machine.

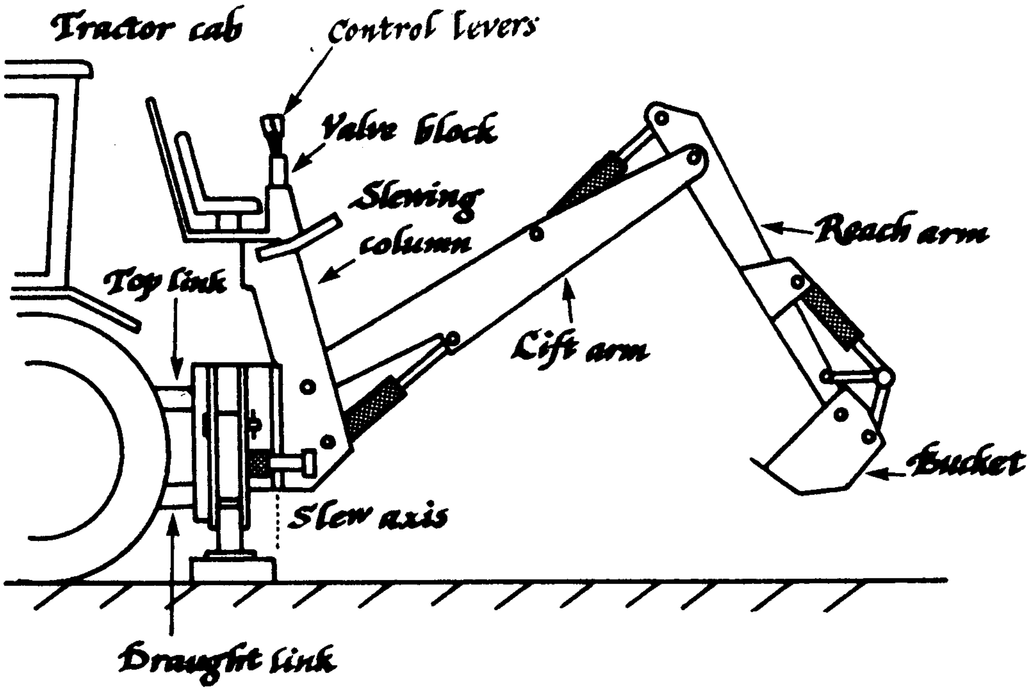


Fig. 2-1: Side View of Machine

Dimensions and masses of the arms and the bucket are as follows:

Main Arm:	Pivot to pivot length	2.28 m
	Mass	68 kg
Dipper Arm:	Pivot to pivot length	1.57 m
	Mass	53 kg
Bucket:	Pivot to blade length	0.4 m
	Mass	60 kg

The operator's seat is situated on the slewing column on the machine and he operates the proportional valves by levers on the valve block. The layout of the control joysticks is shown in Fig. 2-2: the Lift or Main Arm moves Up and Down, the Reach or Dipper Arm moves In and Out. The Open and Close functions operate the Bucket, and Right and Left the Slew. Alternatively he may sit in the tractor cab with mechanical cables linking the control levers to the valve block. The digger is primarily intended for use as a farm maintenance tool and is attached to the three point linkage of an agricultural tractor and powered by the tractor engine.

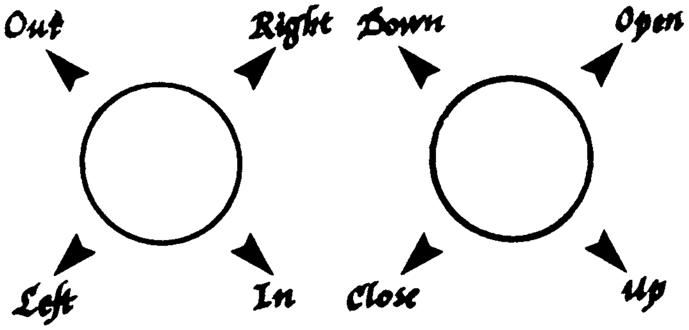


Fig. 2-2: Layout of Joystick Control Functions

Three links attach the digger to the tractor: two draught links and an adjustable top link. Associated with each draught link is an additional 'Instant Weight Transfer' (IWT) ram which, when activated by the operator, exerts a lifting force against the tractor via the draught links and presses the feet of the machine onto the ground and increasing the machine's rigidity. The slewing axis may be set vertically by adjusting the top link and the feet at the side of the machine; on later models the top link is hydraulically adjustable as is the sideways tilt.

The power for the machine is derived from the tractor Power Take Off (PTO) shaft, which through a gearbox drives a

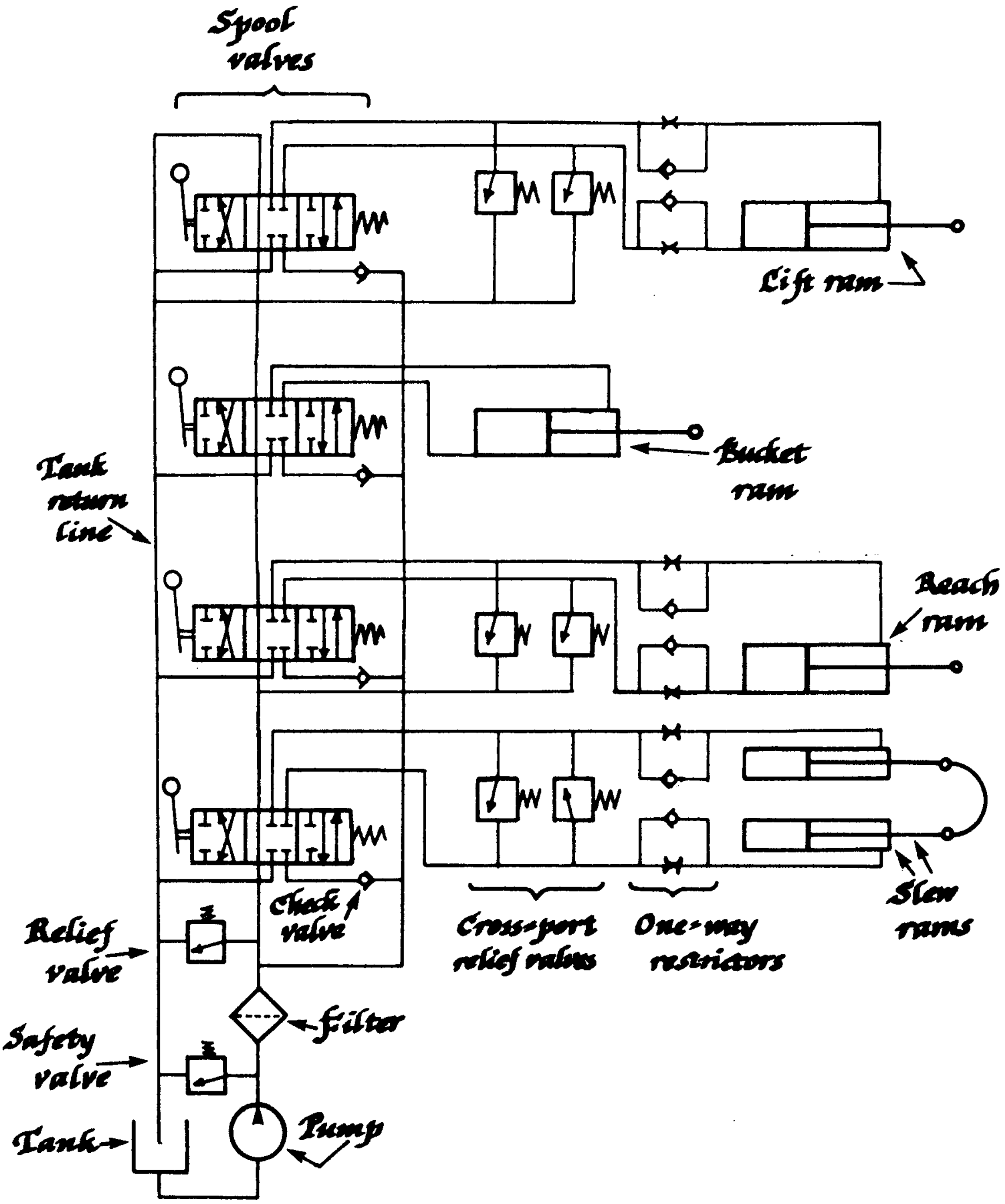


Fig. 2-3: Hydraulic Circuit

constant displacement pump. The basic hydraulic circuit is shown in Fig. 2-3[22]. The PTO shaft is set to rotate at approximately 540 rev/min which gives a pump flow rate of 0.25 l/s (4 g.p.m.). The safety valve connects the pump output back to the tank and opens in the event of a blockage in the output line. The relief valve is set to 1.7 x 10^7 Pa (2500 p.s.i.) and limits the supply pressure to the system. When none of the services (Slew, Lift, Reach, or Bucket) is selected, the spool valves are in the position shown and the output from the pump is fed straight back to the tank.

When any of the services is selected the tank return line is closed and oil passes through the check valve to one port of the corresponding ram. The other port of the ram is simultaneously connected to the tank via a one-way restrictor which restricts oil flow from the ram to prevent cavitation. The check valves between the pump and the spool valve prevent any back flow from the ram if the supply pressure should be reduced because of high demand from more than one service or if a high load is applied. The IWT is not shown in this diagram.

In normal operation the supply pressure is lower than the relief valve pressure and there is hydraulic interaction between the services. As more than one service is selected the supply flow will divide depending on the valve opening, restrictors and load forces on the rams.

2.2 Machine Usage

The digger is a versatile machine and for different operations a range of buckets and implements may be fitted in place of the bucket shown above. These include auto-eject trenching buckets, wide and narrow digging and ditch cleaning buckets, a grab, and pick tine. Also the machine configuration (i.e. pivot positions) may be changed to suit the task in hand.

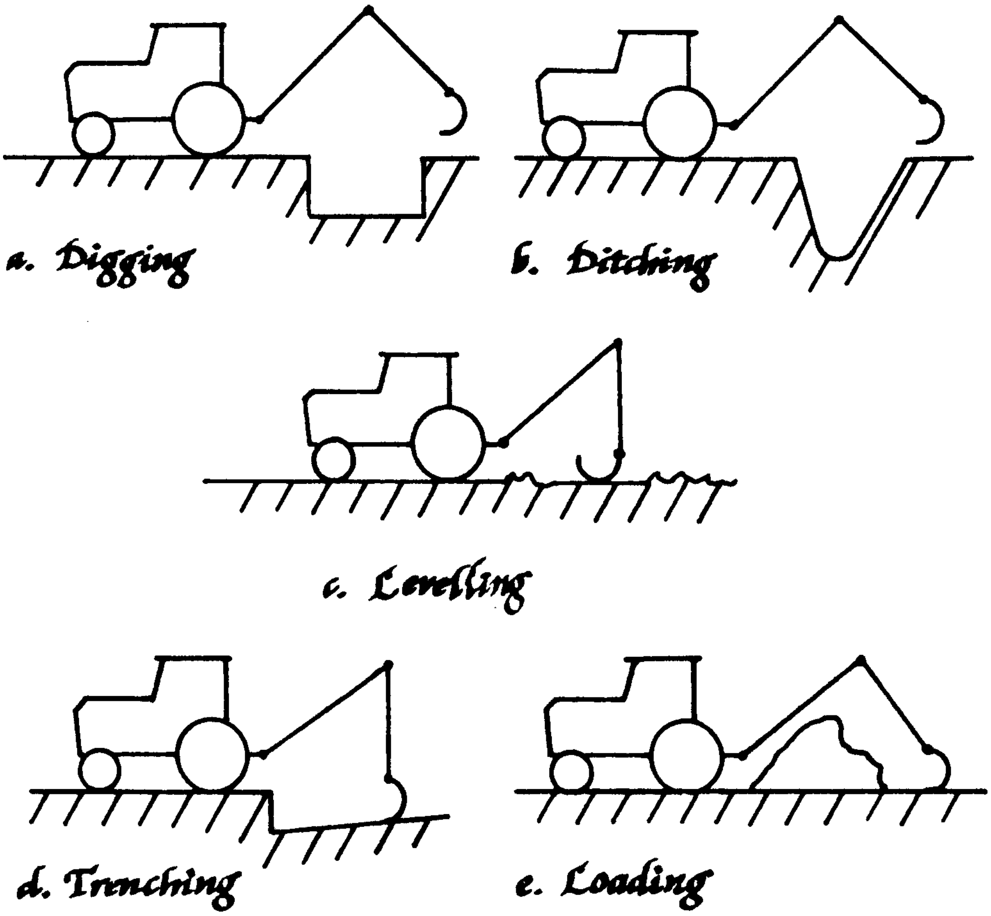


Fig. 2-4: Principal Operations

The principal operations for which the digger is used are digging, ditching, trenching, levelling, and loading (see Fig. 2-4). However considerable practice is required to do work accurately and rapidly. There are five main aspects to the skill developed by an operator over a period of time:

1. Relating the control joystick axes to the corresponding rams.
2. Combining ram movements and valve settings to give the desired bucket blade movement given the mechanical and hydraulic interaction between the services.
3. Judging the inclination of planes to be cut.
4. Positioning the arms and bucket to bring maximum cutting force to bear against an obstruction.
5. Judging the behaviour of the material being handled

When an operator has acquired a "feel" for the machine and the task, these five aspects of the skill are developed and there is no need for him to stop and think to operate the machine once the task is defined. Whereas for an inexperienced operator considerable mental effort is required, and pauses and errors are made. The main users of the machines tend to be farmers who do not run the machines all the year round but only intermittently for maintenance tasks. Therefore they do not develop and maintain the level of proficiency of, for example, a full time operator employed on a larger machine. Let us now look in more detail at the tasks for which the machine is used.

For digging it is often required to cut holes with flat bottoms or sides and in rough, uneven ground it is not always easy to judge vertical and horizontal planes by eye. Having filled the bucket in making a cut, care must be taken not to allow material to tip from the bucket by closing or opening it too far in moving it to the point where the spoil is to be dumped.

In ditching there are two cases to be considered: the cutting of new ditches and the cleaning out of existing ones. For new ditches it is desirable to keep the sides straight and smooth and to maintain a constant profile along the length of the ditch, moving the tractor along from one cut to the next. For clearing existing ditches the process is more one of piecemeal attention to local obstructions.

Trenching involves the cutting of a channel in line with the direction of travel of the tractor and at a constant pitch. This tends to be a very repetitive process and care must be taken to maintain a constant slope on the trench bottom.

The levelling of ground is effected in two stages: firstly using the bucket blade to shift peaks of ground into troughs, then a smoothing process using the bottom of the bucket to flatten the ground. For the inexperienced operator there are two main difficulties: the very precise combined control of the valves to obtain linear bucket movement and the judging of the location of the level plane to be achieved.

When loading the operator is often picking up material from level ground and the need then arises to move the blade in the plane of the floor. Having filled the bucket, it is necessary to adjust the bucket angle as the machine moves so that material does not spill out through its being too far open or closed.

2.3 Potential Functions, Advantages & Limitations of Computer Control

The first question which must be asked is whether the operator could be replaced by a computer controlled system. There are strong technical, economic, and social arguments against trying to do so. The control system would have to have a visual sensing system and very sophisticated intelligent software to interpret and execute instructions for anything other than a repetitive task without obstructions or irregularities to accommodate. In addition an interface to the tractor would be required adding to the cost and introducing considerable safety problems. It is socially undesirable to increase unemployment, particularly if there are no economic benefits in automation.

Potential gains in learning time, accuracy, and speed of completion many tasks may be made if the process of combining control functions in order to effect linear movements of the bucket blade is automated. In addition similar gains may be made in automatic compensation for the hydraulic and mechanical coupling of the arms tending to deflect the blade of the bucket from the intended path. So rather than have control lever axis correspond to particular ram speeds they correspond to particular directions of bucket blade travel. For cutting the sides of ditches, sloping ground, and the bottoms of trenches a calibrated control of the inclination or pitch of bucket blade movement is desirable. The blade may then be set to cut at any desired angle relative to the machine.

For repetitive tasks, e.g. trenching, an automated digging cycle would allow the operator to concentrate on driving the tractor once the cutting cycle had been "taught" to the machine manually. The mechanical constraints of the machine are unaffected by the control system, for example the maximum cutting force i.e. the load which will stall the machine. In automated digging cycles the machine is unable to correct automatically for the problem of earth falling back into the cut ditch, or to respond to the particular form of obstructions encountered.

2.4 Objectives and Functional Specification

With the availability of cheap microprocessors and electrohydraulic valves the general objective of the study was defined to develop and evaluate a microprocessor-based digger controller to assist the operator with many of the difficulties mentioned above.

From the discussion of machine usage the main areas which emerge where computer assisted control may be of value are:

1. Simultaneously controlling ram speeds to produce linear bucket movement.
2. Accurately gauging the pitch of sloping cuts.
3. Automatic repetition of taught cutting profiles.

A general advantage of electronic controls is that they enable the operator to work the machine remotely as the control panel need only be connected to the machine by an electric cable. Thus an electronic unit is easier to install in the cab than conventional cable controls and may be used off the machine for better visibility and comfort provided appropriate safety precautions are taken. Control lever loads may also be considerably reduced from those required on a cable operated system or a system with levers mounted on the valve block, making the machine easier to operate.

The objectives then are:

1. To develop and evaluate a control system to provide these functions using the lowest level of technology suitable for the task to minimise cost.
2. To evaluate the functional benefits to experienced and inexperienced operators in terms of learning time reduction and work throughput.
3. To determine the economic viability of the system as a product.

The specification for the system is to achieve linear bucket blade movement by using the computer to create lift and reach functions which move the bucket blade in nominally horizontal and vertical, H and V, directions. The conventional machine gives to operator control of α, β, and γ (see Fig. 2-5(a)) whereas the computer system gives control of x, y, and θ. The slew control is the same on both systems. The bucket angle is kept constant relative to these axes as the blade moves. To cut slopes at defined pitches one may rotate the axes in Fig. 2-5(b) through a pitch angle variable from +45° to -45° using a calibrated dial on the control panel.

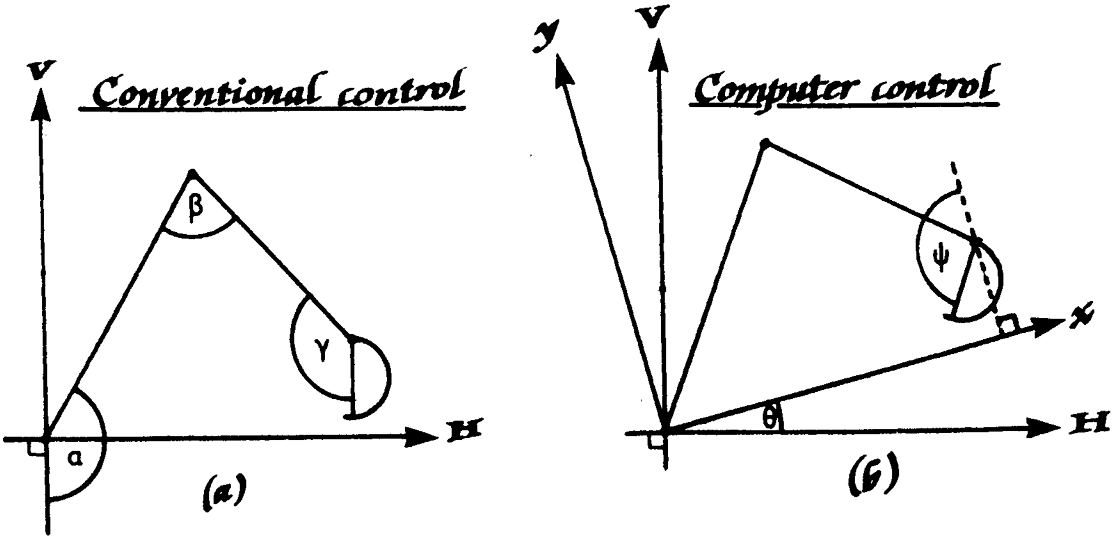


Fig. 2-5: (a) Conventional and (b) Computer Control Coordinates

For the automation of repetitive tasks it was decided to implement a learn and repeat facility operating in such a way that in Learn Mode the movements of the bucket blade from its initial position are recorded. When one of the repeat modes, Repeat Fast or Repeat Slow, is selected the stored path is executed from the new starting point (see Fig. 2-6).

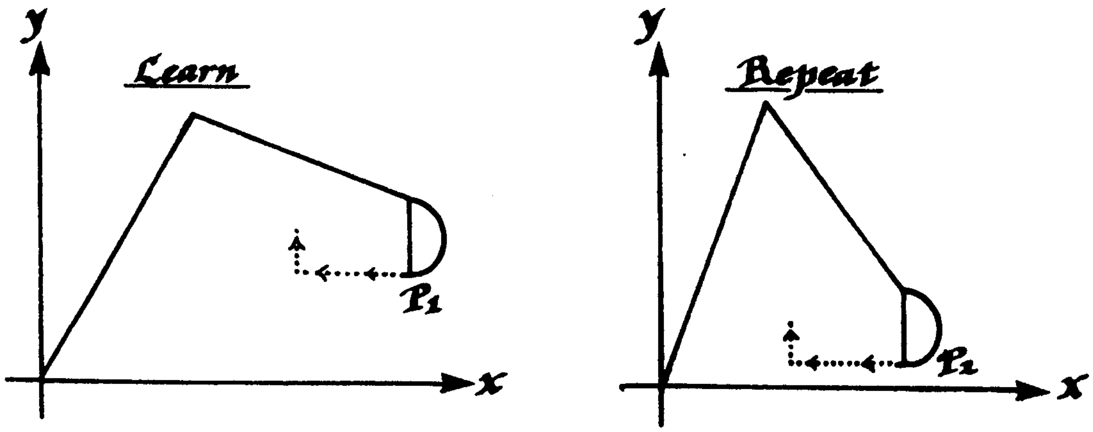


Fig. 2-6: Learn and Repeat Operations

2.5 Design Constraints

From a commercial viewpoint, manufacturing and components costs are major factors in considering the viability of a product. In order that the cost of any commercially produced electronic control system be minimised it is important that mechanical changes to the machine be kept as few and as minor as possible: the control system should be an optional fitting to an otherwise standard machine. It was decided to design the system keeping the cost of components to a minimum with the limits of the functional specification and the other design constraints with the overall view of having a working system which, with very little development or experimental work, could be put into production. Where possible in the design, standard, readily available parts should be used to minimise cost and availability problems in manufacture.

Typical agricultural working environments for electronic equipment are extremely harsh, and that of field machinery is the most demanding. As the system operates outside, protection must be given against water and damp to all parts of the system not mounted in the tractor cab. The entire machine is subject to continuous vibration from the tractor engine and the pump while the machine is in operation and there are additional shocks to the machine from the bucket when digging which must not affect the system operation.

All transducers must be weatherproof, damp-proof, unaffected by the vibration, protected from damage if they are immersed as happens when cleaning ditches, and must be sufficiently mechanically robust to withstand contact with earth, stones, branches, and any other material encountered as the digger is used. The machine must be able to withstand wide range of operating temperature as the diggers may be used in all climates. The system must function in the range -10°C to +35°C. The sealing and corrosion-proofing of the controller and transducers must be such that when the machine is stored for long periods no deterioration or corrosion occurs: it must work first time when switched on.

The power for the system is derived from the 12 V tractor supply and must be immune to drift in the supply voltage of ±2 V according to the state of the battery. Spikes on the supply line from inductive loads must be filtered out and' the system protected against the "load dump" phenomenon when the battery is accidentally disconnected from the alternator and a high current surge is applied to the 12 V line. The circuit must be able to withstand indefinite reverse polarity connection of the supply, have minimum current consumption, and be free from interference and electromagnetic noise.

The diggers are frequently attached to and detached from the tractor and the control system must be built to withstand rough handling and have reliable connectors. The control system must also be easy to service so that faults can easily be found and the construction such that system modules can be replaced when faulty by the operator. This necessitates some self-diagnostics to assist in detecting the faulty module. An important ergonomic consideration is that the layout of the controls must be such as not to create difficulties for an operator already familiar with the conventional mechanical control system. This is achieved by having the x, y, bucket, and slew axes on the joysticks correspond to the reach, lift, bucket, and slew axes of the conventional machine.

As the system is experimental, the facility must be provided for altering the control software as well as having the facility for altering control parameters in the field without having to reprogram EPROM's for example. A production machine must be able to accommodate changes in the machine geometry arising from the use of different pivot positions, digging implements and rams. Also it should not be difficult to modify the system to accommodate future design changes in the mechanics of the digger.

As well as providing proportional control of the bucket blade cutting speed, the maximum speed available should correspond to zero relief valve oil flow so that machine power is not wasted. The dynamic characteristics of the machine should not be critically dependent upon the PTO speed which may not be well regulated by the tractor.

2.6 Method of Approach

As a first stage in the development of the microprocessor system it was decided to first construct a simple electric proportional control circuit functionally similar to the conventional mechanical control system. The construction of an electronic control unit for the machine involves the selection of appropriate valves and a hydraulic circuit which can then be used as the basis of the microprocessor system interface. It was also considered to be of potential value by F.W. McConnel, Ltd. as such a system has advantages of reduced lever loads, ease of installation, and electronic simplicity. This preliminary system is the subject of the next chapter.

CHAPTER THREE

DEVELOPMENT OF MANUAL PROPORTIONAL CONTROLLER

3.1 Introduction

The function of the manual or open loop controller is essentially to simulate conventional mechanical cable controls for the digger, but using electrohydraulic valves, giving a valve spool deflection and hence speed of arm movement varying with control joystick deflection. This forms a valuable basis for the microprocessor system as, having selected appropriate valves and developed a satisfactory hydraulic circuit for manual control, the valves may then be interfaced to the microprocessor in conjunction with appropriate feedback transducers to obtain the desired control functions described in Chapter Two.

3.2 Selection of Electrohydraulic Valves

There have recently been a number of developments in low cost electrohydraulic valves, particularly for use in computer based control systems. The standard valve to use for proportional flow control from a computer is a two stage electrohydraulic valve using a digital to analogue converter to drive the valve control input. The main spool position is controlled by a flapper valve, the position of the flapper being set by the actuating current. These valves are very fast, having a bandwidth over 100 Hz, and can pass high flow rates but they are also very expensive[23].

The Japanese manufacture digital hydraulic flow control valves with pressure compensators; the position of the flapper is controlled by a stepper motor and the main spool follows the flapper[24]. The use of the stepper motor simplifies the interfacing of the valve to a computer. Another type of digital valve which has been produced has a rotary spool positioned by a stepper motor. There are also being developed low cost spool valves with d.c. motor drives but these were not on the market at the time the work was carried out[25].

The cost of two stage valves suitable for use on the digger, with a flow rating of 0.3 l/s (4 g.p.m.) and pressure rating of 17 MPa (2500 p.s.i.) is in the order of £200 each. As the basic machine sells for approximately £3500 is was decided that the total cost to manufacture the microcomputer control system should be around £1000 maximum. Two stage valves were thus ruled out on a cost basis.

Experimentation using bang-bang solenoid operated valves showed that they are not suitable, as variable speed control is required and when bang-bang valves are used high acceleration changes occur in starting and stopping which could only be overcome by reducing the maximum speed to a prohibitively low level. The possibility was also explored of pulsing bang-bang valves on and off with a view to getting proportional control by varying the mark-space ratio. This did not work however: at low frequencies the pulsing caused the machine to oscillate and at high frequencies the valve latched on or off.

In view of the high cost or lack of availability of the types of valve discussed above it was decided to initially use proportional solenoid valves as supplied by A & D Fluid Power Ltd. which cost £50 each. A section through the valve is shown in Fig. 3-1[26].

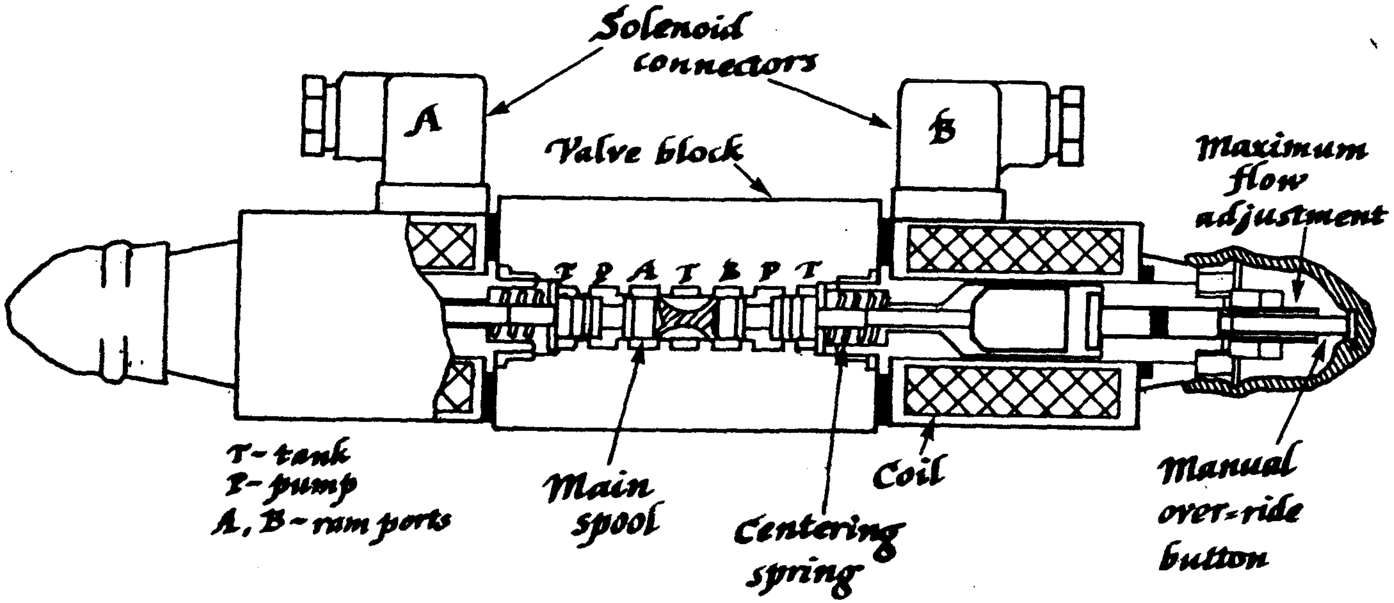


Fig. 3-1: Section through Proportional Solenoid Valve (Redrawn from data sheet with kind permission of A & D Fluid Power Ltd.)

The valve comprises a valve block with a sliding spring centred spool which can be moved either way by a pair of solenoids. By controlling the mean solenoid current and hence the solenoid force, the spool position is continuously variable. In the past this type of valve, which has a bandwidth from 0 to between 10 and 20Hz, has not been used a great deal. The reason being that flow reaction forces and stiction effects tend to give the device high hysteresis and poor repeatability. These can be overcome by the use of stronger springs and more powerful solenoids but this increases the power consumption and heating effects.

An alternative means of improving the valve performance, employed in the A & D valves, is to drive the solenoids from a pulse width modulator circuit which pulses the current through the coils and gives variable spool deflection by varying the mark-space ratio. The frequency of the pulse train is set to vibrate the spool about a mean position determined by the mark-space ratio so as to minimise stiction effects. The solenoids are rated at a nominal 8 V, 28 W and were run at a frequency of 50 Hz. Also the spool is machined so as to be balanced and to minimise flow reaction forces at the orifices.

3.3 Hydraulic Circuit

The hydraulic circuit[27] for the digger employing the electric valves is given in Fig. 3-2. When none of the services is selected, the cut-off valve is open allowing oil from the pump to flow straight back to the tank. When any of the services is selected the cut-off valve is closed, the supply pressure rises

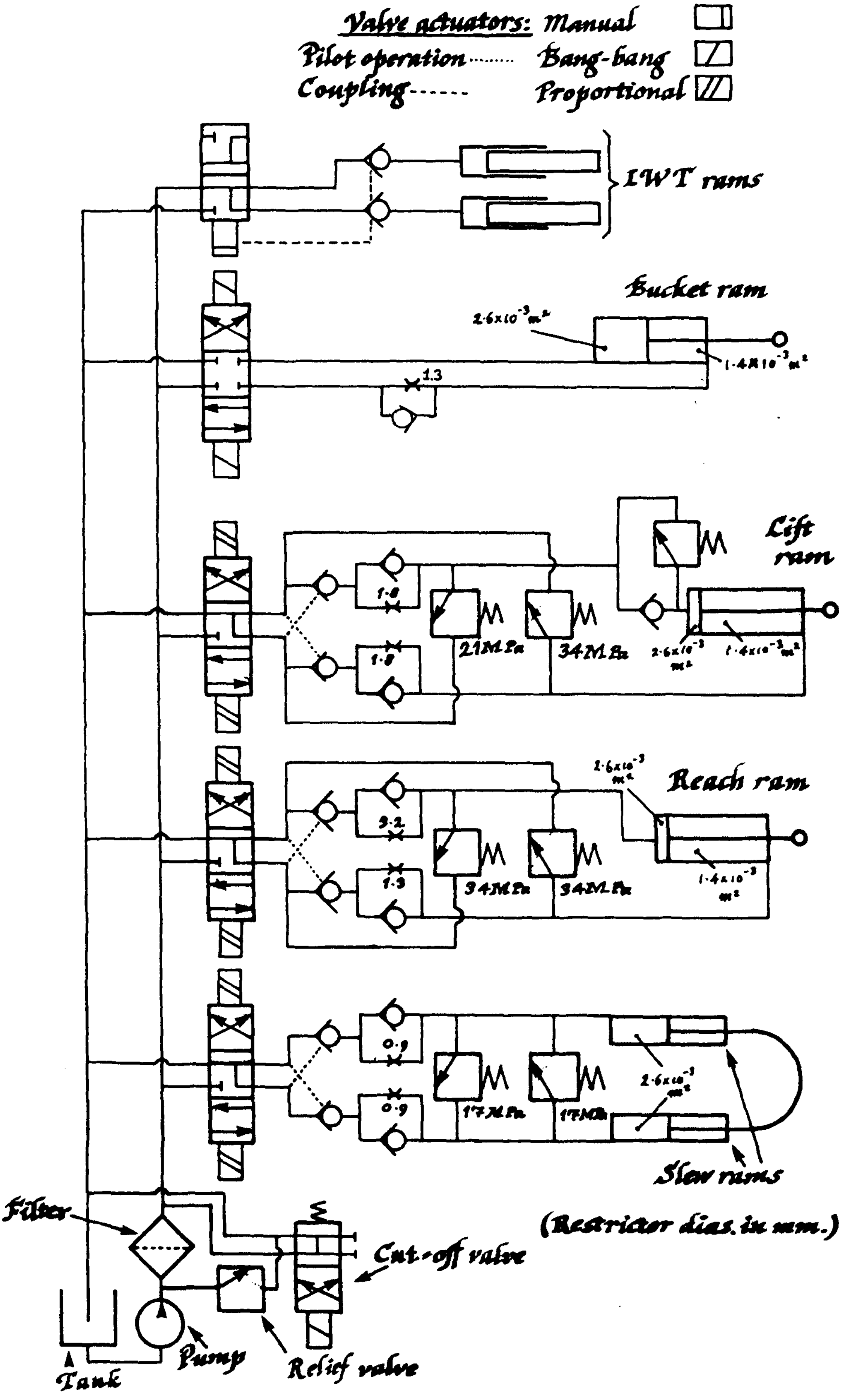


Fig. 3-2: Hydraulic Circuit for Electric Proportional Control

and fluid flows through the valve from the supply line and through the two check valves to one port of the selected ram. Simultaneously the output from the ram flows through the corresponding restrictor and the pilot operated check valve which is unseated by the supply pressure.

The valve metering occurs on the oil inlet side to the ram, i.e. the valve spool is of the "meter in" type. The bucket is operated using a bang-bang valve in conjunction with the one way restrictor which restricts flow into the gland end of the ram as the required maximum speed of bucket movement is relatively slow. The use of the bang-bang valve instead of a proportional valve introduces a cost saving and simplifies the control circuitry. On the lift service the one way relief valve which has an adjustable pressure setting, is connected to the base end of the ram to prevent cavitation as the arm moves down assisted by the strong gravitational force acting upon it. Without this relief valve, at low flows from the control valve, the arm was found to move down in a series of jerks as the pilot operated check valve between the base end of the ram and the return line opened and shut.

3.4 Control Circuit

A simplified schematic for the electronic circuit, just showing the control of the lift service and the cut-off is given in Fig. 3-3. The control voltage from the joystick potentiometer is subtracted from the output from the triangle wave oscillator by the summing amplifier. The output from the summing amplifier is fed to a pair of comparators, with threshold voltages V_{T1} and

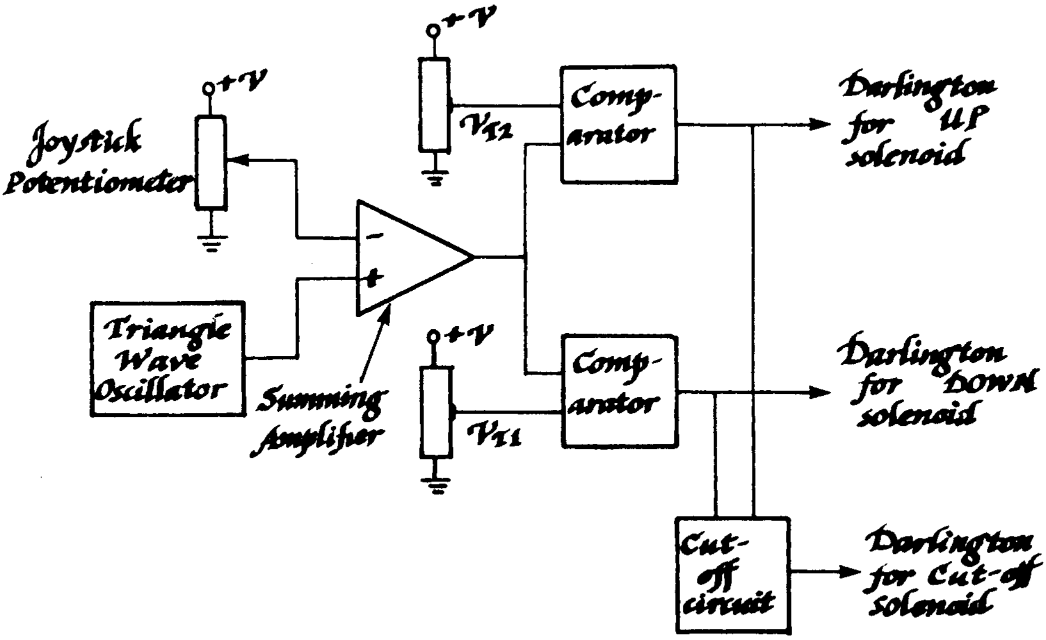


Fig. 3-3: Schematic of Control Circuit for Lift Service

V_{T2}, which switch the power transistors driving the proportional valve solenoids. As the joystick is deflected in one direction or the other from its central position the mark-space ratio of the

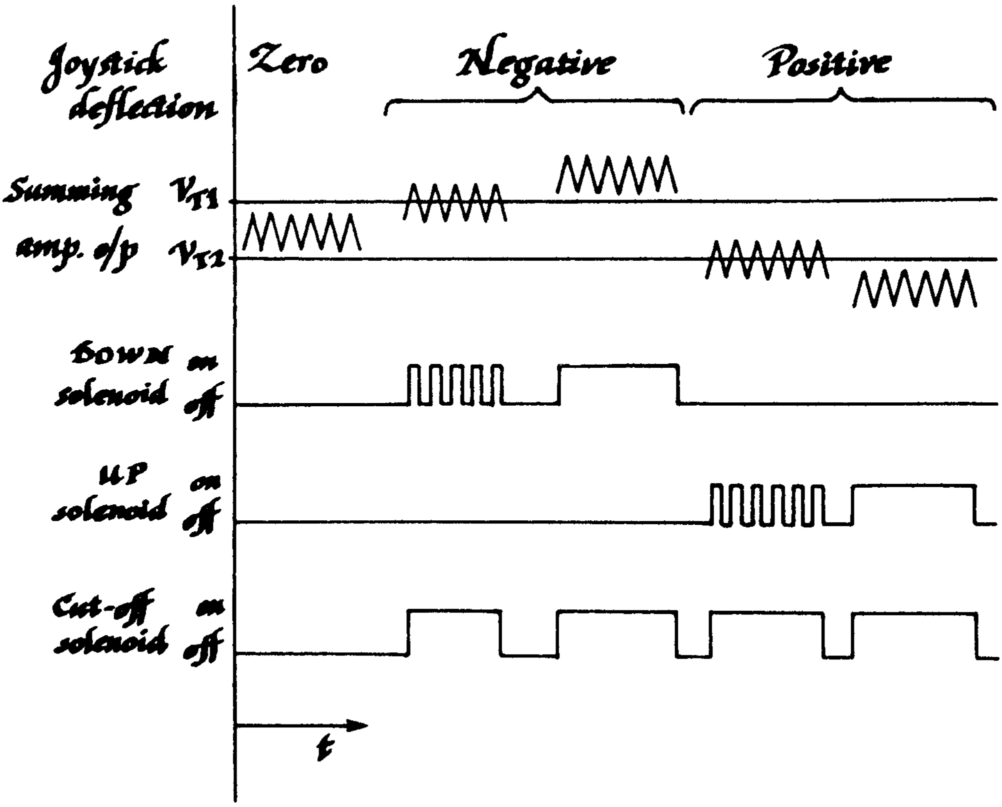


Fig. 3-4: Timing Diagram for Lift Service

current through the corresponding solenoid valve varies accordingly. When a solenoid is activated, this is sensed by the cut-off circuit which activates the cut-off solenoid closing the cut-off valve which is of the bang-bang type. The circuit operation is shown in Fig. 3-4; this shows the waveforms produced and the resulting solenoid switching for different joystick deflections.

The full circuit diagram is shown in Fig. 3-5 and the component values and specifications are given in Table 3-1. The power source for the circuit is the tractor battery, nominally 12 V, but which may vary between 10 V and 16 V. To provide a stable supply for the pulse width modulators and switching circuitry, a semiconductor regulator RG1 is used with feedback resistors R1 and VR1 to provide a stable supply (V+) of 8.2 V. Capacitors C1 and C2 provide smoothing for the regulator. Resistor R2 and Zener diode Z1 provide a 4.2 V reference for the triangle wave oscillator.

The oscillator is of relaxation type and comprises operational amplifier A1, potentiometer VR2, variable resistor VR3 and capacitor C3. VR2 and VR3 set the amplitude and frequency of the output waveform, taken from capacitor C3. The output is not a perfect triangle wave, as the capacitor voltage rises and falls exponentially, but it is a satisfactory approximation. The single oscillator circuit is used to drive all three pulse width modulators for the slew, lift, and reach services. The oscillator is set to give an output of 0.25 V peak to peak at 50 Hz.

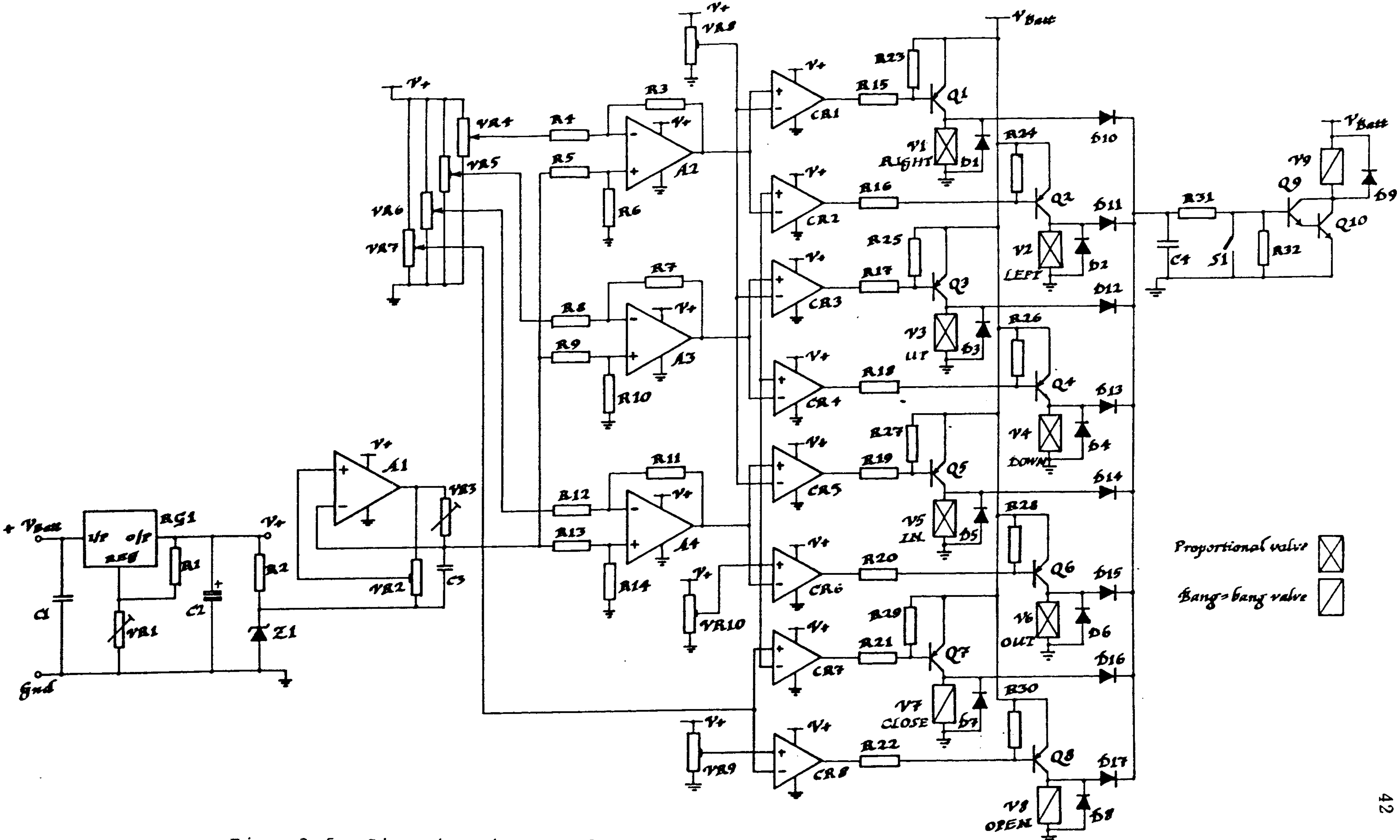


Fig. 3-5: Circuit Diagram for Proportional Controller

C1	100 nF		
C2	1 μF Electrolytic		
C3	22 μF		
C4	20 μF		
VR1	5 kΩ 10 turn Cermet		
VR2	10 kΩ " " "		
VR3	2 kΩ " " "		
VR4-7	Type JS4 joystick from Flight Link, Alton, Hants.	Dropper resistors for proportional valves: 1Ω 17 W	
VR8-10	10 kΩ 10 turn Cermet		
		RG1	317K regulator
R1	240Ω 0.25 W Carbon	A1-4	324 Quad op-amp
R2	120Ω " "	CR1-7	LM319
R3-14	68 kΩ " "	Q1-8	BDX54C
R15-22	460Ω " "	Q9	BFX85
R23-30	220Ω " "	Q10	2N3055
R31	270Ω " "	Z1	4.3 V 1.3 W
R32	220Ω " "	D1-17	1N4001

Table 3-1: Components for Proportional Control Circuit

The joystick potentiometers VR4 to VR7 are in fact inductive devices manufactured by Flight Link Controls Ltd., and have an equivalent circuit of a potentiometer, with a 1.8 kΩ resistor in series with the wiper. The devices have no sliding parts to wear out, they are linear, noise free, mechanically robust, and very low priced at £15 for each dual axis unit. The devices give a 3V output for zero mechanical deflection and 0.8 V swing (10% of supply) each way.

The three unity gain summing amplifiers using operational amplifiers A2, A3, and A4 have the oscillator output connected to their non-inverting input and the slew, lift and reach control voltages to their respective inverting inputs. The output from each amplifier is fed to a pair of comparators, which detect when the control voltage crosses the threshold voltages for opening and closing. The threshold voltages are provided by VR10 and VR9.

Comparators CR1 to CR8 have open collector outputs. Devices Q1 to Q8 are PNP Darlington pairs, drawn here for simplicity as single PNP transistors. R15 to R22 limit the base currents and R23 to R30 ensure that their corresponding transistors turn off. Diodes D1 to D9 connected across the solenoid coils suppress the inductive transients occuring when the current through the coils is turned off. In series with each of the proportional solenoid coils is a 1Ω resistor, between each coil and ground (not shown) to limit the current through the coils operating from the 12 V supply.

The cut-off valve V9 requires a continuous current to activate it as it is operated by a simple bang-bang solenoid. When any of the valves V1 to V8 is turned on, capacitor C4 charges through the base of Q9 via R31, turning on the Darlington pair between successive pulses of current through any of the proportional valves. R32 ensures that Q9 and Q10 do not conduct due to any leakage currents. Switch S1 is a safety switch mounted on the control box which prevents activation of the cut-off solenoid when thrown hence rendering the machine immobile.

The physical layout of the different sections of the circuit is shown in Fig. 3-6. The control cable, linking the control box to the junction box, only carries signal currents and the supply to the control circuit; the cable is also screened to minimise electromagnetic pick-up. The heavy valve current switching takes place in the junction box to avoid interference with the control circuitry. The joystick axes and functions are aligned as on a conventional, mechanically controlled digger so that a direct comparison of performance could be made by experienced operators without their having to learn a new control configuration.

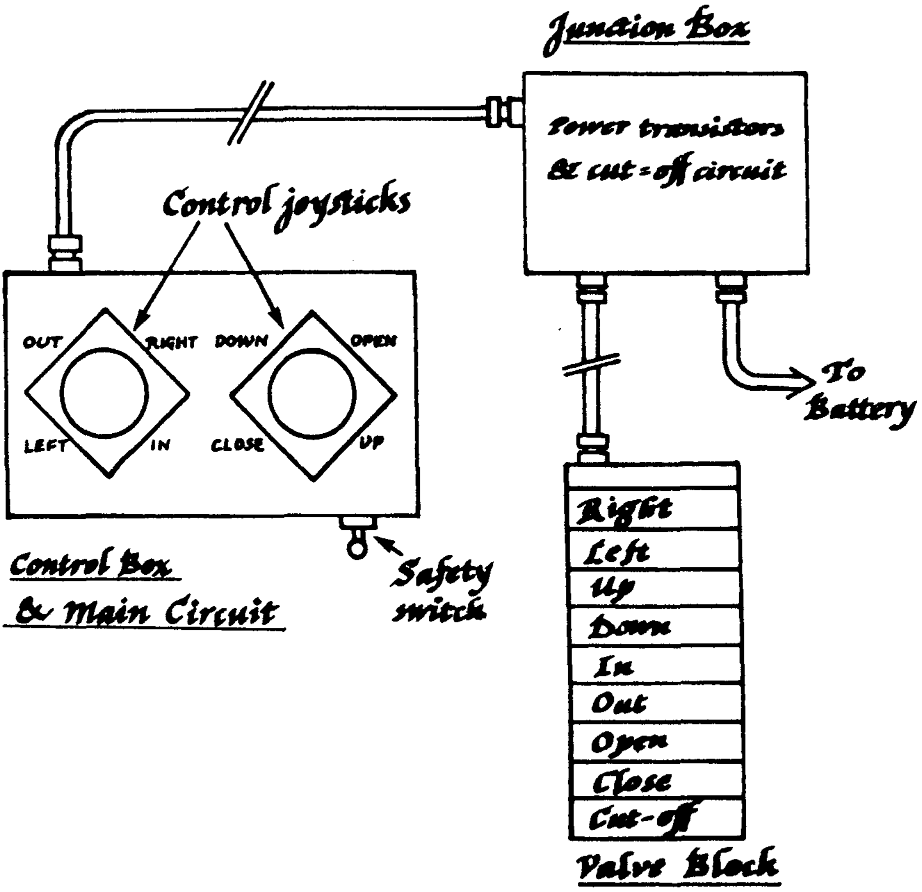


Fig. 3-6: Constructional Schematic of Proportional Controller

3.5 Performance Evaluation

The proportional manual control system was tested by the author and two experienced digger operators who performed machine evaluation trials for F.W. McConnel Ltd. The system was found to give controllability equivalvent to that of a direct mechanical link from joystick to spool. Hysteresis effects in the valve were not noticeable and the unloaded speed range of arm movement was the same as that on a conventional system ($\dot{\alpha}$: 0 - 0.3 rad s^{-1}, $\dot{\beta}$: 0 - 0.4 rad s^{-1}).

The operator lever loads were lighter which was an advantage and greater operator mobility was available as the control box is portable. A further advantage is that the control box may easily be installed in a tractor cab as it is only necessary to accommodate a single electric cable leading into the cab as against a set of heavy mechanical cables. The only disadvantage of the system was that the control box was difficult to support when used off the machine; a problem readily overcome by attaching a strap to each side of the box so that it may be worn around the neck.

3.6 Discussion

The proportional valves selected and hydraulic circuit, used in conjunction with the control circuitry described were found to give perfectly satisfactory control of the digger. This implies that, used in conjunction with appropriate feedback transducers and control algorithm the valves may be used satisfactorily for the microprocessor system to provide X-Y movement and a learn/repeat facility. The cost of parts for making the prototype circuit was £160 which is quite acceptable from a potential production viewpoint.

There are improvements to be made to the circuit, however. The proportional valves should be supplied from regulators deriving a steady 8 V supply from the battery. Also the power switching, effected in the above prototype by the battery connectors, should be done using a relay in the junction box switched from the control box; this would add to the safety of the system.

The circuit has been redesigned to incorporate these features as well as modifications for the control of a type PA8 digger, a later machine, the king post of which may also be tilted level under electrohydraulic control.

CHAPTER FOUR

CONTROL SCHEME

4.1 Introduction

The development of a control algorithm for a manipulator system falls into two main parts: kinematics and dynamics. The first concerns the derivation of the joint coordinates, and their necessary derivatives, in real time to execute the motion of the tool as demanded by the operator. The second, a potentially much more difficult problem, is that of implementing a control system to apply the necessary torques at the pivots to make the linkage follow the desired trajectory. With the growth in the use of industrial robots, a great deal of work has been done on the development of both kinematic and dynamic algorithms for manipulators.

4.2 Kinematics

There are two ways in which the input velocity command from the joysticks (x_i, y_i) may be used to derive the path to define the machine coordinate trajectory. By the first method, at each sampling instant the input velocities x_i and y_i are read and the equations relating the joint velocities to the input velocities are solved to provide inputs to joint rate servos:

$$\dot{\alpha} = \frac{\alpha}{x}\dot{x}_i + \frac{\alpha}{y}\dot{y}_i$$

$$\dot{\beta} = \frac{\beta}{x}\dot{x}_i + \frac{\beta}{y}\dot{y}_i$$

This method, however, produces a trajectory subject to cumulative error as illustrated in Fig. 4-1. The machine starts at point S with the horizontal input vector shown. When the machine encounters an obstacle (shown shaded), a small positional error d arises which the system does not correct.

The desired trajectory is shown dashed with the maximum value of d as small as practicable so that the feedback system operates so as to maintain the machine on the original path.

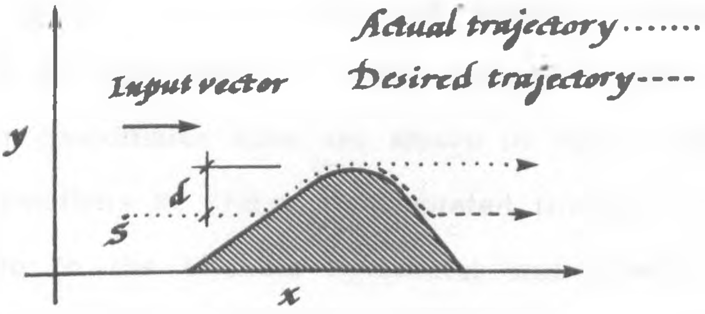


Fig. 4-1: Simple control scheme allowing cumulative error

The alternative method which overcomes the drift problem is to generate a 'Target Point' in software which follows the desired trajectory and to have a position control servo system to make the machine track the Target Point. This may be done, as here, by directly inverting the machine geometry (i.e. converting user coordinates to machine coordinates) or by Resolved Rate Motion control, particularly useful for reducing the computational load for complex linkages[28].

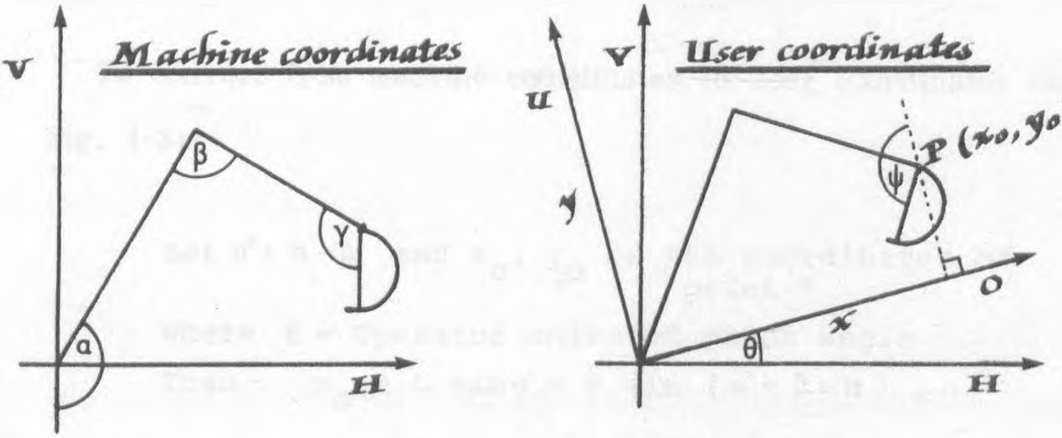


Fig. 4-2: Machine and User Coordinate Systems

To implement the control of horizontal and vertical bucket blade movement it is necessary to be able to convert machine coordinates (i.e. angles measured at the pivots) to Cartesian user coordinates and to convert user coordinates to machine coordinates. The machine coordinates are shown in Fig. 4-2(a); H and V designate the horizontal and vertical directions in relation to the machine body, V being parallel to the slewing axis. The user coordinates axes are shown in Fig. 4-2(b); the Out and Up directions x, and y, are rotated through the pitch angle θ relative to the machine horizontal and vertical. The machine configuration is described by the x and y coordinates of the bucket pivot P and the bucket angle ψ, measured from the user vertical.

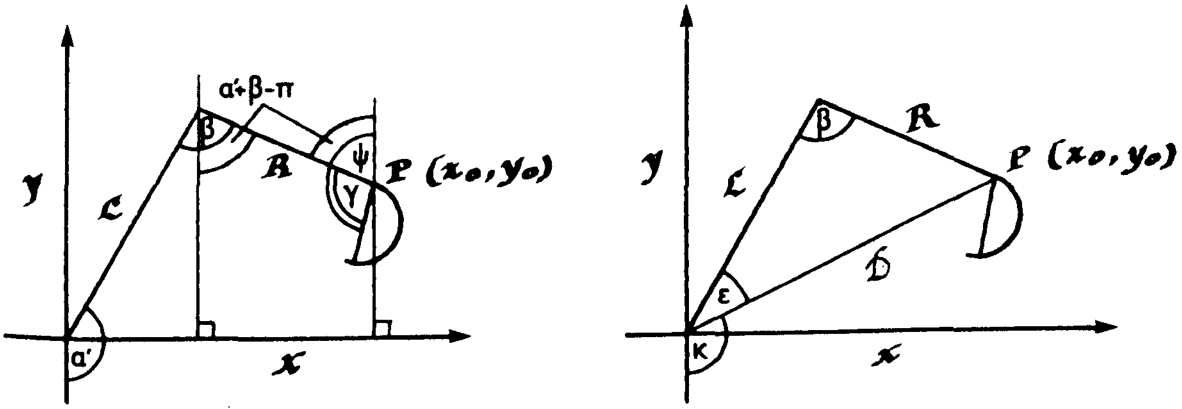


Fig. 4-3: Conversion between coordinate systems

To convert from machine coordinates to user coordinates (see Fig. 4-3):

Let $\alpha' = \alpha - \theta$ and x_o, y_o be the coordinates of point P

Where θ = Operator selected pitch angle

Then

$$x_o = L \sin\alpha' + R \sin(\alpha' + \beta - \pi)$$

$$y_o = - L \cos\alpha' - R \cos(\alpha' + \beta - \pi)$$

$$\psi = \alpha' + \beta + \gamma - \pi$$

To convert from user coordinates to machine coordinates:

$$D = \sqrt{x_o^2 + y_o^2}$$

$$\text{Let} \quad A_1 = \cos^{-1}\left[\frac{L^2 + D^2 - R^2}{2\ L\ D}\right]$$

$$\text{and } A_2 = \cos^{-1}(- y_o / D)$$

$$\alpha = A_1 + A_2 + \theta$$

$$\beta = \cos^{-1}\left[\frac{L^2 + R^2 - D^2}{2\ L\ R}\right]$$

$$\gamma = (\psi + \pi) - (\alpha + \beta)$$

4.3 Generation of Target Point

If the machine is static and the joysticks are deflected to select x and y velocities $\dot{x}$, and $\dot{y}$, then the Target Point onto which the bucket pivot is servoed should move from the current output position at the selected velocity. When the input velocity is changed by the operator the Target Point should begin a new trajectory from the position of the machine at the time of the input change. It is necessary therefore to threshold a 'significant' change of joystick input otherwise the target point may be reset by the slightest unsteadiness of the operator's hand or by signal noise.

An additional consideration in determining the movement of the Target Point is what should happen if the machine is stalled by an immovable obstacle. It is necessary to stop the movement of the Target Point when the positional error exceeds a critical value determined by the characteristics of the control scheme.

4.4 Bucket Kinematics

In moving the bucket pivot in the x and y directions the control system must act in such a way as to maintain a constant bucket angle ψ. To do this it is necessary to feedback the angle γ by means of an appropriate transducer. Rather than mount a transducer on the bucket pivot where it may be vulnerable to physical damage it was decided to mount it so as to measure the angle δ and from this to derive γ.

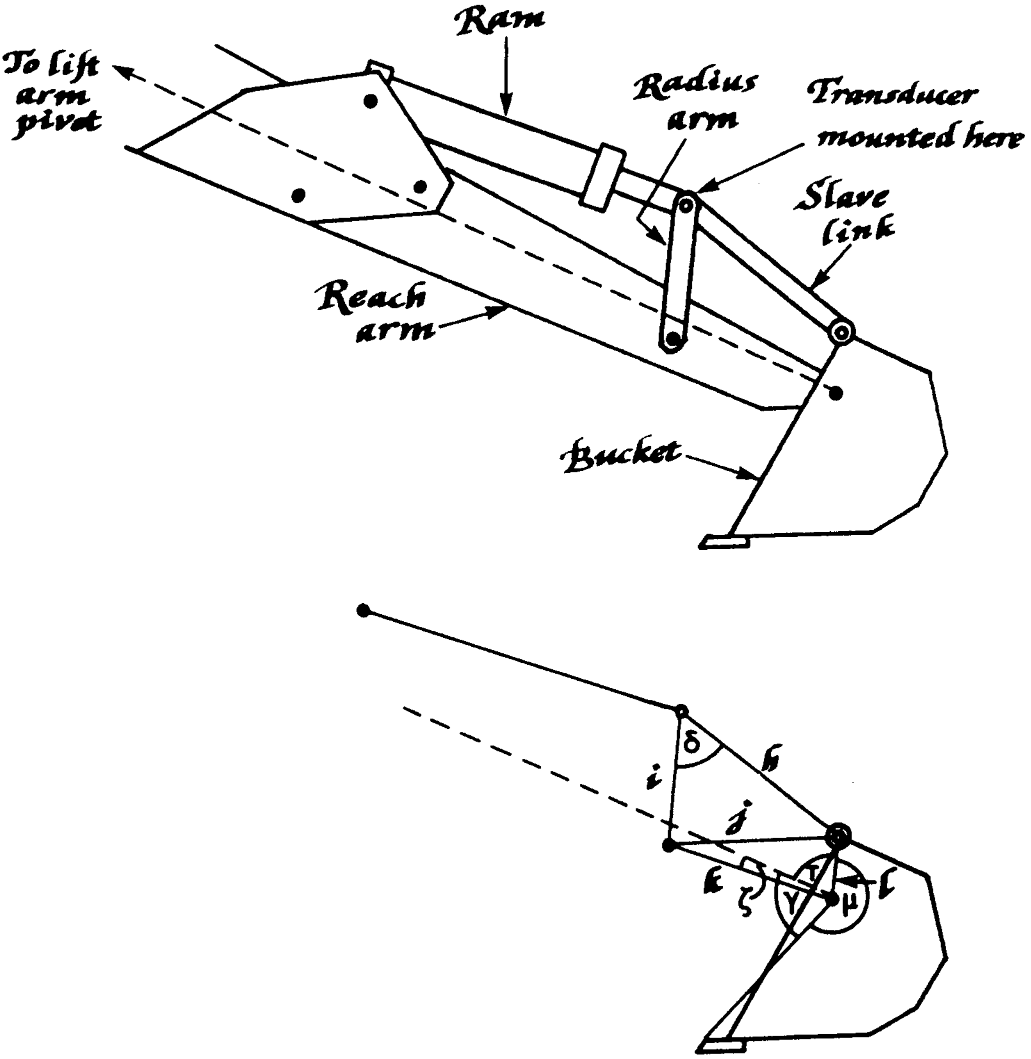


Fig. 4-4: Bucket Linkage and Geometry

The relationship between γ and δ may be derived as follows (See Fig. 4-4):

$$j^2 = (h^2 + i^2 - 2\ h\ i\ \cos\delta\ )$$

$$\tau = \cos^{-1}\left[\frac{k^2 + l^2 - j^2}{2\ k\ l}\right]$$

$$\gamma = 2\pi + \xi - (\ \tau + \mu\ )$$

The dimensions of the bucket linkage are as follows:

$i = 0.228\text{m}$ $\quad\xi = 2.83^{\circ} = 0.049$ rad

$h = 0.335\text{m}$ $\quad\mu = 136^{\circ} = 2.37$ rad

$l = 0.164\text{m}$

Hence:

$$j^2 = 0.164 - 0.153\ \cos\delta$$

$$\tau = \cos^{-1}\left[\frac{0.104 - j^2}{0.091}\right]$$

$$\gamma = 3.96 - \tau$$

$$\therefore\ \gamma = 3.96 - \cos^{-1}\ (\ -0.660 - 0.153\ \cos\delta\ )$$

4.5 Learn and Repeat

The function of the Learn facility is to record the movements of the bucket blade from the starting position when the Learn mode is selected to the moment it is deselected. In Repeat mode, the blade cuts the same path as executed in Learn mode relative to the x and y axes but offset to the new starting point, being the position of the machine when repeat mode is selected.

There are two basic ways in which the Learn process may be executed: one method is to record points of the path at regular intervals in time and the other is to record points at even spacing. The first method retains information on the velocity of the blade whilst the second does not. However to record the speed of movement as the path was taught is not particularly useful as an operator may deliberately slow down certain parts of the learned operation to perform them accurately whilst such speed reduction in Repeat mode may be undesirable.

The method of recording a path at regular spacing has other advantages. The method is more economic in terms of memory usage i.e. a longer path may be stored in a finite memory space. With a constant sampling frequency and finite memory space there would be a time constraint on the operator in executing the path in Learn mode which is obviated by regularly spaced sampling. Having equispaced points in memory facilitates speed control in Repeat mode as the repeat speed may be determined by the rate at which data is sequentially retrieved from the list of input points. It was decided to allow the operator a choice of two repeat speeds selected by switches on the control panel.

When Repeat mode is selected the offset to be added to the path points in memory is calculated by subtracting the x,y coordinates of the starting point on the path in memory from the current output position of the machine. The trajectory for the Target Point is then generated by accessing and offsetting the successive points in memory at a rate corresponding to the selected repeat speed. The bucket angle at the successive points is unaffected by the change in starting point of the path and requires no offset.

Let successive points on the learned path be represented by vectors

$$\underline{L}_i = (x_{L_i}, y_{L_i}, \psi_{L_i}) \qquad i = 1,.., n$$

Let the starting point for the repeat be

$$\underline{S} = (x_S, y_S, \psi_S)$$

Then Offset $\underline{O} = (x_S - x_{L_1}, y_S - y_{L_1}, 0)$

and repeat path points $\underline{R}_i = \underline{L}_i + \underline{O} \qquad i = 1,.., n$

4.6 Transducer Resolution

A major factor in determining the minimum resolution required of the transducers for measuring α, β, and δ angles is the maximum acceptable positional error at the bucket blade. A worst case configuration for error in calculating the y coordinate of the bucket pivot arises when the machine is in the position shown in Fig. 4-5. The reach arm is fully extended, $\beta = 142.0°$, and $\alpha = 105.4°$ then $\frac{\partial y}{\partial \alpha}$ and $\frac{\partial y}{\partial \beta}$ are at maxima and $y = 0$. For eight bit resolution of α and β the worst case error in y is 15 mm.

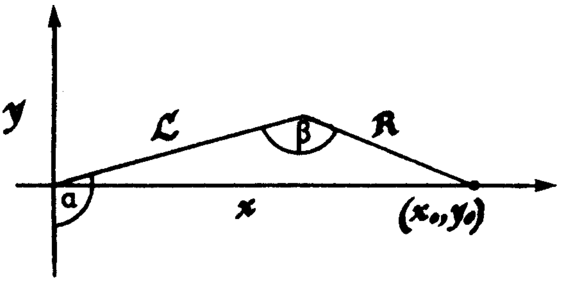


Fig. 4-5: Position for worst case error in determination of y coordinate

Thus positional resolution of eight bits is quite sufficient for digging purposes; the additional error introduced by quantisation of the bucket angle may be neglected as the bucket pivot to blade distance is relatively small.

4.7 Dynamics

Having established the kinematic requirements of the system and solved the machine geometry, a control scheme of minimum cost and complexity was sought which would give satisfactory performance. For the purpose of analysis the machine to be controlled may be divided into the sections of hydraulics and mechanics, including load.

4.8 Hydraulics

The complete hydraulic circuit for the control of digger using A & D Hydraulics' proportional valves is given in Fig. 3-3. The sections for the supply and the Lift service are shown in Fig. 4-6. The accumulators C_A and C_B represent the compliances of the hoses supplying the ram. This example of the Lift service is taken as it is the most complex individual service in the circuit. Given the valve setting V_L and the ram velocity $\dot{X}_L$, the ram force F_L and the flow Q_L may be found computationally as follows. Consider the case where the valve deflection is negative:

$$P_{RB_n} = P_{RB_{n-1}} + \frac{1}{C} Q_{CB_{n-1}} \Delta t$$

Where subscripts n-1, n denote successive samples at interval Δt

$$Q_L = K_V V_L \sqrt{P_S - P_{RB_n}}$$

$$Q_{CB_n} = Q_L - A_A \dot{X}_{L_n}$$

$$P_{x_n} = \frac{1}{C} Q_{CA_{n-1}} \Delta t + P_{x_{n-1}}$$

$$Q_{CA_n} = -A_A \dot{x} - R_A \sqrt{P_{x_n}}$$

$$P_{RA} = P_{RV} + R_A \sqrt{P_{x_n}}$$

$$F_L = P_{RA} A_A - P_{RB} A_B$$

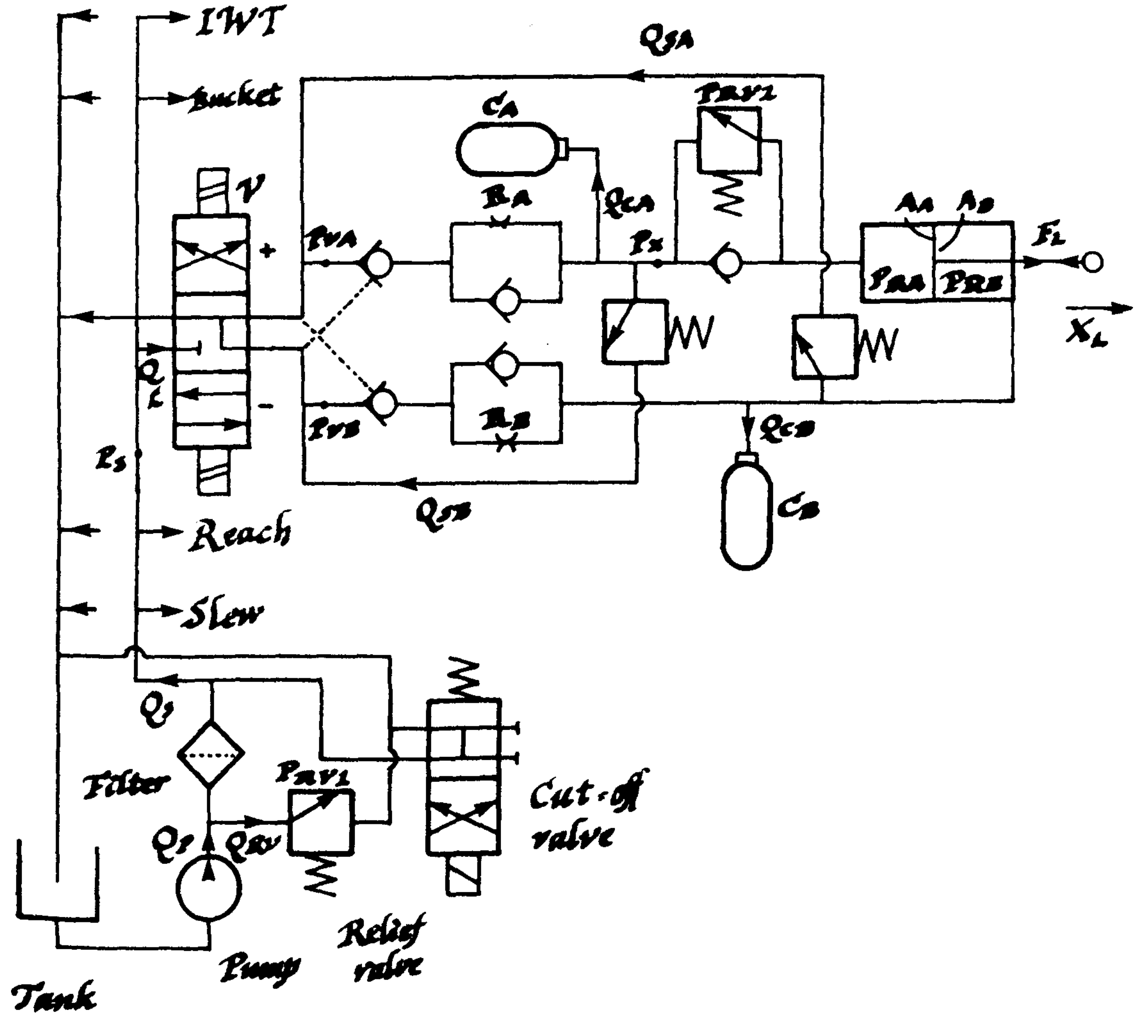


Fig. 4-6: Hydraulic Circuit for Supply and Lift Service

Similar sets of equations may be drawn up for each of the other services. The supply, comprising the pump and the relief valve, is governed by the following equations:

$$Q_P = Q_S + Q_{RV}$$

$$Q_{RV} = 0 \;\Big|_{P_S < P_{RV1}}$$

The value of P_S may be found at each sampling instant by performing an interval bisection type iteration varying P_S from 0 to P_{RV1} until the flow continuity constraint is satisfied:

$$Q_S = Q_{SLEW} + Q_{LIFT} + Q_{REACH} + Q_{BUCKET} + Q_{IWT}$$

It may be seen from the above that the hydraulic circuit is highly non-linear with saturation effects and interaction between the services. In addition there is the offset, hysteresis, leakage and dynamics of the valves to accommodate. The pump rate is subject to variation due to mis-setting and tractor governor imperfections. The oil viscosity changes significantly with temperature (changing effective restrictor and valve constants) becoming lower as the oil heats up and making the machine move noticeably faster.

4.9 Mechanics

In modelling the mechanics of the digger, in general, the following forces and corresponding torques must be considered:

1. Accelerational
2. Gravitational
3. Centrifugal
4. Frictional
5. Stictional
6. Coriolis

For very complex robotic systems Lagrangian dynamics provides a systematic and efficient method for solving the equations of motion. For a digger with a relatively simple geometry, the equations may be written and solved applying Newton's Laws directly. For slow moving manipulators the inertial forces may be negligable and the device may be treated purely kinematically[28]. Slow moving in this context means about 1 m/s or less and the maximum speed of motion of the bucket blade of the digger in a horizontal cut at mid reach is 0.5 m/s.

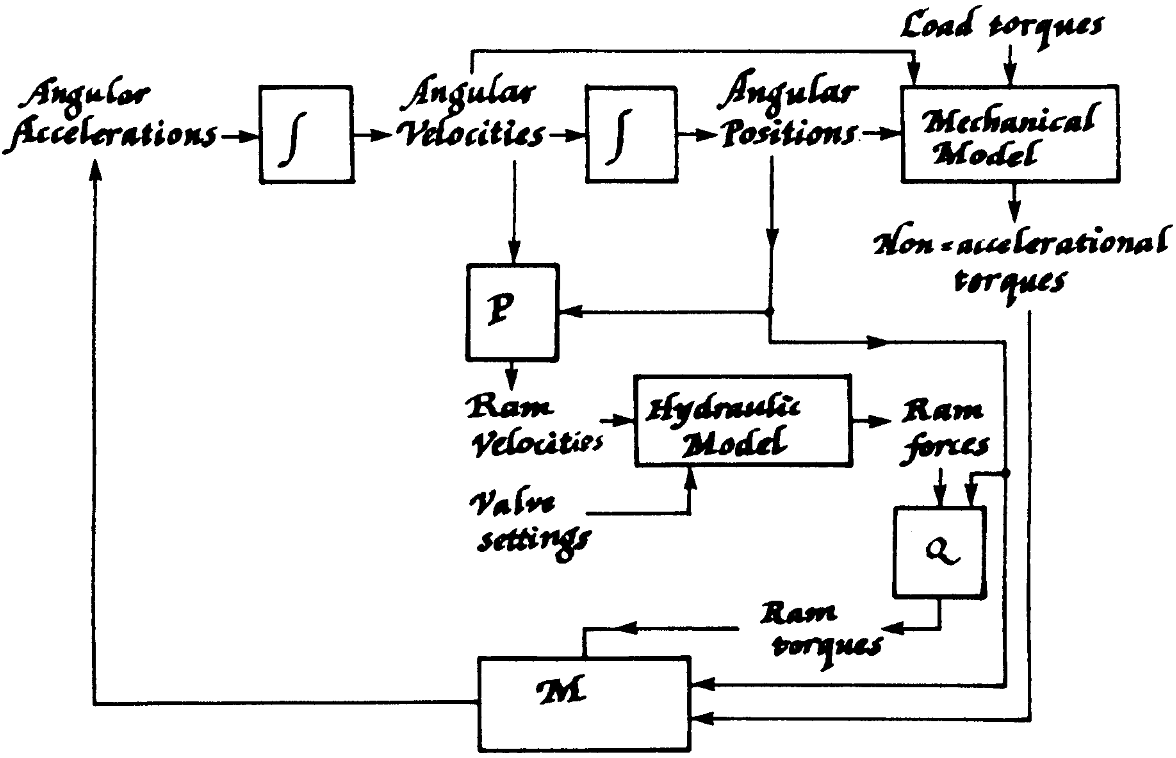


Fig. 4-7: Schematic of System Model

The overall structure of a complete model of the machine is shown in Fig. 4-7. The model operates by integrating the angular acceleration at each sampling instant to give velocities and positions; this data in conjunction with the load torques and valve settings enables the net acceleration torque to be calculated for the next sampling instant. Block P solves the geometry associated with each ram to convert the angular velocities at the pivots to ram velocities. This data is fed into the hydraulic model constructed as described above along with the valve setting to give the ram forces. Block Q converts the ram forces into angular torques at the corresponding pivots. The Mechanical Model M calculates the direct and induced torques listed above and hence the total non-accelerational torques using the basic laws of mechanics.

The derivation of the equations of motion is a lengthy but straightforward piece of mechanical analysis. The load forces acting on the bucket may change with position from that of a pure mass in the bucket to frictional forces as the blade cuts ground. To simulate a microprocessor controlled system care must be taken to include the effects of quantisation and finite word length arithmetic. It can readily be seen that the mechanics constitute a highly non-linear time-varying coupled system.

4.10 Control Algorithm

Two control schemes particularly suited to non-linear interacting robotic system are sliding mode[29,30] control and invariant control[28]. Both of the schemes require minimal information of the system to be controlled in terms of modelling.

Sliding mode control operates by switching between two control schemes which may be individually unstable chosen so as to keep the system in the region of a chosen switching line in phase space. Invariant control uses measurement of acceleration to eliminate the disturbances caused by the mechanical interaction of the joints to be controlled. Both these systems require additional transducers for measurement of velocity or acceleration in addition to sensing position, or a sufficiently well resolved position measurement to permit sufficiently accurate differentiation.

In view of the complexity of modelling it was decided to initially adopt an empirical approach to the development of a suitable control scheme. The most important question about the control scheme so far as the hardware specification is concerned is the number and type of feedback transducers required. Position, velocity, acceleration, and ram pressure are all variables required by different robotic control systems.

Early crude experimental work was carried out using a valve driver supplied by A & D Fluid Power, realising the scheme shown in Fig. 4.8 (a) using the apparatus shown schematically in Fig. 4.8 (b). Experiments were done using the lift arm as the linkage for this service has the highest moment of inertia about the pivot. An SDK-85 microcomputer was used to run a program to give proportional feedback using 8-bit integer arithmetic. An 8-bit digital to analogue converter was used to drive the analogue voltage controlled pulse width modulator supplied by A & D Fluid Power. This device was found to have a varying frequency with control voltage.

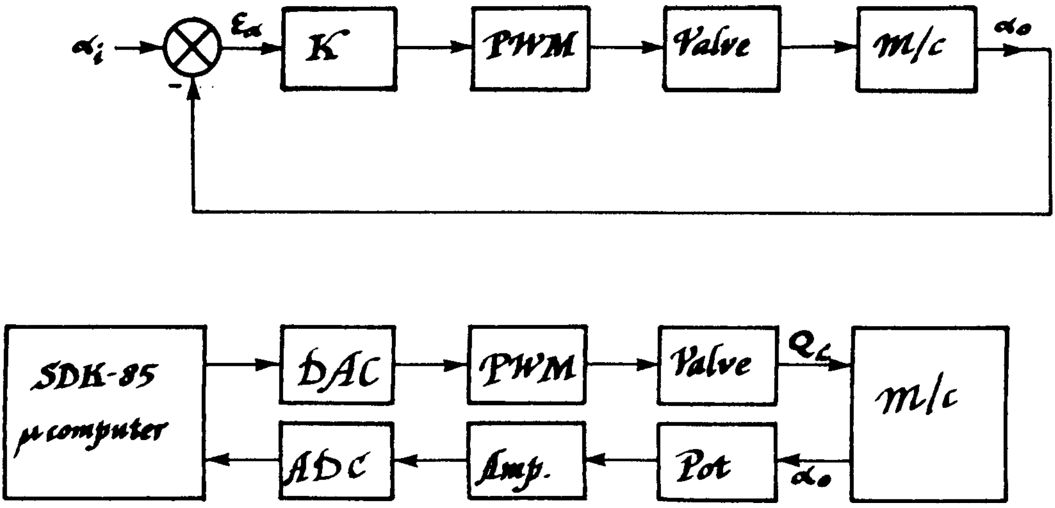


Fig. 4-8: Control Loop (a) and Hardware Schematic (b) for experimental system

A carbon potentiometer mounted on the spindle of the pivot was used to measure the output angle giving a voltage fed through a gain and offset stage to an 8-bit analogue converter. The resulting step response, by adjusting the gain K was fast and without overshoot similar to that of a first order system but had a small erratic residual error due possibly to non-repeatability of the valves.

It was decided therefore to start by building a system with more precise hardware to implement proportional control, adjusting the gains to obtain the fastest possible response without overshoot. The main effect of the hydraulic interactions is to reduce the gain of the services individually so if a gain is selected which gives a stable response for a service in isolation it will remain stable in conjunction with the other services. The faster the step response of the system, the better tracking is obtained to a ramp input.

Fig 4-9 shows a simplified schematic for control of the lift and reach (α and β) pivots to give x-y control of the bucket pivot. The control voltages V_x and V_y from the joysticks (J/S) are fed into the analogue to digital converter (ADC) to the computer. The corresponding velocities $\dot{x}_i$ and $\dot{y}_i$ are integrated to give x_i and y_i, the coordinates of the Target Point, onto which the bucket pivot is servoed. Code segment G calculates the corresponding coordinates α_i and β_i; the corresponding errors are multiplied by the gain constants A_α and A_β and the results output to the pulse width modulators which drive the valves. It is necessary to prevent excessive errors accumulating if the machine encounters an obstacle that stalls it i.e. causes the relief valve to blow. The is detected by thresholding the x and y errors (ε_x and ε_y) and disconnecting the x_i and y_i inputs to the integrators when a critical error magnitude arises.

The controller for the bucket angle is shown in Fig. 4-10 (a). The overall effect of the system is to maintain the bucket angle constant in the user coordinate system as the bucket pivot is moved, this function being over-ridden by control signals from the bucket control joystick. With zero joystick deflection the Sample and Hold outputs the angle to be maintained to summing point S_1 which calculates the error signal which is used to switch the bucket valve. When the joystick is deflected the sample and hold is put in sample mode and becomes zero and the value of the joystick voltage is fed to the valve controller. When the joystick is released the sample and hold holds the value of the bucket angle at release which then becomes the new input to the regulator.

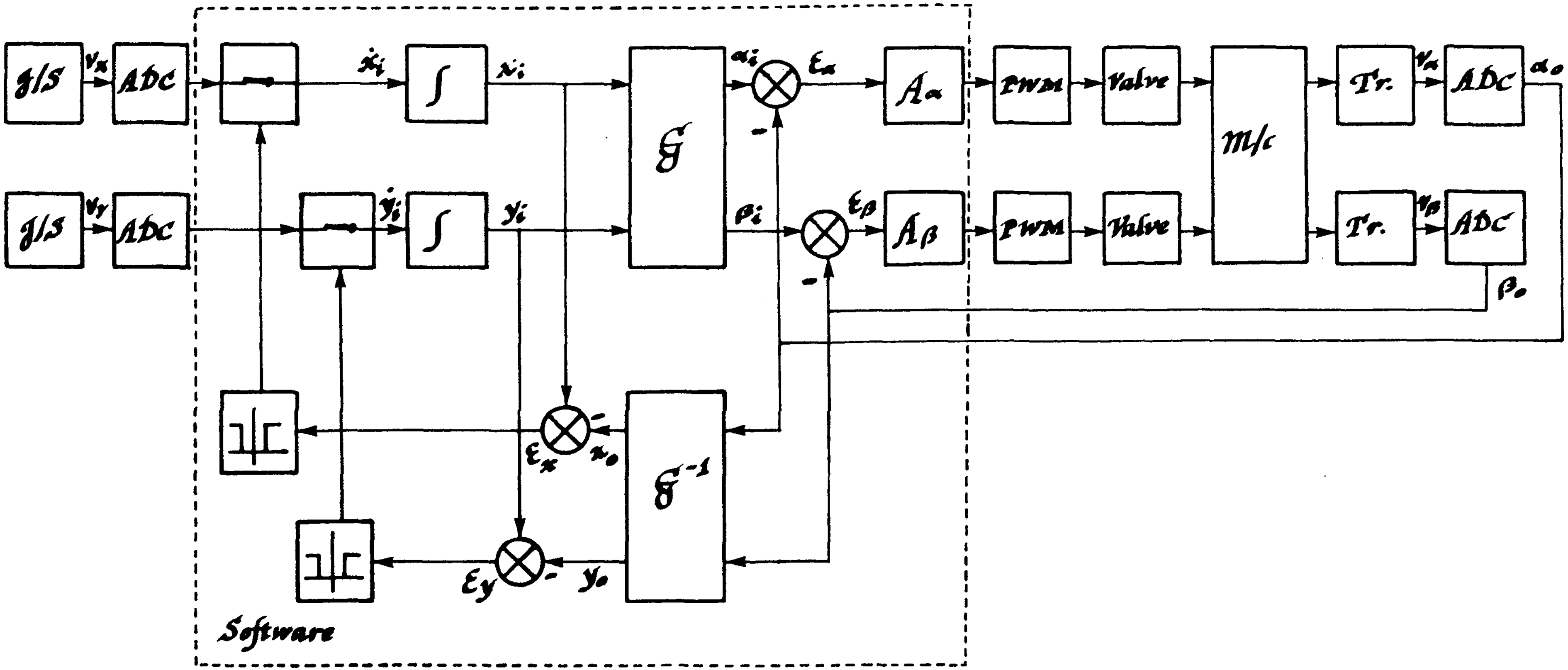


Fig. 4-9: Control System for Lift (α_o) and Reach (β_o)

The slew controller (see Fig. 4.10 (b)) is functionally equivalent to that of the proportional electric control system but implemented through the computer. The control joystick voltage V_s is fed to the ADC, multiplied by a gain constant A_{Ω} and output to the PWM to drive the valve.

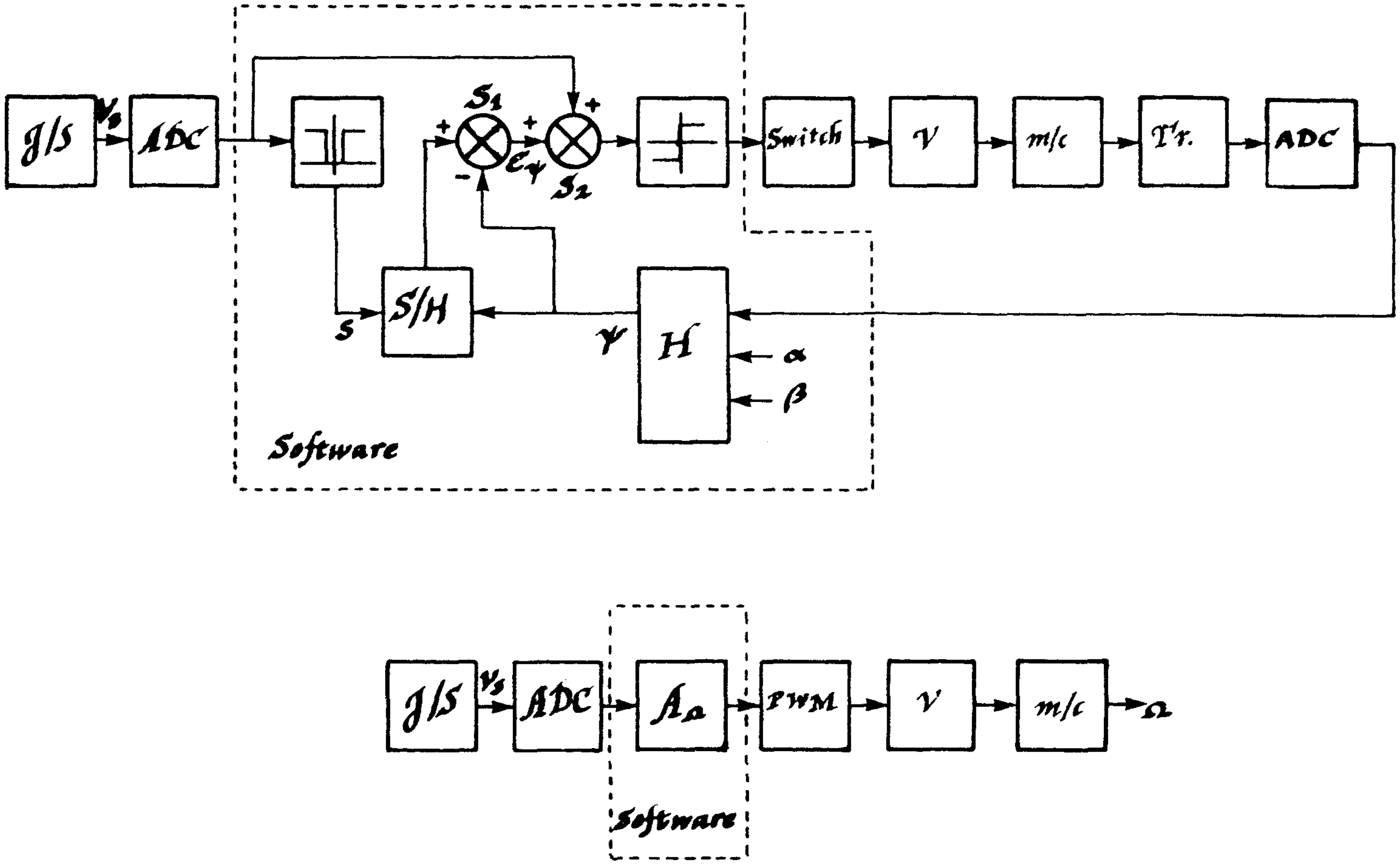


Fig. 4-10: Bucket Control Loop (a) and Slew Control Schematic (b)

CHAPTER FIVE

TRANSDUCERS

5.1 Design Constraints

With the availability of cheap microprocessors, a major part of the total hardware cost of a computer-based control system can lie in the feedback transducers. As the cost of the diggers is relatively low, the cost of the output transducers must be kept as low as possible.

The transducers must be able to give eight bit resolution over the measured angle of travel and must be repeatable to less that half a least significant bit. The devices used must also be mechanically robust: vibration is transmitted to the transducers from the tractor engine and from the pump. They are also subject to mechanical shocks from the bucket when digging. The transducers must be made waterproof to withstand weathering and mud splashes; the bucket transducer may even be immersed if the machine is being used for clearing waterlogged ditches.

They must be easy to fit to a standard machine in the sense that no significant mechanical modifications have to be made. They must also be able to withstand the rough handling of the agricultural environment as well as any impact in use if the machine hits an obstacle. All electrical connections must be well screened to prevent electromagnetic interference from other circuits on the machine (e.g. solenoid valves) or from nearby.

Easy access to the workings of the transducers is desirable for ease of servicing. Also it should be possible to replace any one independently of the others if a fault should arise.

5.2 Selection Possibilities

There exists a number of types of transducer commercially available for angular position measurement. The most simple to interface to a computer is an absolute encoder which gives a bit parallel output in binary or Gray code corresponding to the measured angle. The objections to using this type of encoder are cost and the number of wires to be connected to the computer. Connectors capable of withstanding the working environment of field machinery are expensive and the cost increases with the number of ways that are connected.

Incremental encoders overcome the problem of a large number of connectors but they are still relatively expensive and they must be re-datumed if the machine is switched off. Hydraulic rams exist which have capacitive transducers built in; they are well protected but have the disadvantage again of cost. The possibility was considered of using an ultrasonic pulse-echo technique to measure ram extension with the transducers mounted inside the ram. This was not pursued however, owing to the difficulty in finding a suitable piezo-electric material, the complexity of the driving circuitry, and the necessity for temperature compensation.

In view of the drawbacks with various other measurement systems it was decided to design a transducer using a high quality plastic film potentiometer. These devices have 0.5% linearity and virtually infinite resolution giving a calculated total worst case positional error of ±26 mm.

5.3 Construction

The set of three transducers may then be interfaced to the computer using an analogue multiplexer and an analogue to digital converter. An exploded section through the device is shown in Fig. 5-1. The potentiometer is mounted on a steel ring attached by a brass strip to the transducer body; the strip is flexible to accommodate any mis-alignment of the potentiometer spindle relative to the spindle block.

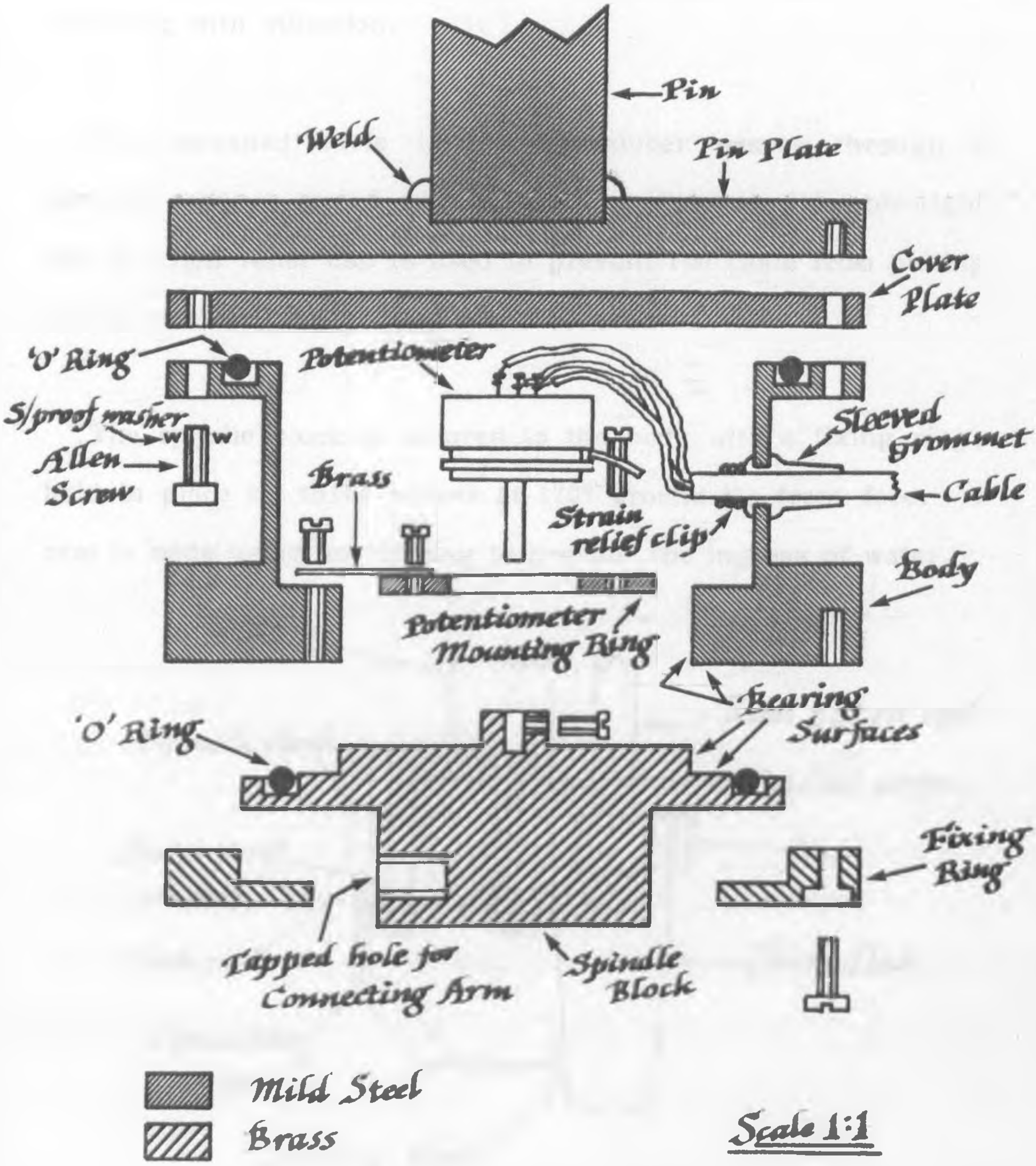


Fig. 5-1: Exploded Section through Transducer

The pin at the top of, the diagram acts as the pivot for the two arms, the angle between which is being measured. The pin or pin plate is secured to one or other of the arms by a cotter pin or by a weld. The cover plate serves to protect the interior of the transducer if it is removed from the machine and there is a water-tight 'O' ring seal between the plate and the transducer body. The plate is secured to the body using an allen screw fitted with a shakeproof washer to prevent it from loosening with vibration.

The screened cable to the transducer passes through a sleeved grommet sealed with plastic glue to make it water-tight and a strain relief clip is used to prevent the cable from pulling out or stressing the potentiometer connections.

The spindle block is secured to the body with a fixing ring, held in place by three screws at 120° around its front face. A seal is made using an 'O' ring to prevent the ingress of water.

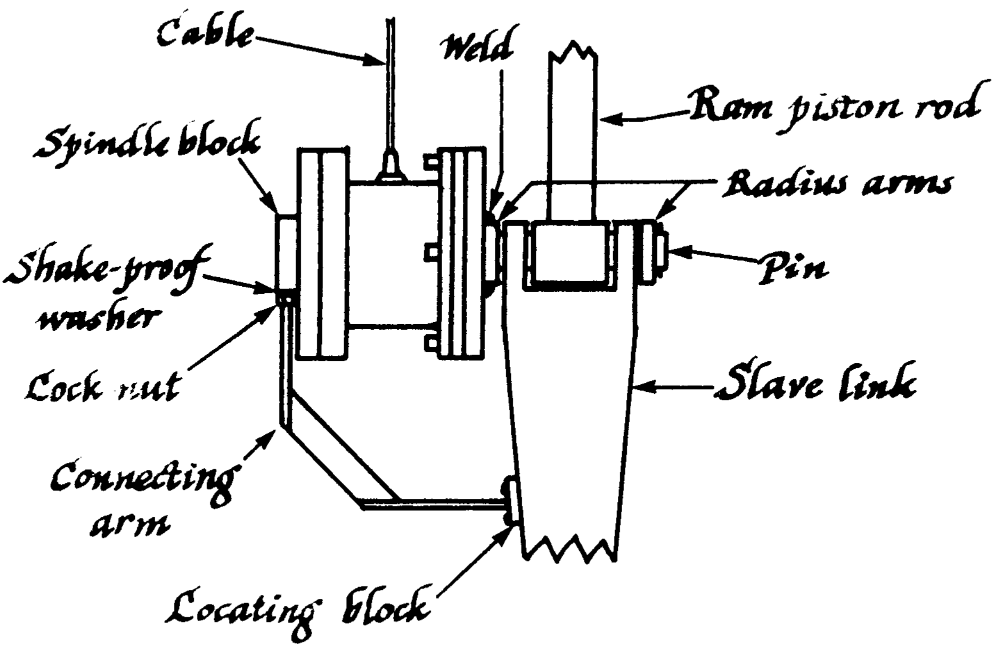


Fig. 5-2: Mounting of Bucket Angle Transducer

Fig. 5-2 shows a side view of the assembled transducer attached to the bucket linkage (see also Plate I). The pin plate is welded onto the radius arm of the bucket linkage to prevent the transducer body from rotating. The connecting arm engages in the slot in the locating block. The locating block is shown in detail in Fig. 5-3.

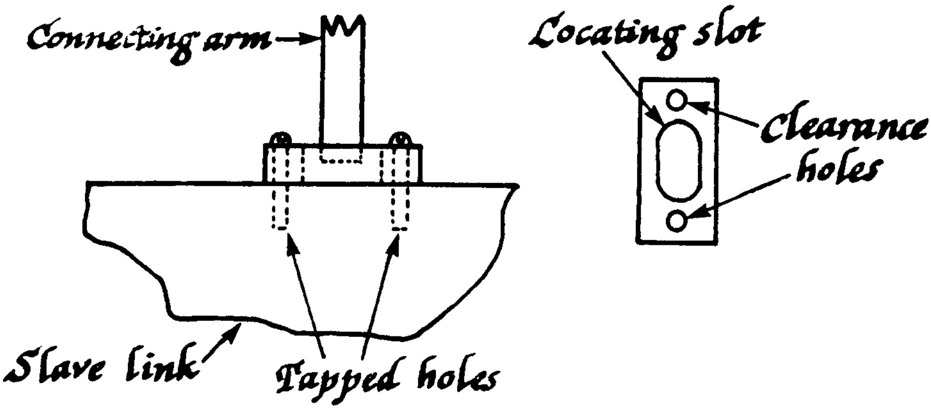


Fig. 5-3: Detail of Locating Block

The elongation of the slot serves to accommodate any movement of the transducer in the plane of the connecting arm due to pin wear. The space between the connecting arm and the slave link accommodates any movement axially along the pin. Plates II and III show the transducers fitted on the machine for measuring angles α and β respectively.

The locating pin shown in Plate II above the transducer prevents it from rotating; the junction box for the transducer connections can also be seen on the machine body. The pin for the transducer measuring angle β is fixed by a cotter pin to the lift arm.

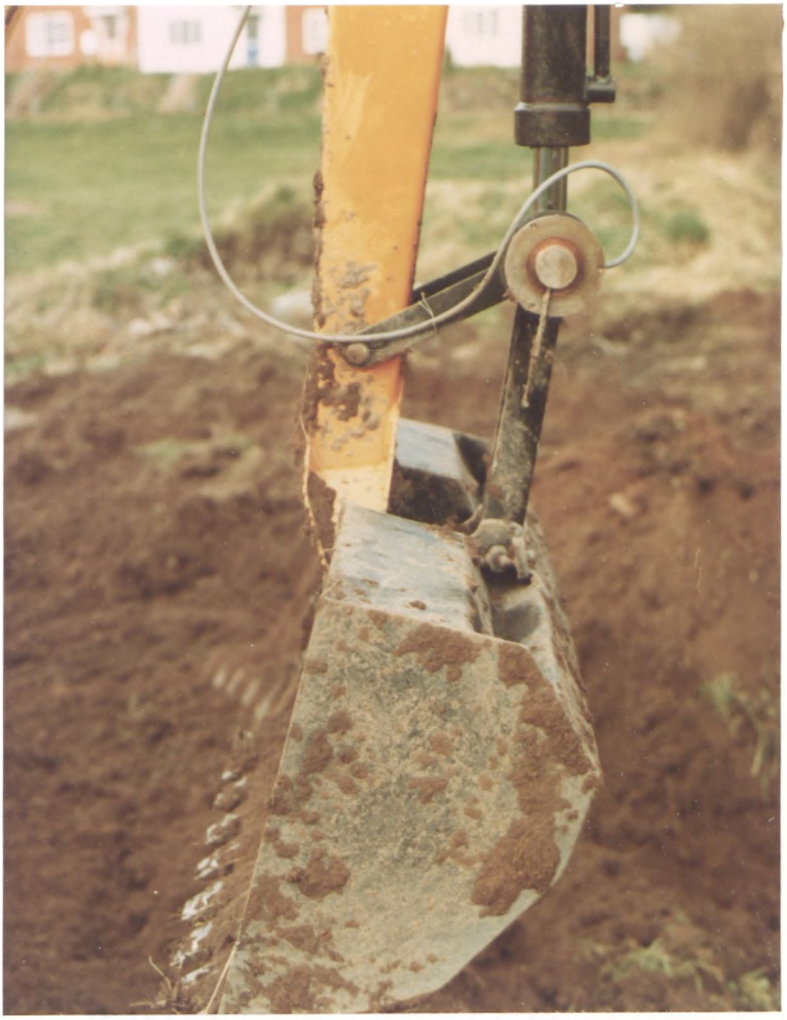


Plate I: Bucket Transducer

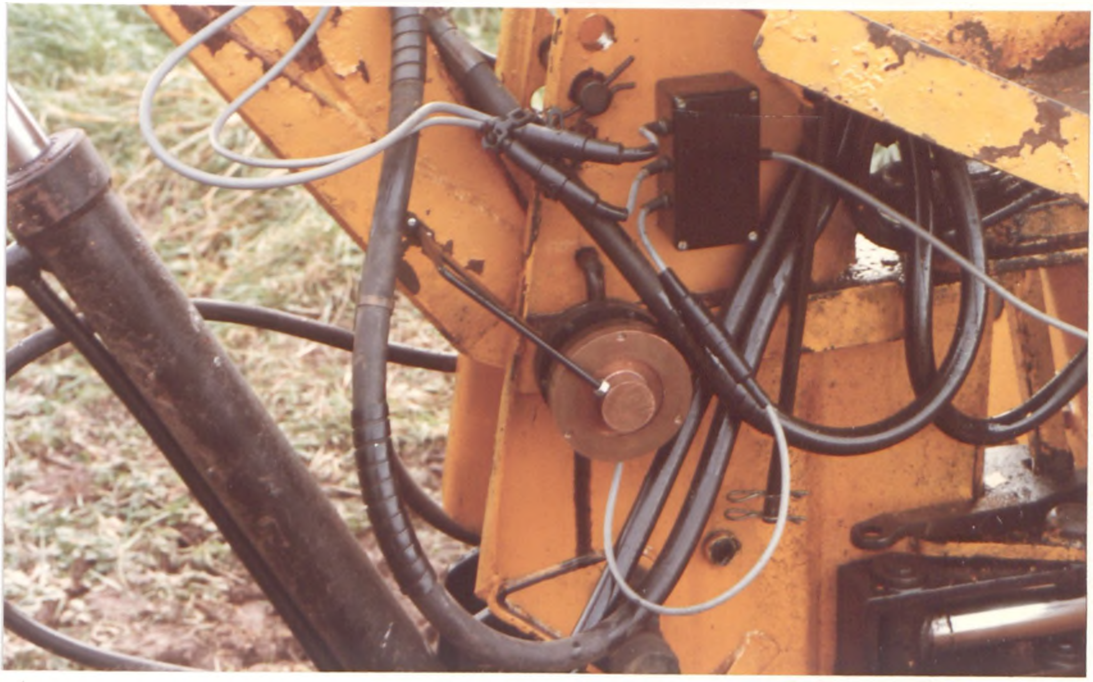


Plate II: Lift Transducer showing Junction Box

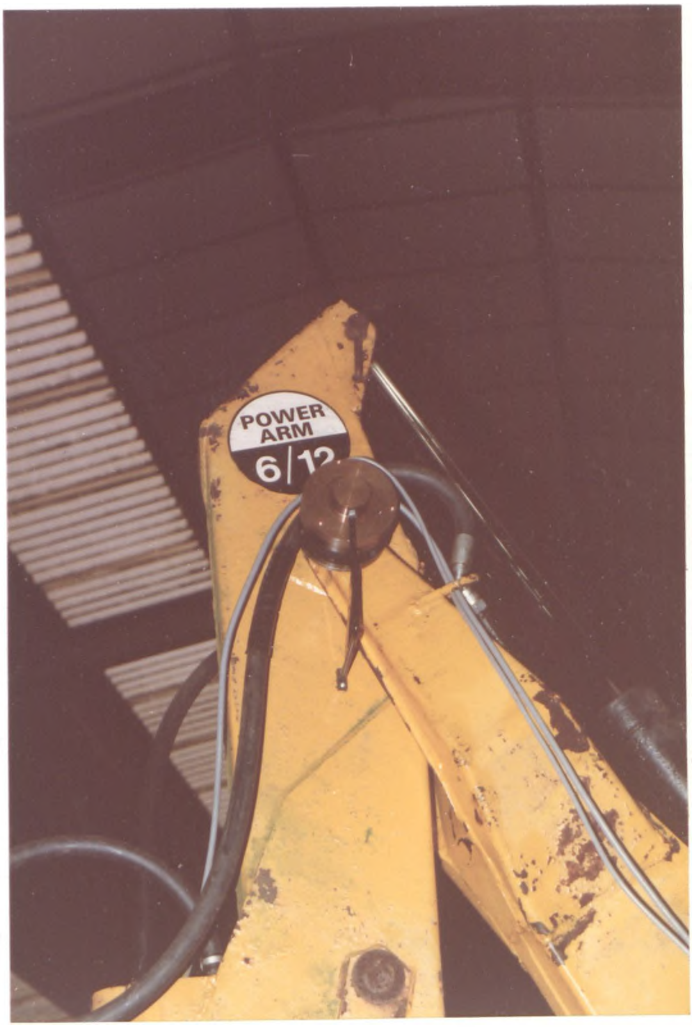


Plate III: Reach Transducer

CHAPTER SIX

HARDWARE I:
SYSTEM STRUCTURE & PROCESSOR BOARD

6.1 System Structure

A block diagram of the control system hardware is shown in Fig. 6-1. The system is based upon an Intel SDK-85 single board microcomputer. It uses an Intel 8085A microprocessor and the unit includes a hexadecimal keyboard, display, a monitor, and in its most basic form 2K of ROM and 256 bytes of RAM. The processor has as eight bit word length and is run on a 6 MHz crystal. The system is compatible with the Intel "Intellec" development system in the departmental microprocessor laboratory allowing the use of an in-circuit emulator for debugging hardware and for software development. The 8085A is also a widely available industry standard device.

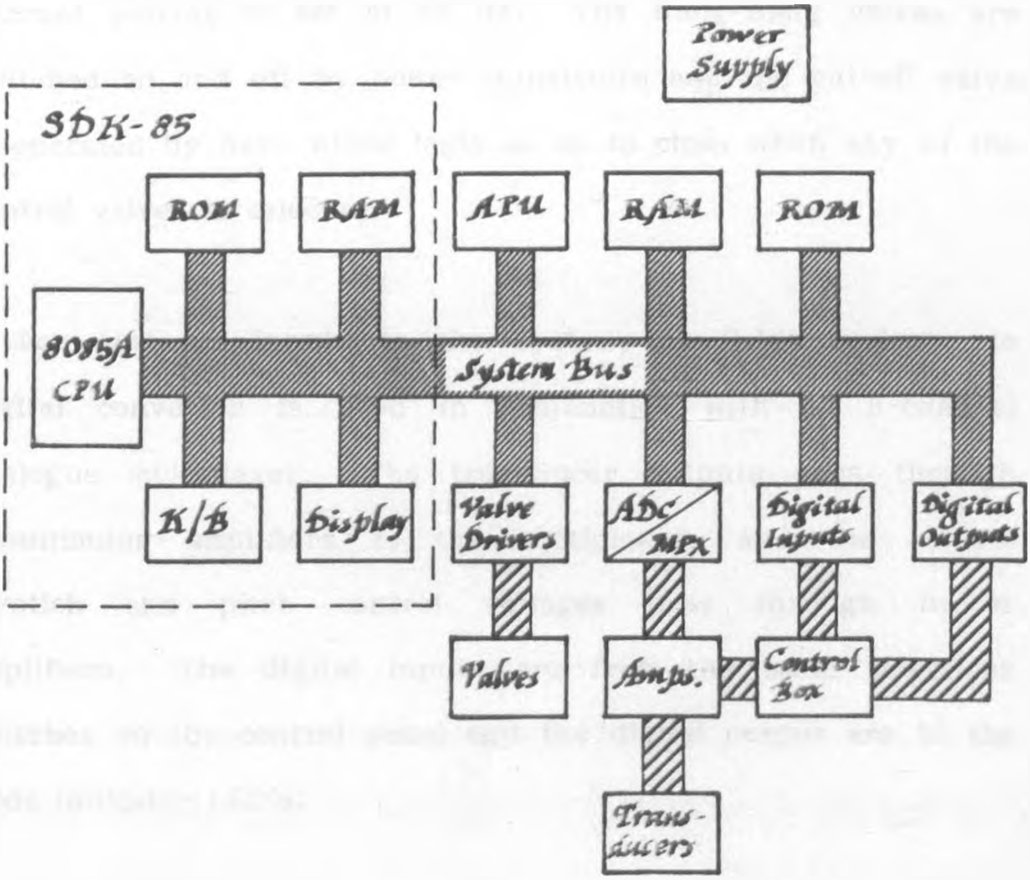


Fig. 6-1: Block Diagram of System Hardware

The memory was expanded to give a total of 4½K of RAM and 8K of EPROM.

The arithmetic processor unit (APU) is an Advanced Micro Devices AM9511 which will operate on 32 bit floating point data, as well as 32 bit and 16 bit integers. The device performs arithmetic and trigonometric operations and runs with a 3 MHz clock giving a maximum floating point multiply time of 56μs.

The Valve Drivers interface the CPU to the proportional and Bang-Bang solenoid valves. The current through the proportional valves is controlled to seven bit accuracy, with an eighth sign bit, from zero to full, and the frequency of the current pulsing is set at 50 Hz. The Bang-Bang valves are switched on and off by power transistors and the cut-off valve is operated by hard wired logic so as to close when any of the control valves is selected.

For analogue inputs to the system, an 8-bit analogue to digital converter is used in conjunction with an 8-channel analogue multiplexer. The transducer outputs pass through conditioning amplifiers to the multiplexer, and the control joystick and pitch control voltages pass through buffer amplifiers. The digital inputs are from the mode selections switches on the control panel and the digital output are to the mode indicator LED's.

The power supply provides the 5V digital supply for the computer and logic circuits using the tractor battery as the power source and employing smoothing circuits and regulators. DC to DC converters are used to provide the dual rail supplies to the amplifier circuitry and for the stable +12 V supply for the APU.

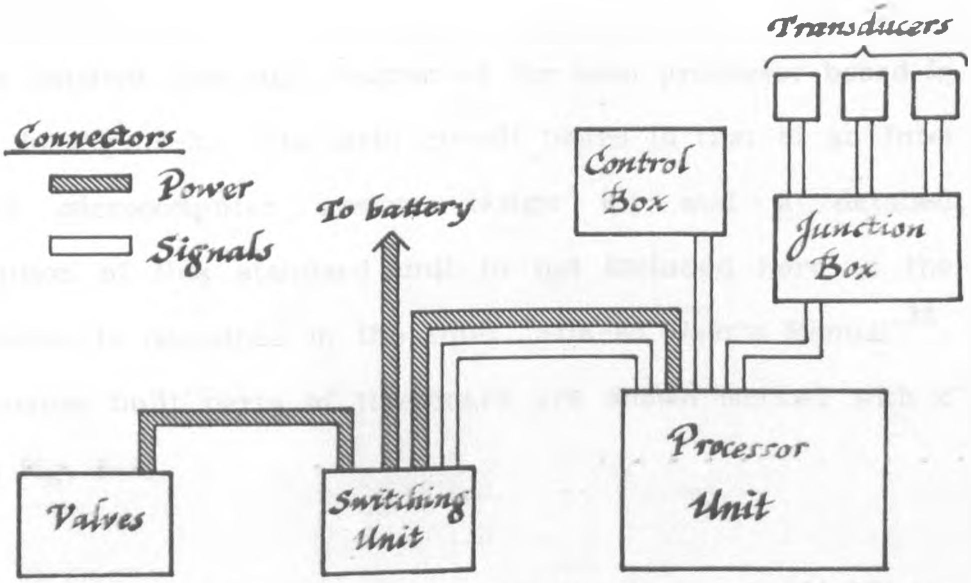


Fig. 6-2: Layout and interconnection of sub-units

The physical layout and interconnection of the different units of the controller are shown in Fig. 6-2. The transducers are connected by screened leads to a junction box mounted on the machine from which a single screened cable then runs to the processor unit. The control box, which houses the control joysticks, pitch control, mode selection and indication circuitry, is linked by a single screened cable to the processor unit.

The switching unit contains the main relay which switches the battery supply to the system on and off, activated by a switch on the control panel. It also supplies the regulators for the proportional valves and the power transistors for all the valves as well as the switching circuit for the cut-off valve. Two cables link the switching unit to the processor unit: one is a screened signal cable for operating the valves and the other is the power cable for the processor unit.

6.2 Processor Board

The detailed schematic diagram of the main processor board is shown in Fig. 6-3. The main circuit board is that of an Intel SDK-85 microcomputer system design kit and a detailed description of this standard unit in not included here as the information is contained in the Intel "SDK-85 User's Manual"[31]. The custom built parts of the board are shown marked with a dot in Fig. 6-3.

The 8085A crystal which is normally supplied at 6.144 MHz is replaced by one of 6 MHz so that the AM9511 arithmetic processor unit may derive its clock signal of 3 MHz from the CLK pin of the CPU which produces a signal at half the crystal frequency.

The 8205 Address Decoder decodes the bottom 4K of memory into eight 2K blocks. The utilisation of each of the decoder outputs is shown in the Memory Map given below. The 2K Monitor ROM, to which control jumps on power on, may be replaced by an EPROM programmed to transfer control the the digger program stored in the 4K EPROM thus making the computer transparent to the user. To facilitate swapping of these chips, as the monitor is often required in experimental work, the board is fitted with a zero insertion force socket. The monitor ROM, or its substitute, and the two 8155 RAM and

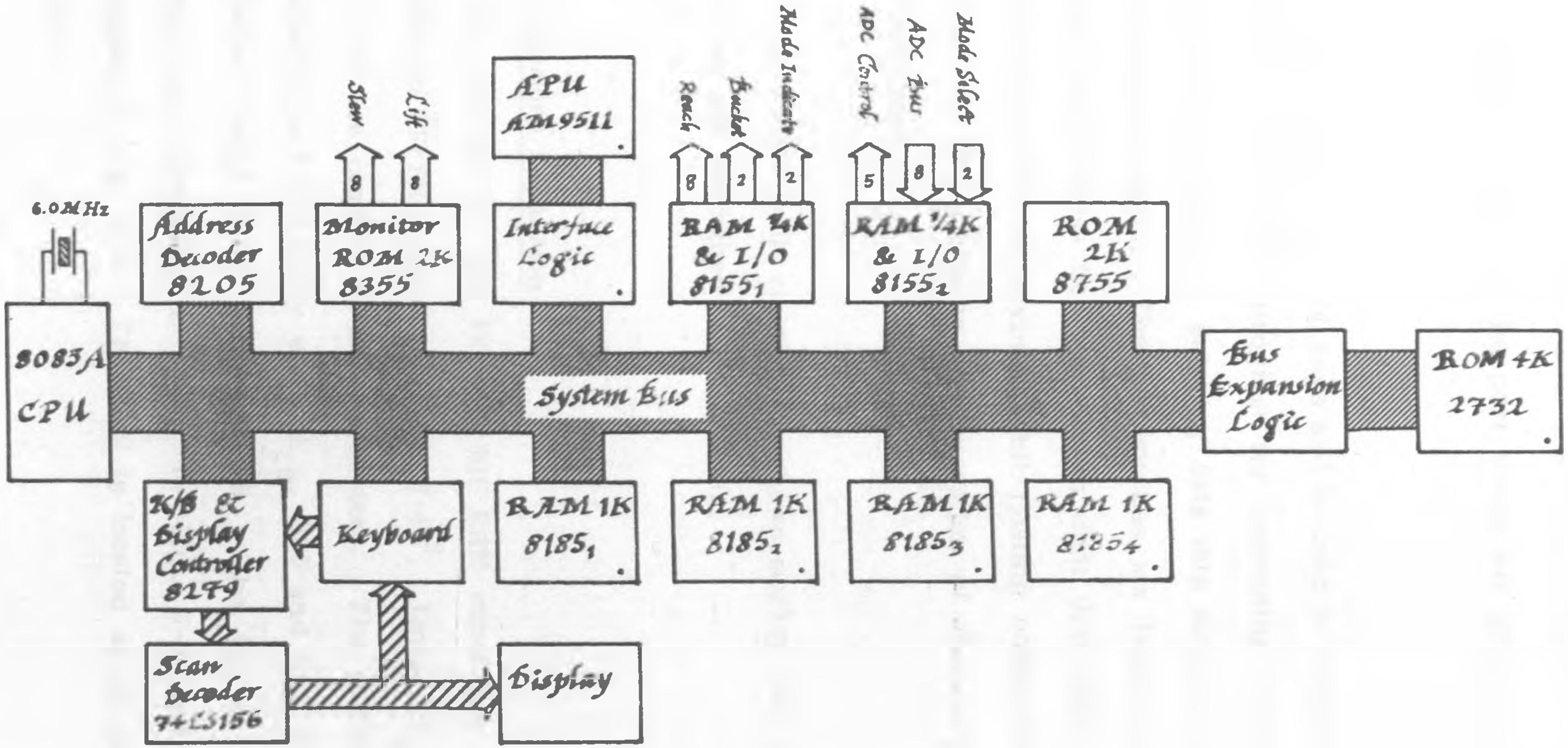


Fig. 6-3: Processor Board Schematic

I/O chips have bit programmable I/O ports used for interface to the valves, the ADC, and the mode selection and indication circuitry. Details of the port usage are given in the I/O map below.

The keyboard has 24 keys and is used in conjunction with the display and monitor program for inspecting memory locations and register contents, entering data into memory, and initiating program execution. The display has six hexadecimal digits: a four digit address field and a two digit data field. A program was written for displaying 32 bit floating point variables stored in memory for checking the operation of the programs during development.

The custom built circuits are shown marked with a dot in Fig. 6-3 and are described in detail later.

6.3 Memory Expansion

The circuit for the 4K x 8 bit RAM expansion for locations 3000H to 3FFFH is shown in Fig. 6-4[32]. Lines AD_0 to AD_7 and A8, A9 are common to all the devices. The additional address decoding is effected by using A_{10}, CS6 and CS7 and control is effected using ALE, RD, and WR. The 4K x 8 bit EPROM expansion schematic is shown in Fig. 6-5 and the circuit diagram in Fig. 6-6. The ROM is located at address 8000H to 8FFFH.

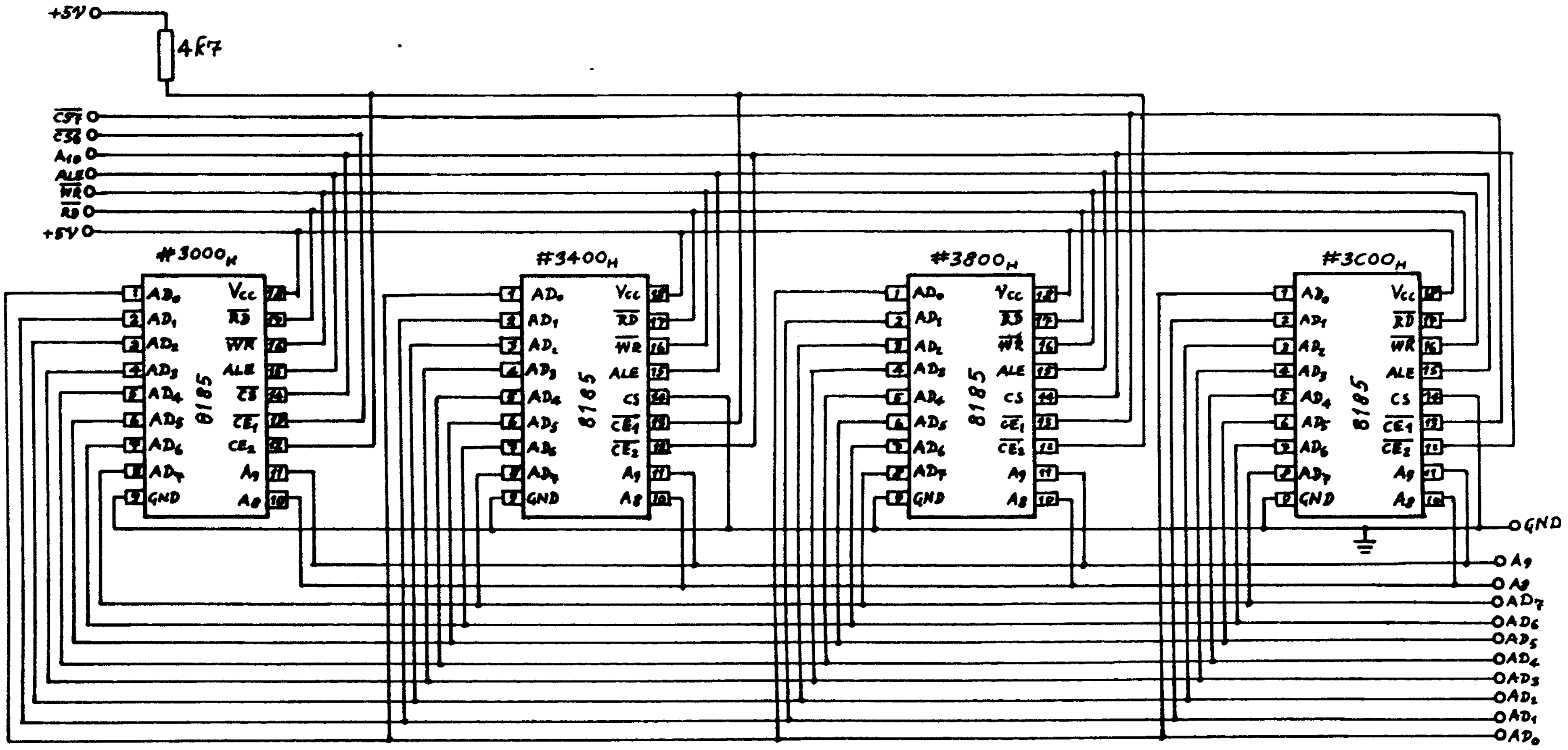


Fig. 6-4: 4K RAM Expansion Circuit

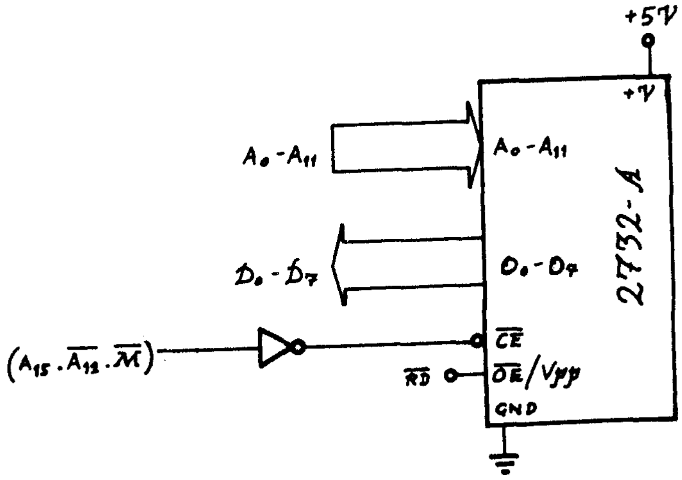


Fig. 6-5: 4K EPROM Expansion Schematic

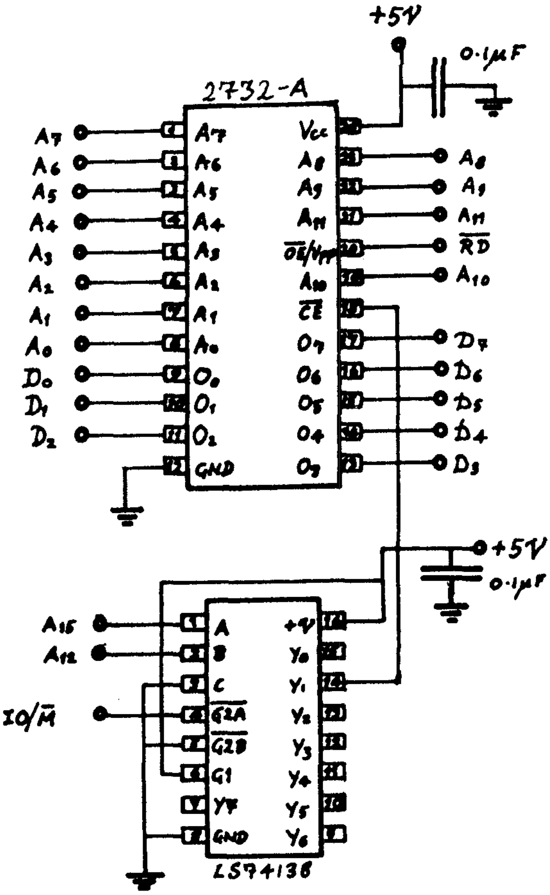


Fig. 6-6: 4K EPROM Expansion Circuit

6.4 Arithmetic Processor Unit

The arithmetic processor unit interface schematic is shown in Fig. 6-7. The APU has an internal stack to which data bytes are pushed and pulled, and a command/status register both accessed by the eight bit bidirectional data bus[33]. The stack is located at address 1000H and the command/status register at address 1100H.

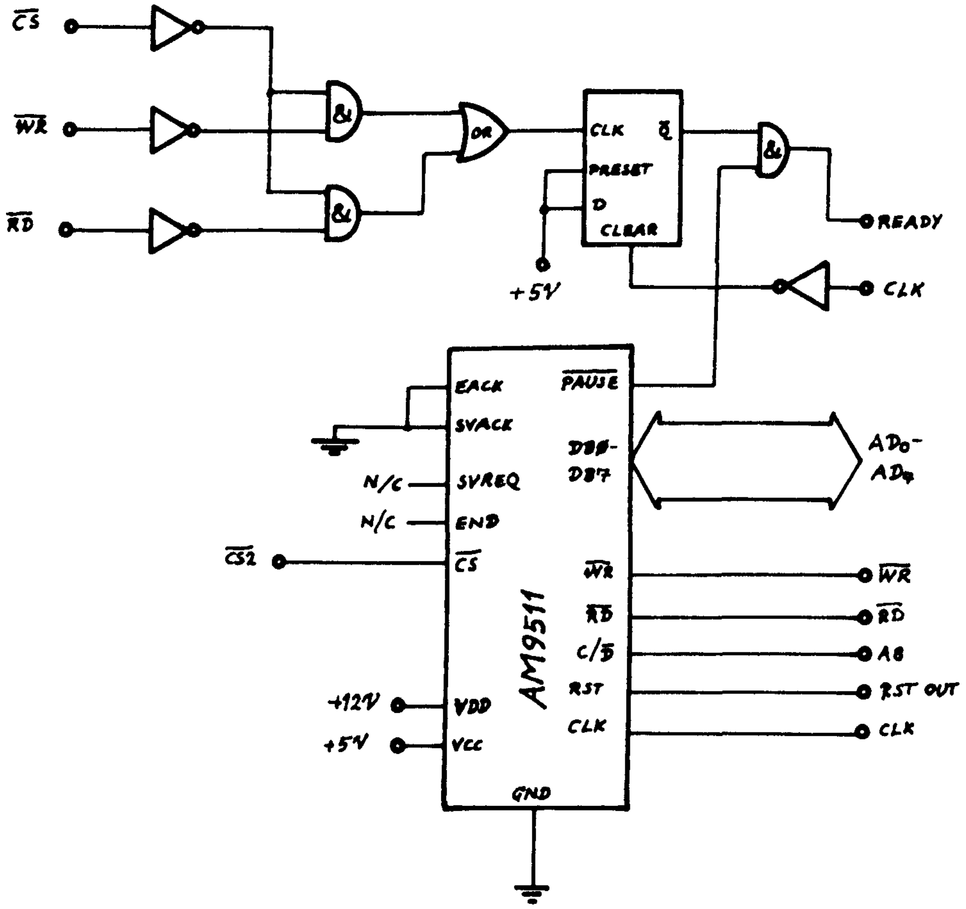


Fig. 6-7: AM9511 APU Interface Schematic

The device has a 3 MHz clock input derived from the CLK pin of the CPU which synchronises the two devices. At power on the device is reset from the RST OUT line of the CPU.

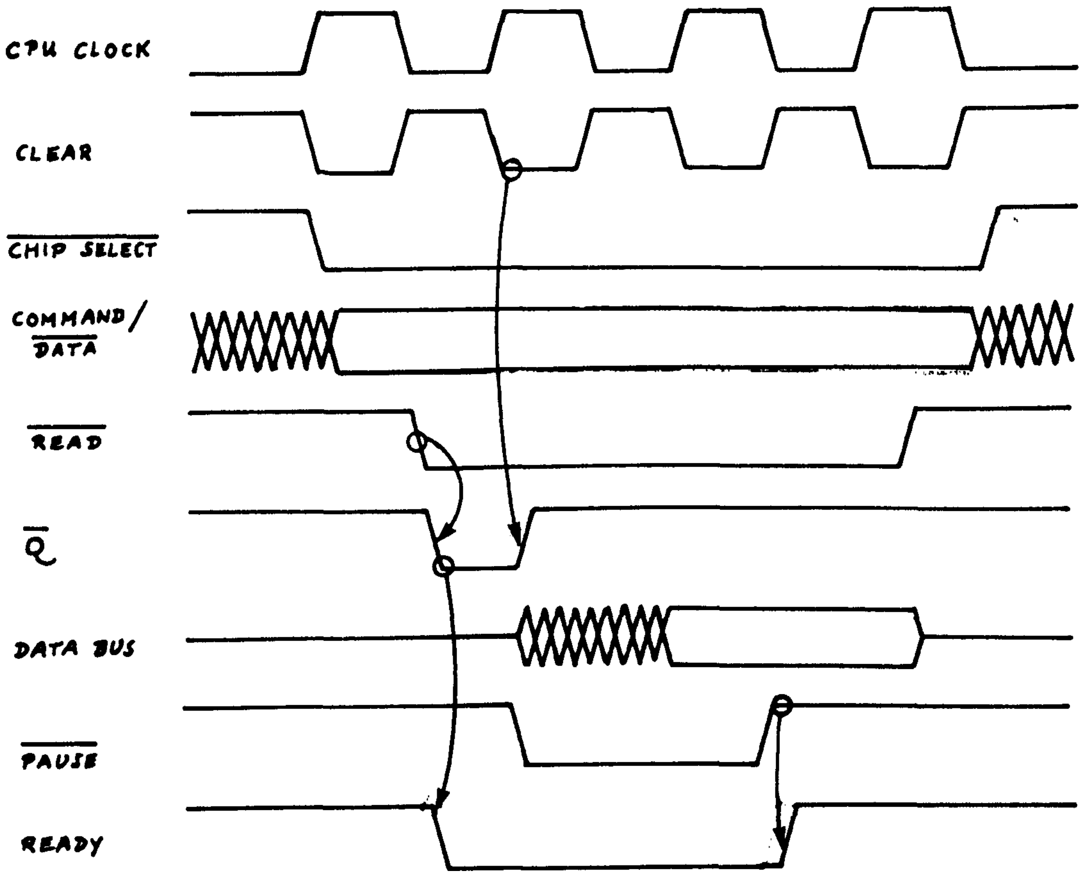


Fig. 6-8: APU Interface Timing Diagram

When reading data from the device with the PAUSE line of the APU connected directly to the CPU READY pin it was found that errors occured owing to delay in the PAUSE line going low when the APU was accessed by the CPU. The CPU was reading data from the bus before it had settled. The logic shown in Fig. 6-7 pulls the READY line low immediately the device is selected allowing it to return high when PAUSE goes high. The timing and wiring diagrams are shown in Figs. 6-8 and 6-9 respectively.

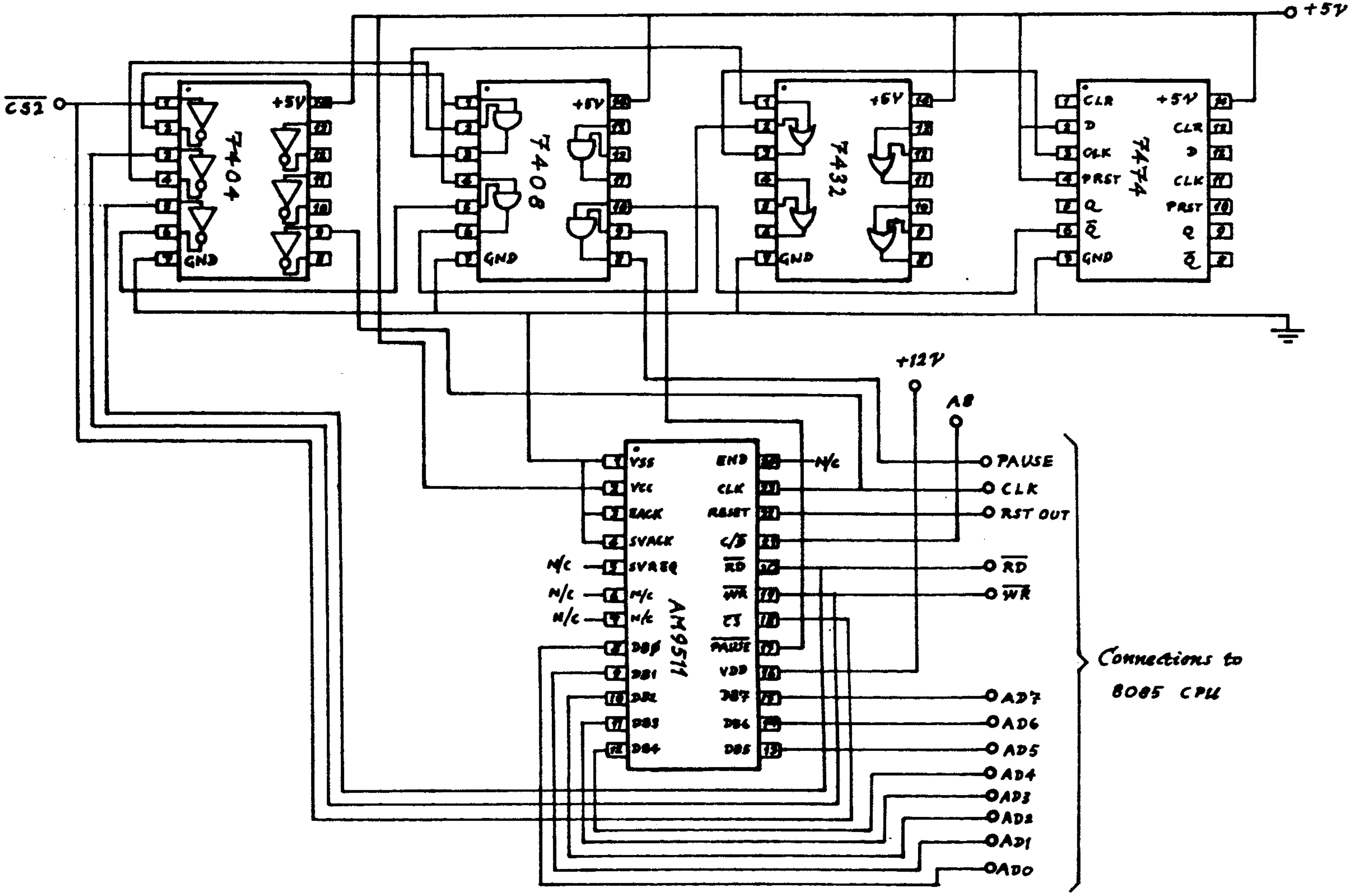


Fig. 6-9: APU Interface Circuit

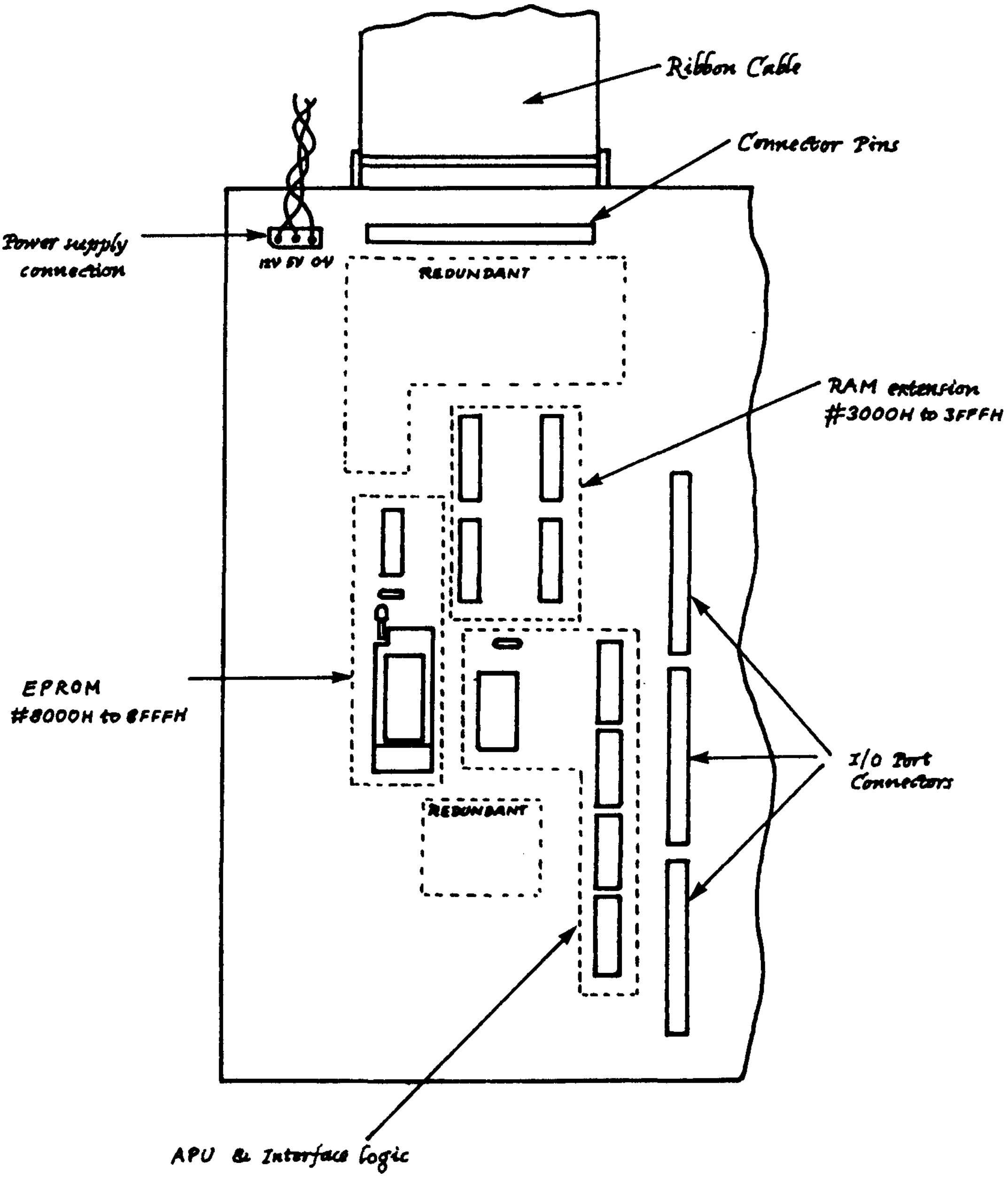


Fig. 6-10: *Layout of Modifications to SDK-85 Board*

6.5 Board Layout

The layout of the custom built circuits is shown in Fig. 6-10. The diagram also shows the power supply connection to the processor board and the ribbon cable connectors. Plate IV shown a plan of the complete main circuit board. The details of the complete ribbon cable connections are given later, in the chapter covering the rack wiring.

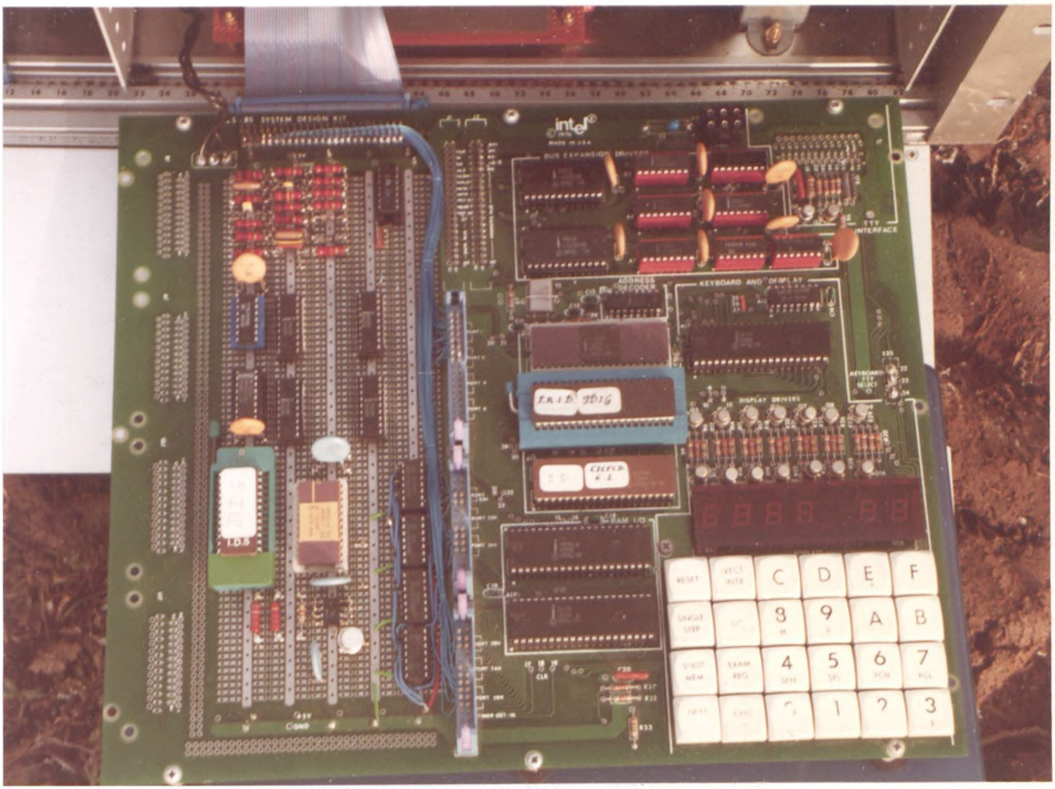


Plate IV: Modified Intel SDK-85 Board

6.6 Memory and I/O Maps

Tables 6-1 and 6-2 respectively show the memory map (including the active 8205 chip select lines) and the I/O map with the usage of the different ports.

I/O Map

Port Address	Chip	Port	Function	No. of bits used
00H	8355	A	Slew	8
01H	8355	B	Lift	8
21H	8155$_1$	A	Reach	8
22H	8155$_1$	B	Bucket	2 of 8
23H	8155$_1$	C	Mode Indicate	2 of 6
29H	8155$_2$	A	ADC Bus	8
2AH	8155$_2$	B	Mode Select	2 of 8
2BH	8155$_2$	C	ADC Control	5 of 6

Table 6-2: System I/O Map

Memory Map		
Address	Function	Active 8205 chip select
0000H 07FFH	Monitor ROM (8355)	CS0
0800H 0FFFH	Expansion EPROM (8755)	CS1
1000H	APU Data (AM9511)	CS2
1001H 10FFH		
1100H	APU Command/ Status (AM9511)	
1101H 17FFH		
1800H 1FFFH	1800H: Keybd./ Display Ctlr. Command Loc.	CS3
	1900H: Keybd./ Display Ctlr. Data Loc. (8279)	
2000H 20FFH	Basic RAM (8155_1)	CS4
2100H 27FFH	Basic RAM fold back	
2800H 28FFH	Expansion RAM (8155_2)	CS5
2900H 2FFFH	Expansion RAM fold back	
3000H 33FFH	Expansion RAM (8185_1)	CS6
3400H 37FFH	Expansion RAM (8185_2)	
3800H 3BFFH	Expansion RAM (8185_3)	CS7
3C00H 3FFFH	Expansion RAM (8185_4)	
4000H 7FFFH		
8000H 8FFFH	Expansion EPROM (2732)	

Table 6-1: System Memory Map

CHAPTER SEVEN

HARDWARE II: INTERFACE CARDS, POWER SUPPLIES, & RACK CONNECTIONS

7.1 Analogue Interface Card

The circuit schematic for the analogue interface card is shown in Fig. 7-1. The 5 V reference supply acts as the reference voltage source for the position transducers, the control joysticks, and the pitch control. The voltage reference is also connected to the Analogue to Digital Converter, the ADC0816 manufactured by National Semiconductor, as the reference supply across the divider chain. The ADC has eight bit resolution and the chip incorporates a sixteen channel multiplexer for analogue inputs of which only eight are used here.

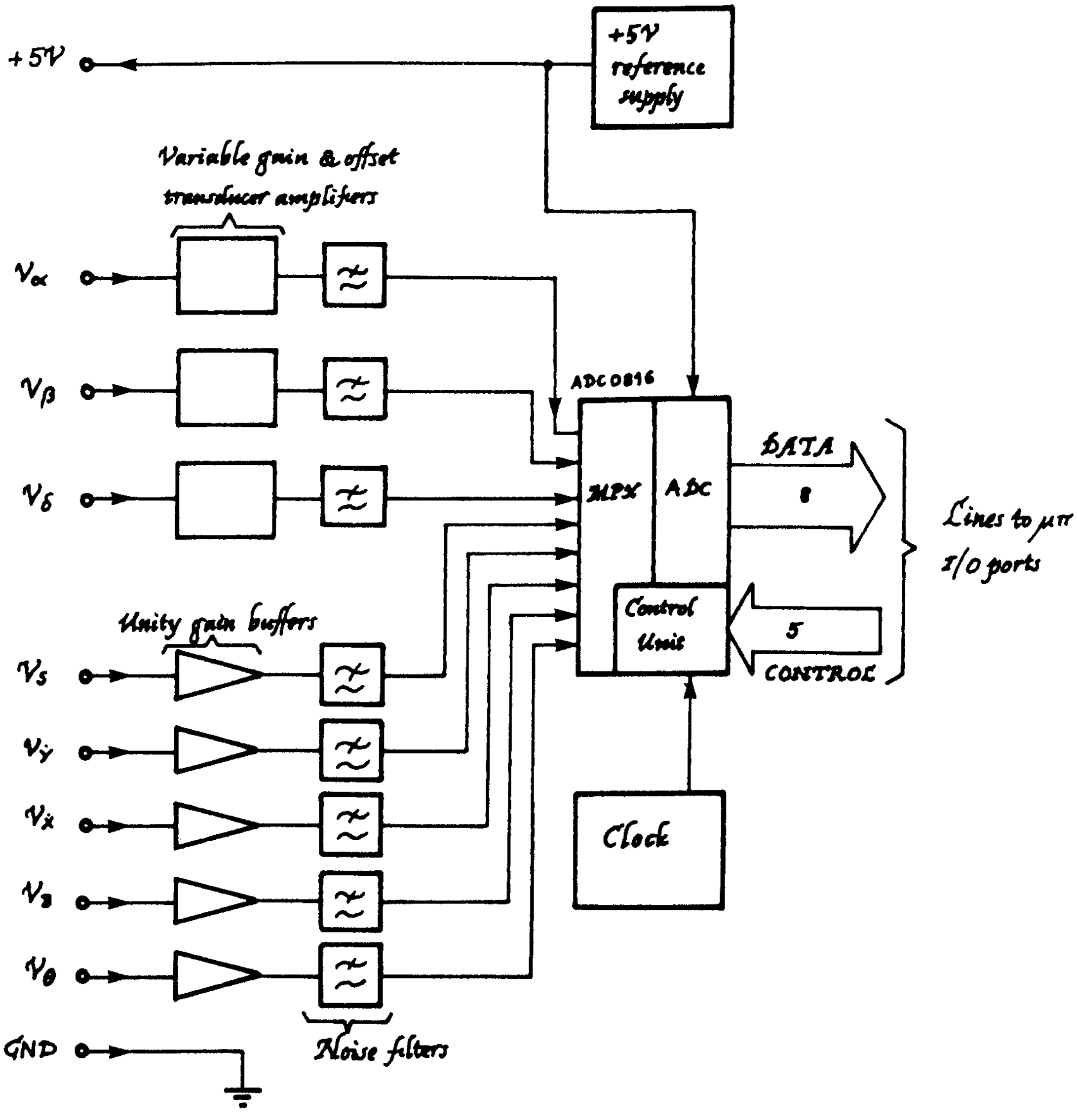


Fig. 7-1: Analogue Interface Card Schematic

The analogue inputs from the transducers pass through signal conditioning amplifiers with a variable gain and offset. The function of these is to map the full scale output swing of the transducers onto the full range of the converter. The joystick and pitch control voltages are fed into unity gain buffers. The range of joystick voltage variation does not require any amplification and the pitch control potentiometer is variable between 0 V and 5 V.

The analogue inputs to the multiplexer all pass through low pass filters to keep the overall noise at the input to the ADC below 10 mV; the cut-off frequency of the filters is set at 1 kHz. The clock for the ADC runs at 640 kHz to give a maximum conversion time of 114 µs. The control lines select the analogue input, initiate conversion, and signal the data to be output onto the 8 bit bus at the end of the conversion.

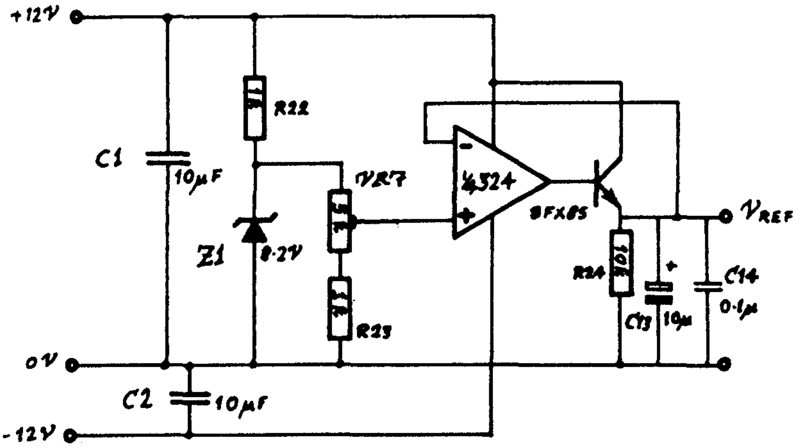


Fig. 7-2: 5 V Analogue Reference Circuit

The circuit for the 5 V analogue reference is shown in Fig. 7-2; the two 10 µF capacitors C1 and C2 smooth the supply for the operational amplifier and the Zener Z1. The voltage across the Zener is 8.2 V and from this is derived 5 V using the potential divider of VR7 and R23. This voltage is buffered by the op-amp, and the BFX85 transistor is used to boost the buffer output current. The 10 k resistor provides a load for output stability if no other load is connected. Output smoothing is provided by C13 and C14.

The circuit used for the variable gain and offset amplifiers is shown in Fig. 7-3. Operational amplifier B acts as an input buffer for the transducer and amplifier A buffers the offset voltage into the unity gain summing amplifier C. Amplifier D provides the gain stage. The wiring diagram for the three transducer amplifiers is shown in Fig. 7-4. Operational amplifier 324_4 is used to buffer the voltages from the joysticks.

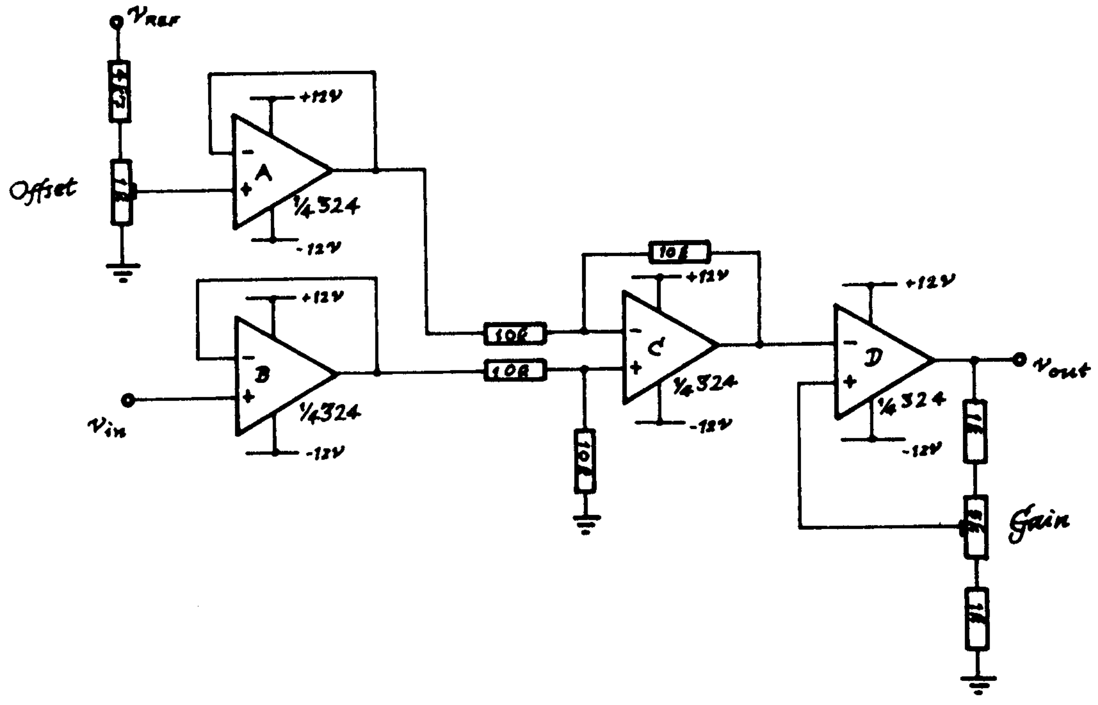


Fig. 7-3: Transducer Signal Conditioning Amplifier

The circuit for the ADC is shown in Fig. 7-5; the ADC0816 has a built-in analogue multiplexer with sixteen inputs of which

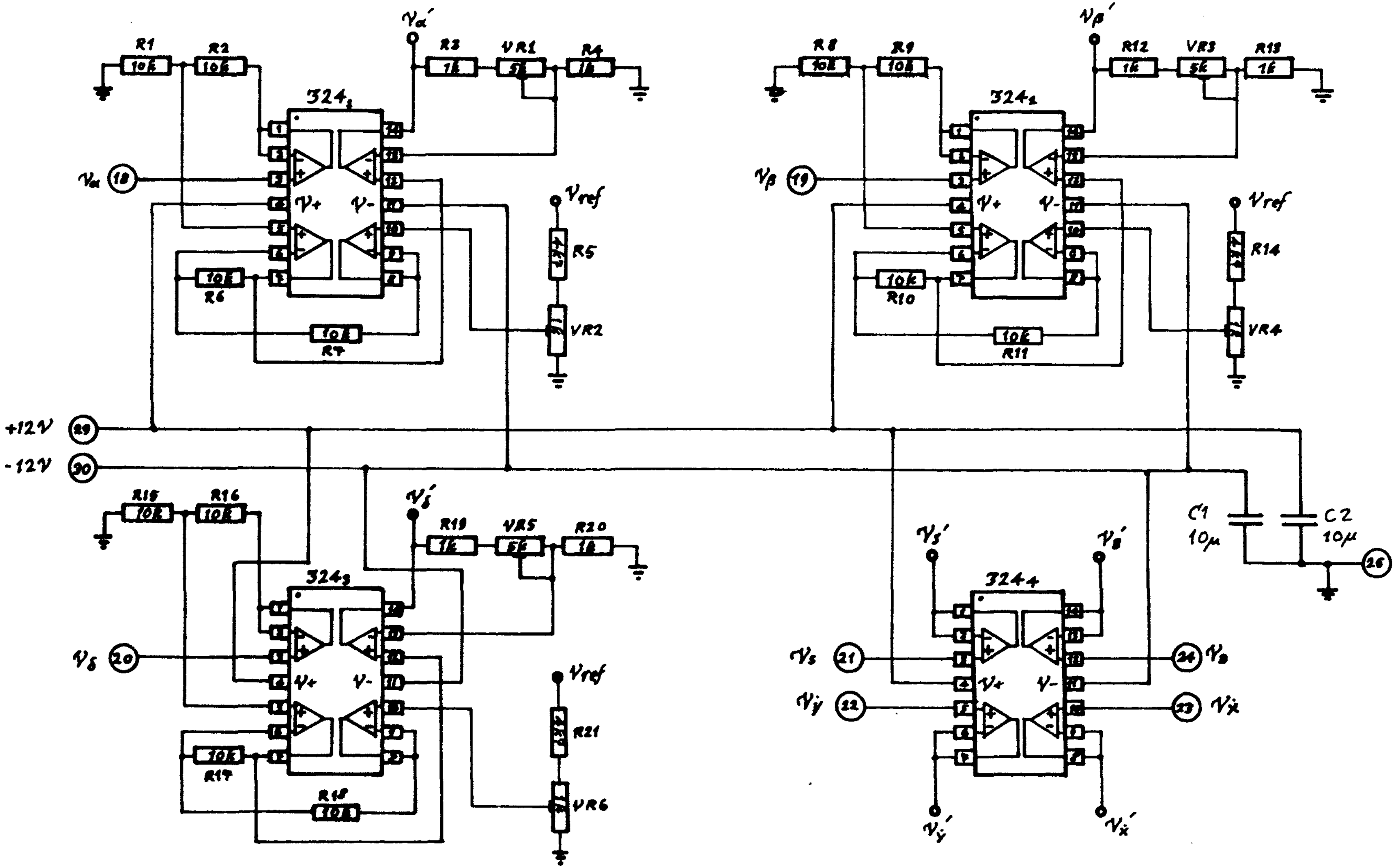


Fig. 7-4: Wiring Diagram of Amplifiers and Buffers

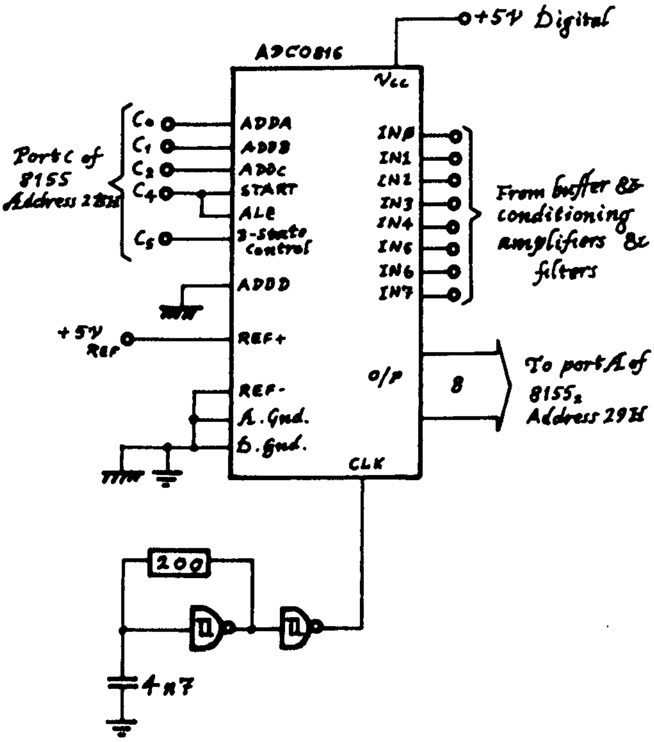


Fig. 7-5: Analogue to Digital Converter

eight, IN0 to IN7, are used here. The chip runs off the 5 V logic supply and also has a 5 V reference input for the divider chain in the ADC. Control lines ADD A, ADD B, ADD C are used to select the input line address. ADD D is tied low as only eight of 16 inputs are used. The START and address latch enable (ALE) are connected to control line C4 which is pulsed high to initiate a conversion once the address for the input has been presented on ADD A-C (see timing diagram Fig 7-6). C5 goes high to activate the tri-stated 8-bit output port at the end of the conversion. The ADC has a clock input of 640 kHz provided by the Schmitt Trigger inverter with the feedback resistor and capacitor to ground, the second gate acting as a buffer.

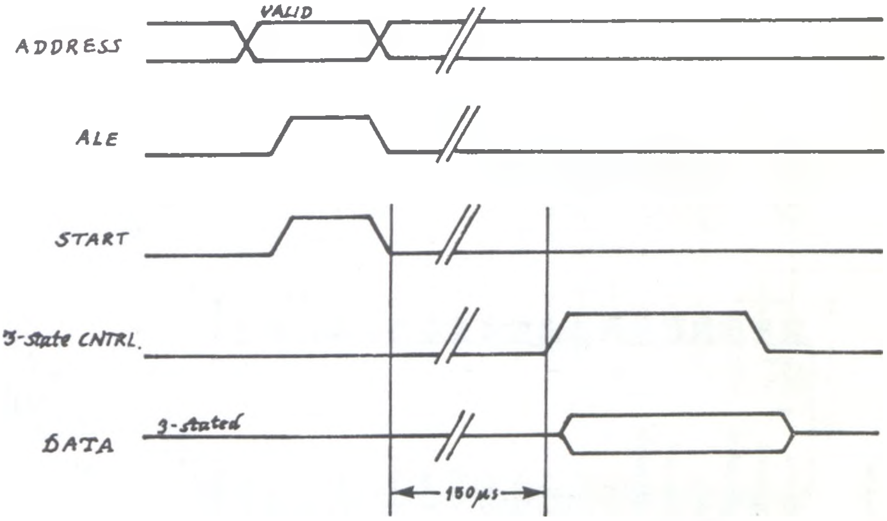


Fig. 7-6: ADC Timing Diagram

The wiring diagram for the ADC circuitry is shown in Fig. 7-7, and the layout in Fig. 7-8 and Plate V.

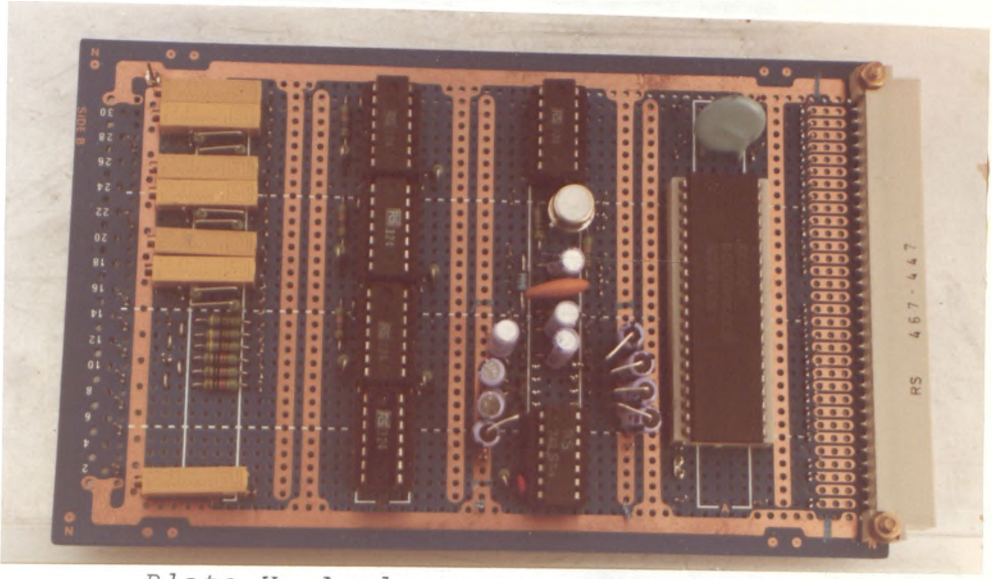


Plate V: Analogue Interface Card

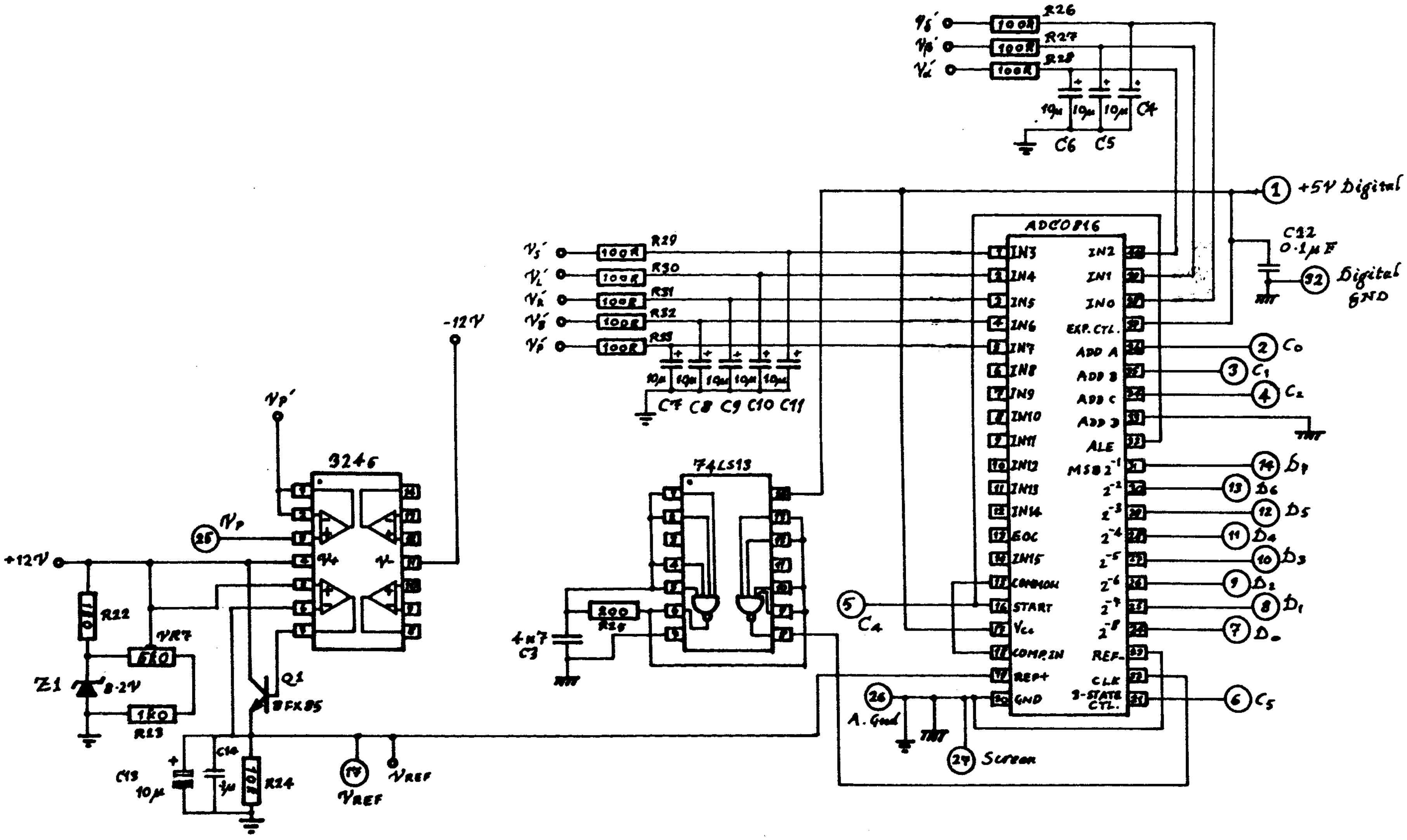
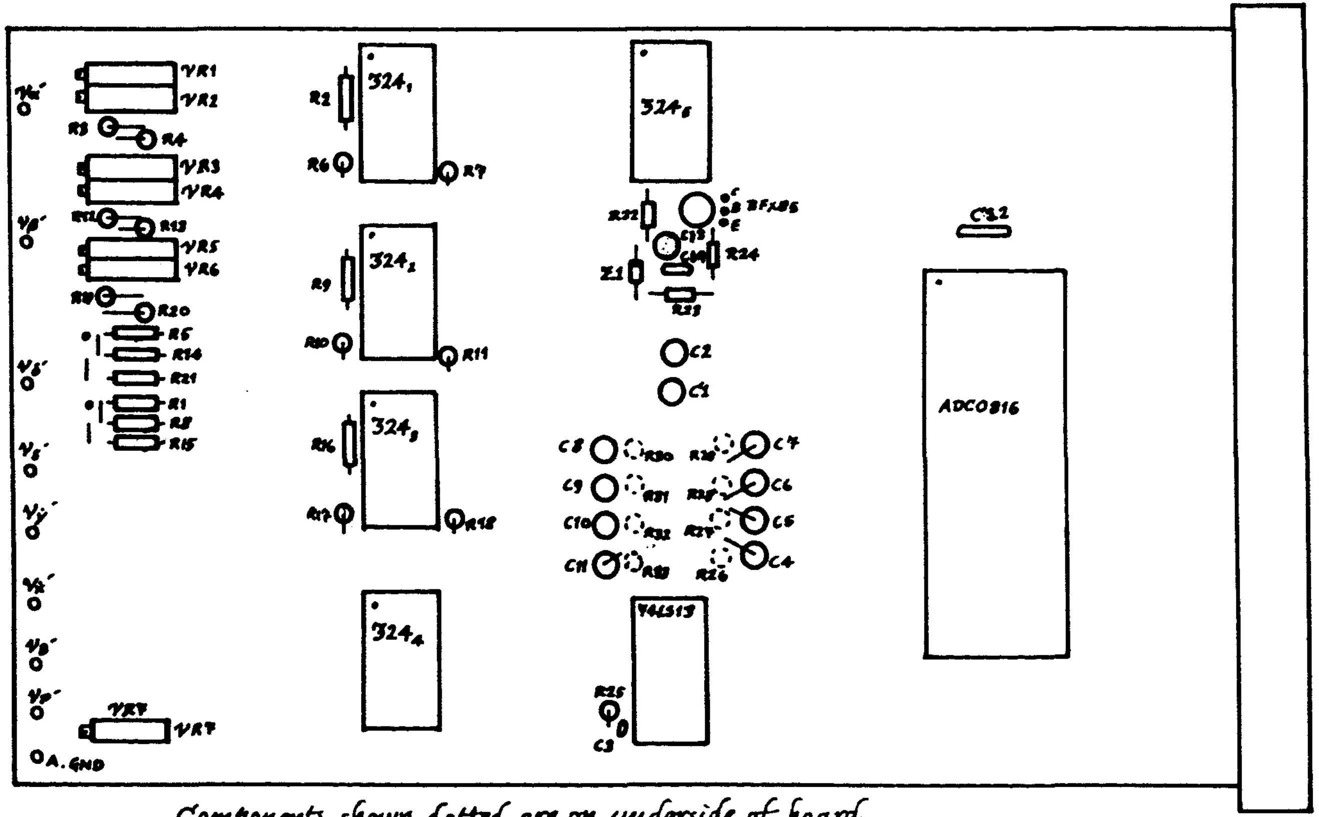


Fig. 7-7: ADC Wiring Diagram



Components shown dotted are on underside of board.

Fig. 7-8: Analogue Card Layout

7.2 Valve Driver Card

The valve driver card is essentially a 3-channel digital pulse width modulator circuit for driving the SLEW, LIFT, and REACH valves. There are three 8-bit digital inputs, seven bits for each channel are used to select the mean valve current and the eighth to select the direction of movement: Right or Left etc.

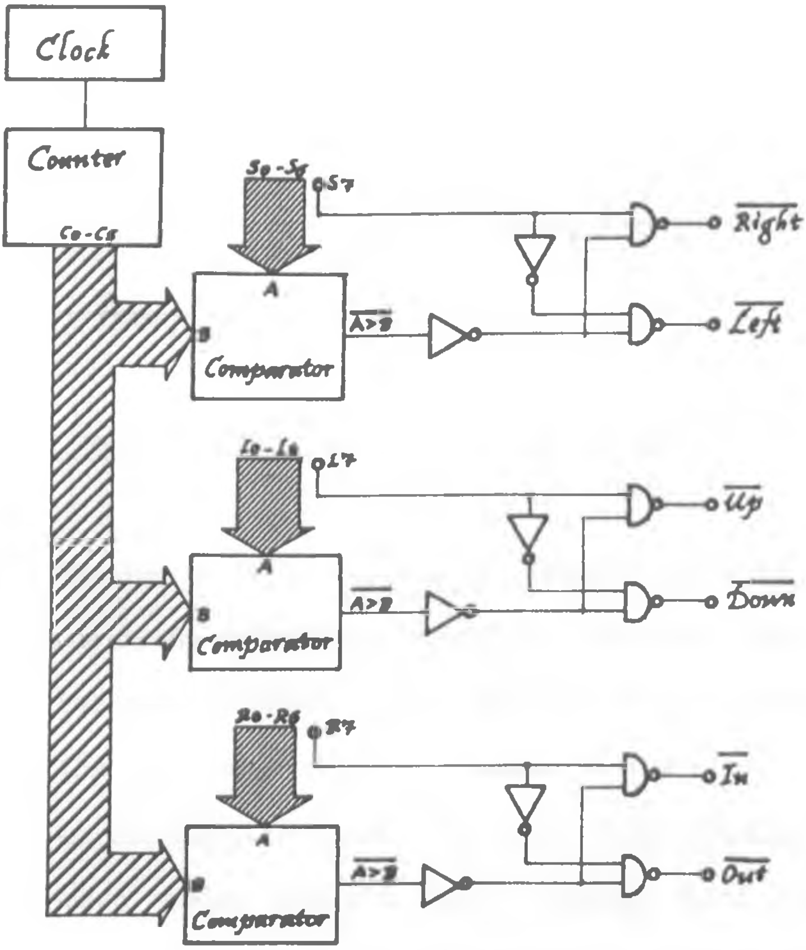


Fig. 7-9: Valve Driver Schematic

The circuit schematic is shown in Fig. 7-9. The three control inputs S0-S7, L0-L7, and R0-R7 are for the Slew, Lift, and Reach functions respectively, line 7 selecting the direction in each case.

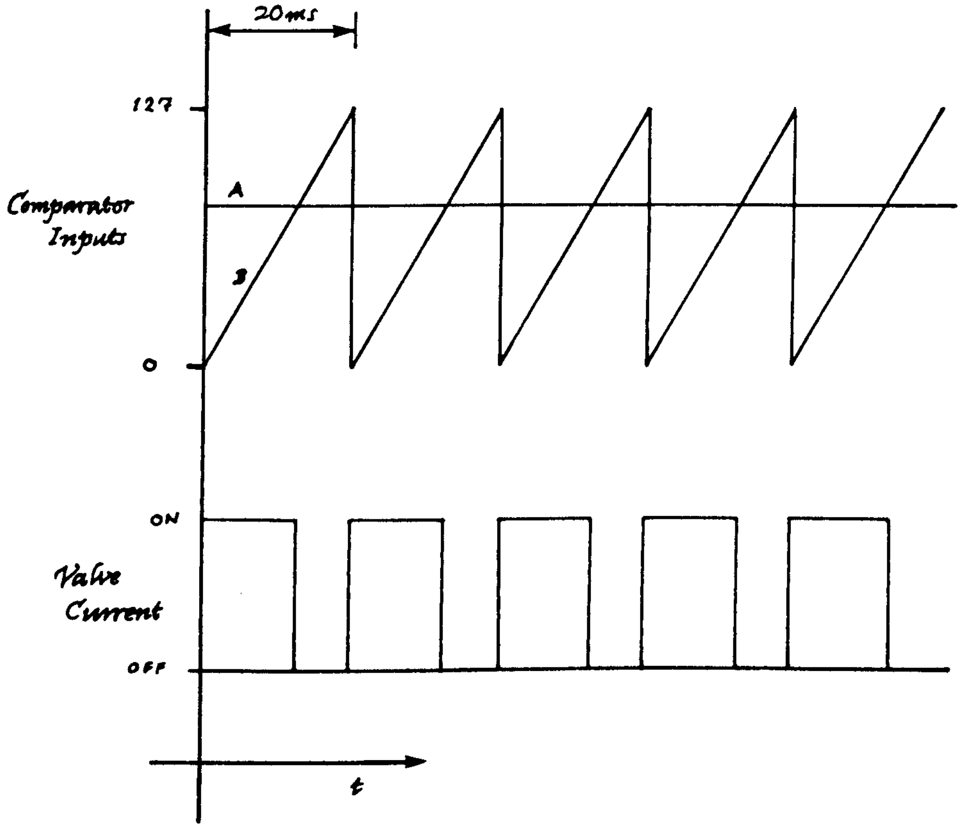


Fig. 7-10: *Valve Driver Timing Diagram*

For each channel there is a seven bit digital comparator: one input is from a cyclic counter generating a sawtooth output and the other is the control signal. The logic operates as shown in Fig. 7-10 so that the valve current is ON when the control input is greater than the counter value. So over an input range of 0 to 127 the mean valve current varies linearly from zero to maximum. The frequency of the valve switching pulse train is set to 50 Hz by adjusting the clock to run at 6.4 kHz.

The wiring diagram for the clock and counter circuit is shown in Fig. 7-11. A 555 timer is used for generating the clock signal, adjusted by potentiometer VR1. The counter employs two 74LS163 four bit counter chips, the output being taken from the

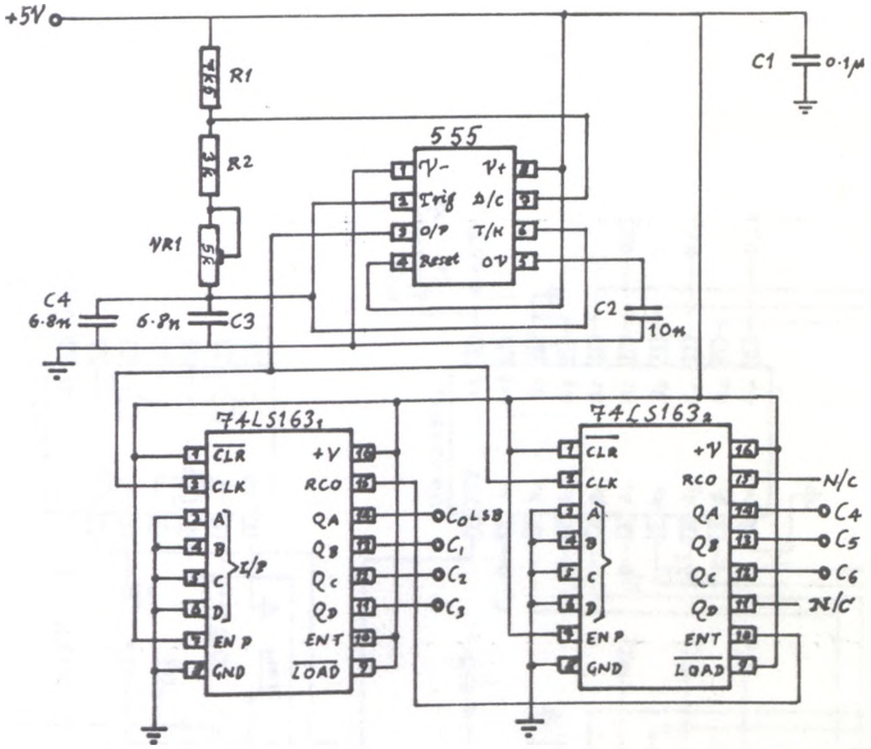


Fig. 7-11: Wiring Diagram of Clock & Counter Circuit

seven least significant bits. Fig. 7-12 shows the wiring of the comparator and logic circuitry. The outputs from the card to the valve switching circuits are active low. The circuit layout is shown in Fig. 7-13 and Plate VI.

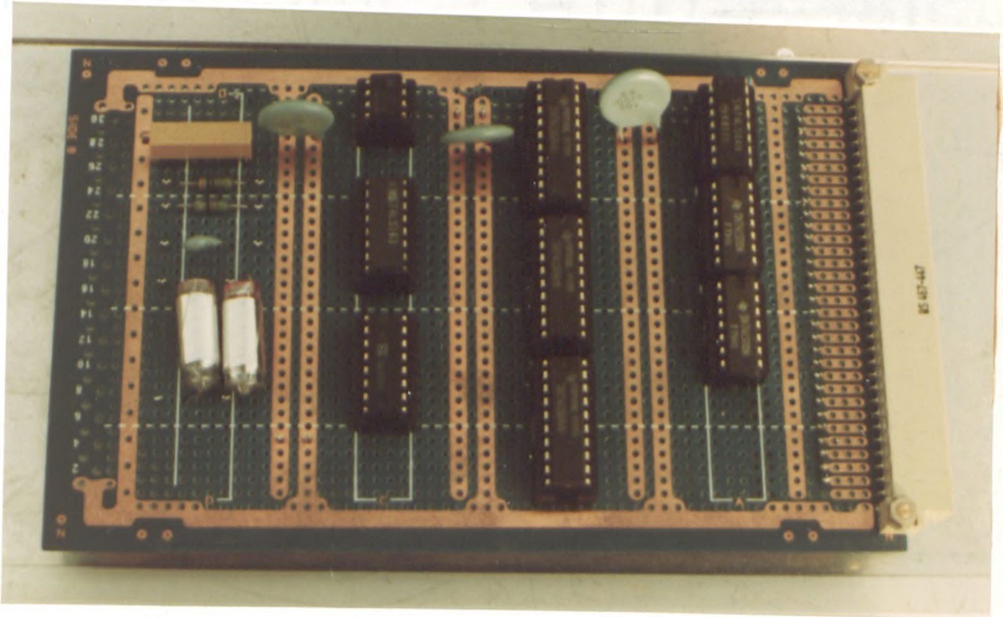


Plate VI: Valve Driver Card

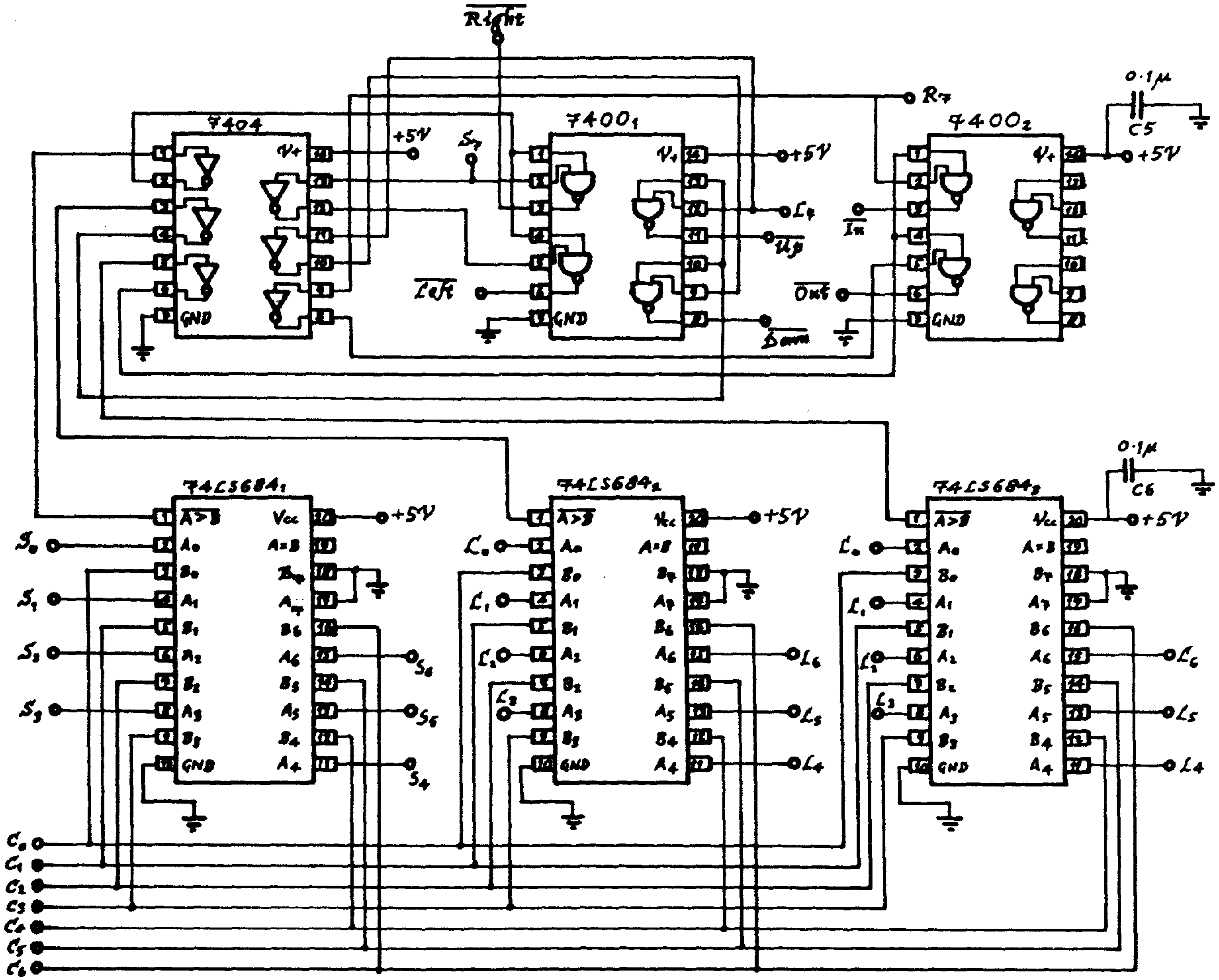


Fig. 7-12: Wiring Diagram of Valve Driver Comparator & Logic Circuitry

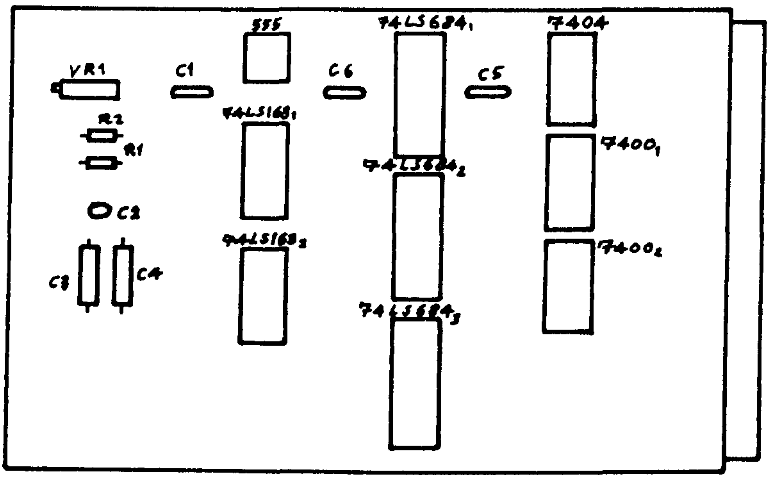


Fig. 7-13: Valve Driver Circuit Layout

7.3 Power Supplies

The main 5 V power supply for the logic circuitry is shown in Fig. 7-14. The input comes from the tractor battery via the power switching relay situated in the switching unit. The 27 V Zener is to act as protection against any high voltage spikes or surges; the smoothing circuit comprising L1, L2, C1, C2 removes ripple and high frequency noise from the input to the regulator RG1. The feedback network of R1 and VR1 may be adjusted to give the desired output of 5V and C3 and C4 provide output smoothing.

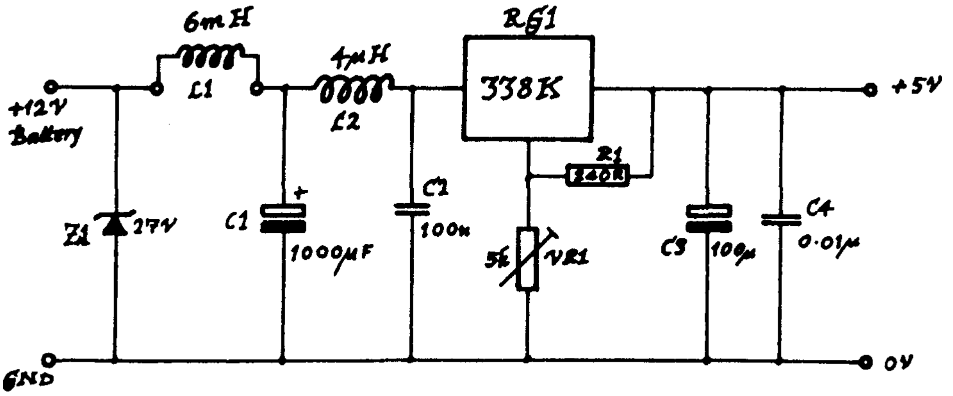


Fig. 7-14: 5 V Regulator Circuit

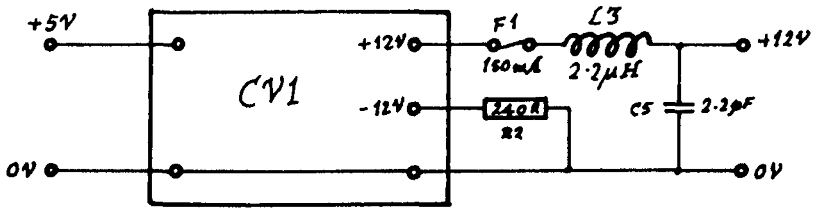


Fig. 7-15: 12 V APU Supply

The +12 V supply for the APU is shown in Fig. 7-15. CV1 is a DC to DC converter with a 100 mA output rating, L3 and C5, serve to eliminate high frequency noise from the output probably due to internal switched mode operation of the converter. The 240 dummy load on the negative output is necessary to preserve regulation of the positive output.

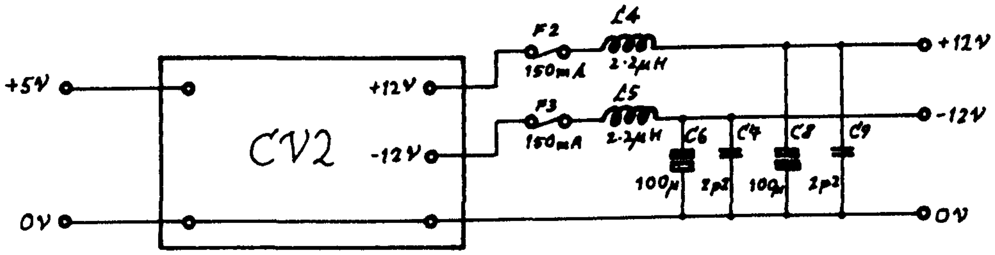


Fig. 7-16: ±12 V Analogue Supply

A similar converter is used in the DC supply for the analogue board (Fig. 7-16) which additionally has 100 μF capacitors on each output line to eliminate ripple. The circuit board layout is shown in Fig. 7-17 and Plate VII.

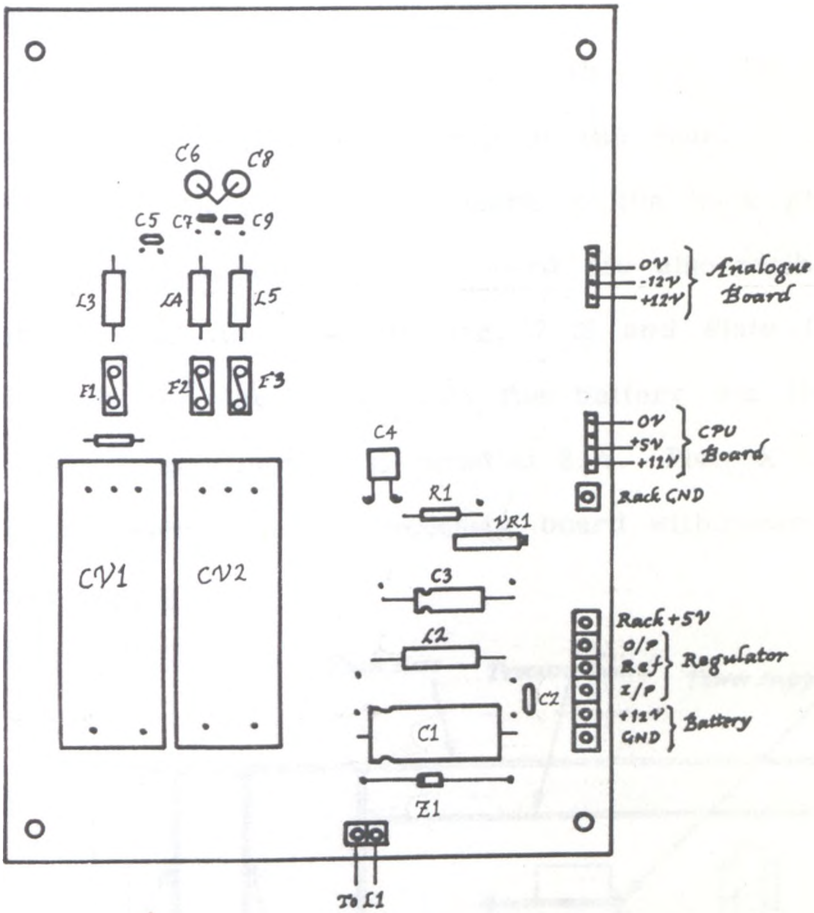


Fig. 7-17: Power Supply Board Layout

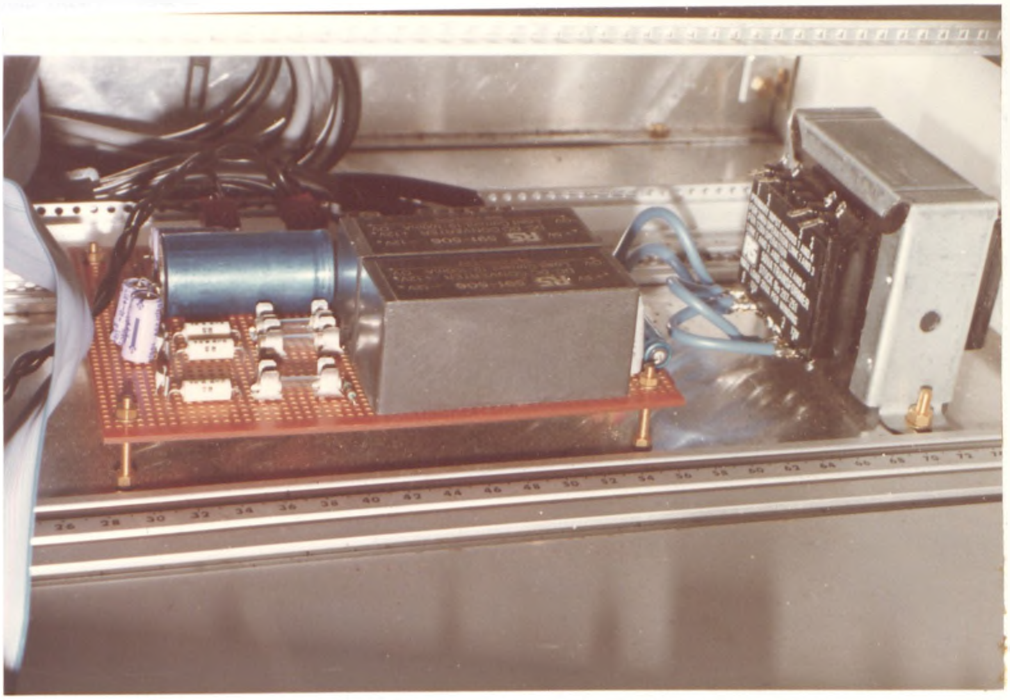


Plate VII: Power Supply Circuitry

7.4 Rack Layout and Connection Tables

The front view of the main rack is shown in Fig. 7-18 and Plate VIII show the interior wiring at the rear. The blue ribbon cable connects the main board to the back plane; the connections to the power supply board are also visible. The rear of the rack is shown in Fig. 7-19 and Plate IX. The fuseholder is for the input from the battery via the power switching unit and the fuse is rated at 2 A. Plate X shows the front of the rack with the processor board withdrawn to show the power supply.

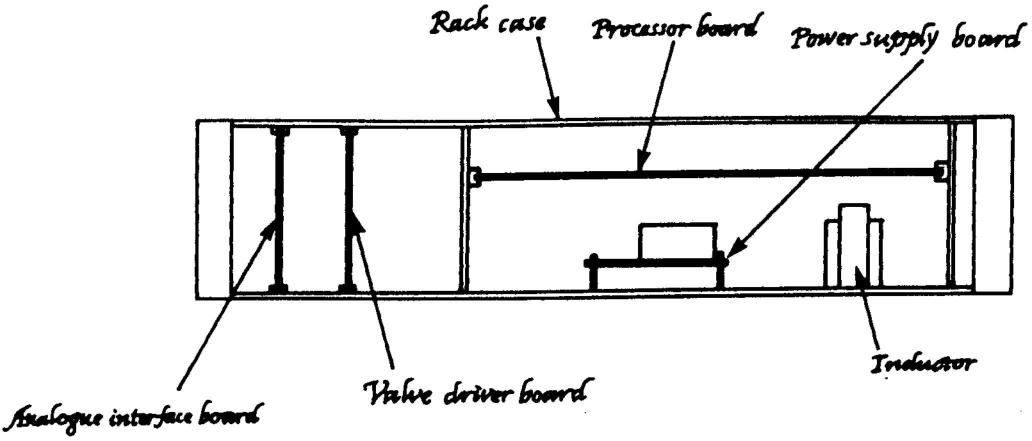


Fig. 7-18: Front View of Main Rack

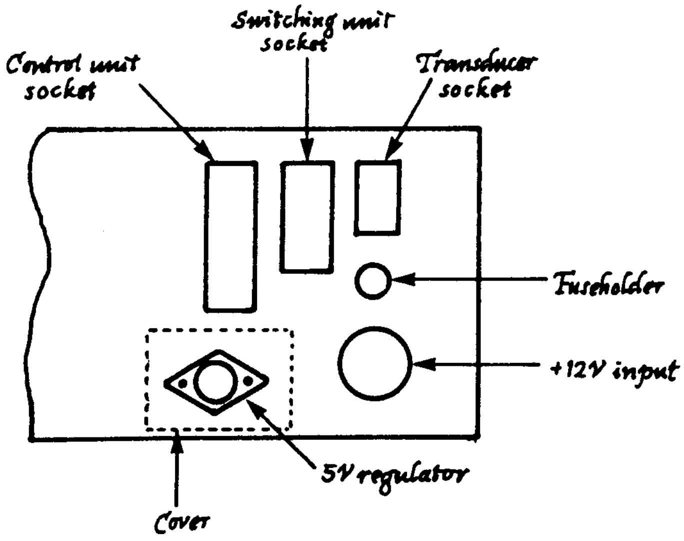


Fig. 7-19: Rear View of Main Rack

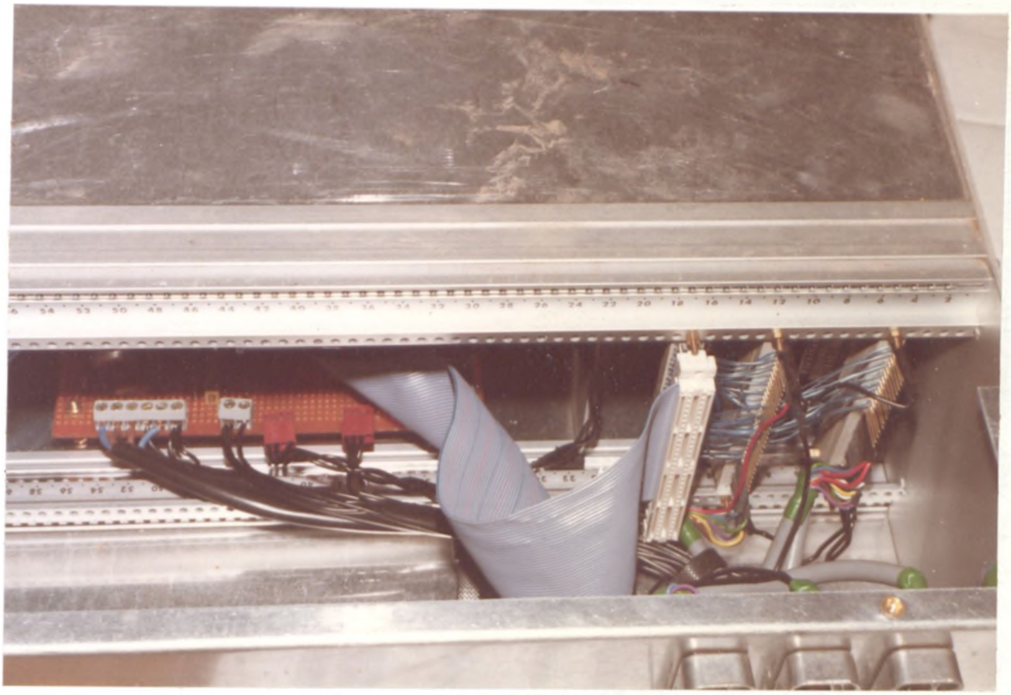


Plate VIII: Wiring at Rear of Main Rack

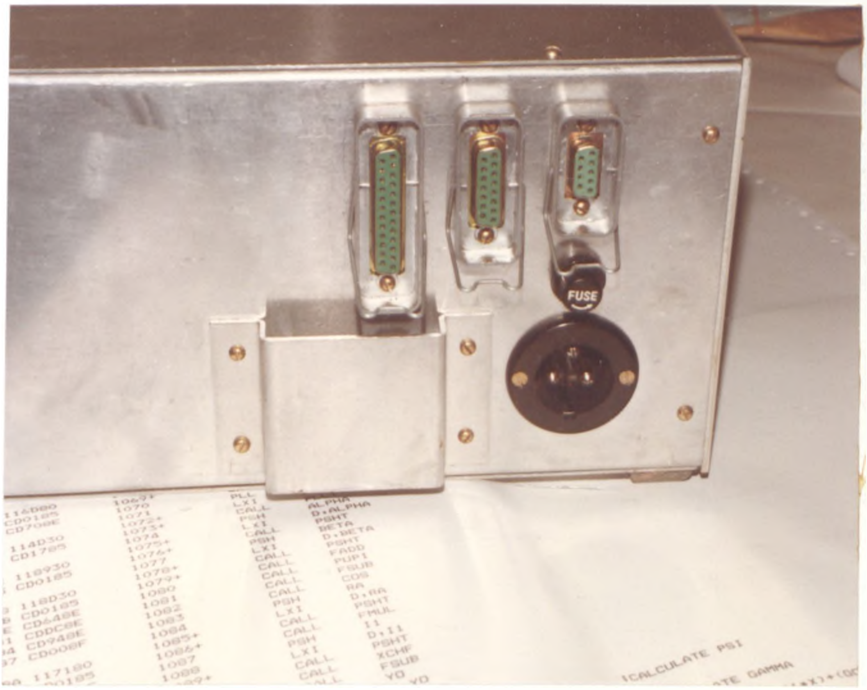


Plate IX: Rear Panel of Main Rack

Tables 7-1 to 7-4 list the connections to the circuit boards and the sockets on the back panel of the rack.

Rack Connections				
SDK-85 Edge Connector	Rack Connector	Function	Analogue Card	Driver Card
1	c 1	SO		3
2	a 1	S1		4
3	c 2	S2		5
4	a 2	S3		6
5	c 3	S4		7
6	a 3	S5		8
7	c 4	S6		9
8	a 4	S7		10
9	c 5	LO		11
10	a 5	L1		12
11	c 6	L2		13
12	a 6	L3		14
13	c 7	L4		15
14	a 7	L5		16
15	c 8	L6		17
16	a 8	L7		18
17	c 9	RO		19
18	a 9	R1		20
19	c 10	R2		21
20	a 10	R3		22
21	c 11	R4		23
22	a 11	R5		24
23	c 12	R6		25
24	a 12	R7		26
25	c 13	OPEN		
26	a 13	CLOSE		
27	c 14	MIO		
28	a 14	MI1		
29	c 15	MSO		
30	a 15	MS1		
31	c 16	MS2		
32	a 16	CO	2	
33	c 17	C1	3	
34	a 17	C2	4	
35	c 18	C4	5	
36	a 18	C5	6	
37	c 19	DO	7	
38	a 19	D1	8	
39	c 20	D2	9	
40	a 20	D3	10	
41	c 21	D4	11	
42	a 21	D5	12	
43	c 22	D6	13	
44	a 22	D7	14	

Table 7-1: Main Circuit Board (SDK-85) Rack Connections

Analogue and Driver Card Connectors		
Pin no.	Analogue Card	Driver Card
1	5V	5V
2	C0	RIGHT
3	C1	S0
4	C2	S1
5	C4	S2
6	C5	S3
7	D0	S4
8	D1	S5
9	D2	S6
10	D3	S7
11	D4	L0
12	D5	L1
13	D6	L2
14	D7	L3
15	n/c	L4
16	n/c	L5
17	VREF	L6
18	V	L7
19	V	R0
20	V	R1
21	VS	R2
22	VY	R3
23	VX	R4
24	VB	R5
25	VP	R6
26	A. Gnd.	R7
27	Screen	LEFT
28	n/c	UP
29	+12V	DOWN
30	-12V	IN
31	n/c	OUT
32	GND	GND

Table 7-2: Analogue and Driver Card Connections

Supply	
V_{input}	Brown
GND	Blue

Regulator	
Input	Brown
Ref.	Black
Output	Blue

Position Transducers				
Function	Socket Pin	Colour	Cable No.	Rack Connection
V_{REF}	1	Red	3	A 17
Lift	2	Blue	3	A 18
Reach	3	Yellow	3	A 19
Bucket	4	White	3	A 20
GND	5	Green	3	A 26
Screen	6	Screen	3	A 27
ON/OFF	7&8	Black		Jystk. 8
		Black		Sw. Unit 20

Control Unit					
Function	Socket Pin	Colour	Cable No.	Connections	
				Rack	Other
V_{REF}	1	Red	1	A 17	
5V Dig.	2	Black			Power supply board
Slew	3	Blue	1	A 21	
Lift	4	Yellow	1	A 22	
Reach	5	White	1	A 23	
Bucket	6	Brown	1	A 24	
Pitch	7	Purple	1	A 25	
On/	8	Black			Transducer Skt. 7
Off	9	Black			Switching Unit 11
IWT	10	Black			Switching Unit 9
MSO	11	White	2	c 15	
MS1	12	Purple	2	a 15	
MS2	13	Blue	2	c 16	
MIO	14	Green	2	c 14	
MI1	15	Red	2	a 14	
Dig. GND	16	Black			Power supply board
An. GND	17	Green	1	A 26	
Screen	18	Screen	1	A 27	

Table 7-3: Back Panel Connections (I)

Switching Unit					
Function	Socket Pin	Colour	Cable No.	Connections	
				Rack	Other
Up	1	Green	4	D 28	
Down	2	Purple	4	D 29	
In	3	Yellow	4	D 30	
Out	4	Brown	4	D 31	
Right	5	Red	4	D 2	
Left	6	Blue	4	D 27	
Open	7	Black	4	c 13	
Close	8	White	4	a 13	
IWT	9	Black			Joystk. Unit 10
On/	10	Black			Transducer 8
Off	11	Black			Joystk. Unit 9
GND	12	Black			Power supply Board
Screen	13				
Screen 4					
Screen 2					

Table 7-4: Back Panel Connections (II)

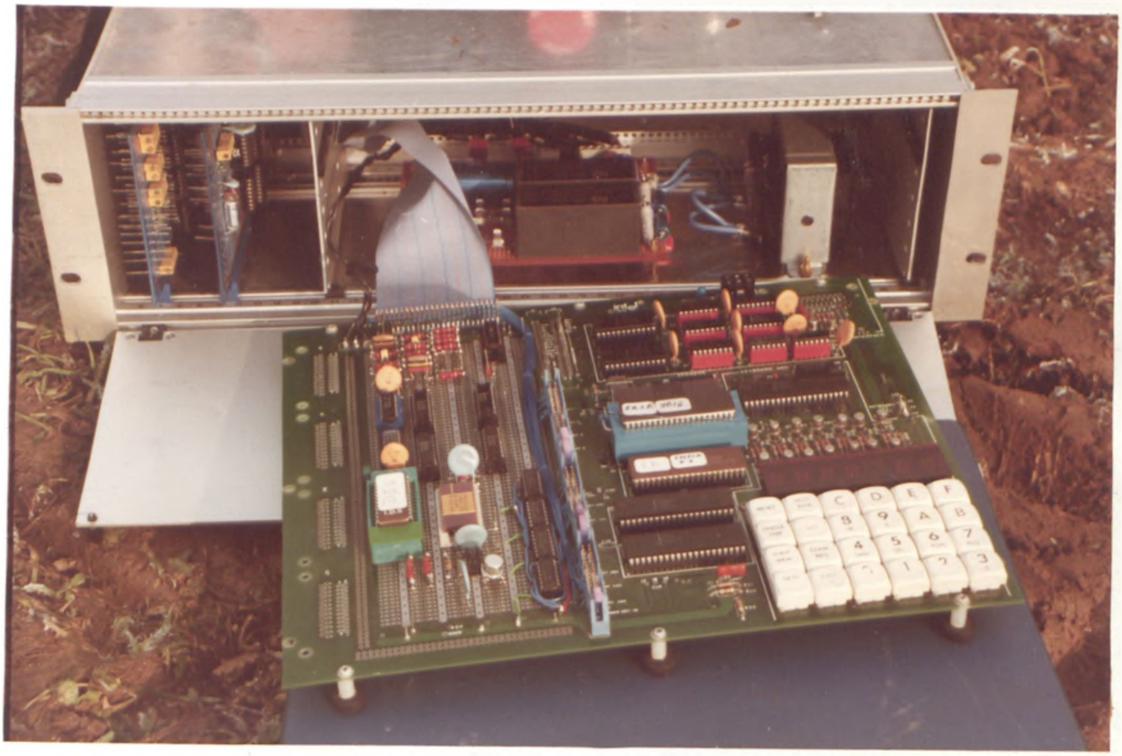


Plate X: Front View of Main Rack

CHAPTER EIGHT

HARDWARE III:
CONTROL UNIT, TRANSDUCER WIRING, &
POWER SWITCHING UNIT

8.1 Control Unit

The layout of the controls on the Control Unit is shown in Fig. 8-1. The joystick units are spring centred inductive devices which are very reliable as there are no potentiometer wipers to wear out. The orientation of the joystick axes and their corresponding functions is in a similar fashion to that of a conventional mechanically controlled digger. This is to minimise the re-learning necessary for operators already familiar with conventional controls. The carry strap supports project out from the case approximately 40 mm on each side to keep the strap, worn around the operator's neck, away from his hands while operating the unit.

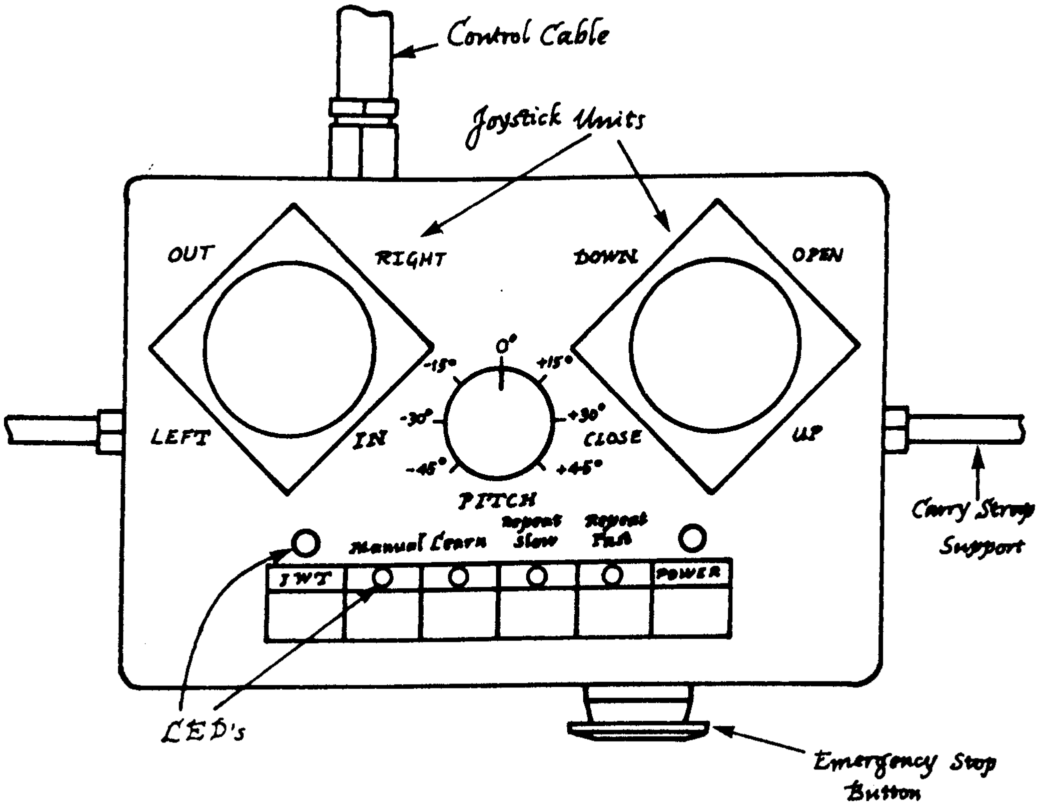


Fig. 8-1: Layout of Controls

The pitch control is situated in the centre of the control panel and comprises a plastic film potentiometer calibrated to correspond to pitch angles of -45° to +45°. The power and Instant Weight Transfer (IWT) switches are of the latching type with LED's mounted above them to indicate their status. The mode selection switches are of momentary type and have integral LED's; this arrangement allows mode selections and changes to be made in software e.g. to start up at power on in Manual Mode and to revert to Manual Mode at the end of a Repeat sequence. The large Emergency Stop button is mounted on the front of the control unit and latches when depressed, being released by a twist.

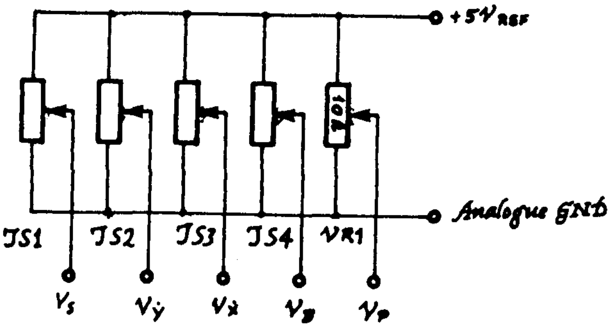
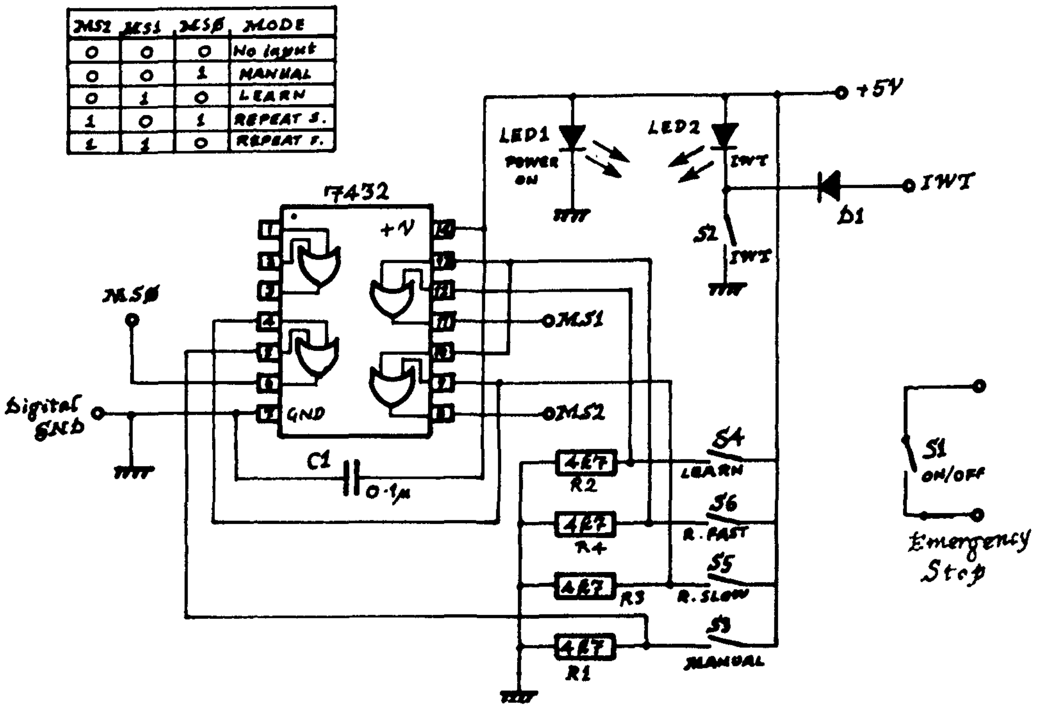


Fig. 8-2: Connection of Joysticks & Pitch Control

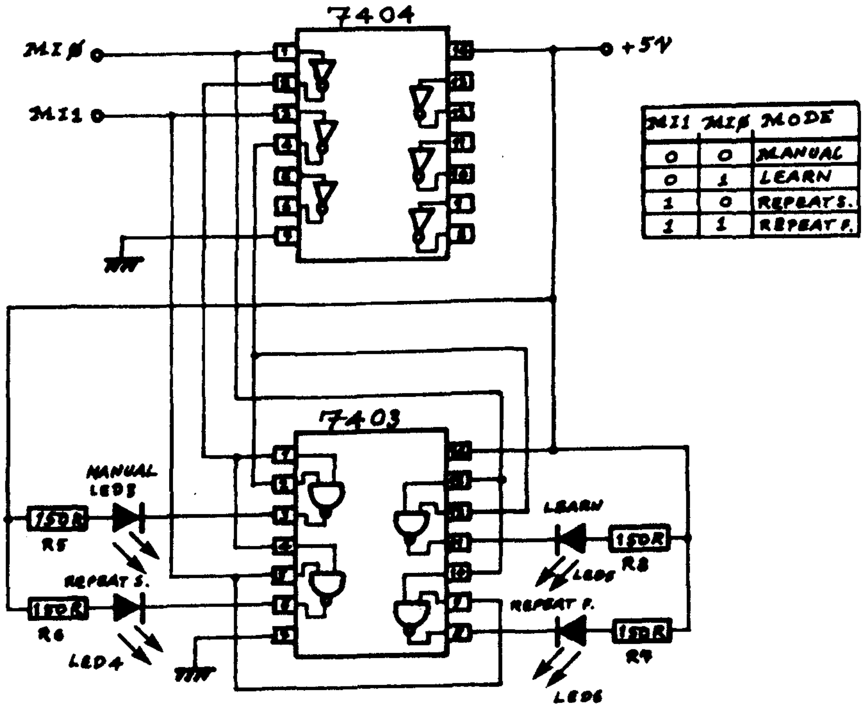
The circuit for the joysticks and the pitch control is shown in Fig. 8-2. The 5 V reference is from the analogue interface card; the output voltage swing of the joysticks is ½ V from a central position with a standing output of 2½ V and they have an output resistance of 1.8 kΩ.

The mode selection switch circuitry is shown in Fig. 8-3 along with the truth table for encoding the five possible switch settings to the three mode select lines MS0, MS1, and MS2. The



MS2	MS1	MSØ	MODE
0	0	0	No input
0	0	1	MANUAL
0	1	0	LEARN
1	0	1	REPEAT S.
1	1	0	REPEAT F.

Fig. 8-3: Logic for Mode Selection



MI1	MIØ	MODE
0	0	MANUAL
0	1	LEARN
1	0	REPEAT S.
1	1	REPEAT F.

Fig. 8-4: Logic for Mode Indication

normally closed emergency stop switch is in series with the on/off switch and closes the path for operating the power switching relay. The mode indication circuit is shown in Fig. 8-4 and decodes the two mode indication lines MI0 and MI1 to operate the four LED's according to the truth table. The four NAND gates in the 7403 have open collector outputs, turning the corresponding LED on when the output goes low. The layout of the circuit board for the mode selection and indication circuits is shown in Fig. 8-5, and Fig. 8-6 shows the layout of the connecting strip mounted at the bottom of the case and the colour coding of the connector cable. Colour coding for the analogue control leads is given in Table 8-1.

Joysticks	
V_{ref}	Red
Gnd.	Black
Slew	Blue
Lift	Blue
Reach	Yellow
Bucket	Yellow

Pitch Control	
Wiper	Grey
V_{ref}	Violet
A. Gnd.	White

Table 8-1: Colour Coding of Analogue Control Leads

A top view of the control unit is shown in Plate X, and front view with it placed on the processor unit in Plate XI.

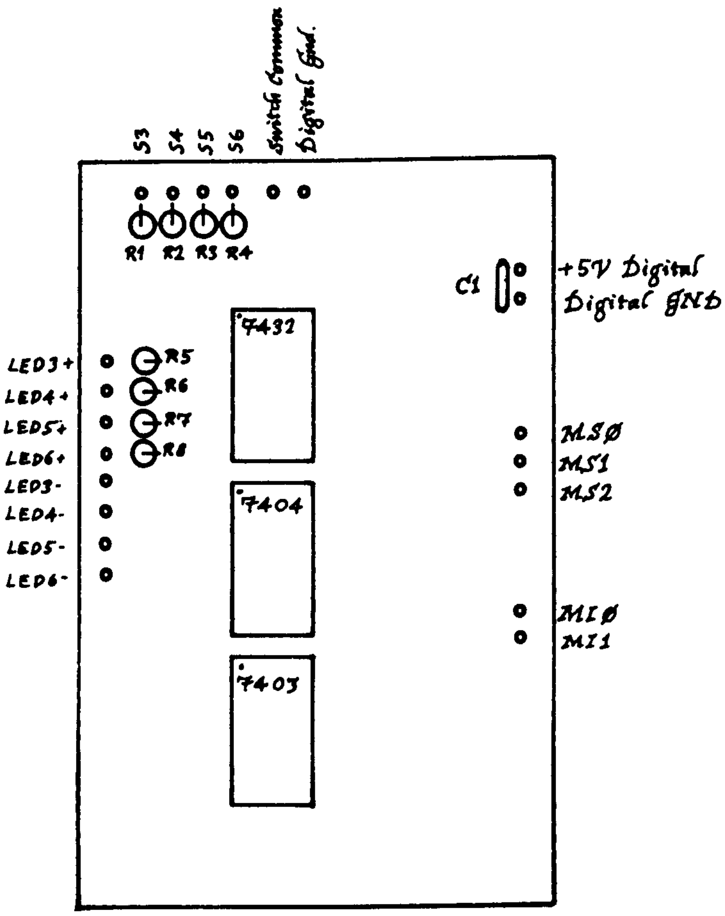


Fig. 8-5: Layout of Logic Board

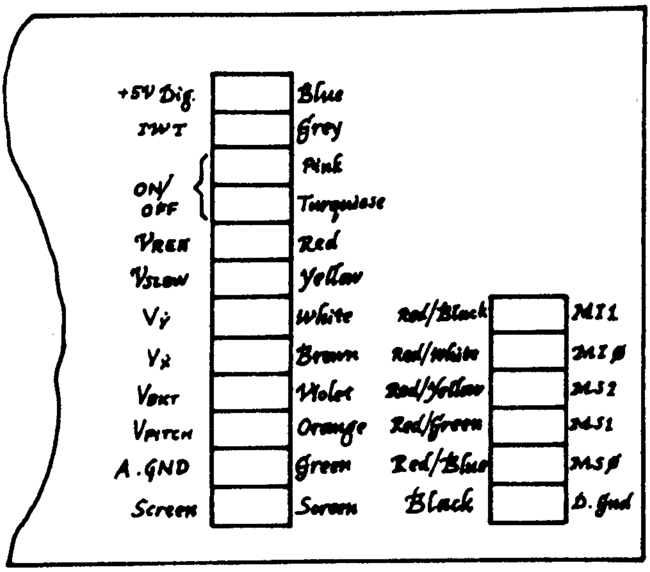


Fig. 8-6: Connector Layout & Control Cable Colour Coding

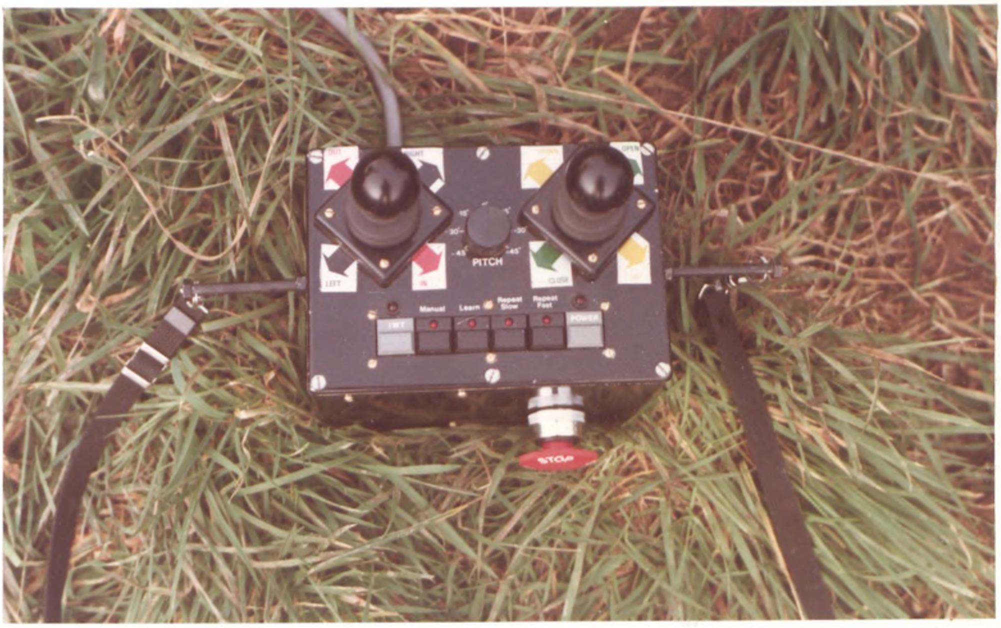


Plate XI: Top View of Control Unit

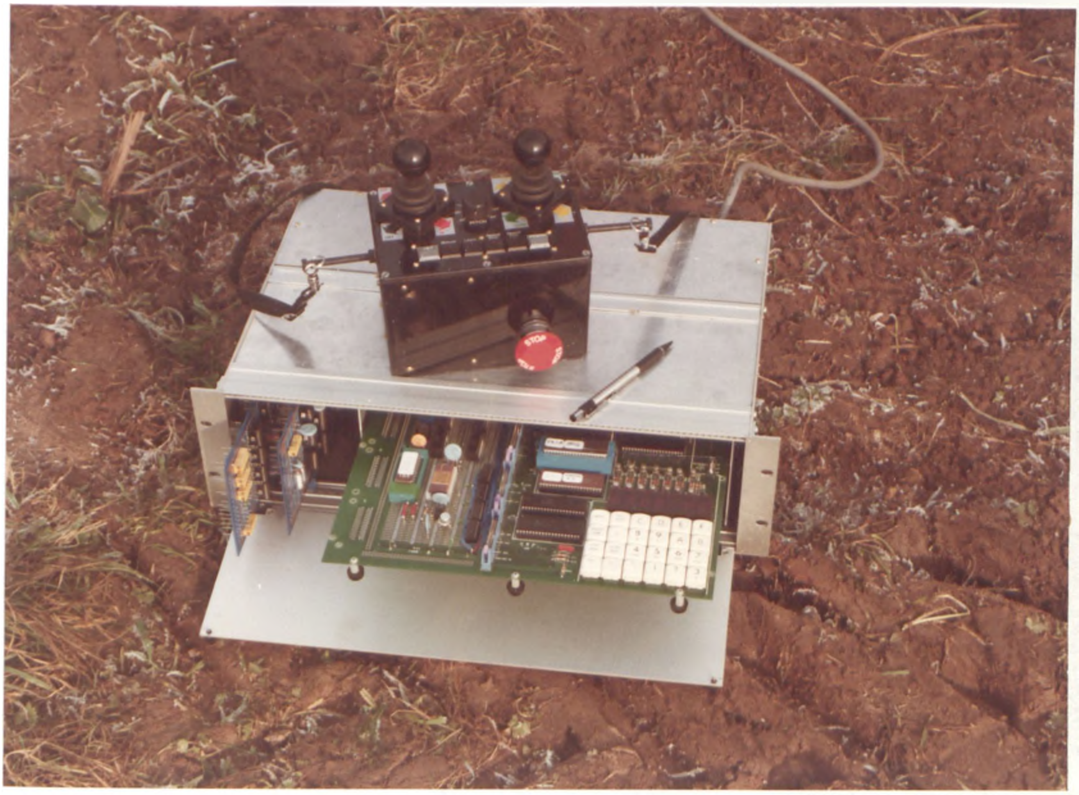


Plate XII: Control Unit & Processor Unit

8.2 Transducer Wiring

Fig. 8-7 and Plate XII show the wiring diagram and junction box mounted on the side of the digger. The cable to each transducer is screened to minimise any pick-up from electromagnetic fields. Linking each transducer to the junction box is an in-line connector so that each transducer may individually be disconnected and replaced. The use of a junction box also reduces the amount of cabling required to link the set of three transducers to the processor unit.

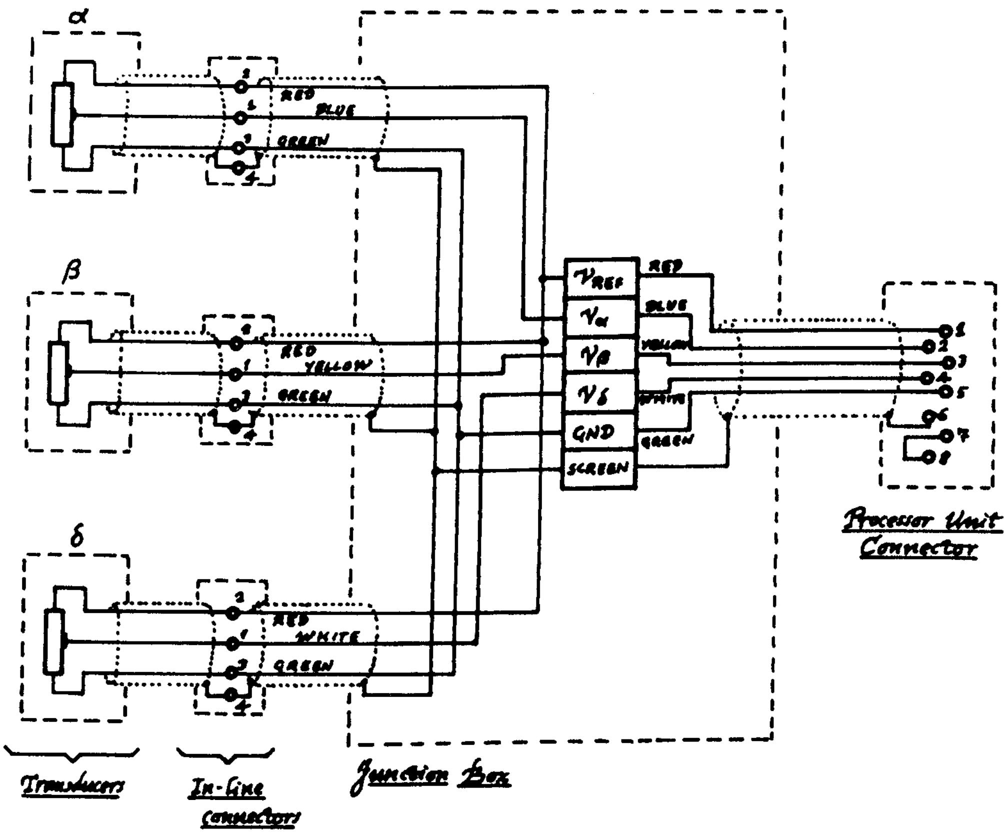
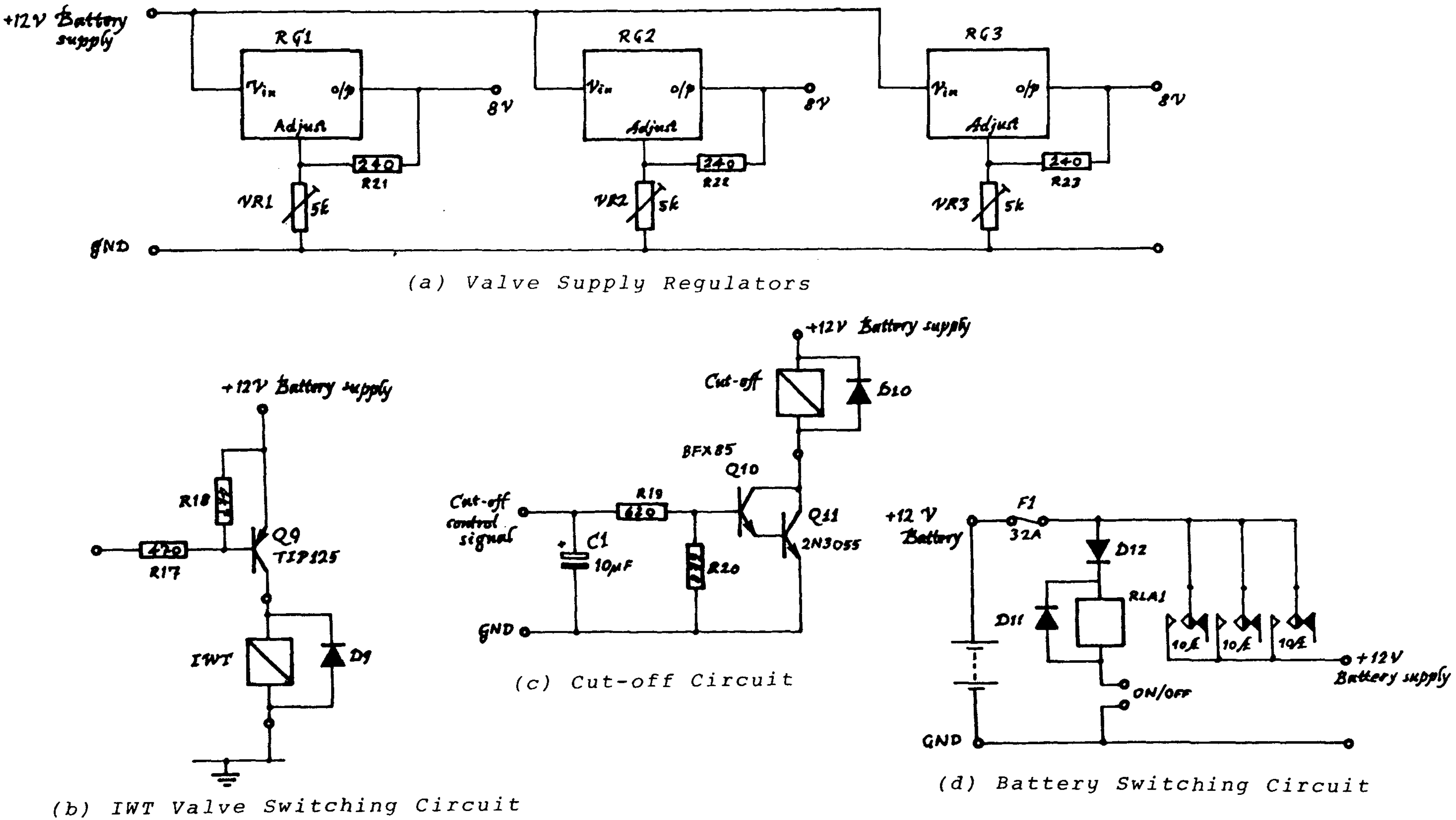


Fig. 8-7: Transducer Circuit

8.3 Power Switching Unit

Fig. 8-8(a) shows the three regulator circuits for driving the solenoid valves at 8 V from the nominal 12 V tractor supply.



(a) Valve Supply Regulators

(b) IWT Valve Switching Circuit

(c) Cut-off Circuit

(d) Battery Switching Circuit

Fig. 8-8: Power Switching Unit Circuitry

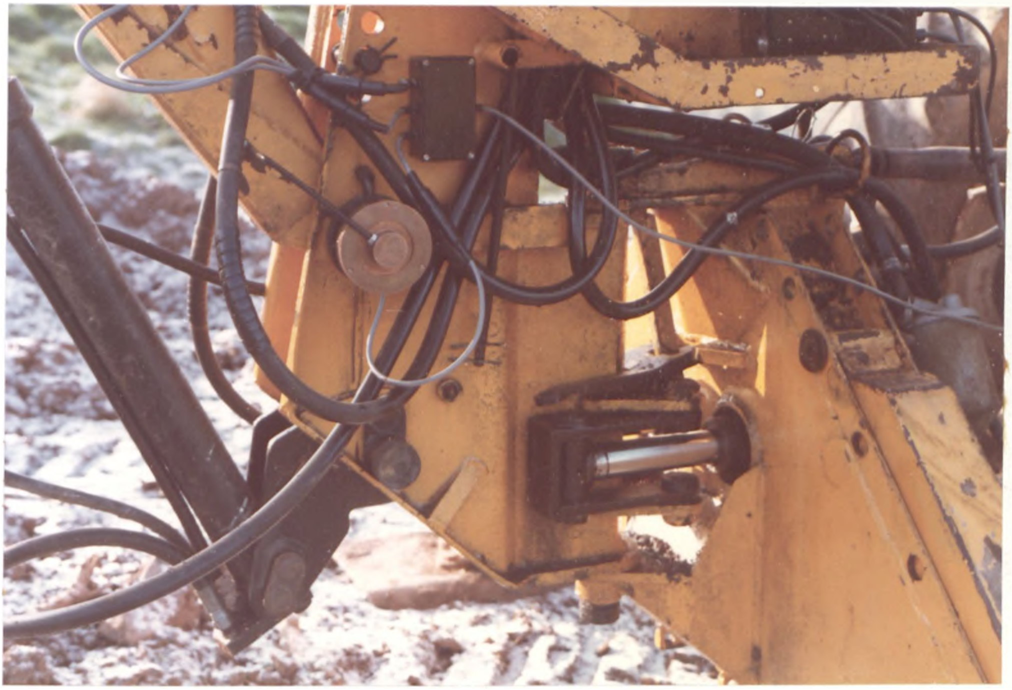


Plate XIII: Side View of Machine Showing Junction Box & Transducer for Main Arm

The IWT valve is driven using a TIP125 transistor (Fig. 8-8 (b)). Resistor R17 limits the base current and R18 ensures that the transistor turns hard off. The operation of the cut-off circuit (Fig. 8-8 (c)) is to switch the cut-off valve using darlington pair Q10, Q11 and delay the turn-off of the valve using C1 and R19 so that the valve is held on between consecutive pulses from one or more proportional valves.

The power switching for the input to the system from the battery is effected using the circuit of Fig. 8-8 (d). Fuse F1 is rated at 32 A to protect the battery and the circuitry against any major short circuit. Relay RLA1 is used to switch the power to the system when the on/off control loop is closed. Diode D12 prevents the relay from operating if the supply is reverse connected by mistake, thus indefinite reverse supply connection does not damage the system.

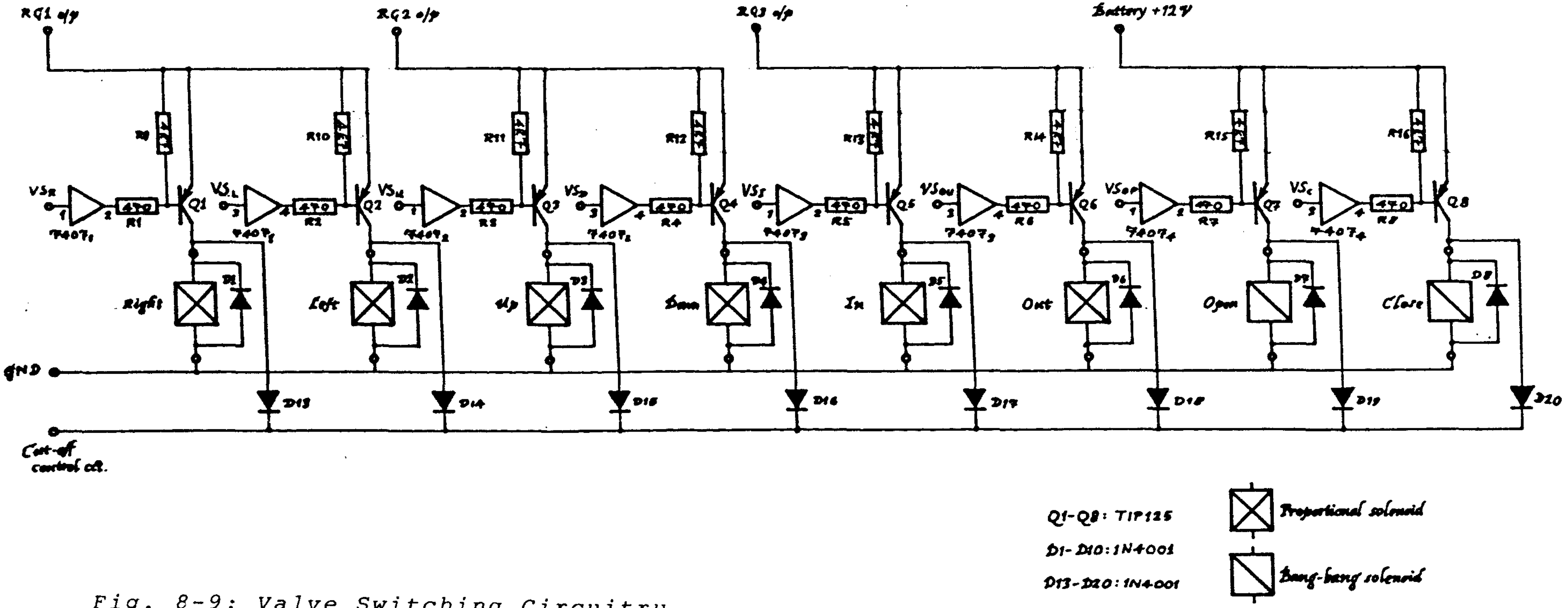


Fig. 8-9: Valve Switching Circuitry

Fig. 8-9 shows the complete circuit for the switching of all the proportional and bang-bang valves for the different services. The control inputs are buffered by the 7407 gates and the open collector gate outputs sink the base currents from the switching transistors Q1-Q8 . Diodes D13 to D20 link each of the valve solenoids to the cut-off control circuit while isolating the services from each other.

The circuit board layout is shown in Fig. 8-10 and the layout of the internal connector in Fig. 8-11 with the wiring details in Fig. 8-12. The colour coding of the control cable is shown in Table 8-2. Figures 8-13 and 8-14 show external views of the box and the component mounting configuration and cable gland layout. Plate XIII shows the switching unit on the digger with the cover plate visible at the left hand end and the cable glands to the right. Sealing cable glands and a screw-on lid to the box were used to prevent the ingress of moisture to this particularly exposed part of the system.

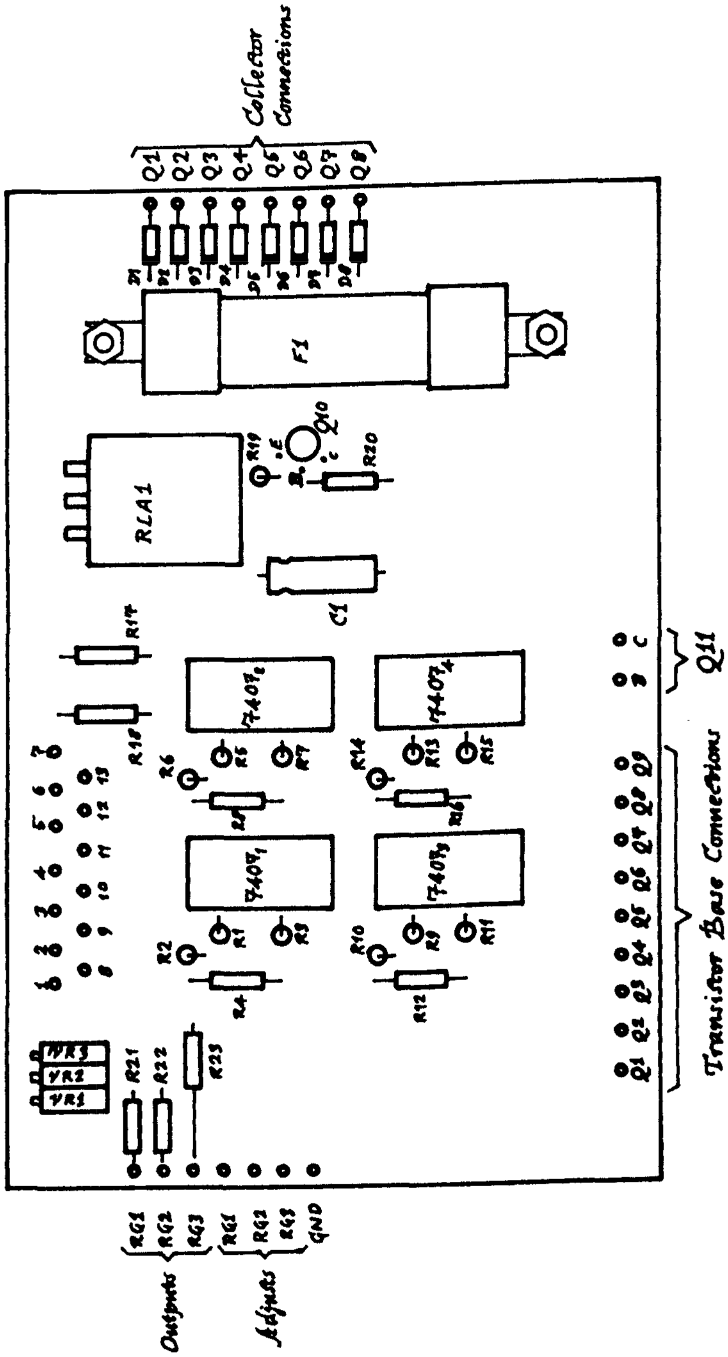


Fig. 8-10: Layout of Power Switching Unit Circuit Board

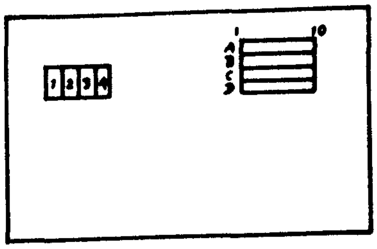


Fig. 8-11: Layout of Power Switching Unit Internal Connecting Blocks

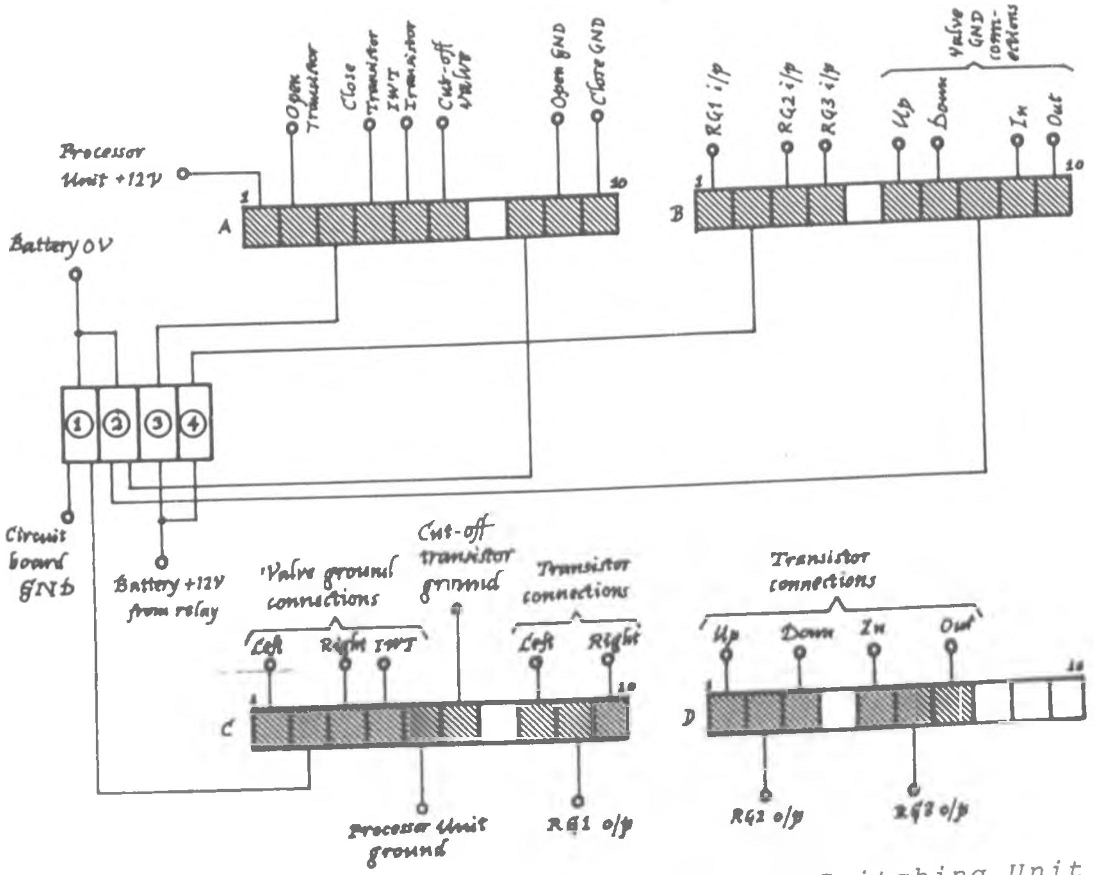


Fig. 8-12: Wiring Diagram of Power Switching Unit Connecting Blocks

Core	Colour	Function
1	Red	Up
2	Blue	Down
3	Yellow	In
4	White	Out
5	Black	Right
6	Brown	Left
7	Violet	Open
8	Orange	Close
9	Pink	IWT
10	Turquoise	On/Off
11	Grey	
12	Green	GND.
13	Screen	n/c

Table 8-2: Colour Coding of Power Switching Unit Control Cable

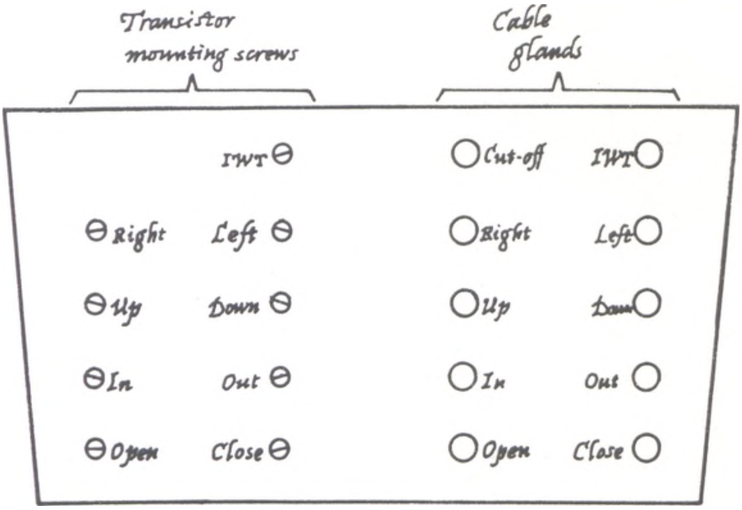


Fig. 8-13: Side View of Power Switching Unit Showing Layout of Power Transistors & Cable Glands

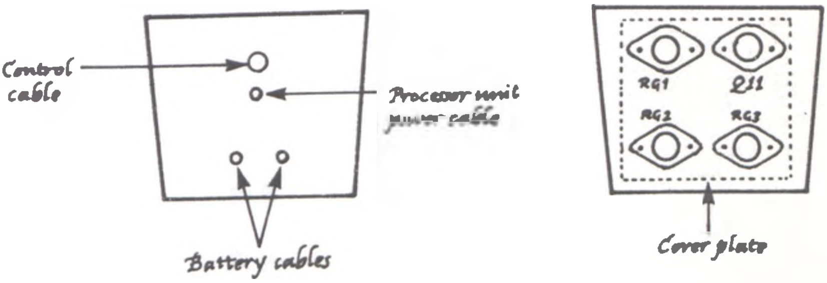


Fig. 8-14: End Views of Power Switching Unit Showing Semiconductors & Cable Glands

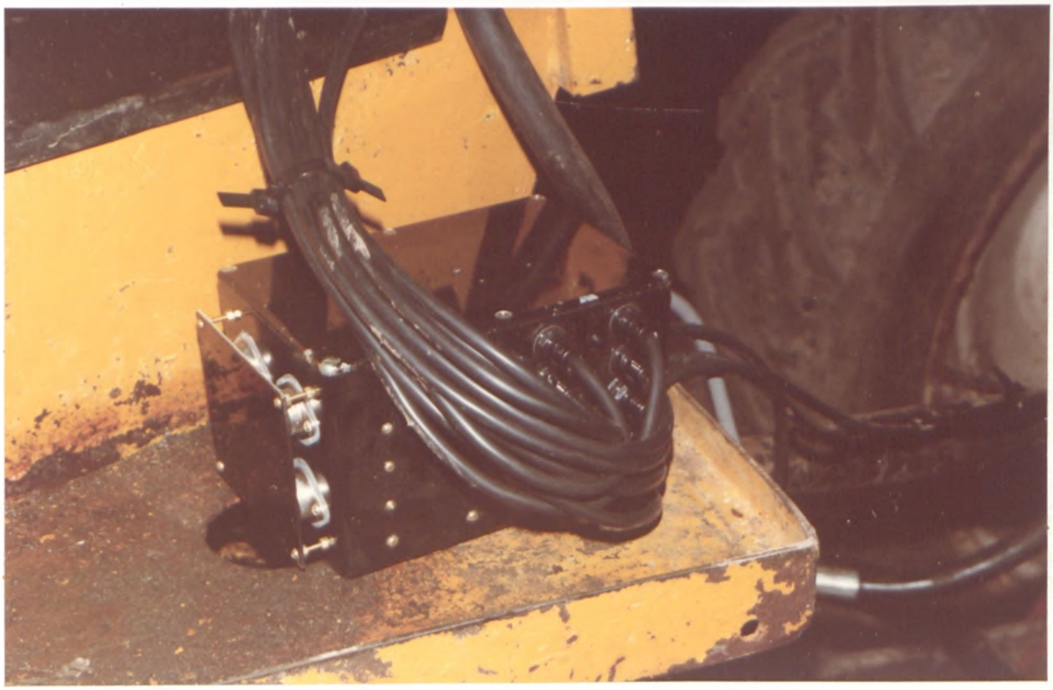


Plate XIV: Power Switching Unit

CHAPTER NINE

SOFTWARE I:

GENERAL PURPOSE APU SUBROUTINES & MACROS

9.1 Arithmetic Processor Unit

The principal advantages of using an Arithmetic Processor Unit (APU) are its speed of operation and the ease with which complex computations may be programmed. Two major programs were written for controlling the digger:

MANCON which mimics the operation of a conventional mechanically controlled digger

and DIG which provides the features described in Chapter Two of automatic straight line cutting, pitch control, and the learn/repeat facility.

Both programs make extensive use of the APU and a set of macros and subroutines common to both programs was written to simplify data transfers and APU commands so that any calculation could be coded as a Reverse Polish sequence of instructions. A macro was also written to effect conditional jumps depending upon the relative values of two 32 bit floating point variables. All the system software was written in assembly language for the 8085A processor using an Intel Intellec Development System.

The arithmetic processor has as internal stack 16 bits wide by 8 levels deep for single precision values or 32 bits wide and 4 levels deep for double precision or floating point values (Fig. 9-1).

Data is entered on the stack in the sequence B1, B2, B3, B4 and removed in the reverse sequence. The stack is located at address 1000H. Commands are written to the APU as 8 bit words to the addresss 1100H and commands operate on either the

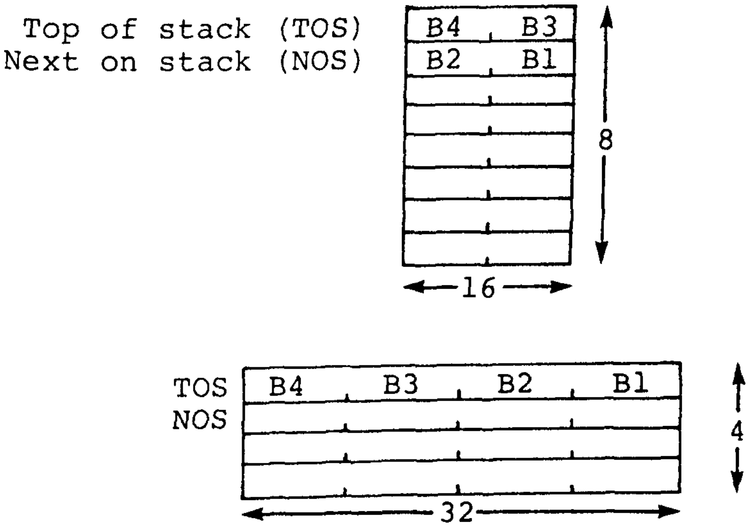


Fig. 9-1: APU Internal Stack Structures for Single and Double Precision Data

TOS or NOS or both. The device status (Busy, Sign, Zero, Error, etc.) may be read from the status register, also located at address 1100H.

Address	Data	
n	byte 0	l.s. byte
n+1	byte 1	
n+2	byte 2	
n+3	byte 3	m.s. byte

Fig. 9-2: Data Format for 32 Bit Floating Point Variable

Thirty-two bit floating point variables and constants used in the programs are stored in RAM or EPROM as a sequence of four consecutive bytes as shown in Fig. 9-2 with the least significant byte at the lowest address. The variable name or identifier acts as a label to the address of the least significant byte.

9.2 Subroutines for APU Stack Data Transfer

Subroutine PSHT pushes a 32 bit variable onto the APU stack. Register pair DE, used as a data pointer, controls the address of the least significant byte on calling and of the most significant byte at return (see Fig. 9-3).

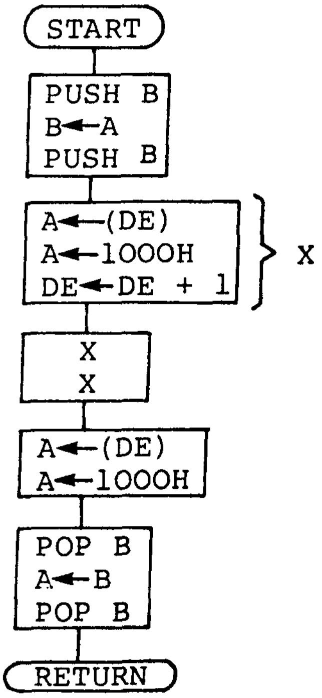


Fig. 9-3: Flowchart of Subroutine PSHT

A more efficient coding for storing the A register would be PUSH PSW, and for recovering it POP PSW.

Subroutine PLLT pulls a 32 bit variable from the APU stack. Register pair DE, used as a data pointer, contains the address in memory of the least significant byte of the variable (see Fig. 9-4).

A more efficient coding for storing the A register would be PUSH PSW, and for recovering it Pop PSW.

Macro PSH generates the code for pushing a 32 bit variable onto the APU stack using subroutine PSHT.

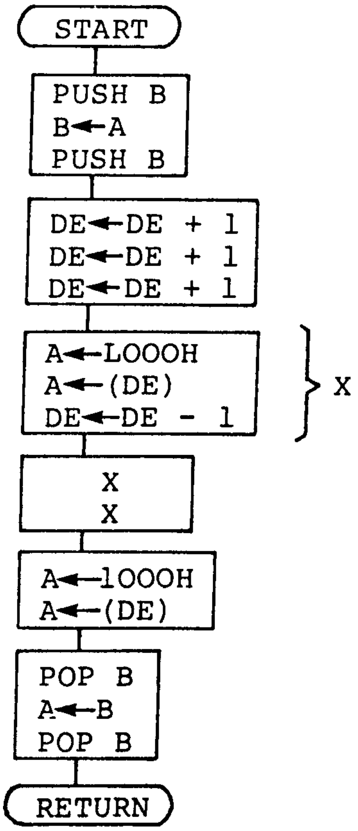


Fig. 9-4: Flowchart of Subroutine PLLT

The call instruction is of the form

```
        PSH   var
```

Where var is the identifier of the variable to be pushed, and the corresponding code generated by the macro is

```
        LXI    D,var          ;Load data pointer
        CALL   PSHT           ;Call APU stack push
                                    subroutine
```

Macro PLL generates the code for pulling a 32 bit variable from the APU stack using subroutine PLLT.

The call instruction is of the form

```
        PLL   var
```

Where var is the identifier of the variable to be pulled, and the corresponding code generated by the macro is

```
        LXI   D,var         ;Load data pointer
        CALL  PLLT          ;Call APU stack
                              pull subroutine
```

9.3 Subroutines for APU Operations

Macro MATHS generates subroutines which when called give commands to the APU to perform different arithmetic operations.

The calling instruction is of the form

```
        MATHS   function,code
```

Where function is the name of the operation carried out by the APU and the name of the subroutine generated by the macro and code is the 8 bit code wirtten to the APU command register to carry out the required operation.

The macro generates code of the form

```
function:   STA   ASTR      ;put A reg. in
                              temporary location
            MVI   A,code    ;A←APU op code
            STA   1100H     ;A→APU command
                                 register
            LDA   ASTR      ;restore A register
            RET
```

Registers affected: None

Subroutine FIX is used to convert the 32 bit floating point contents of the TOS to 8 bit integer format in the A register (see Fig. 9-5).

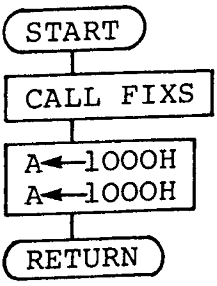


Fig. 9-5: Flowchart of Subroutine FIX

Subroutine FLOAT converts the 8 bit integer contents of the A register to 32 bit floating point format on top of the APU stack (see Fig. 9-6).

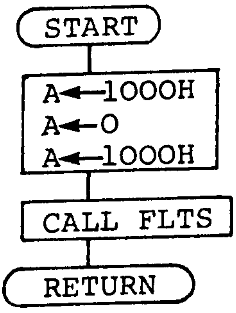


Fig. 9-6: Flowchart of Subroutine FLOAT

9.4 Macros for Conditional Jumps

Macro IFF generates code for conditional jumps depending upon the relative values of two floating point variables. It generates code to operate as follows:

```
IF var1{>|≥|=|≠|≤|<}var2
  THEN GOTO label
  ELSE CONTINUE
```

The calling statement is of the form

IFF var1,{GTHAN|GEQUAL|EQUALS|NEQUAL|LEQUAL|
LTHAN}, var2, label

and the macro generates code as in the flowchart of Fig. 9-7.

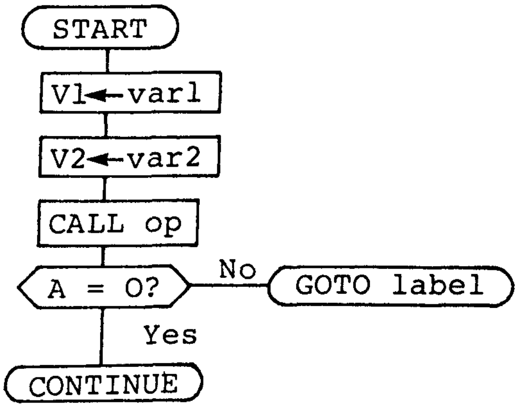
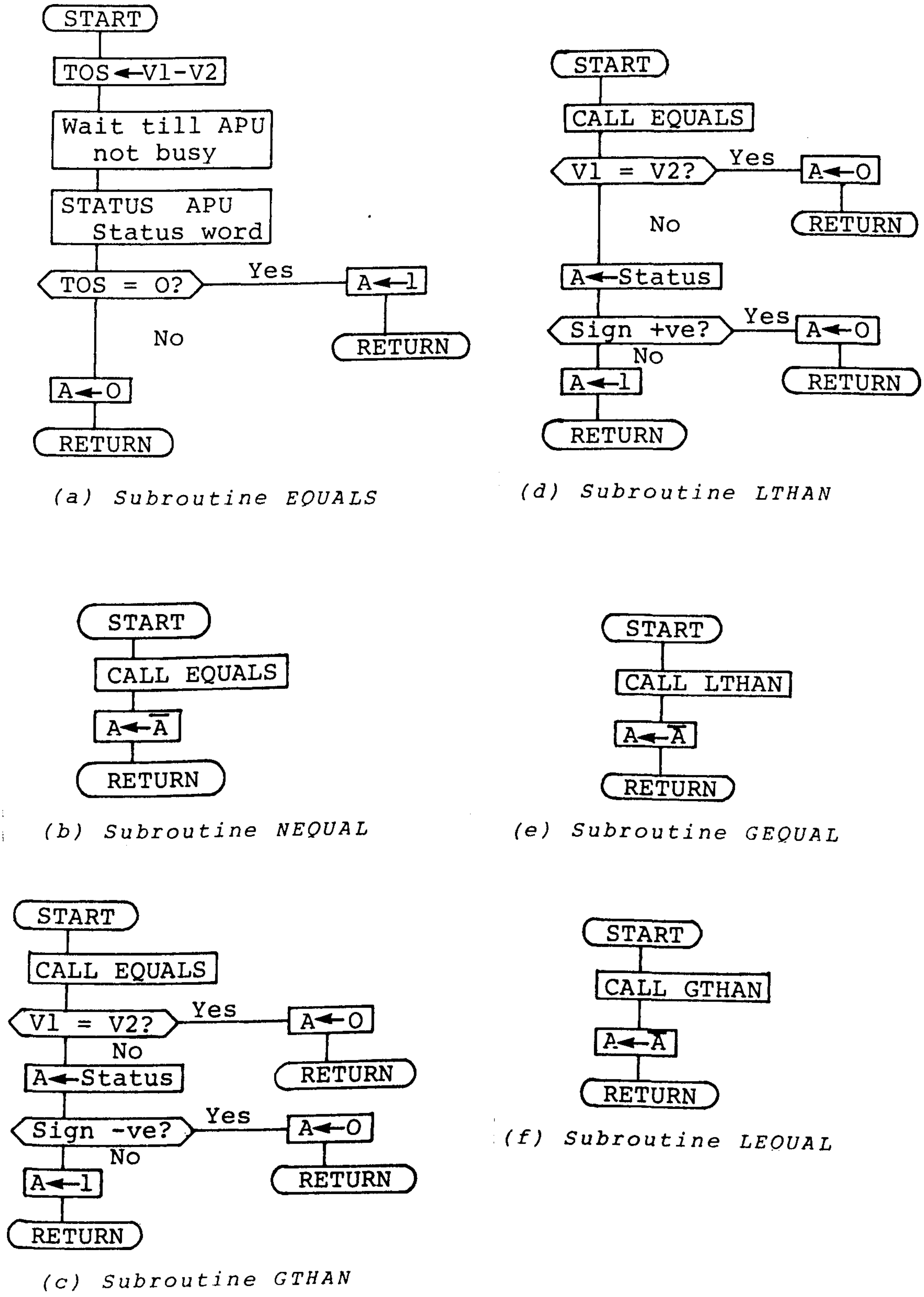


Fig. 9-7: IFF Macro Object Code

Subroutine op tests the validity of the relational operator (>, ≥, etc.) on V1 and V2, returning the result as True (1) or False (0) in the A register. The different cases for subroutine op are flowcharted in Fig. 9-8.



(a) Subroutine EQUALS

(d) Subroutine LTHAN

(b) Subroutine NEQUAL

(e) Subroutine GEQUAL

(c) Subroutine GTHAN

(f) Subroutine LEQUAL

Fig. 9-8: (a)-(f) Flowcharts of Relational Operator Subroutines called in Object Code of IFF Macro

CHAPTER TEN:

SOFTWARE II:
PROGRAM MANCON

10.1 Introduction

Program MANCON simulates the operation of a conventional mechanical control system, opening each hydraulic valve in relation to the corresponding joystick deflection. In addition to the routines for utilisation of the arithmetic processor described in the previous chapter there are a number of subroutines common to program MANCON and program DIG, which is described in the next chapter. These common subroutines are mainly for input and output.

10.2 Algorithm

The flowchart for the main program is shown in Fig. 10-1 indicating which code segment, the main program or a subroutine, executes each function.

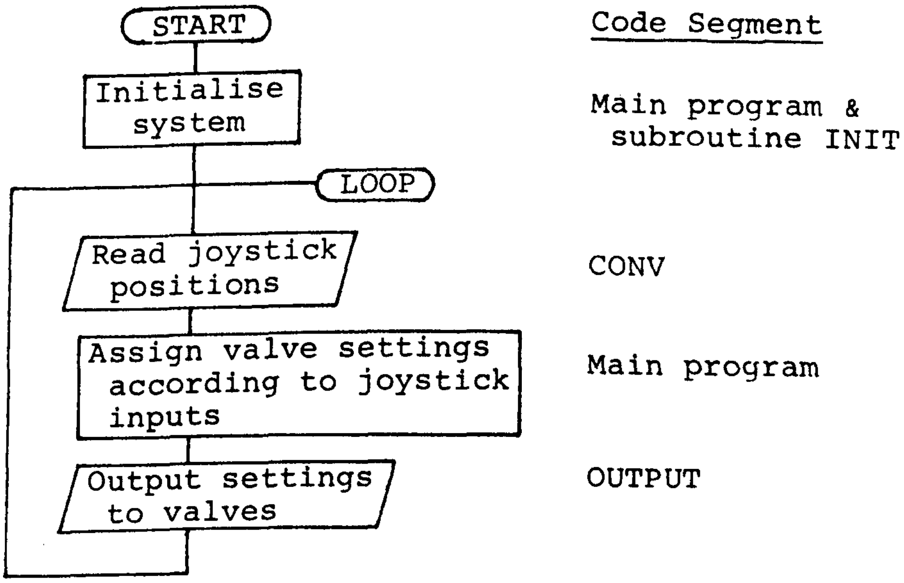

START
Initialise system
LOOP
Read joystick positions
Assign valve settings according to joystick inputs
Output settings to valves
Code Segment
Main program & subroutine INIT
CONV
Main program
OUTPUT

Fig. 10-1: Flowchart for Main Program

The executable code begins at address 80D0H in ROM with the system initialisation procedure. Default values of characteristic constants for the valves are copied from ROM into RAM. This is so that the constants may be changed by the user when operating the system and program execution may be resumed from location 80E0H to avoid corrupting the modified data. The interrupts and stack pointer are initialised to allow the program to be interrupted at a selected point when the Vectored Interrupt key on the keyboard is depressed. Subroutine INIT sets the I/O port data direction registers.

Location 20CEH in RAM, to which control jumps when the Vectored Interrupt key is pressed, is loaded with the instruction code CFH (RST1) to return control to the monitor.

The main control loop first calls subroutine CONV which reads in the joystick deflection JXDOT, JYDOT, JBKT, and JSLEW corresponding to Lift, Reach, Bucket, and Slew. These variables are assigned values in the range -1 to +1 according to the magnitude and sense of the corresponding joystick deflections.

The values of JXDOT, JYDOT, JBKT, and JSLEW are copied via the top of the APU stack to variables VVBETA, VVALFA, VVBKT, and VVSLEW which are the corresponding valve settings.

Subroutine OUTPUT is then called and sets the control signals for the valve drivers. The final part of the main control loop allows an interrupt from the 'Vectored Interrupt' key of the monitor; this allows the program to be halted at this specific point so that the values of variables may be examined. Control then jumps back to the start of the main control loop.

Memory Utilisation

The basic memory utilisation for the program is shown in Fig. 10-2. Program variables are stored in RAM (block A); certain constants, those describing valve characteristics, are also stored in RAM (block B). Default values of user alterable constants are stored in EPROM in block C, and fixed constants in block D. The program code is stored in ROM in block E.

RAM

3000H 3043H	A	Program variables
3044H 304FH	B	User-alterable constants

EPROM

8000H 800BH	C	Default constant values
800CH 803BH	D	Constants
80D0H 8550H	E	Program code

Fig. 10-2: Memory Map

The control structure for setting up default constants is shown in Fig. 10-3. Normally program execution begins at START A and the default constant values are copied from Block C to block B then control moves to the main routines. If the program is halted by depression of the Vectored Interrupt button or Reset then the user alterable constants may be changed and program execution recommenced from START B to preserve the modified data values.

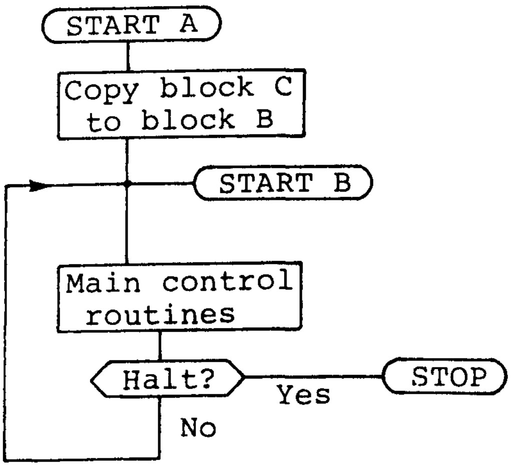


Fig. 10-3: Control Structure for Setting Default Constants

10.4 Code Documentation

Line numbers refer to those on the listing included in Appendix A.

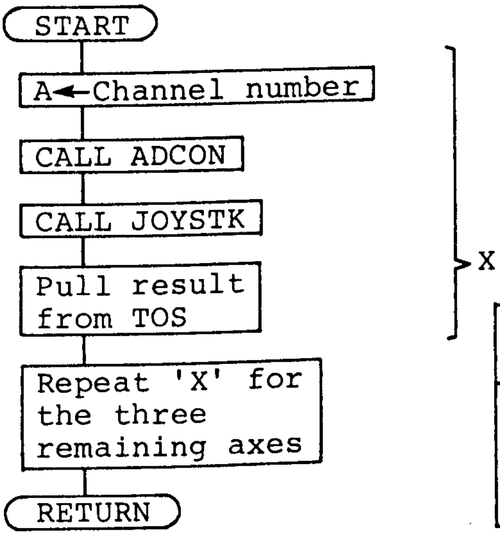
Subroutine INIT (lines 203-210)

This subroutine writes the appropriate bit patterns to the I/O port data direction registers as given in Table 10-1.

Registers affected: A

Subroutine CONV (Lines 219-246)

This subroutine reads the output from each joystick axis



Joystick axis	Channel number	Result
Slew	03H	JSLEW
Lift	04H	JYDOT
Reach	05H	JXDOT
Bucket	06H	JBKT

Fig. 10-4: Flowchart for Subroutine CONV

using subroutine ADCON and sends the result to subroutine JOYSTK which transfers the result to the range -1 to +1 in 32 bit floating point format. This process is effected four times to obtain values for the Slew, Lift, Reach, and Bucket joystick axes. The subroutine is flowcharted below in Fig. 10-4 and the table gives the channel number and result name for the different

I/O Port Address	Function	Data Direction	Data Direction Register	Control Byte
21H	Reach	Out	20H	0FH
22H	Bucket	Out		
23H	Mode indicate	Out		
00H	Slew	Out	02H	FFH
01H	Lift	Out	03H	FFH
29H	ADC Bus	In	28H	0CH
2AH	Mode select	In		
2BH	ADC Control	Out		

Table 10-1: I/O Port Usage and Control Bytes

Registers affected: A,D,E,H,L, Status

Subroutine ADCON (lines 259-273)

This subroutine operates the analogue to digital converter. The channel number is passed to the routine in the A register and the A register contains the eight bit result at return. The flowchart for the routine is shown in Fig. 10-5.

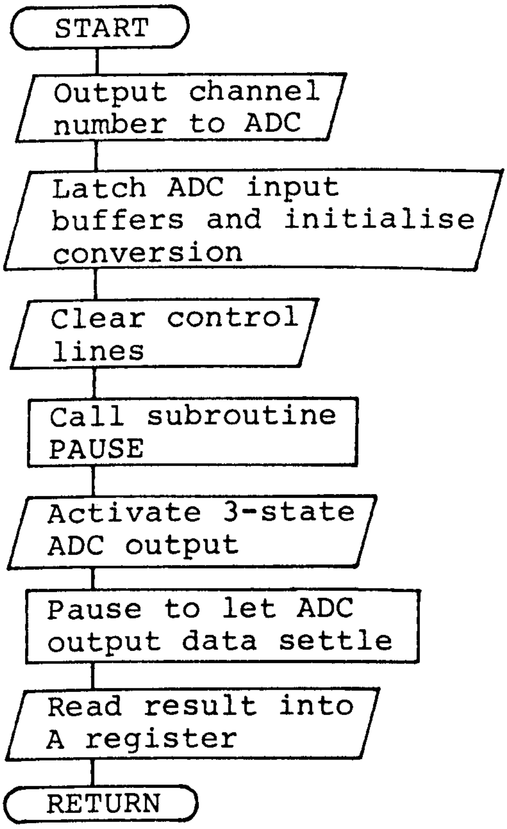

START
Output channel number to ADC
Latch ADC input buffers and initialise conversion
Clear control lines
Call subroutine PAUSE
Activate 3-state ADC output
Pause to let ADC output data settle
Read result into A register
RETURN

Fig. 10-5: Flowchart for Subroutine ADCON

Registers affected: A, H, L, Status

Subroutine PAUSE (lines 284-288)

This subroutine effects a delay, the duration of which is determined by the contents of the HL register pair on calling and given by the formula

Delay = (0.008 C + 0.013) ms

Where C = value of counter in HL register pair on calling.

The subroutine flowchart is given in Fig. 10-6.

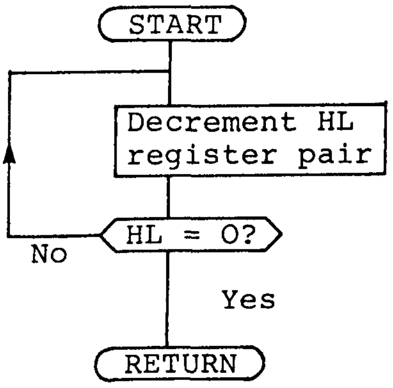


Fig. 10-6: Flowchart for Subroutine PAUSE

Registers affected: H, L.

Subroutine JOYSTK (Lines 439 - 505)

This subroutine converts the eight bit joystick voltage to the range -1 to +1, corresponding to the full mechanical travel of the lever. This is shown graphically in Fig. 10-7 and Fig. 10-8 gives the program flowchart.

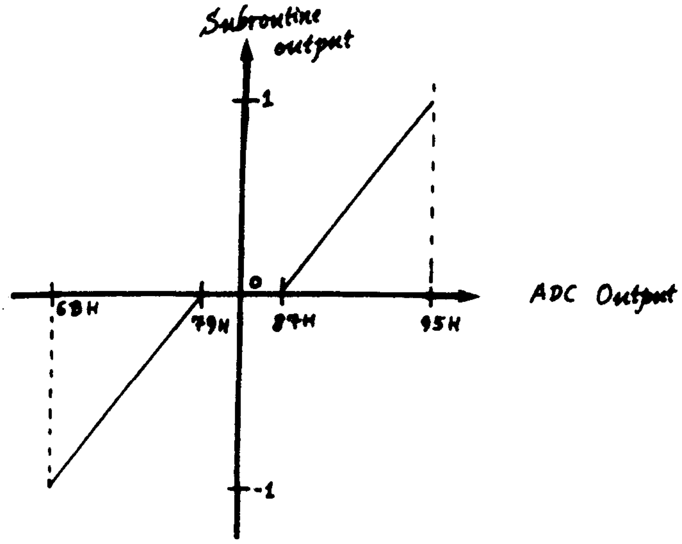


Fig. 10-7: Transfer Characteristic of Subroutine JOYSTK

Registers affected: A, D, E, Status.

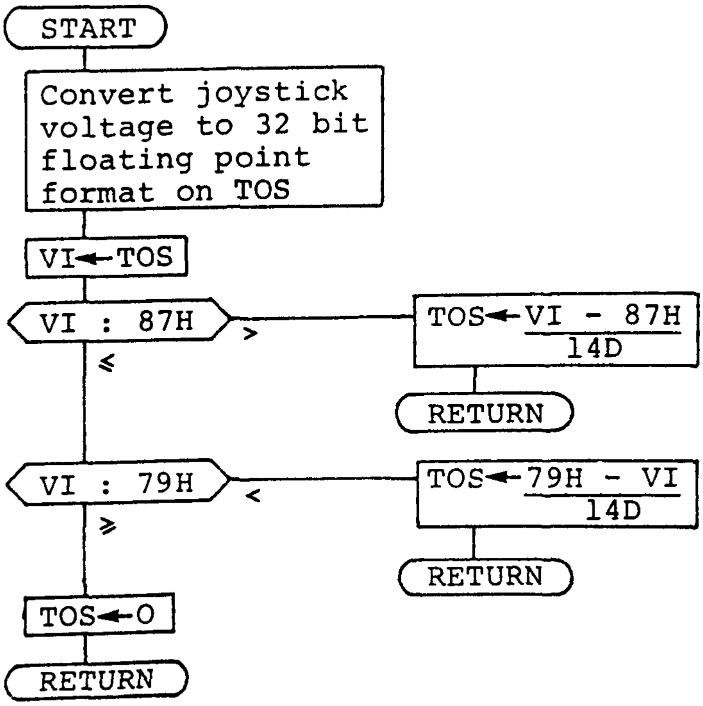


Fig. 10-8: Flowchart for Subroutine JOYSTK

Subroutine OUTPUT (lines 519 - 622)

This subroutine takes as input parameters the fractional valve openings VVSLEW, VVALFA, VVBETA, and VVBKT. They are offset and scaled in turn by subroutine VLIN to give the required valve control bytes which are then output to the valve drivers. The subroutine has the following input parameters.

Fractional valve opening	FVO
Positive Offset	POF
Positive Maximum	PMAX
Negative Offset	NOF
Negative Maximum	NMAX

The driver control byte is returned in the A register.

The input parameter names for the different valves are as follows:

	Slew	Lift	Reach
FVO	VVSLEW	VVALFA	VVBETA
POF	SPOF	APOF	BPOF
PMAX	SPMAX	APMAX	BPMAX
NOF	SNOF	ANOF	BNOF
NMAX	SNMAX	ANMAX	BNMAX
Control byte	VS	VL	VR

The bucket is contolled by a bang-bang valve and is operated by a separate piece of code which switches the bucket valve according to the sign of VVBKT.

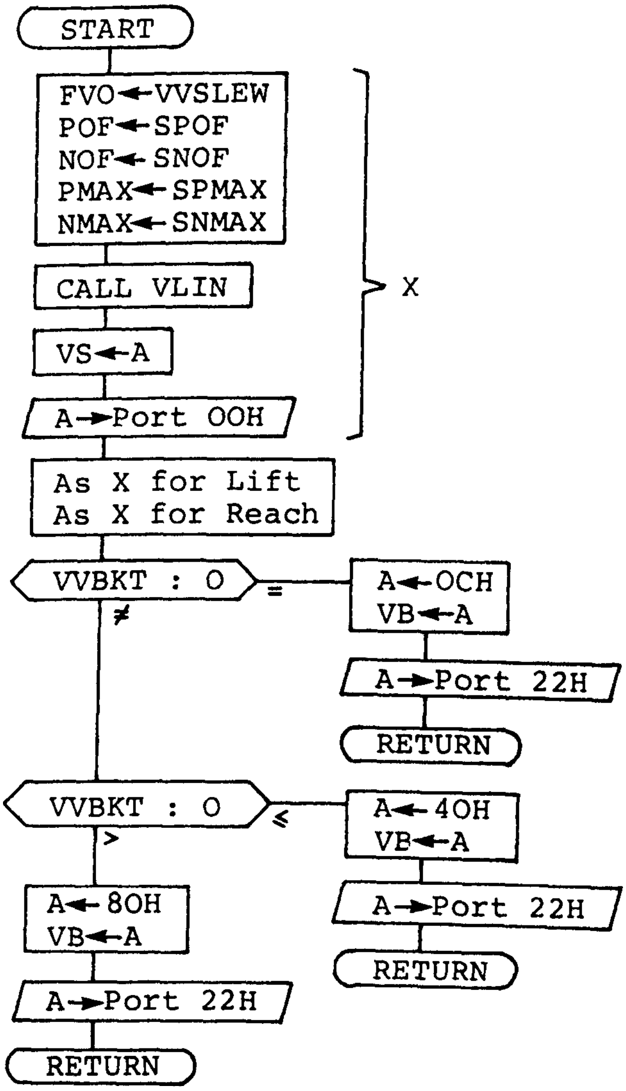
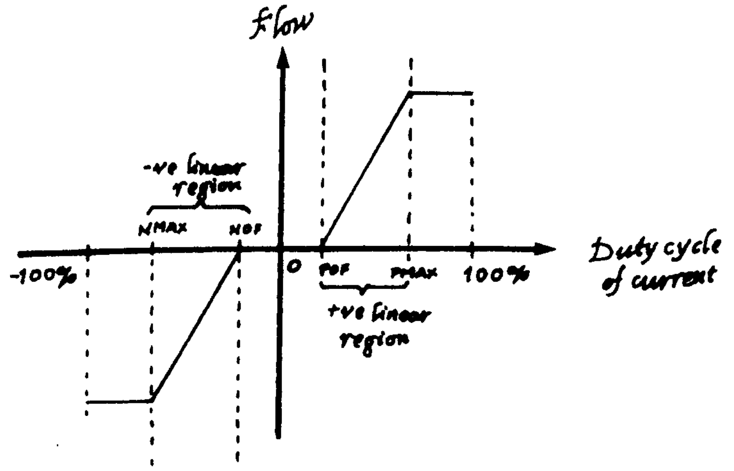


Fig. 10-9: Flowchart for Subroutine OUTPUT

Subroutine VLIN (Lines 661 - 761)

This subroutine derives the control byte to be output to a proportional valve given the demanded fractional valve opening and a set of parameters describing the valve characteristics. The demanded fractional valve opening (FVO) is expressed as a 32 bit floating point quantity in the range -1 to +1. The simplified characteristic of a valve is shown in Fig. 10-10.



POF - Positive Offset
PMAX - Positive Maximum
NOF - Negative Offset
NMAX - Negative Maximum

Fig. 10-10: Simplified Valve Characteristic

The subroutine maps an input in the range 0 to -1 onto the negative linear region. The format of the control word is as shown below in Fig. 10-11.

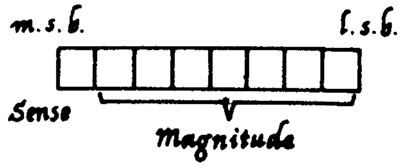


Fig. 10-11: Valve Driver Control Word Format

The most significant bit gives the sense of the movement as follows:

	1	0
Slew	Right	Left
Lift	Up	Down
Reach	In	Out

The seven least significant bits determine the magnitude of the mark to period ratio (duty cycle) of the valve current. The magnitude is calculated for positive inputs as

$$\text{Magnitude} = \text{POF} + \text{FVO}\ (\text{PMAX} - \text{POF})$$

and for negative inputs

$$\text{Magnitude} = \text{POF} + \text{FVO}\ (\text{NMAX} - \text{NOF})$$

The subroutine flowchart is shown in Fig. 10-12.

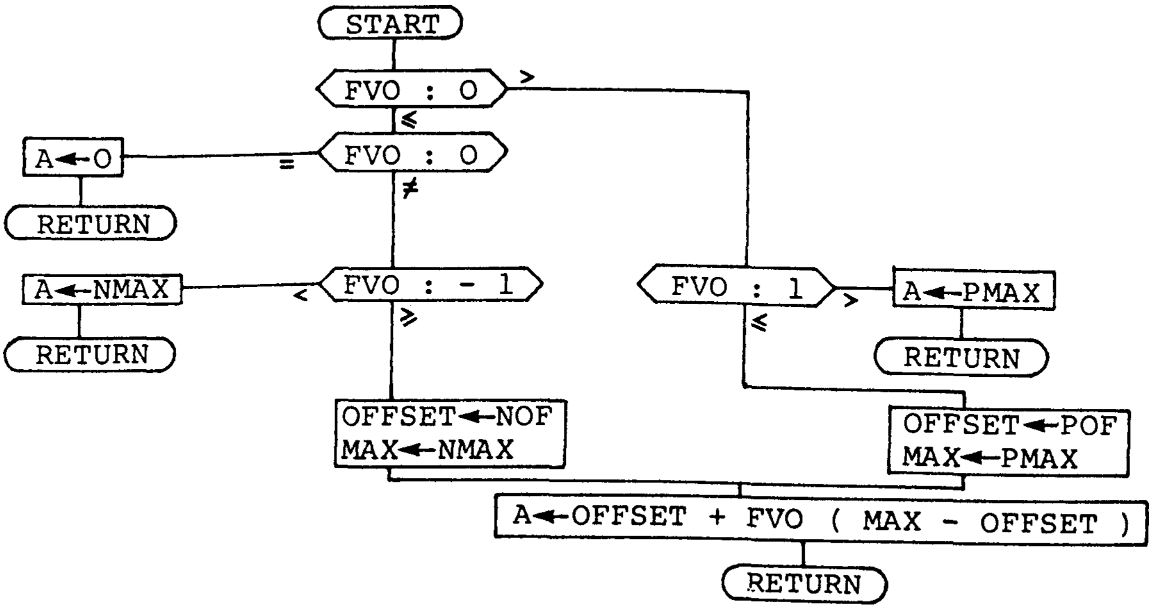


Fig. 10-12: Flowchart for Subroutine VLIN

Registers affected: A, D, E, Status.

CHAPTER ELEVEN

SOFTWARE III:

PROGRAM DIG

11.1 Functional Description and Algorithms

Program DIG is the main control program which implements the function specified in Chapter Two of automatic linear cutting of the blade, calibrated variable pitch, and a learn and repeat facility. The program effects four modes of machine operation:-

Manual: 'X-Y' control of bucket movement, Bucket Angle and Slew from joysticks. Calibrated Pitch control.

Learn: Control is as for Manual but path is recorded as a sequence of X, Y, ψ, coordinates. Any path previously recorded is overwritten.

Repeat Slow: Path is repeated at a slow speed from the machine position when the mode is selected. If this mode is selected when the machine is already in repeat fast mode, the path is not recommenced but continued at the slow speed.

Repeat Fast: Path is repeated at maximum speed from the machine position when the mode is selected. If this mode is selected when the machine is already in Repeat Slow mode, the path is not recommenced but continued at the higher speed.

Figure 11-1 illustrates the different possible mode transitions and the conditions causing them. The flowchart for mode control, which is the highest level of the machine software is shown in Fig. 11-2.

Manual Mode

The manual routine, flowcharted in Fig. 11-3 first sets the mode indicator on the control panel and then enters the main loop. Subroutine XY reads in the machine position and control

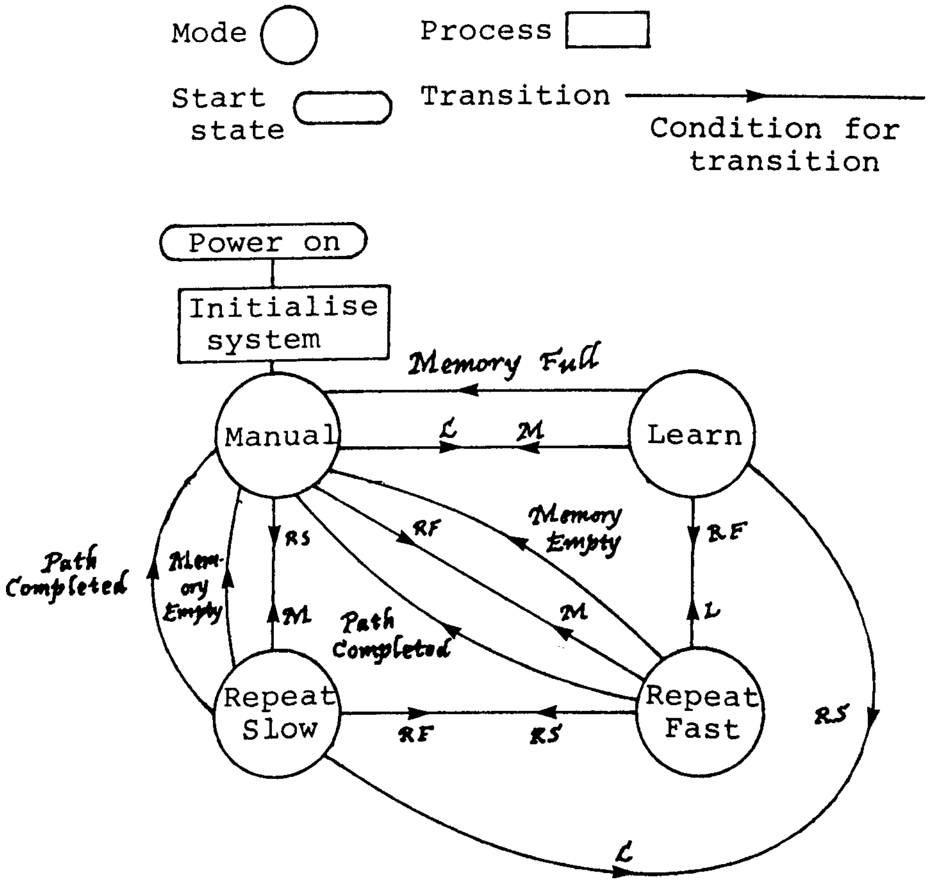


Fig. 11-1: Modes and Mode Transitions

inputs and sets the control valves accordingly. If any mode select key has been depressed then control returns to the main mode control program. The Vectored Interrupt key is briefly enabled so that program operation may be checked, which completes the sequence of operations of the subroutine's main control loop.

Learn Mode

The learn routine allows the user to control the machine as in Manual mode but equi-spaced points in the current X-Y coordinate framework are stored sequentially in memory as the

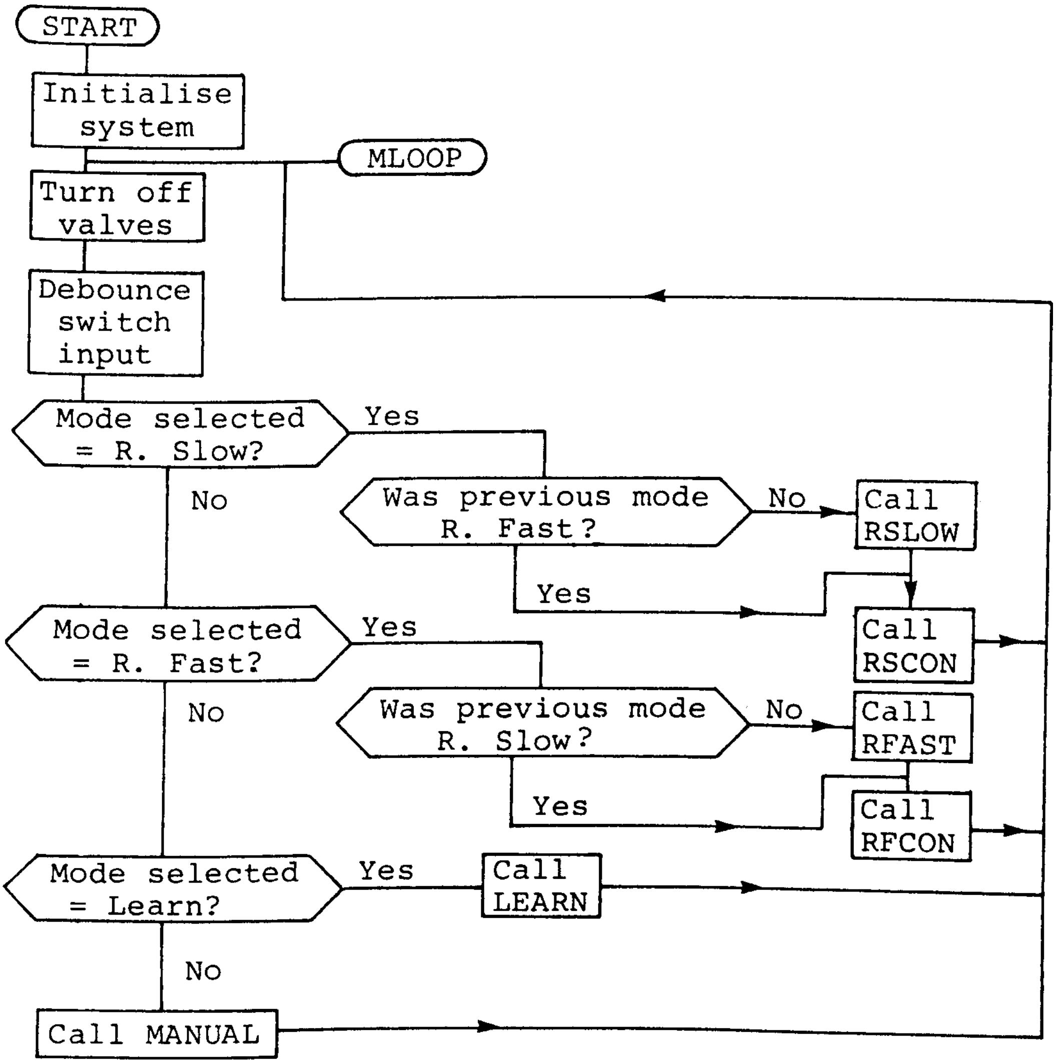


Fig. 11-2: Flowchart for Mode Control

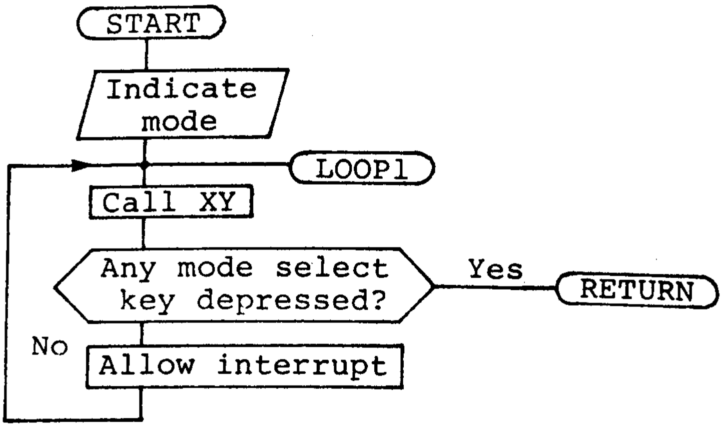


Fig. 11-3: Flowchart for Manual Mode

machine moves. The first point stored is the initial position of the machine when the mode is selected. The routine starts (see Fig. 11-4) by indicating the mode by the appropriate LED on the control panel, then the data pointer and counter are initialised and the current output position stored.

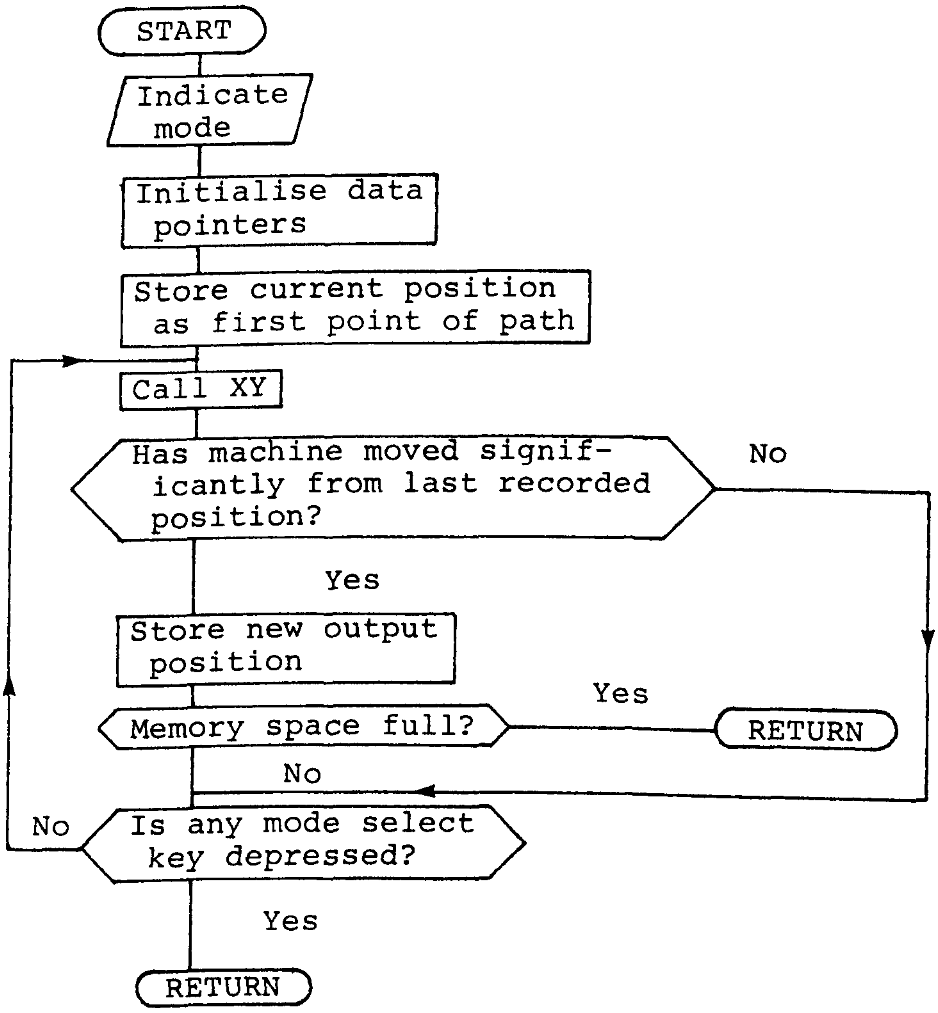

START
Indicate mode
Initialise data pointers
Store current position as first point of path
Call XY
Has machine moved significantly from last recorded position?
No
Yes
Store new output position
Yes
Memory space full?
RETURN
No
No
Is any mode select key depressed?
Yes
RETURN

Fig. 11-4: Flowchart for Learn Mode

In the main loop of the subroutine, subroutine XY is called to read the machine inputs, output position, and to set the valve outputs. The updated machine output position is compared with the latest stored value and if the separation is greater than a critical value then the new position is recorded. Thus approximately equi-spaced points are stored as the trajectory is executed and there is no time constraint upon the operator as would be imposed by sampling at regular time intervals. Once the memory is full then control returns to the mode selection program which defaults the system to manual mode. Control may also leave Learn Mode if one of the mode selection keys is depressed.

Repeat Slow and Repeat Fast Modes

The essential operation of the routine is to feed the stored path points to the position control program as target points, offset to accommodate the new starting point. The stored points are approximately equi-spaced so the delay between each point controls the speed. The main program for Repeat Slow mode is flowcharted in Fig. 11-5.

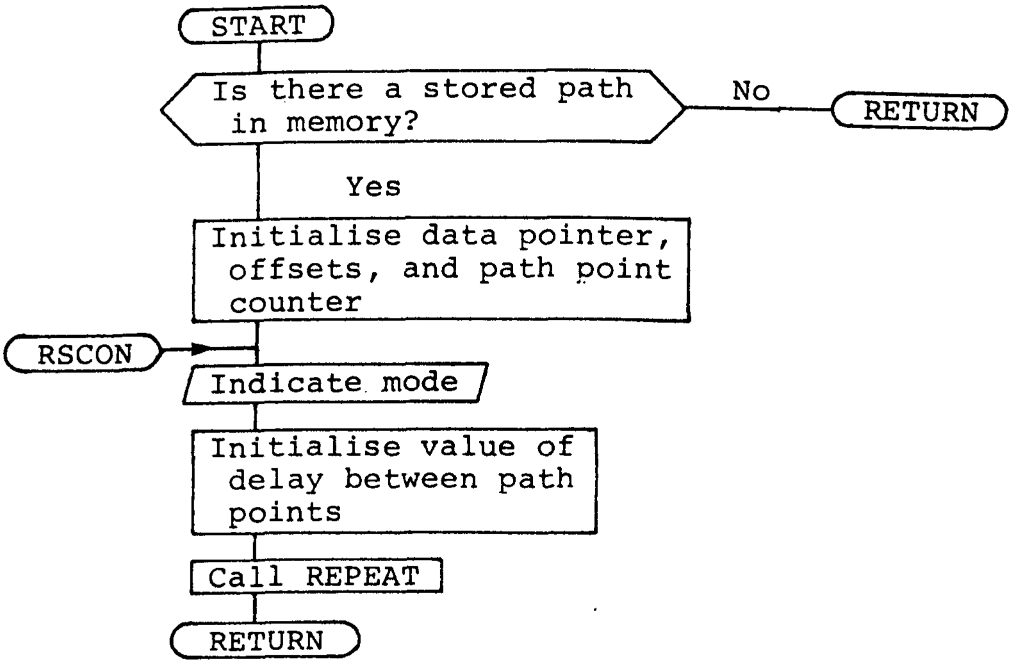

START
Is there a stored path in memory?
No
RETURN
Yes
Initialise data pointer, offsets, and path point counter
RSCON
Indicate mode
Initialise value of delay between path points
Call REPEAT
RETURN

Fig. 11-5: Flowchart for Repeat Slow Mode

The routine starts by checking that there is a path stored in memory and if there is not, control returns to the calling program. If there is a path in memory, the data counter which counts the successive path points is set to zero, and the data pointer to the base address for the stored path. If Repeat Slow mode is selected while the system is in Repeat Fast mode then the path being repeated at the mode change is continued at the new slow speed, so control enters at point RSCON. The Repeat Slow mode indicator on the control panel is then set. The value for the delay between successive path points is set and this determines the speed at which the path is repeated. Subroutine REPEAT is then called which has as calling parameters the number of path points, the data pointer, and the delay between points.

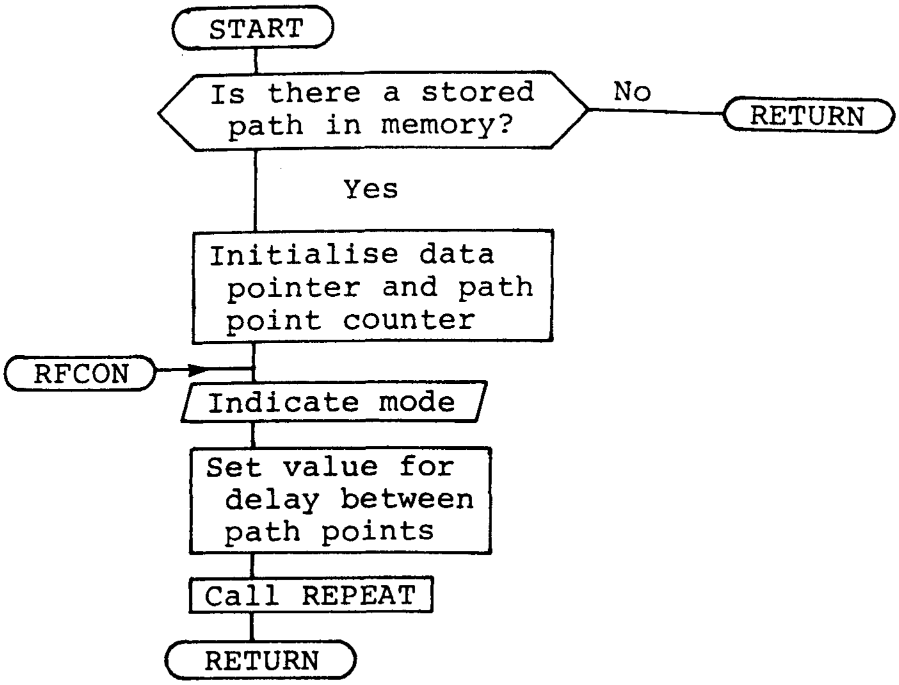

START
Is there a stored path in memory?
No
RETURN
Yes
Initialise data pointer and path point counter
RFCON
Indicate mode
Set value for delay between path points
Call REPEAT
RETURN

Fig. 11-6: Flowchart for Repeat Fast Mode

The operation of Repeat Fast mode (see Fig. 11-6) is very similar to that of Repeat Slow mode described above. Entry point RFCON is used when the mode is changed from Repeat Slow to Repeat Fast so that the path being repeated is continued but at a higher speed. No additional delay is introduced between path points so the path execution is as fast as the system will allow.

11.2 Memory Utilisation

In program DIG, as for program MANCON described in the previous chapter, certain program constants are made user alterable by storing them in RAM, allowing access through the SDK-85 monitor. Default values of the constants are stored in ROM and these are loaded into RAM by the first segment of the main program.

ROM	
0000H	JMP 80D0H
RAM	
3000H 30CCH	Program variables
30CDH 3111H	Program constants
ROM	
8000H 804BH	Default values for constants
804CH 80CCH	Program data
80D0H 8F2FH	Main Program

Fig. 11-7: Memory Utilisation

At power on control goes to address 0000H at which may be located the monitor program or an EPROM programmed so as to send control to the start of the main program at address 80D0H (see Fig. 11-7). The latter arrangement makes the system transparent to the user.

11.3 Code Documentation

(Line numbers refer to those on the listing in appendix C).

Main Program (Lines 189 - 271)

The flowchart for the main program is shown in Fig. 11-8.

The program starts at address 80D0H and the first segment copies the default values of user-alterable program constants from ROM, starting at address 8000H, to RAM, starting at address 30DCH. Register B is used as a data counter and 68_{10} bytes are transferred.

The interrupt mask is set to allow the VECT. INT. key to operate and the interrupt mask is disabled, to be re-enabled at specific points within the program. The stack pointer is then set to 20C2H, and subroutine INIT called to set up the I/O port data direction registers. The byte MODFLG which acts as a mode flag for the previous mode is set to Manual and this completes the initialisation process.

The main control loop starts at label MLOOP and the first operation is to turn off the valves by outputting the appropriate bit patterns to the drivers (Lines 217 - 221). The system then

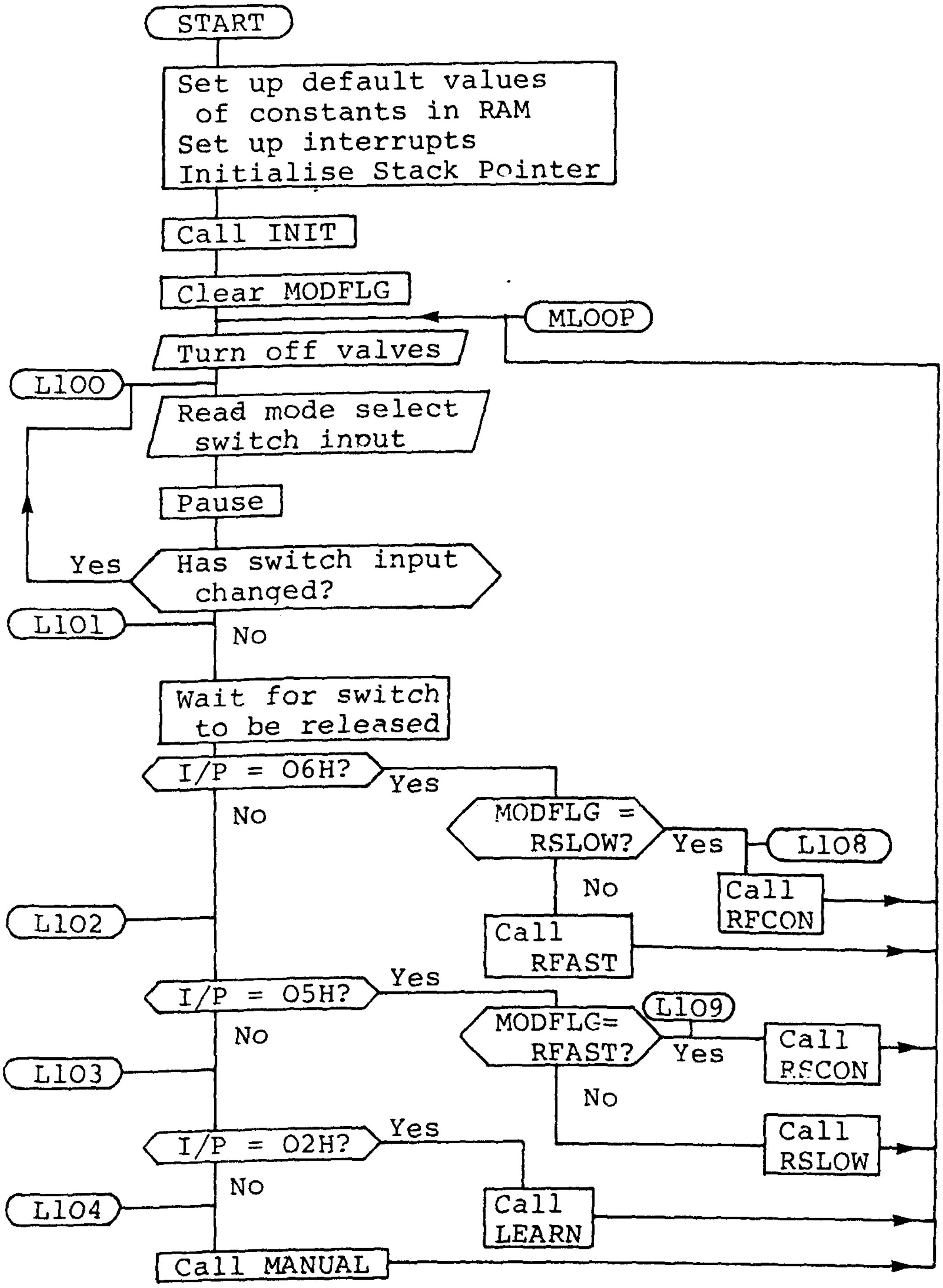


Fig. 11-8: Flowchart for Main Program

reads the status of the mode select switches , MODE, the switch status is debounced by a delay, and the processor waits for the switch to be released. By not proceeding to the selected mode until the switch is released, holding a mode select button down for an extended period does not give rise to any undesired system response by repeatedly entering and immediately leaving the selected mode. According to the bit pattern input from the mode select switches, the appropriate mode subroutine is called (Lines 242 - 271). If two buttons are depressed simultaneously a priority system is effected. The bit patterns are arranged so that the depression of two buttons simultaneously does not generate the pattern of a third. When control returns from the selected mode it re-enters the mode selection segment.

Subroutine MANUAL (Lines 280-290)

MANUAL is the master subroutine called when Manual mode is selected (see Fig. 11-9). MODFLG is updated and the appropriate mode indicator is set on the control panel (lines 280 - 282). The main loop then begins: subroutine XY is called to implement X-Y control of the machine from joystick inputs, the mode switches are checked and control returns if any of the switches is depressed (lines 284 - 286). An interrupt from the Vectored Interrupt key is allowed and then control jumps to the start of the main loop.

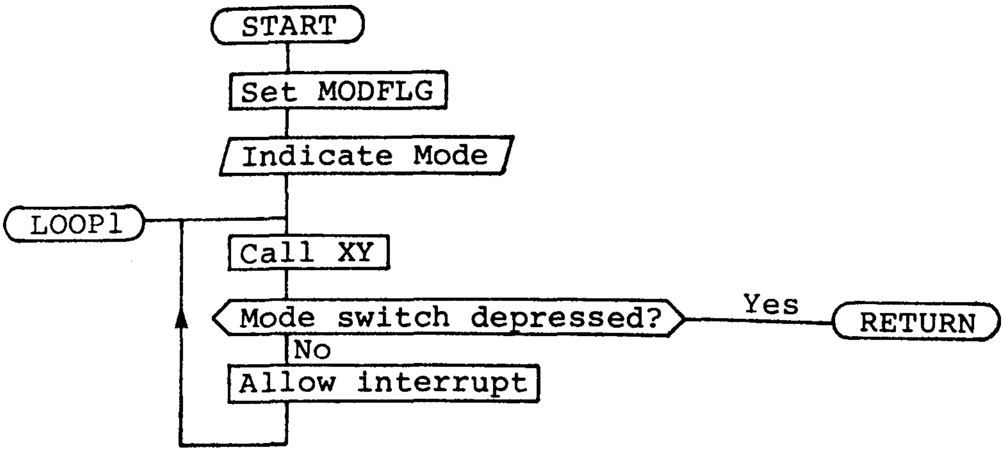


Fig. 11-9: Flowchart for Subroutine MANUAL

Subroutine XY (Lines 303 - 319)

Subroutine XY is the subroutine used in Manual and Learn modes to read the control settings and machine position and assign the valve settings accordingly. It simply calls a sequence of subroutines to effect the different operations (see Fig. 11-10).

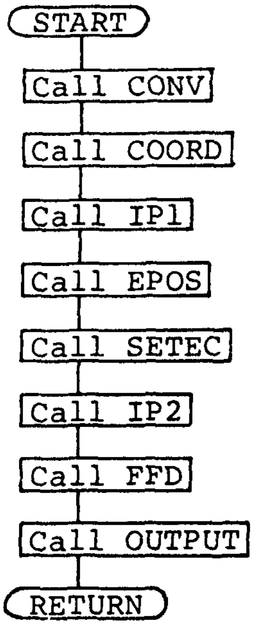


Fig. 11-10: Flowchart for Subroutine XY

Subroutine CONV reads in the joystick positions, pitch control setting, and the position of the machine arms. COORD then calculates the output position in the Cartesian user coordinate system. Subroutine IP1 compares the settings of the joysticks with previous values and if there is significant difference then updates the input velocities to the control system. This has the effect of filtering out any noise due to unsteadiness of the operator's hand. The positional error between the output positon and the latest value of the demanded position or Target Point is calculated by suboutine EPOS. A critical value of position error is set by subroutine SETEC according to the input velocities such that if the system is saturated (i.e. valves fully open) then the target point is frozen.

Subroutine IP2 freezes the target position if the modulus of the positional error, ETA, exceeds ECRIT, otherwise a new position on the demanded trajectory is assigned to the target point. Subroutine FFD assigns the valve openings depending on the angular positional errors at the individual pivots. Subroutine OUTPUT then converts the demanded valve settings to control bytes which are output to the valve drivers.

Subroutine LEARN (Lines 463 - 552)

The first operation performed by the subroutine (Fig. 11-11) is to indicate Learn Mode by outputting the bit pattern 01H to the LED control port at I/O address 23H. PCOUNT which is a counter of the number of points in the stored trajectory is set to zero and the data pointer PPOINT is set to the base address of the path storage area. Subroutine XPXO is called to store the current output position defined by XO, YO, PSIO in the variables XP, YP, PSIP respectively (initialising the so-called Previous Output Position). Subroutine TPUSH pushes the three variables comprising the Previous Output Position onto the stored path stack. This constitutes the first path point and control then enters the main loop at label L206.

The first operation in the main loop is to call subroutine XY which implements the control of the valves. The distance of the

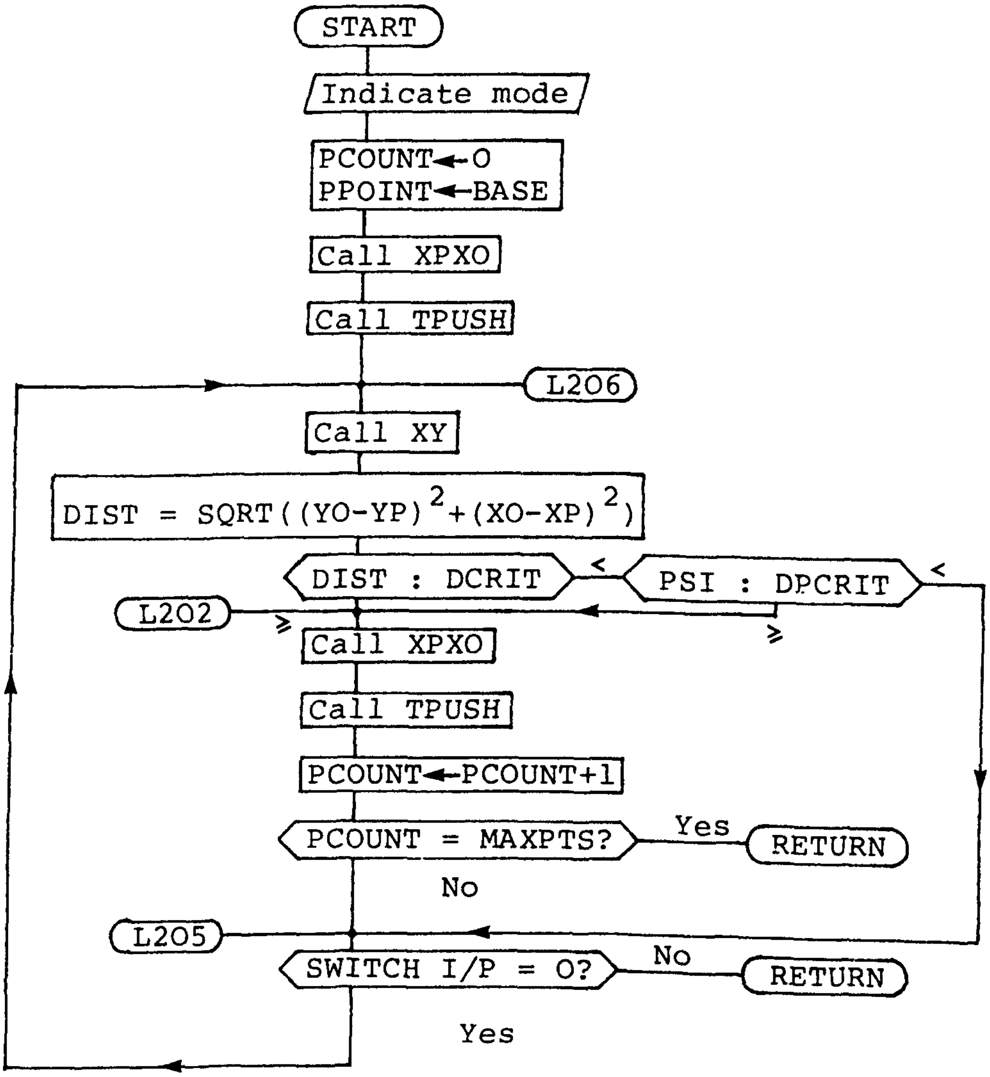


Fig. 11-11: Flowchart for Subroutine LEARN

current XY coordinate from the last stored point XP, YP is calculated and if it exceeds the critical value DCRIT, set at 0.1 m, the new output position is stored on the stack. The bucket angle PSI is also compared with PSIP and if a change greater than DPCRIT, set to 5°, has occured then also is the new position recorded.

The sequence of operations for recording a path point (Lines 540 - 548) is as follows: subroutine XPXO is called to update the value of XP, YP, PSIP to the current output values. Subroutine TPUSH pushes the new point onto the path stack. The path point counter PCOUNT is incremented and compared with MAXPTS, the maximum number of points that can be stored, and if the memory is full control returns to the main program.

The final part to the main loop (Lines 541 - 551) is to check that none of the mode select switches is depressed and to jump to the start of the loop or else to return.

Subroutines RFAST and RFCON (Lines 729 - 744)

Figure 11-12 shows the flowchart for subroutine RFAST and when subroutine RFCON is called control enters at label RFCON. Subroutine RFAST is for repeating a stored path i.e. operating the system in repeat fast mode, and is called when changing from manual or learn mode to Repeat Fast mode. When changing from Repeat Slow mode to Repeat Fast mode RFCON is called to continue, at a faster rate, a path already being repeated.

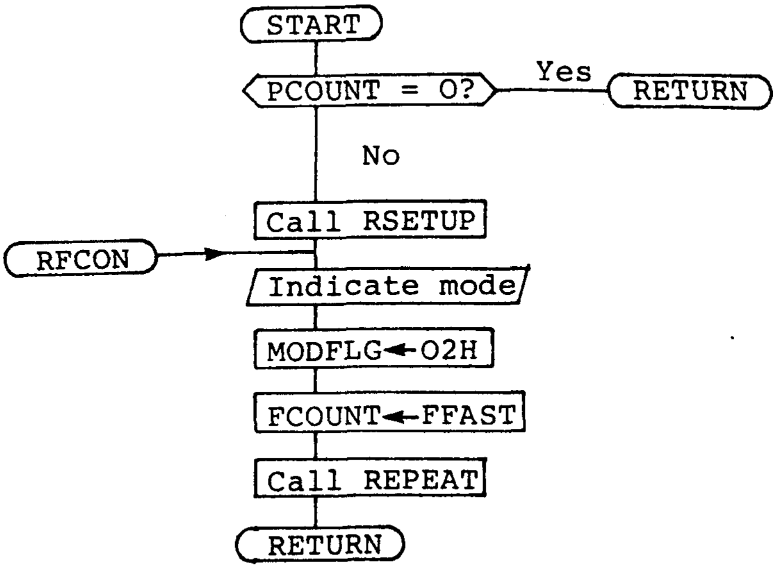


Fig. 11-12: Flowchart for Subroutines RFAST and RFCON

The first operation when RFAST is called is to check that there is a path in memory by examining the value of PCOUNT, the counter of the number of points stored. If PCOUNT is zero then control returns to the calling program (lines 729 - 733). Subroutine RSETUP is then called to initialise the data points and the offsets in the X and Y directions to compensate for the new starting point being different from the first stored point.

The Repeat Fast mode indicator LED on the control panel is then turned on and MODFLG byte is set to indicate repeat fast (Lines 735 - 738). To control the speed of execution of the stored path, the rate at which the target points are presented to subroutine XY is varied. The number of calls of subroutine XY in between successive points is stored in FCOUNT and is assigned the value FFAST, here set to 1. NCOUNT, the number of the path point reached is then initialised to zero. Subroutine REPEAT is then called to execute the repeat process using the above defined initial conditions and parameters.

Subroutines RSLOW and RSCON (Lines 762 - 775)

Subroutine RSLOW (see Fig. 11.13) is for operating the system in Repeat Slow mode and if this mode is selected from Repeat Fast mode then control enters at Label RSCON. The routine is similar to RFAST.

The path point counter is checked to determine if there is a path in memory: if it is zero then control returns. Subroutine RSETUP is called to initialise the data pointer and the position offsets to be added to each successive path point to compensate to the new start point.

The mode indicator LED's are set to indicate RSLOW and MODFLG to the value 01H. PCOUNT is assigned the value of FSLOW (12_{10}) so that a new target point is assigned every 12 calls of routine XY. Subroutine REPEAT is then called to execute the path using the above assigned parameters.

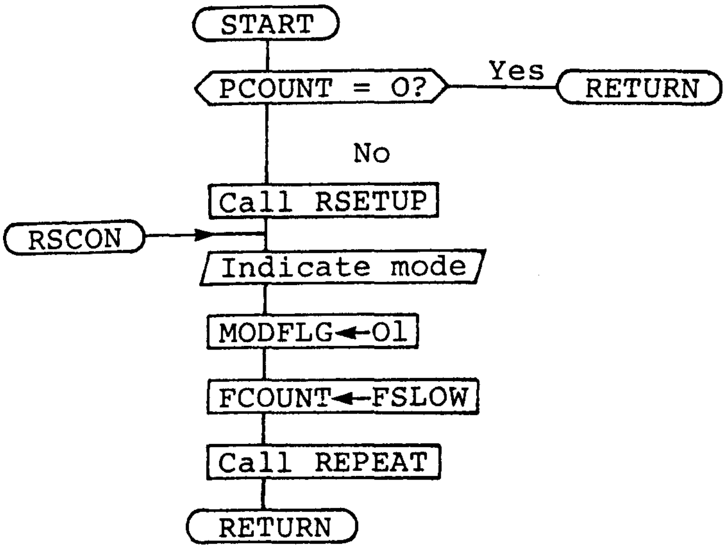


Fig. 11-13: Flowchart for Subroutines RSLOW and RSCON

Subroutine REPEAT (Lines 617 - 713)

This subroutine is called in both Repeat Fast and Repeat Slow modes to pull points from the stored path stack, add the appropriate offset and call the control routines for operating the valves. The subroutine flowchart is shown in Figure 11-14.

The magnitude of the current output error, ETA, is compared with the value ECRIT and if ETA is greater control jumps to the segment for setting the output. This is to ensure that the machine gets close to one target point of the path before inputting the next.

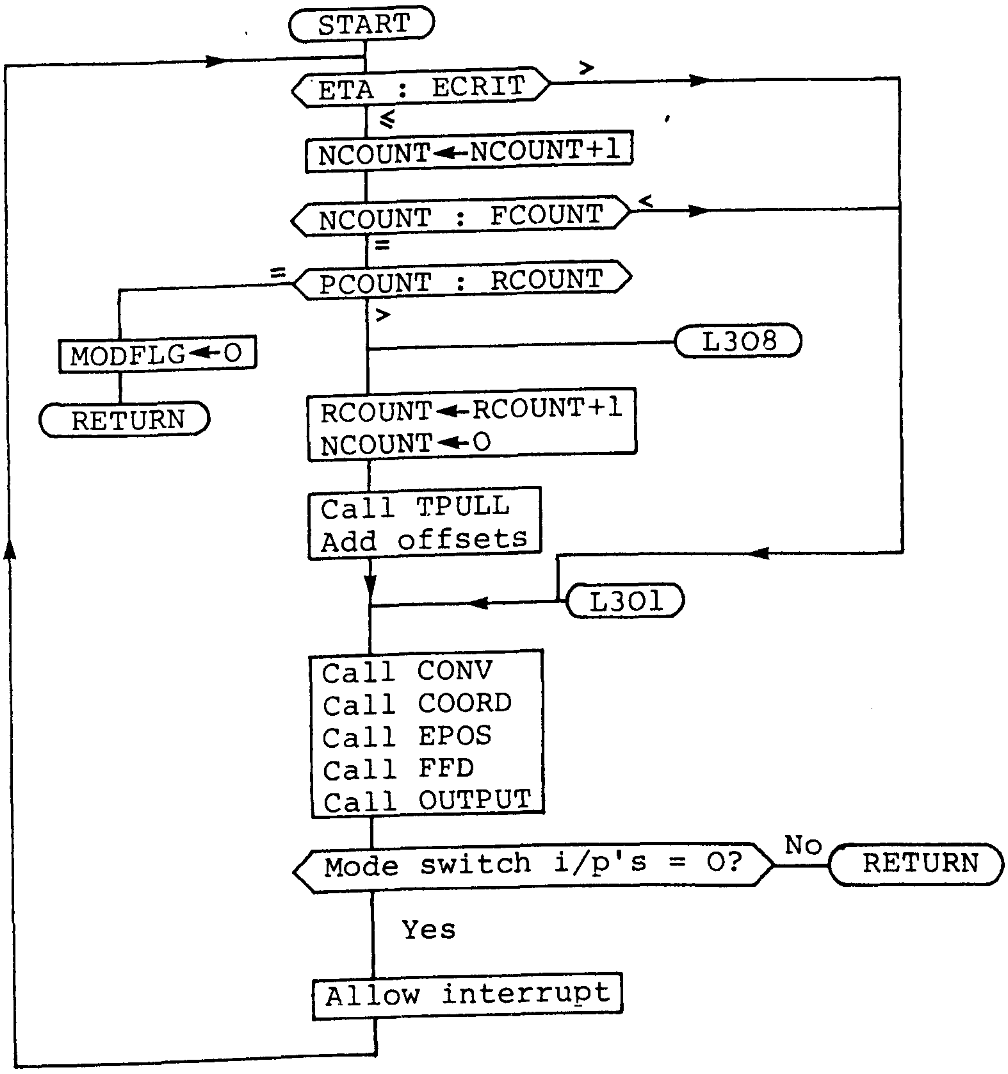


Fig. 11-14: Flowchart for Subroutine REPEAT

NCOUNT, which is a count of the number of calls to the set of position control routines, is incremented and compared with PCOUNT, the value of which determines the frequency at which target points are pulled from the stack. If NCOUNT has not yet reached the value FCOUNT then control moves to L301 to call the position control subroutines.

Otherwise, the path point counter RCOUNT is compared with the total number of points stored, PCOUNT, and if the final point has been pulled from the stack MODFLG is set to zero and control returns to the calling program. At label L308 path point counter RCOUNT is incremented and NCOUNT reset to zero. Subroutine TPULL is called (Line 678) to pull the top of the path stack and assign the values to XI, YI, and PSII which are the inputs to the position control loop. The X and Y offsets are then added (lines 679 - 698). Starting at label L301 the sequence of position control subroutines is called: CONV inputs the machine position, COORD calculates the output X and Y coordinates, EPOS calculates the positional errors, FFD calculates the required valve settings, and OUTPUT sets the valve control bytes. The mode selection switches are checked and if any is depressed then control returns to the calling program (lines 704 - 706). An interrupt is then allowed from the keyboard so that program execution may be stopped at this point.

<u>Subroutine CONV</u> (Lines 808 - 845)

Subroutine CONV reads all the inputs from the control box and the positions of the arms from the transducers. The flowchart is given below in Fig. 11-15. For operating the analogue to digital converter subroutine ADCON (see Chapter 9) is used. The joystick input voltages are normalised to the range -1 to +1 by subroutine JOYSTK (see Chapter 9). Subroutine SLOPE converts the voltages read by the analogue to digital converter from the pitch control knob to the range $-\pi/2$ to $+\pi/2$. Subroutines ALFIP, BETIP, and DELTIP input angles α, β, and δ respectively.

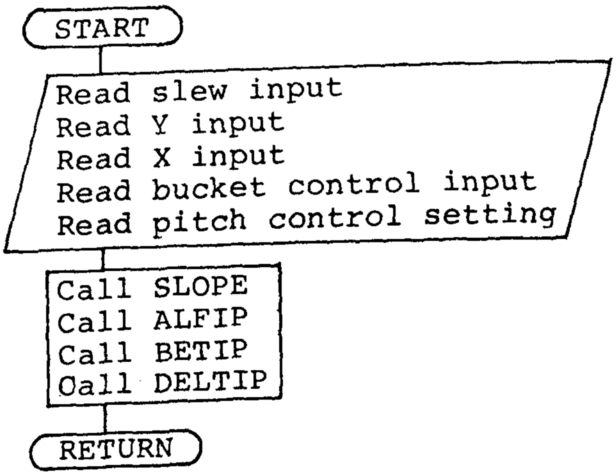


Fig. 11-15: Flowchart for Subroutine CONV

Subroutine COORD (Lines 1209 - 1308)

This subroutine calculates the output coordinates XO, YO, and PSIO from the measured angles α, β, and δ. To increase the speed of calculation a second order polynomial is used to approximate the function γ(δ). In lines 1209 - 1240 XO is calculated, then YO is calculated in lines 1241 - 1274. The polynomial approximation to γ(δ), calculated in lines 1278 - 1294 gives a maximum error of 3% over the range of travel of the bucket, a level of accuracy found to be quite acceptable. The coefficients GC0, GC1, and GC2 were calculated in a separate program to give a least squares approximation to the analytical values of the function γ(δ). PSII is then calculated in lines 1295 - 1307.

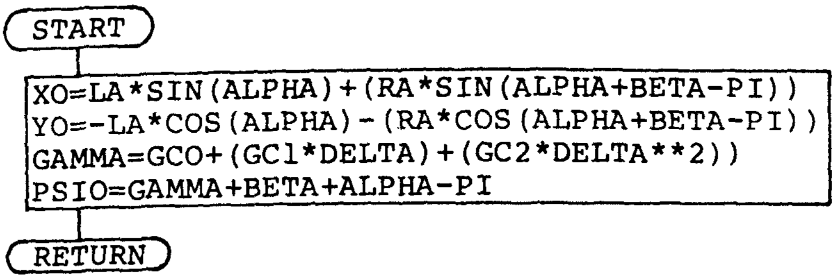

START
XO=LA*SIN(ALPHA)+(RA*SIN(ALPHA+BETA-PI))
YO=-LA*COS(ALPHA)-(RA*COS(ALPHA+BETA-PI))
GAMMA=GCO+(GC1*DELTA)+(GC2*DELTA**2))
PSIO=GAMMA+BETA+ALPHA-PI
RETURN

Fig. 11-16: Flowchart for Subroutine COORD

Subroutine IP1 (Lines 1438 - 1584)

This subroutine is called in Manual and Learn modes and is shown flowcharted in Figure 11-17. When bucket movement is selected by the operator the current bucket output angle, PSIO, is assigned to the variable PSII which is then used as the input to the bucket position control loop to keep the bucket angle constant when bucket movement is deselected. This is effected by lines 1438 - 1459.

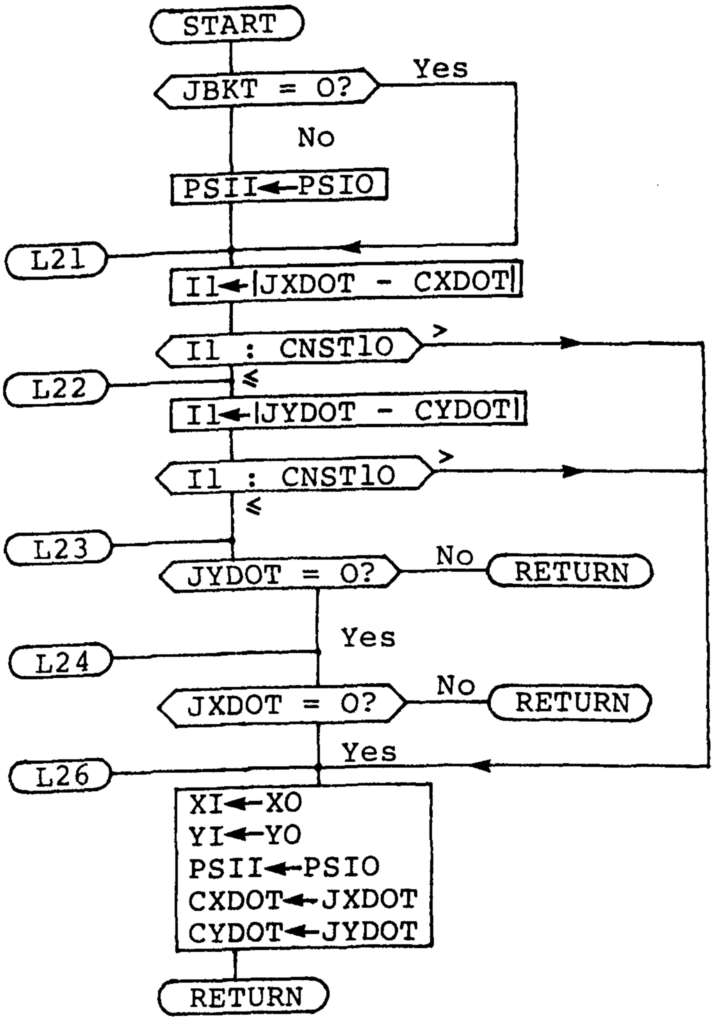


Fig. 11-17: Flowchart for Subroutine IP1

The current X and Y direction joystick input velocities are compared to the current input velocities to the control loop (lines 1460 - 1519). If there is a significant difference in either (>CONST10) then the target point defined by (XI, YI, PSII) is set to the current output position and assigned a new velocity given by JXDOT and JYDOT (Lines 1554 - 1584).

Also if either of the joystick input velocities is set to zero the target point and control loop input velocities are reset (lines 1520 - 1553). This ensures that small changes or noise on the joystick input do not continually reset the target point and that the machine stops abruptly if the joysticks are released.

Subroutine EPOS (Lines 1321 - 1373)

This subroutine, flowcharted in Figure 11-18 calculates the positional errors of the machine in x, y, and ψ (lines 1321 - 1365). As this subroutine is called in all modes an execution timing test segment has been included in it. Byte TFLAG is complemented and output to port 08H so that by monitoring the status of any pin on the port the execution loop time may be measured as half the period of the observed rectangular wave.

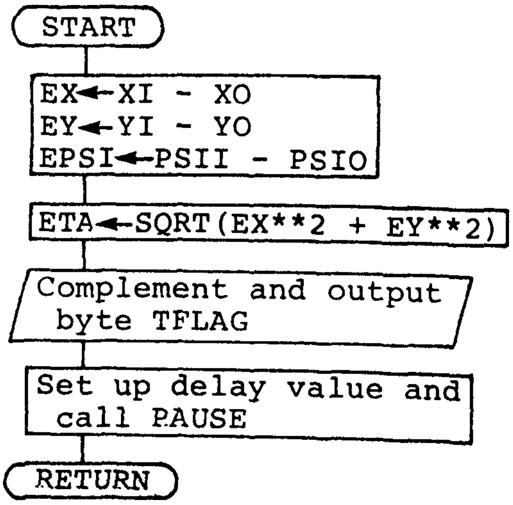


Fig. 11-18: Flowchart for Subroutine EPOS

Also a delay loop is included with a delay which may be set to zero to examine the effects of increased loop execution time. This enables a minimum specification of the hardware and software execution speed necessary for effective control to be achieved.

Subroutine SETEC (Lines 1399 - 1422)

When the position error ETA exceeds a critical value the position of the target point is frozen. Hence if the bucket motion is stalled by an immovable load the target point does not continue moving indefinitely. The maximum allowable error ECRIT is calculated in the routine such that ECRIT has a basic value of ECMIN (set to 0.1 m), increasing with the value of the demanded velocity.

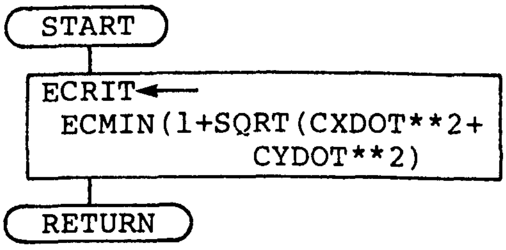


Fig. 11-19: Flowchart for Subroutine SETEC

Subroutine IP2 (Lines 1649 - 1903)

This subroutine (see Figure 11.20) is for updating the target point coordinates in each cycle of the main control loop. If the positional error of the bucket pivot ETA exceeds ECRIT then the target point coordinate is left unchanged. Otherwise the X and

Y input coordinates XI an YI are incremented according to their corresponding input velocities.

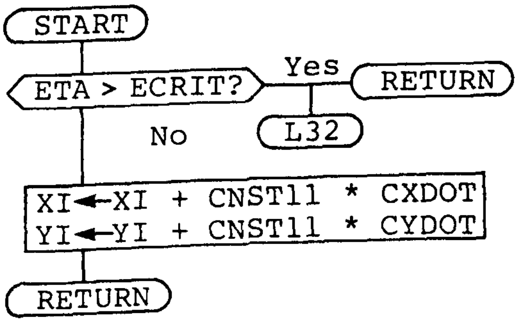


Fig. 11-20: Flowchart for Subroutine IP2

Subroutine FFD (Lines 1649 - 1903)

Subroutine FFD is the code segment which sets the fractional valve openings. The slew valve setting VVSLEW is assigned the value of the slew joystick input JSLEW (Lines 1649 - 1654). MODFLG is then checked to determine if the system is in Manual mode and if not the JXDOT and JYDOT joystick inputs are disregarded (Lines 1656 - 2658). If in manual mode and both joystick inputs are zero then subroutine FREEZE is called to set the lift and reach valve settings to zero (Lines 1661 - 1695). This is to ensure that the machine stops when the joysticks are in their central positions.

If motion of the bucket pivot is not to be frozen then the geometry of the machine is solved to derive the β and α values, BI and AI, required to position the bucket pivot at the target position (lines 1713 - 1774).

The error in α, EALPHA, is calculated and if the error is smaller than the quantisation level of the ADC input then the

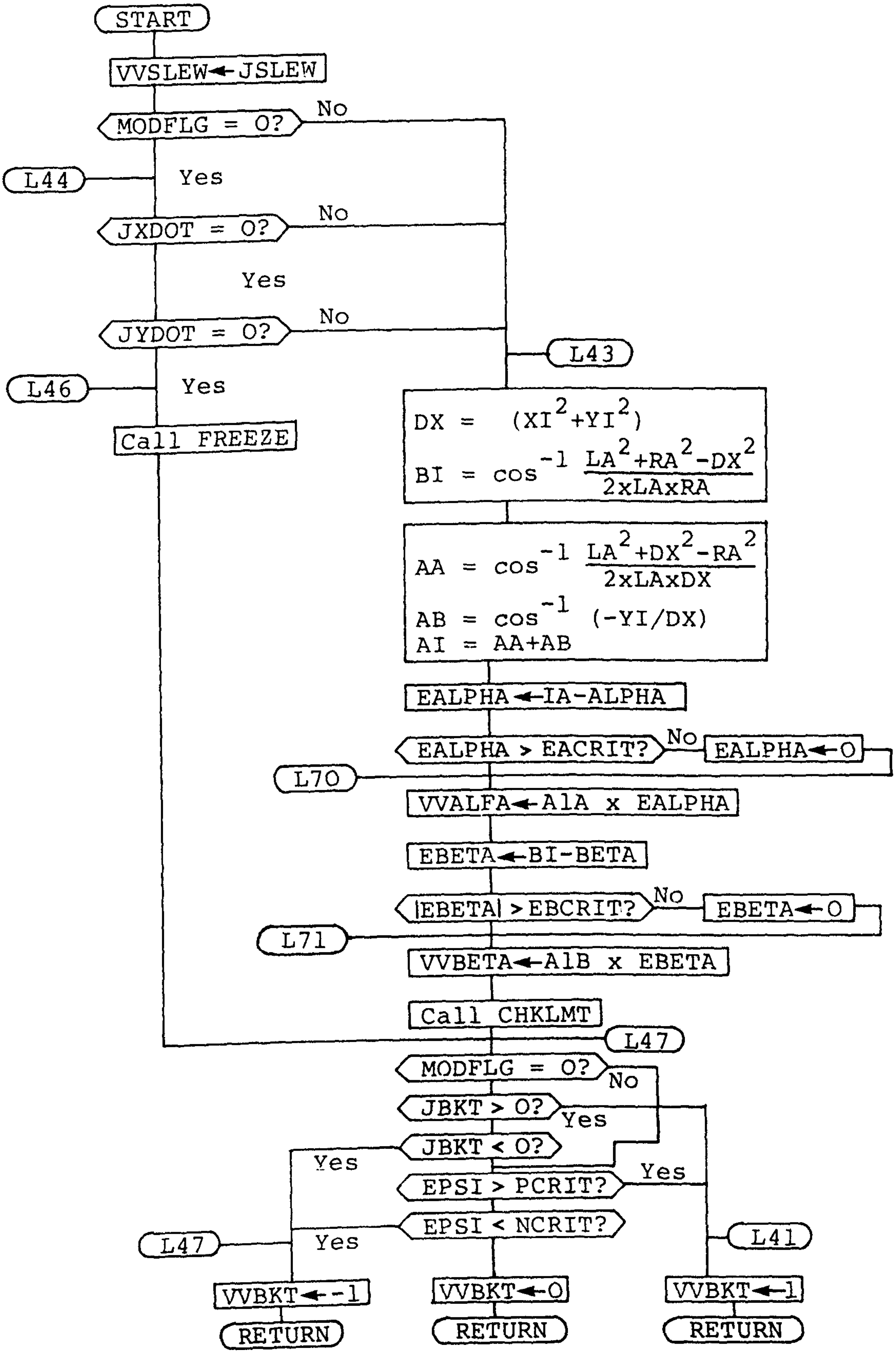


Fig. 11-21: Flowchart for Subroutine FFD

error is assigned the value zero. The value of the valve opening for the alpha valve is then the gain constant A1A x EALPHA. A similar operation is then carried out to set the beta valve opening VVBETA (Lines 1775 - 1810).

Subroutine CHKLMT is called to check if the machine position and the valve setting are such as to try and make a ram move beyond the limit of its travel; if so then subroutine FREEZE is called. The final part of the subroutine (Lines 1812 - 1903) is for determining the required bucket valve opening. If the system is in repeat mode then the joystick input is ignored (Lines 1812 -1814), if manual or learn mode the valve is set according to the joystick (Lines 1818-1849).

If the machine is in repeat mode or the joystick inputs are zero then the bucket valve setting is assigned a value according to the sign and magnitude of the angular positional error EPSI (Lines 1850 - 1903); threshold values PCRIT and NCRIT are set just larger than the quantisation value of the bucket position input.

<u>Subroutine XPXO</u> (Lines 391 - 400)

This subroutine is called in Learn mode to copy the set of output coordinates XO, Y, PSIO (memory locations 3064H thro' 306FH) to XP, YP, PSIP (memory locations 3020H thro' 302BH). Register pair DE acts as the source data pointer and HL as the destination data pointer. Register B acts as the data counter. The routine is flowcharted in Fig. 11-22.

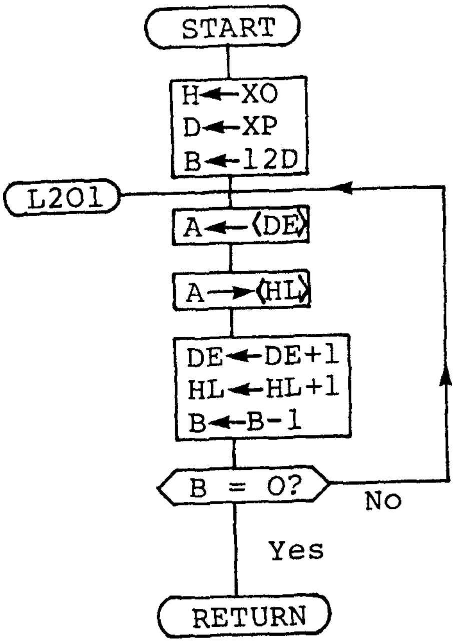


Fig. 11-22: Flowchart for Subroutine XPXO

Subroutine TPULL (Lines 414 - 426)

This subroutine, called in Repeat modes, pulls path coordinates from the stack and puts them in XI, YI, PSII. PPOINT contains the address of the top of the stack and register B acts as a byte counter.

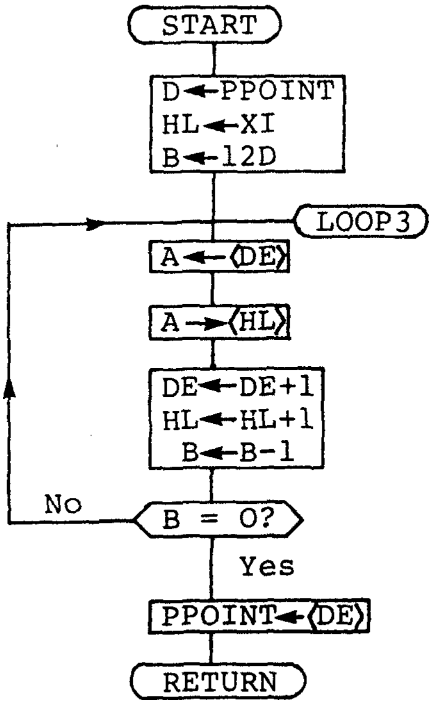


Fig. 11-23: Flowchart for Subroutine TPULL

Subroutine TPUSH (Lines 414 - 426)

This subroutine is used in Learn mode and pushes the output coordinates XO, YO, PSIO onto the path stack. PPOINT is the path stack pointer and the B register is a data counter to the 12 bytes transferred.

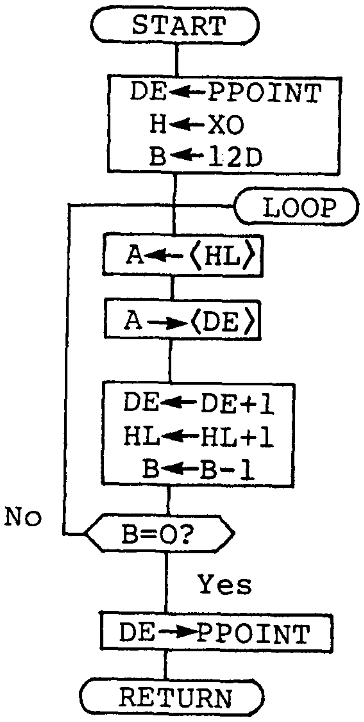


Fig. 11-24: Flowchart for Subroutine TPUSH

Subroutine ALFIP (Lines 855 - 880)

This subroutine (see Fig. 11-25) is for inputting the machine coordinates MCALFA, and ALPHA, the user coordinate lift arm angle, the two being related by the pitch angle selected on the control panel. The appropriate channel of the ADC is read and the result put on the top of the APU stack and converted to 32 bit floating point format. MCALFA is found using the scale factor MA and offset CA.

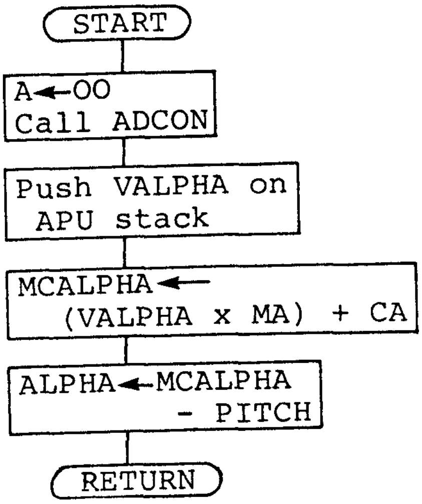


Fig. 11-25: Flowchart for Subroutine ALFIP

Subroutine BETIP (Lines 890 - 907)

Subroutine BETIP (see Fig. 11-26) inputs angle BETA between the reach and lift arms. The appropriate channel of the ADC is read to give VBETA which is then scaled and offset by MB and CB to give BETA.

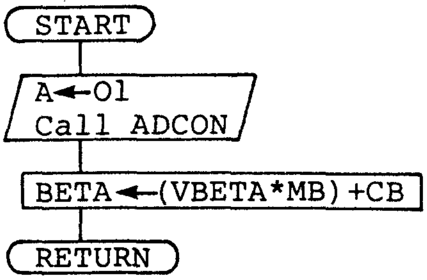


Fig. 11-26: Flowchart for Subroutine BETIP

Subroutine DELTIP (Lines 918 - 935)

Subroutine DELTIP (see Fig. 11-27) inputs the bucket linkage angle DELTA. The appropriate ADC input is read and the result, VDELTA, scaled and offset by MD and CD.

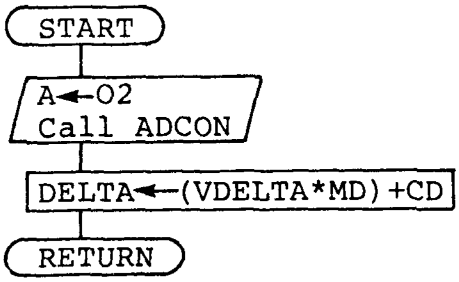


Fig. 11-27: Flowchart for Subroutine DELTIP

Subroutine SLOPE (Lines 1183 - 1198)

This subroutine, flowcharted in Figure 11-28 reads in the pitch angle from the knob on the control panel. The ADC input channel number is in the A register on calling and the result is put into the APU and scaled and offset by CNST13 and CNST14 to give the pitch angle in the range -π/4 to +π/4.

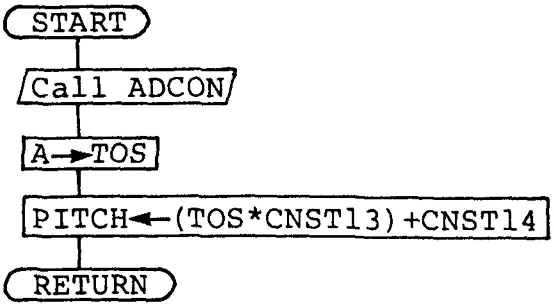


Fig. 11-28: Flowchart for Subroutine SLOPE

Subroutine RSETUP (Lines 569 - 604)

This routine is for setting up the necessary variables before repeating a stored path. NCOUNT, the counter for the number of control routine calls per point, is set to zero as is the repeat path point counter RCOUNT. The data pointer PPOINT is set to the base address of the FIFO path stack. Subroutine TPULL is called to pull the first path point and the X and Y offsets XOF and YOF, to be added to subsequent path points, are calculated.

The inputs to the position control loop are set equal to the outputs and subroutine EPOS is called, setting the positional errors in X and Y to zero.

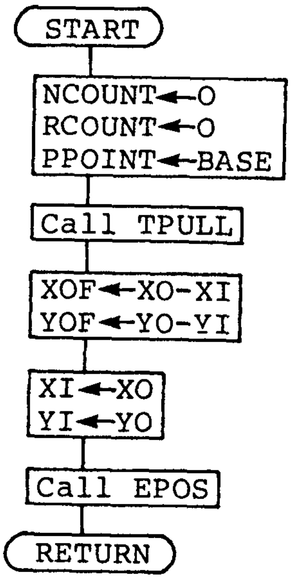


Fig. 11-29: Flowchart for Subroutine RSETUP

Subroutine CHKLMT (lines 1914 - 2048)

Subroutine CHKLMT (see Figure. 11-30) checks the machine position and valve setting to determine if an attempt is being made to move an arm beyond the limit of its travel. If so, subroutine FREEZE is called to set alpha and beta valve openings to zero.

Subroutine FREEZE (Lines 2058 - 2068)

Subroutine FREEZE (see figure 11-31) simply sets the alpha and beta valve openings VVALFA and VVBETA to zero.

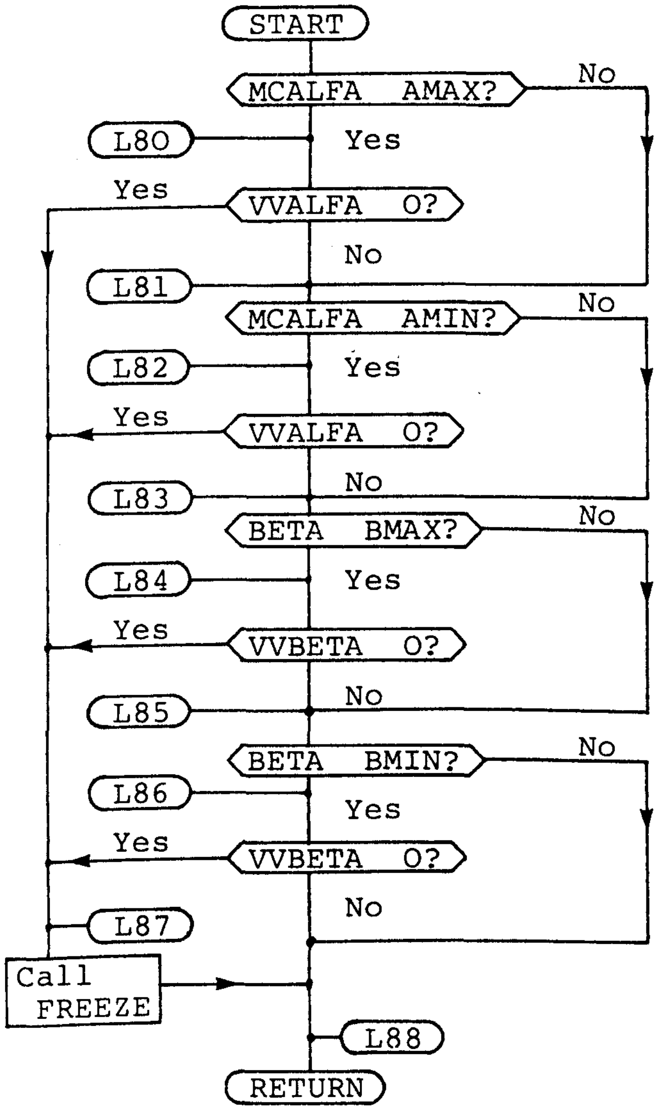


Fig. 11-30: Flowchart for Subroutine CHKLMT

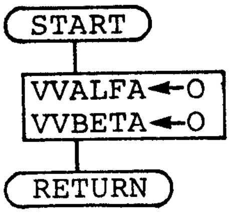


Fig. 11-31: Flowchart for Subroutine FREEZE

CHAPTER TWELVE

FIELDWORK AND SYSTEM EVALUATION

12.1 Introduction

This chapter deals with the experiments carried out and observations made to assess the technical and functional aspects of the system as built. Also considered are the economic factors influencing the viability of the system as a commercial product.

12.2 Tuning of Control Parameters

Havings established the basically correct operation of the software with the digger fixed to the floor in the Mechanical Engineering Laboratories at Liverpool University, the electronic hardware and the transducers were taken to the premises of F.W.McConnel Ltd., Ludlow for adjustment and evaluation when used on a tractor mounted digger.

For experimental work and development, the facility for varying control parameters via the SDK-85 keyboard and monitor was found to be effective and simple to use. It was readily posssible in the field to change parameters to determine their effect on system performance.

Valve Offsets

The code was originally written in such a way that diffeent values of offset and maximum valve currents could be stored for each valve so that individually they could be operated over their linear region. In practice however it was found that this was unnecessary and that common values could be used for all valves. By setting the offset current of the valves sufficiently low it was found unnecessary to threshold angular errors in alpha and beta to their quantisation levels as the dead band on the valves provided an automatic threshold. Also the hysteresis of typically 4 bits, and drift of the valve characteristic of a measured maximum of 16 bits, were overcome in this way.

Gains for Angular Position Control

The values of A1A and A1B were varied to find maximum stable values so that the highest possible speed of response could be obtained without any instability or overshoot. On the reach service the value of 5.1 rad/s/rad was used and on the lift service 2.6 rad/sec/rad (both these figures are equivalent to a fractional valve opening of 10/rad). It was found that values much higher than this gave overshoot, and lower values reduced the speed of movement, and so did not make the best use of available power.

Target Coordinate Increment Factor

Having set the gains for satisfactory control the Target Coordinate Increment Factor (CNST11 in the program code) was adjusted to give the maximum speed range over the full joystick travel. The parameter was set by increasing it until in general, at maximum joystick deflection, no oil would flow through the relief valve. Relief valve flow was detected by monitoring the supply line pressure and could also easily be heard.

12.3 Kinematic Evaluation

A series of experiments were carried out to test the accuracy of the straight line cutting of the bucket blade with the bucket moving in air and also when cutting ground.

The maximum deviation from a straight path when driven against an immovable obstacle was found to be 50 mm ± 5 mm at the blade and was measured against a straight piece of wood laid alongside the path of the bucket. The angular accuracy of the machine was measured over the range of pitch settings and the mean error was found to be 3° with a maximum error of 6°.

The speed range with a pump flow rate of 0.28 l/s (4.5 g.p.m.) was from 0.14 m/s to a maximum of 0.44 m/s measured over 2 m horizontally in air above ground.

The system positional accuracy was measured by positioning the bucket at various places on its envelope of movement, measuring its position with a steel tape measure, and comparing it with the calculated values of XO and YO as displayed on the monitor display using a data inspection program. The pitch control was set to zero so the X and Y axes were horizontal and vertical respectively. The mean error was found to be 30 mm.

A summary of the kinematic evaluation results is give below:

Correctness of Manual, Learn, and Repeat algorithms and code

Controllability of machine using single stage valves and eight bit ADC resolution of position

Sampling frequency 33 Hz

Minimum workable sampling frequency 26 Hz

Maximum deviation from straight path 50 mm

Angular accuracy 3°

Speed range at 1200 r.p.m. engine speed 0.14 - 0.44 m/s.

12.4 System Reliability

The evaluation phase of the project, carried out on the premises of F.W. McConnel Ltd., was conducted over a period of two months. The system construction was found to be such that very little time had to be spent finding and rectifying hardware faults arising, rather than fine tuning the software and conducting experiments. The problems which did arise however were as follows.

The weight of the transducers and the length of the screws used to secure the transducer bodies to the machine were such that vibration would tend to loosen the screws over a period of time despite the use of shake-proof washers. This is a design fault which could easily be recified by using larger screws or by moulding the transducer body out of plastic. Vibration again caused a problem in the wiring of the junction box housing the power switching transistors for the solenoid valves when a screw came loose. The use of double nuts, shakeproof washers, or nut locking compound should eliminate the problem. A spring loaded fuse holder on the back of the main rack also gave some trouble with a bad connection due to slight tension in the internal wiring.

The system was used in the field in conditions of frost and drizzle giving no other hardware problems. Use in heavy rain was not possible as a tractor with an enclosed cab was not available for housing the main rack.

12.5 Functional Evaluation

A series of trials was carried out to determine the relative merits of the computerised system against a conventional control system. The evaluation objective was defined to determine the relative work rates and quality of work for both experienced and inexperienced users. A total of six subjects were used in the course of the evaluations, two of whom were expert users of diggers, evaluating systems for F.W. McConnel, Ltd., and three of whom had no experience of using a digger at all, the remaining subject having limited experience.

When the equipment was first constructed the layout of the controls did not conform to that of a standard machine and this made the system totally unaccepable to experienced operators running the system under program DIG. The system was modified and was then found to be quite comfortable and easy to use for extended periods but the lever loads, if anything, were too light to readily discriminate by feel between the two different axes, sometimes causing selection of the wrong service. To avoid any problem of different joystick handling characteristics it was possible to use the same joystick unit for both systems and just change the EPROM in the computer to change from one program to the other.

It was decided to assign simple, well-defined tasks to different users and measure the time taken to perform the tasks and the quality of finish achieved over a range of tasks. All the digging operations were carried out on the premises of F.W. McConnel, Ltd. on a piece of ground of uniform soil composition and structure to eliminate any effects due to variation in terrain.

XY Control

With two of the novice users it was decided to attempt to reduce the effect of learning on performance evaluation of the two systems by having one subject run the system under program DIG then under MANCON, and the other subject in the reverse order. The actual digging process is a complex combination of vision, physical coordination, and judgement of how the material being dug behaves, as well as audible and visual cues from the machine. In view of this it was thought that whichever system a novice used first it may improve his performance on the second.

The experimental procedure taken was to explain the operation of the machine to the user, making sure that they fully understood the operation of the controls. For safety they were instructed to keep well out of reach of the machine but to stand wherever they wanted for visibility. The task to be performed was then explained and they were advised not to rush but to work steadily and get as good a finish as they reasonably could.

The first task was defined as to dig a rectangular hole the width of the bucket (1 m) and 2 m long and 60 cm deep, estimating the dimensions of the hole from the bucket. Two such holes were dug side by side to provide uniformity of dimensions, one hole being dug under program DIG and the other under program MANCON, the times being noted for each. Without being given their times the operators were asked which system they would choose to use firstly to perform the task in minimum time, and secondly to perform the task as precisely as possible.

The second task was defined as filling up the original hole and levelling off the surface as flat as possible.

The times taken by the two novice users are given in the following table:

User	Task	Mode	Time (Min.)
A	Dig trench	XY	10
		Conventional	8
	Fill and	Conventional	7
	level	XY	10
B	Dig trench	Conventional	22
		XY	22
	Fill and	XY	20
	level	Conventional	30

Different users vary dramatically in their ability to learn to control the machine when fitted with conventional mechanical controls. It was not surprising therefore to find a considerable difference between the two novice users in the time taken to perform nominally the same task under program MANCON.

Both operators expressed a marked preference for the machine operating under program DIG i.e. X-Y control.

A timed trial was also carried out with one of the experienced operators in digging a similar trench and the times taken were 9 minutes for the conventional and 14 minutes for the XY control system.

The feature of XY control was found not in general to significantly increase the work rate, in fact the indications are to the contrary. However, for making the final precise cuts necessary for a straight bottom or side to a hole the XY mode was very effective and the operator could trim the pitch control to get exactly the desired angle of cut.

Ditching

The XY facility was found to be of little value for the digging part of the ditch construction but readily gave uniform slopes to the sides of the ditch once the bulk of the earth had been removed.

Trenching

As described above for digging, the cutting of flat bottomed trenches was greatly facilitated for novice users as the exact desired slope could be obtained from a single control lever by setting the pitch to the appropriate angle.

Leveling

Novice users were immediately able to achieve results similar to those of experienced operators by setting the pitch to the horizontal and using the bottom of the bucket to spread the soil. The degree of coordination required to get a level surface with conventional controls takes a great deal of practice to acquire.

12.6 Learn & Repeat Facility

The Learn and Repeat algorithms and code were tested and operated as designed. One problem which presented itself in repeat mode was that of the bucket encountering an immovable obstacle and stalling i.e. being brought to a halt and with the relief valve blowing. It was found however that if the machine was set then to Manual Mode the bucket could almost invaribaly be freed by just opening and closing it through a small angle. This operation could be built into the software so that when the machine is stalled automatic correcticve action is taken.

For digging and trenching the learn and repeat facility was not found to be particularly useful even allowing for the tendency of the machine to stall. In Repeat Mode the principal difficulty was to start the repeat trajectory at an appropriate point to make the machine do useful work as it has no sensitivity or response to how full or empty the bucket may be. The repeat slow mode was found to be of no value at all.

The learn and repeat facility was evaluated on the cutting of ditches by an experienced operator and by the author. A problem which arose was the large number of piecemeal preliminary cuts to form the basic ditch. A further problem was in estimating where to commence the repeat process. The actual repeat cutting process itself was accurate and smooth, i.e. kinematically to specification.

12.7 Estimation of Cost

In order to asses any potential commercial viablilty of a microprocessor based system a specification of the hardware was given to the company Monolog for preliminary costing of a small batch of control units excluding the transducers. The price that they quoted was £1100 pounds per unit and the cost of the basic conventional digger is £3500 retail. Therefore very substantial performance gains have to be demonstrated to justify the extra cost on a functional basis.

The set of three transducers used in the experimental prototype were made by an apprentice and took one month. However, if the bodies and spindle block were cast out of a suitable plastic material or automatically machined, they could be made rapidly for a fraction of the cost.

CHAPTER THIRTEEN

DISCUSSION

13.1 Hardware

The system hardware as constructed was found to meet quite adequately the functional and experimental requirements for evaluation purposes. Inevitably there were some short-comings in the design, a number of which have been mentioned in the hardware chapters and some of a more general nature are discussed below. If the system were to be manufactured there are a number of modifications and additions which would have to be made.

Transducers

The principal fault with the transducers as produced was that of the securing screws working undone with vibration. This can be rectified by lengthening the screws and increasing their diameter. Access to the screws with allen keys was difficult and could be eased by the use of hexagonal headed bolts. Plastic film potentiometers were employed as the sensing elements and they have and extremely long life but if these were subject to wear they could be replaced by inductive potentiometers of appropriate resolution. The 'O' ring seal on the spindle block could also be replaced with a type better suited to rotation.

Computer

In terms of cost, speed, and I/O capabilities the combination of the SDK-85 and AM9511 Arithmetic Processor Unit were ideal, however as costs come down Intel 8086 and 8087 devices may become a viable alternative. The minimum satisfactory sampling frequency was found to be 26 Hz, corresponding to a loop cycle time of 38 ms. Throughout the program there is overkill in precision of numerical computation which is almost exclusively carried out in 32-bit floating point format. However, even if the word length were halved, it is unlikely that the APU could be replaced with a sequence of software routines for mathematical operations and achieve a sufficiently short loop execution time. Relative times for APU computations and software computations on 32 bit floating point numbers given by AMD are:

	AM9511	Software
	(Times in microseconds)	
Multiply	200	7,000
SQRT	400	77,000
Sin(x)	2,000	118,000

Thus for a 32-bit word length, a single software square root takes over double the required minimum loop execution time. It is unlikely therefore that the software could be written to run effectively on a single 8-bit processor. Sine and cosine calculations could be done at high speed with a look-up table to eight bit accuracy but there are still over 70 basic arithmetic operations to be carried out in the main loop in manual mode.

I/O Capability

The keyboard and display are only necessary for developmental purposes and could be dispensed with on a commercial machine. Additional valve control circuitry should be used to replace the bang-bang valve on the bucket with a proportional valve. The bang-bang valve used at present gives rise to sharp pressure transients in the supply. For use on a machine with changeable geometry a set of rotary thumbwheel switches are required to input data on the machine configuration being employed. The number of analogue input channels should be increased by one to allow the slew function to be incorporated in the Learn and Repeat facility and a certain amount of memory expansion to contain the additional slew position data would be required.

Controls

Better waterproofing of the mode selector switches could be achieved by using customised tacitle pressure switches which are cheap and reliable. The joystick axis directional sense could also be improved by stronger springing to prevent accidental selection of the wrong service.

Circuitry

For a commercial machine the circuitry should be constructed on printed circuit boards and ideally built in a modular form so that whole assemblies may be replaced if a fault arises in the field. Self-diagnostics would be useful for this purpose provided that they did not add significantly to the cost. The packaging of the rack and control panel should also be made watertight. Waterproof connectors to the rack should also be used despite their price as they do provide weather-proofing.

13.2 Software

Very considerable simplifications could be made to the existing software to shorten it. The emphasis is the way it was written in the project has been on readability and convenience of coding by extensive use of the APU. Also the data structure is such that program constants may be varied which is not necessary as optimal values are now obtained. A commercial system should have the control of the slew service incorporated into the learn and repeat facility which was omitted in the present system because there was not enough room to test this function in the laboratory. Also, different configurations of the machine, requiring different program constants, should be accommodated in any commercial system.

13.3 Safety

To be completely safe from any contact with the moving arms or the bucket the operator should at all times stand behind the machine, out of reach. However with a portable control panel the operator may walk forward to improve his visibility of the bucket. The potential dangers of slipping on wet ground and falling in the path ot the bucket or in the hole being dug are lethal. The dangers may be reduced by the use of an emergency stop button on the front of the control panel as included on the circuit built and the use of a mercury switch internally to disable the power supply if the box should be tilted as the operator falls or drops it.

Besides the danger of the operator straying or falling into the path of the machine there is the danger of a circuit malfunction causing some erratic or unexpected behaviour of the machine thereby also endangering the operator or any other person within range.

The Health and Safety Executive recommendations on operating procedures for microprocessor controlled manipulators[34] state that safety should be ensured by either ensuring the operator cannot come with in the range of the machine or that a working procedure be adopted which guarantees against any dangers from machine malfunction. In an agricultural environment the only way to ensure this is to have the control panel mounted in the tractor cab or on the machine itself.

13.4 Hydraulics

The question may be asked as to whether the machine work rate may not be increased by raising the supply pressure and hence the system speed and cutting force. There is however a limit to the acceleration which can be tolerated without material spilling from the bucket and also, particularly in the case of the slewing service, the angular momentum which is imparted to the machine may cause overshoot under manual control.

The IWT and tilt functions necessary for the later model of machine should be incorporated into the electronic design so that all function may be operated from one control panel. Also a proportional valve for operating the bucket would improve the smoothness of response of the system by eliminating the sharp pressure transients imposed on the supply by the opening and closing of the bang-bang valve.

13.5 Functional Aspects

The trials carried out demonstrate that there is no consistent significant increase in work rate for new users. Despite the effective rationalisation of the lever functions to bucket blade movements so that linear cuts may readily be obtained the overall digging process was not facilitated.

Part of the reason for this may lie in the fact that the movement produced by the deflection of a particular lever is not obvious from the geometry of the machine. On the conventional control system the effect of each control axis is to operate a particular ram so by viewing the geometry of the machine it is clear which rams need to be activated to move the bucket in particular directions. With the XY control system a single joystick axis in conjunction with the pitch control will give any straight cut but the path has to be visulaised and is not determined from the machine geometry.

In the levelling process however, and in cutting smooth planes, the XY control is extremely effective. To get a planar cut with conventional controls it is necessary to continuously vary the bucket, lift, and reach valve openings as against operating one lever with appropriate pitch setting.

Another problem for the novice user is that of selecting the appropriate joystick axis for the movement required: this still has to be learned even though the number of simultaneous selections is reduced.

The lack of workrate increase for experienced operators must be attributed to their optimal use of conventional control so that maximum power is used from the machine in all operation and no wrong service selections are made. Having to unlearn the ingrained experience of conventional machine use may detract from their performance in the XY system.

More detailed trials on a larger number of subjects would yield more insight into the different factors of the complex man-machine interaction such as error rates and learning effects. However conditions and time constraints did not allow for more numerous and detailed investigations.

13.6 Commercial Considerations

To evaluate the microprocessor based system as a potential product it is necessary to weigh up the various pros and cons comparing it with the conventional mechanical system which is tried and tested. The functional advantages include the improved accuracy and control for novice users, the facility for cutting at defined inclinations, ease of installation in the cab, and reduced lever loads giving less fatigue. It also has a definite technological gimmick value for those susceptible to such things! The novice users preferred it both for speed and precision even though for speed there was no gain.

However, cost, reliability, based on the number of parts to fail, and also possible servicing, count heavily against the system. The technological and manpower investment necessary to launch commercially into the development and support of such a high technology device could only be justified on the grounds of very significant functional advantages, far greater than the marginal benefits shown by the experimental system produced in this project. In addition there may be a certain amount of technologial resistance, which would have to be assessed, from those having to start dealing in a new technology be it from salesmen, dealers, or customers.

The mechanical control systems currently employed have evolved over a period of years to a high degree of reliability. Commercial experience with functionally relatively simple electric valve controllers for hedge cutters working bang-bang valves has shown that exceedingly high standards of design and manufacture are necessary to make the product a success. With a functionally much more complex system the task can be no easier.

The case for the commercial development of the simpler electronic controller described in its basic form in Chapter 3 is much stronger however, as the system is much simpler electronically and offers the advantages of ease of installation and light lever loads. Ease of installation is important as the digger may frequently be attached to and detached from the tractor, and mechanical cables can be difficult to accommodate and to feed into the cab; they also impose higher lever loads on the operator than levers mounted on the valve block.

CHAPTER FOURTEEN

CONCLUSIONS & FURTHER WORK

14.1 Conclusions

The work carried out shows that the solenoid operated proportional valves can be effectively used for both manual open loop control of the machine and computer closed loop control. The open loop controller is functionally advantageous over the conventional mechanical control system with cables for in-cab operation. It is both easier to install and reduces the lever loads resulting from spool return springs and the connecting cables, which can become tiring.

The algorithm developed for control of the machine effectively converts the control functions from individual rams to those of veclocity control in a Cartesian framework with an accuracy sufficient for all digging operations. The pitch control allows control of the angle of cut to an accuracy of ±3°. The learn and repeat software functioned as designed allowing any profile once taught to the machine to be repeated from any new starting point at any angle selected on the pitch control.

The computer hardware and the transducers functioned reliably and as designed. With a few modifications given in the Discussion the hardware could be put into production if desired. The work demonstrates the technical feasibility of producing a closed loop microprocessor based control system at a cost commensurate with that of the machine.

Evaluation trials, carried out with both experienced and inexperienced digger operators, however showed that there was no consistent significant increase of work rate using the computer control system in either its manual or learn and repeat modes of operation. The operations of making straight cuts and levelling were facilitated for both classes of user and novice operators were able to achieve results otherwise impossible without extensive practice.

In the light of these results it may be said that the benefits to the operator are not such as to justify development of the existing prototype computerised system for commercial production. However, the open loop electronic controller, provided a sufficiently reliable and robust design and construction are employed, is a far more viable product.

14.2 Further Work

It has been shown that the automation of the cutting of straight lines does not effectively increase work throughput, a necessary condition for a viable product. The decision making stage in lever selection is not eliminated. However this does suggest that a telechiric type of system with the control handle mounted on a miniature linkage similar to that of the digger may prove more successful. If the manually imposed troques at the pivots of the control linkage are sensed and used to operate the corresponding valves, while at the same time the position of the control inkage is sevoed by say d.c. motors to correspond to that of the machine then a sense of feel would also result. The digger would automatically mimic the movements of the control handle and the operator would not have to consciously control individual rams.

Tractor mounted hedge cutters are limited in their speed of operation be the rate at which the operator can adjust the inclination of the head to the hedge and tractor position. It may be possible to apply a control regime, as here developed for a digger, to obtain independent control of up-and-down and in-and-out movement from two levers. The hardware built for the digger could readily be re-programmed to operate a hedge cutter if appropriate transducers were fitted and either using a similar control regime or resolved rate motion.

If successful, simplification could then be made to the mechanical construction of the machine offsetting the cost of the electronics and transducers. Automation of control of the cutter to compensate for varying tractor-hedge distance as well as variations in tractor inclination would be extremely complex and expensive. The principal problem is to find a suitable reference line in the hedge being cut from which the cutter can be positioned. A further possibility would be to employ a telechiric system for hedge cutter control.

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APPENDIX A

PROGRAM MANCON

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ASM80 :F1:MANCON.SRC


ISIS-II 8080/8085 MACRO ASSEMBLER, V4.0        MODULE   PAGE    1

  LOC  OBJ         LINE        SOURCE STATEMENT

                      1 $MOD85 MACROFILE
 3000                 2          ORG      3000H                       ;UNIVERSITY OF LIVERPOOL
                      3                                               ;DEPARTMENT OF ELECTRICAL ENGINEERING
                      4                                               ; AND ELECTRONICS
                      5                                               ;
                      6                                               ; E.R.I. DEANE
                      7                                               ;
                      8                                               ;THIS IS AN ASSEMBLY LANGUAGE PROGRAM
                      9                                               ; FOR MANUAL CONTROL OF A PA6 DIGGER
                     10                                               ;
                     11                                               ;CODE EDITED 1530 4TH JANUARY 1983
                     12                                               ; DISK: NO. 4   VERSION 2.6
                     13                                               ;
                     14                                               ;
                     15                                               ;** RAM LOCATIONS FOR PROGRAM VARIABLES **
                     16                                               ;
  3000               17 JXDOT:  DS       4                            ;JOYSTICK INPUT XDOT IN USER CO-ORDS
  3004               18 JYDOT:  DS       4                            ;    "          "    YDOT   "  "       "
  3008               19 JSLEW:  DS       4                            ;    "          "    SLEW RATE
  300C               20 JBKT:   DS       4                            ;    "          "    BUCKET MOVEMENT
  3010               21 I1:     DS       4                            ;INTERMEDIATE RESULT LOCATION
  3014               22 I2:     DS       4                            ;INTERMEDIATE RESULT LOCATION
  3018               23 STATUS: DS       1                            ;STATUS OF APU
  3019               24 S:      DS       4                            ;INTERMEDIATE RESULT LOCATION
  301D               25 V1:     DS       4                            ;LOCATION FOR IFF DATA TRANSFER
  3021               26 V2:     DS       4                            ;LOCATION FOR IFF DATA TRANSFER
  3025               27 VVSLEW: DS       4                            ;SLEW VALVE SETTING (32 BIT FORMAT)
  3029               28 VVALFA: DS       4                            ;ALPHA VALVE   "          "      "
  302D               29 VVBETA: DS       4                            ;BETA VALVE    "          "      "
  3031               30 VVBKT:  DS       4                            ;BUCKET VALVE  "          "      "
  3035               31 VS:     DS       1                            ;SLEW VALVE SETTING (8 BIT FORMAT)
  3036               32 VL:     DS       1                            ;LIFT   "      "      "     "
  3037               33 VR:     DS       1                            ;REACH  "      "      "     "
  3038               34 VB:     DS       1                            ;BUCKET "      "      "     "
  3039               35 FVO:    DS       4                            ;FRACTIONAL VALVE OPENING USED AS
                     36                                               ; A PARAMTER FOR SUBROUTINE VLIN
  303D               37 ASTR:   DS       1                            ;STORAGE LOCATION FOR A REGISTER
  303E               38 OFFSET: DS       1                            ;WORKSPACE FOR SUBROUTINE VLIN
  303F               39 MAX:    DS       1                            ;     "      "      "       "
  3040               40 POF:    DS       1                            ;     "      "      "       "
  3041               41 NOF:    DS       1                            ;     "      "      "       "
  3042               42 PMAX:   DS       1                            ;     "      "      "       "
  3043               43 NMAX:   DS       1                            ;     "      "      "       "
  3044               44 APOF:   DS       1                            ;ALPHA +VE OFFSET
  3045               45 APMAX:  DS       1                            ;ALPHA +VE SATN. O/P
  3046               46 ANOF:   DS       1                            ;ALPHA -VE OFFSET
  3047               47 ANMAX:  DS       1                            ;ALPHA -VE SATN. O/P
  3048               48 BPOF:   DS       1                            ;BETA +VE OFFSET
  3049               49 BPMAX:  DS       1                            ;BETA +VE SATN. O/P
  304A               50 BNOF:   DS       1                            ;BETA -VE OFFSET
  304B               51 BNMAX:  DS       1                            ;BETA -VE SATN. O/P
  304C               52 SPOF:   DS       1                            ;SLEW +VE OFFSET
  304D               53 SPMAX:  DS       1                            ;SLEW +VE SATN. O/P
  304E               54 SNOF:   DS       1                            ;SLEW -VE OFFSET
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ISIS-II 8080/8085 MACRO ASSEMBLER, V4.0          MODULE   PAGE    2

 LOC  OBJ          LINE        SOURCE STATEMENT

 304F                55 SNMAX:  DS      1                          ;SLEW -VE SATN. O/P
                     56                                            ;
 8000                57 ORG     8000H                              ;** EPROM LOCATIONS CONTAINING
                     58                                            ;                      PROGRAM DATA **
                     59                                            ;
                     60                                            ;DEFAULT VALUES FOR VALVE OFFSETS
 8000 C0             61 XAPOF:  DB      0C0H
 8001 FF             62 XAPMAX: DB      0FFH
 8002 40             63 XANOF:  DB      40H
 8003 7F             64 XANMAX: DB      7FH
 8004 40             65 XBPOF:  DB      40H
 8005 7F             66 XBPMAX: DB      7FH
 8006 C0             67 XBNOF:  DB      0C0H
 8007 FF             68 XBNMAX: DB      0FFH
 8008 C0             69 XSPOF:  DB      0C0H
 8009 FF             70 XSPMAX: DB      0FFH
 800A 40             71 XSNOF:  DB      40H
 800B 7F             72 XSNMAX: DB      7FH
                     73                                            ;PROGRAM CONSTANTS
 800C 00             74 TEN:    DB      00H,00H,0A0H,04H           ;10D
 800D 00
 800E A0
 800F 04
 8010 00             75 TWO:    DB      00H,00H,80H,02H            ;2D
 8011 00
 8012 80
 8013 02
 8014 00             76 H87:    DB      00H,00H,87H,08H            ;87H = 135D
 8015 00
 8016 87
 8017 08
 8018 00             77 H79:    DB      00H,00H,0F2H,07H           ;79H = 121D
 8019 00
 801A F2
 801B 07
 801C 00             78 ZERO:   DB      00H,00H,00H,00H            ;0D
 801D 00
 801E 00
 801F 00
 8020 00             79 ONE:    DB      00H,00H,80H,01H            ;1D
 8021 00
 8022 80
 8023 01
 8024 FE             80 HALF:   DB      0FEH,0FFH,0FFH,7FH         ;0.5D
 8025 FF
 8026 FF
 8027 7F
 8028 00             81 MINONE: DB      00H,00H,80H,81H            ;-1D
 8029 00
 802A 80
 802B 81
 802C 00             82 D14:    DB      00H,00H,0E0H,04H           ;14D
 802D 00
 802E E0
 802F 04
 LOC  OBJ          LINE        SOURCE STATEMENT

8030 00              83 CNST20: DB      00H,00H,0F0H,06H        ;3CH=60D
8031 00
8032 F0
8033 06
8034 00              84 CNST21: DB      00H,00H,98H,07H         ;4CH=76D
8035 00
8036 98
8037 07
8038 00              85 H255:   DB      00H,00H,0FFH,08H        ;FFH=255D
8039 00
803A FF
803B 08
                     86                                         ;
80D0                 87         ORG     80D0H                   ;** MAIN PROGRAM **
                     88                                         ;
                     89                                         ;APU STACK PUSH MACRO
                     90 PSH     MACRO   XYZ
-                    91         LXI     D,XYZ
-                    92         CALL    PSHT
                     93         ENDM
                     94                                         ;APU STACK POP MACRO
                     95 PLL     MACRO   PQR
-                    96         LXI     D,PQR
-                    97         CALL    PLLT
                     98         ENDM
                     99                                         ;
80D0 060C           100         MVI     B,0CH                   ;SET UP DEFAULT VALVE CONSTANTS
80D2 110080         101         LXI     D,XAPOF
80D5 214430         102         LXI     H,APOF
80D8 1A             103 DLOOP:  LDAX    D                       ;LOOP TO COPY DEFAULT OFFSET
80D9 77             104         MOV     M,A                     ; VALUES FROM ROM TO RAM
80DA 13             105         INX     D
80DB 23             106         INX     H
80DC 05             107         DCR     B
80DD C2D880         108         JNZ     DLOOP
                    109                                         ;
80E0 3EF8           110         MVI     A,0F8H                  ;UNMASK AND DISABLE INTERRUPTS
80E2 30             111         SIM
80E3 F3             112         DI
                    113                                         ;
80E4 31C220         114         LXI     SP,20C2H                ;SET STACK POINTER
                    115                                         ;
80E7 CD2B81         116         CALL    INIT                    ;INITIALISE SYSTEM
                    117                                         ;
80EA 3ECF           118         MVI     A,0CFH                  ;SET UP VECTORED INTERRUPT RESET
80EC 32CE20         119         STA     20CEH                   ; INSTRUCTION BY LOADING LOCATION
                    120                                         ; 20CEH WITH 0CFH
                    121                                         ;
                    122                                         ;** MAIN CONTROL LOOP **
                    123                                         ;
80EF CD3A81         124 LOOP:   CALL    CONV                    ;SUBROUTINE CONV READS IN CONTROL
                    125                                         ; SETTINGS JXDOT, JYDOT, JBKT
                    126                                         ; AND JSLEW
                    127                                         ;
                    128         PSH     JXDOT                   ;ASSIGN TO EACH VALVE SETTING THE
 LOC  OBJ          LINE         SOURCE STATEMENT

80F2 110030         129+         LXI     D,JXDOT
80F5 CD9481         130+         CALL    PSHT
                    131          PLL     VVBETA                       ; CORRESPONDING JOYSTICK DEFLECTION
80F8 112D30         132+         LXI     D,VVBETA
80FB CDAE81         133+         CALL    PLLT
                    134          PSH     JYDOT
80FE 110430         135+         LXI     D,JYDOT
8101 CD9481         136+         CALL    PSHT
                    137          PLL     VVALFA
8104 112930         138+         LXI     D,VVALFA
8107 CDAE81         139+         CALL    PLLT
                    140          PSH     JBKT
810A 110C30         141+         LXI     D,JBKT
810D CD9481         142+         CALL    PSHT
                    143          PLL     VVBKT
8110 113130         144+         LXI     D,VVBKT
8113 CDAE81         145+         CALL    PLLT
                    146          PSH     JSLEW
8116 110830         147+         LXI     D,JSLEW
8119 CD9481         148+         CALL    PSHT
                    149          PLL     VVSLEW
811C 112530         150+         LXI     D,VVSLEW
811F CDAE81         151+         CALL    PLLT
                    152                                           ;
8122 CDB782         153          CALL    OUTPUT                   ;OUTPUT DATA TO VALVE CONTROL
                    154                                           ; INTERFACE
                    155                                           ;
8125 FB             156          EI                               ;ALLOW INTERRUPT FROM KEYBOARD
8126 00             157          NOP
8127 F3             158          DI
                    159                                           ;
8128 C3EF80         160          JMP     LOOP
                    161                                           ;
                    162                                           ;
                    163                                           ;** MACRO FOR CONDITIONAL JUMPS **
                    164                                           ;
                    165                                           ; THIS MACRO GENERATES CODE FOR MAKING
                    166                                           ;CONDITIONAL JUMPS DEPENDING ON THE VALUES
                    167                                           ;OF TWO FLOATING POINT VARIABLES ID1 AND ID2
                    168                                           ;
                    169                                           ;IF ID1 GTHAN;GEQUAL;EQUALS;NEQUAL;LEQUAL;LTHAN ID2
                    170                                           ; THEN GOTO LABL
                    171                                           ; ELSE CONTINUE
                    172                                           ;
                    173                                           ;REGISTERS AFFECTED: A,D,E,STATUS
                    174                                           ;
                    175                                           ; DATA IS PASSED TO SUBROUTINE OP IN TEMPORARY
                    176                                           ; VARIABLES V1 AND V2.  THE RESULT IS RETURNED
                    177                                           ; IN THE ACC.: 1=TRUE, 0=FALSE.  THE RESULT OF
                    178                                           ; OP IS CHECKED AND CONTROL JUMPS OR CONTINUES
                    179                                           ; ACCORDINGLY.
                    180                                           ;
                    181 IFF      MACRO   ID1,OP,ID2,LABL
                    182          PSH     ID1
                    183          PLL     V1
 LOC  OBJ          LINE        SOURCE STATEMENT

-                   184         PSH     ID2
-                   185         PLL     V2
-                   186         CALL    OP
-                   187         ANI     01H
-                   188         JNZ     LABL
                    189         ENDM
                    190                                                    ;
                    191                                                    ;
                    192                                                    ;
                    193                                                    ;
                    194                                                    ;
                    195                                                    ;
                    196                                                    ;** SUBROUTINE INIT **
                    197                                                    ;
                    198                                                    ; SETS UP I/O PORT DATA DIRECTION
                    199                                                    ; REGISTERS
                    200                                                    ;
                    201                                                    ;REGISTERS AFFECTED: A
                    202                                                    ;
 812B 3E0F          203 INIT:   MVI     A,0FH                              ;SET PORTS 21,22,23 FOR OUTPUT
 812D D320          204         OUT     20H
 812F 3EFF          205         MVI     A,0FFH
 8131 D302          206         OUT     02H
 8133 D303          207         OUT     03H
 8135 3E0C          208         MVI     A,0CH
 8137 D328          209         OUT     28H
 8139 C9            210         RET
                    211                                                    ;
                    212                                                    ;** SUBROUTINE CONV **
                    213                                                    ;
                    214                                                    ; READS IN CONTROL JOYSTICK SETTINGS:
                    215                                                    ;JSLEW, JYDOT, JXDOT, JBKT
                    216                                                    ;
                    217                                                    ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                    218                                                    ;
 813A 3E03          219 CONV:   MVI     A,03H                              ;LOAD A REGISTER WITH SLEW CONTROL
                    220                                                    ; JOYSTICK CHANNEL NUMBER
 813C CD7381        221         CALL    ADCON                              ;PERFORM A TO D CONVERSION
 813F CD2E82        222         CALL    JOYSTK                             ;TRANSFORMS JOYSTICK INPUT TO
                    223                                                    ; RANGE -1 TO +1 LEAVING THE RESULT
                    224                                                    ; ON THE TOP OF THE APU STACK
                    225         PLL     JSLEW
 8142 110830        226+        LXI     D,JSLEW
 8145 CDAE81        227+        CALL    PLLT
 8148 3E04          228         MVI     A,04H                              ;READ YDOT INPUT FROM JOYSTICK
 814A CD7381        229         CALL    ADCON
 814D CD2E82        230         CALL    JOYSTK
                    231         PLL     JYDOT
 8150 110430        232+        LXI     D,JYDOT
 8153 CDAE81        233+        CALL    PLLT
 8156 3E05          234         MVI     A,05H                              ;READ XDOT INPUT FROM JOYSTICK
 8158 CD7381        235         CALL    ADCON
 815B CD2E82        236         CALL    JOYSTK
                    237         PLL     JXDOT
 815E 110030        238+        LXI     D,JXDOT
 LOC  OBJ          LINE        SOURCE STATEMENT

 8161 CDAE81        239+         CALL    PLLT
 8164 3E06          240          MVI     A,06H                        ;READ BUCKET VELOCITY INPUT FROM
 8166 CD7381        241          CALL    ADCON                        ; JOYSTICK
 8169 CD2E82        242          CALL    JOYSTK
                    243          PLL     JBKT
 816C 110C30        244+         LXI     D,JBKT
 816F CDAE81        245+         CALL    PLLT
 8172 C9            246          RET
                    247                                               ;
                    248                                               ;
                    249                                               ;
                    250                                               ;** SUBROUTINE ADCON **
                    251                                               ;
                    252                                               ;OPERATES THE ANALOGUE TO DIGITAL
                    253                                               ; CONVERTER. THE CHANNEL NUMBER
                    254                                               ; IS IN THE A REGISTER ON CALLING
                    255                                               ; AND THE RESULT AT RETURN
                    256                                               ;
                    257                                               ;REGISTERS AFFECTED: A,H,L,STATUS
                    258                                               ;
 8173 D32B          259 ADCON:   OUT     2BH                          ;OUTPUT CHANNEL NUMBER
 8175 C608          260          ADI     08H                          ;LATCH CHANNEL NUMBER
 8177 D32B          261          OUT     2BH                          ;
 8179 AF            262          XRA     A                            ;CLEAR CONTROL WORD
 817A D32B          263          OUT     2BH
 817C 211100        264          LXI     H,0011H                      ;SET DELAY VALUE
 817F CD8D81        265          CALL    PAUSE                        ;CALL DELAY ROUTINE
 8182 3E10          266          MVI     A,10H                        ;SET TRISTATE OUTPUT
 8184 D32B          267          OUT     2BH
 8186 00            268          NOP
 8187 00            269          NOP
 8188 00            270          NOP
 8189 00            271          NOP
 818A DB29          272          IN      29H                          ;READ RESULT
 818C C9            273          RET
                    274                                               ;
                    275                                               ;
                    276                                               ;** PAUSE **
                    277                                               ;
                    278                                               ;SUBROUTINE FOR DELAY
                    279                                               ; DECREMENTS INPUT IN HL
                    280                                               ; REGISTER PAIR UNTIL ZERO
                    281                                               ;
                    282                                               ;REGISTERS AFFECTED: H,L,STATUS
                    283                                               ;
 818D 2B            284 PAUSE:   DCX     H
 818E 7C            285          MOV     A,H
 818F B5            286          ORA     L
 8190 C28D81        287          JNZ     PAUSE
 8193 C9            288          RET
                    289                                               ;
                    290                                               ;
                    291                                               ;
                    292                                               ;** SUBROUTINE PSHT **
                    293                                               ;
```

```
  LOC  OBJ         LINE        SOURCE STATEMENT

                    294                                                   ;PUSHES A 32-BIT FL. PT. VARIABLE
                    295                                                   ; ONTO THE APU STACK
                    296                                                   ; DE CONTAINS THE ADDRESS
                    297                                                   ; OF THE LS BYTE OF THE
                    298                                                   ; OPERAND ON CALLING
                    299                                                   ; AND OF THE MS BYTE AT
                    300                                                   ; RETURN
                    301                                                   ;
                    302                                                   ;REGISTERS AFFECTED: D,E
                    303                                                   ;
  8194 C5           304 PSHT:   PUSH    B                                 ;PUSH ACC ON STACK
  8195 47           305         MOV     B,A
  8196 C5           306         PUSH    B
  8197 1A           307         LDAX    D                                 ;LD ACC WITH LS BYTE
  8198 320010       308         STA     1000H                             ;PUSH ACC TO APU
  819B 13           309         INX     D                                 ;INCREMENT DATA POINTER
  819C 1A           310         LDAX    D
  819D 320010       311         STA     1000H
  81A0 13           312         INX     D
  81A1 1A           313         LDAX    D
  81A2 320010       314         STA     1000H
  81A5 13           315         INX     D
  81A6 1A           316         LDAX    D
  81A7 320010       317         STA     1000H
  81AA C1           318         POP     B
  81AB 78           319         MOV     A,B
  81AC C1           320         POP     B
  81AD C9           321         RET
                    322                                                   ;
                    323                                                   ;
                    324                                                   ;** SUBROUTINE PLLT **
                    325                                                   ;
                    326                                                   ;PULLS A 32-BIT FL. PT. VARIABLE
                    327                                                   ; FROM THE APU STACK
                    328                                                   ; DE CONTAINS ADDRESS OF LS
                    329                                                   ; BYTE ON CALLING AND MS
                    330                                                   ; BYTE AT RETURN
                    331                                                   ;
                    332                                                   ;REGISTERS AFFECTED: D,E
                    333                                                   ;
  81AE C5           334 PLLT:   PUSH    B
  81AF 47           335         MOV     B,A
  81B0 C5           336         PUSH    B
  81B1 13           337         INX     D
  81B2 13           338         INX     D
  81B3 13           339         INX     D
  81B4 3A0010       340         LDA     1000H
  81B7 12           341         STAX    D
  81B8 1B           342         DCX     D
  81B9 3A0010       343         LDA     1000H
  81BC 12           344         STAX    D
  81BD 1B           345         DCX     D
  81BE 3A0010       346         LDA     1000H
  81C1 12           347         STAX    D
  81C2 1B           348         DCX     D
```

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 LOC  OBJ          LINE        SOURCE STATEMENT

 81C3 3A0010        349         LDA     1000H
 81C6 12            350         STAX    D
 81C7 C1            351         POP     B
 81C8 78            352         MOV     A,B
 81C9 C1            353         POP     B
 81CA C9            354         RET
                    355                                         ;
                    356                                         ;
                    357                                         ;** SET OF SUBROUTINES FOR EVALUATING
                    358                                         ; OPERATORS IN CONDITIONAL JUMPS **
                    359                                         ;
                    360                                         ;EACH SUBROUTINE RETURNS 01H IN THE
                    361                                         ; ACCUMULATOR IF THE CONDITION IT TESTS  IS VALID.
                    362                                         ;
                    363                                         ;REGISTERS AFFECTED A,D,E,STATUS
                    364                                         ;
 81CB CD0682        365 GTHAN:  CALL    EQUALS                  ;CALL EQ TO CHECK FOR EQUALITY AND
                    366                                         ; SET SIGN BIT
 81CE E601          367         ANI     01H                     ; OF THE APU FOR THE SUBTRACTION V1-V2
 81D0 CAD581        368         JZ      L2                      ;IF VARIABLES ARE NOT EQUAL THEN L2
 81D3 AF            369         XRA     A                       ; ELSE CLEAR ACCUMULATOR AND RETURN
 81D4 C9            370         RET
 81D5 3A1830        371 L2:     LDA     STATUS                  ;CHECK SIGN OF RESULT V1-V2
 81D8 E640          372         ANI     40H
 81DA CADF81        373         JZ      L3
 81DD AF            374         XRA     A                       ;NEGATIVE RESULT SIGN: CLR ACC & RETURN
 81DE C9            375         RET
 81DF 3E01          376 L3:     MVI     A,01H                   ;POSITIVE RESULT SIGN: SET ACC TO 01 & RET
 81E1 C9            377         RET
                    378                                         ;
                    379                                         ;
 81E2 CD0882        380 LTHAN:  CALL    EQUALS                  ;CALL EQ TO CHECK FOR EQUALITY AND SET
 81E5 E601          381         ANI     01H                     ; SIGN BIT OF APU FOR THE SUBTRACTION
                    382                                         ; V1-V2
 81E7 CAEC81        383         JZ      L4                      ;IF VARIABLES ARE NOT EQUAL THEN L4 ELSE
 81EA AF            384         XRA     A                       ; CLEAR ACC & RETURN
 81EB C9            385         RET
 81EC 3A1830        386 L4:     LDA     STATUS                  ;CHECK SIGN OF RESULT OF SUBTRACTION V1-V2
 81EF E640          387         ANI     40H
 81F1 C2F681        388         JNZ     L5
 81F4 AF            389         XRA     A                       ;POSITIVE SIGN: CLR ACC AND RETURN
 81F5 C9            390         RET
 81F6 3E01          391 L5:     MVI     A,01H                   ;NEGATIVE SIGN: SET ACC TO 01 AND RET
 81F8 C9            392         RET
                    393                                         ;
                    394                                         ;
 81F9 CDE281        395 GEQUAL: CALL    LTHAN                   ;CALL LT AND INVERT RESULT
 81FC 2F            396         CMA
 81FD C9            397         RET
                    398                                         ;
                    399                                         ;
 81FE CDCB81        400 LEQUAL: CALL    GTHAN                   ;CALL GT AND INVERT RESULT
 8201 2F            401         CMA
 8202 C9            402         RET
                    403
 LOC  OBJ          LINE        SOURCE STATEMENT

 8203 CD0882        404 NEQUAL: CALL EQUALS
 8206 2F            405         CMA
 8207 C9            406         RET
                    407                                         ;
                    408                                         ;
                    409 EQUALS: PSH      V1                     ;SUBTRACT V2 FROM V1
 8208 111D30        410+        LXI      D,V1
 820B CD9481        411+        CALL     PSHT
                    412         PSH      V2
 820E 112130        413+        LXI      D,V2
 8211 CD9481        414+        CALL     PSHT
 8214 CDB584        415         CALL     FSUB
 8217 3A0011        416 L6:     LDA      1100H                  ;WAIT TILL APU NOT BUSY
 821A E680          417         ANI      80H
 821C C21782        418         JNZ      L6
 821F 3A0011        419         LDA      1100H
 8222 321830        420         STA      STATUS                 ;TRANSFER APU STATUS TO CORE
 8225 E620          421         ANI      20H                    ;CHECK ZERO BIT
 8227 C22B82        422         JNZ      L7
 822A C9            423         RET                             ;RETURN 00 IN A REG INDICATING INEQUALTY
 822B 3E01          424 L7:     MVI      A,01H                  ;RETURN 01 IN A REG INDICATING EQUALITY
 822D C9            425         RET
                    426
                    427
                    428                                         ;
                    429                                         ;
                    430                                         ;** SUBROUTINE JOYSTK **
                    431                                         ;
                    432                                         ;THE JOYSTICK VOLTAGE IS IN THE A REGISTER
                    433                                         ; ON CALLING. THE SUBROUTINE CONVERTS
                    434                                         ; IT TO THE RANGE -1 TO +1 AND LEAVES
                    435                                         ; THE RESULT ON TOP OF THE APU STACK
                    436                                         ;
                    437                                         ;REGISTERS AFFECTED: A,D,E,STATUS
                    438                                         ;
 822E 320010        439 JOYSTK: STA      1000H                  ;CONVERT JOYSTICK VOLTAGE TO 32 BIT
 8231 AF            440         XRA      A                      ; FORMAT
 8232 320010        441         STA      1000H
 8235 CDA984        442         CALL     FLTS
                    443         PLL      I1
 8238 111030        444+        LXI      D,I1
 823B CDAE81        445+        CALL     PLLT
                    446         IFF      I1,GTHAN,H87,L50       ;IF JOYSTICK VOLTAGE>87H THEN L50
                    447+        PSH      I1
 823E 111030        448+        LXI      D,I1
 8241 CD9481        449+        CALL     PSHT
                    450+        PLL      V1
 8244 111D30        451+        LXI      D,V1
 8247 CDAE81        452+        CALL     PLLT
                    453+        PSH      H87
 824A 111480        454+        LXI      D,H87
 824D CD9481        455+        CALL     PSHT
                    456+        PLL      V2
 8250 112130        457+        LXI      D,V2
 8253 CDAE81        458+        CALL     PLLT
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 LOC  OBJ          LINE        SOURCE STATEMENT

 8256 CDCB81        459+        CALL     GTHAN
 8259 E601          460+        ANI      01H
 825B C28582        461+        JNZ      L50
                    462         IFF      I1,LTHAN,H79,L51          ;IF JOYSTICK VOLTAGE<79H THEN L51
                    463+        PSH      I1
 825E 111030        464+        LXI      D,I1
 8261 CD9481        465+        CALL     PSHT
                    466+        PLL      V1
 8264 111D30        467+        LXI      D,V1
 8267 CDAE81        468+        CALL     PLLT
                    469+        PSH      H79
 826A 111880        470+        LXI      D,H79
 826D CD9481        471+        CALL     PSHT
                    472+        PLL      V2
 8270 112130        473+        LXI      D,V2
 8273 CDAE81        474+        CALL     PLLT
 8276 CDE281        475+        CALL     LTHAN
 8279 E601          476+        ANI      01H
 827B C29E82        477+        JNZ      L51
                    478         PSH      ZERO                      ;JOYSTICK IN CENTRAL DEAD BAND:
 827E 111C80        479+        LXI      D,ZERO
 8281 CD9481        480+        CALL     PSHT
 8284 C9            481         RET                                ; RETURN ZERO RESULT
                    482 L50:    PSH      I1                        ;OFFSET AND SCALE JOYSTICK VOLTAGE
 8285 111030        483+        LXI      D,I1
 8288 CD9481        484+        CALL     PSHT
                    485         PSH      H87                       ; FOR POSITIVE DEFLECTION
 828B 111480        486+        LXI      D,H87
 828E CD9481        487+        CALL     PSHT
 8291 CDB584        488         CALL     FSUB
                    489         PSH      D14                       ;PUSH 14 BASE 10
 8294 112C80        490+        LXI      D,D14
 8297 CD9481        491+        CALL     PSHT
 829A CDC184        492         CALL     FDIV
 829D C9            493         RET
                    494 L51:    PSH      I1                        ;OFFSET AND SCALE JOYSTICK VOLTAGE
 829E 111030        495+        LXI      D,I1
 82A1 CD9481        496+        CALL     PSHT
                    497         PSH      H79                       ; FOR NEGATIVE DEFLECTION
 82A4 111880        498+        LXI      D,H79
 82A7 CD9481        499+        CALL     PSHT
 82AA CDB584        500         CALL     FSUB
                    501         PSH      D14
 82AD 112C80        502+        LXI      D,D14
 82B0 CD9481        503+        CALL     PSHT
 82B3 CDC184        504         CALL     FDIV
 82B6 C9            505         RET
                    506                                            ;
                    507                                            ;
                    508                                            ;
                    509                                            ;
                    510                                            ;
                    511                                            ;** SUBROUTINE OUTPUT **
                    512                                            ;
                    513                                            ;OPERATES CUT-OFF, OFFSETS
 LOC  OBJ         LINE        SOURCE STATEMENT

                   514                                                 ; AND OUTPUTS VOLTAGES TO
                   515                                                 ; VALVES
                   516                                                 ;
                   517                                                 ;REGISTERS AFFECTED: A,D,E,STATUS
                   518                                                 ;
                   519 OUTPUT: PSH      VVSLEW                         ;SET SLEW VALVE
 82B7 112530       520+            LXI      D,VVSLEW
 82BA CD9481       521+            CALL     PSHT
                   522                                                 ;SET UP PARAMETERS FOR SUBROUTINE
                   523                                                 ; VLIN WHICH CONVERTS 32 BIT VALVE
                   524                                                 ; SETTING VVSLEW TO 8 BIT CONTROL BYTE
                   525                                                 ; TO BE OUTPUT TO THE VALVE DRIVER
                   526                                                 ; CIRCUIT
                   527                                                 ;
                   528             PLL      FVO                        ;FVO=VVSLEW
 82BD 113930       529+            LXI      D,FVO
 82C0 CDAE81       530+            CALL     PLLT
 82C3 3A4C30       531             LDA      SPOF
 82C6 324030       532             STA      POF                        ;POF=SPOF
 82C9 3A4E30       533             LDA      SNOF
 82CC 324130       534             STA      NOF                        ;NOF=SNOF
 82CF 3A4D30       535             LDA      SPMAX
 82D2 324230       536             STA      PMAX                       ;PMAX=SPMAX
 82D5 3A4F30       537             LDA      SNMAX
 82D8 324330       538             STA      NMAX                       ;NMAX=SNMAX
 82DB CDAB83       539             CALL     VLIN                       ;SUBROUTINE VLIN RETURNS RESULT
                   540                                                 ; IN A REGISTER
 82DE 323530       541             STA      VS
 82E1 D300         542             OUT      00H                        ;OUTPUT DATA TO SLEW VALVE DRIVER
                   543 L52:        PSH      VVALFA                     ;SET LIFT VALVE
 82E3 112930       544+            LXI      D,VVALFA
 82E6 CD9481       545+            CALL     PSHT
                   546             PLL      FVO
 82E9 113930       547+            LXI      D,FVO
 82EC CDAE81       548+            CALL     PLLT
 82EF 3A4430       549             LDA      APOF
 82F2 324030       550             STA      POF
 82F5 3A4630       551             LDA      ANOF
 82F8 324130       552             STA      NOF
 82FB 3A4530       553             LDA      APMAX
 82FE 324230       554             STA      PMAX
 8301 3A4730       555             LDA      ANMAX
 8304 324330       556             STA      NMAX
 8307 CDAB83       557             CALL     VLIN
 830A 323630       558             STA      VL
 830D D301         559             OUT      01H
                   560 L53:        PSH      VVBETA                     ;SET REACH VALVE
 830F 112D30       561+            LXI      D,VVBETA
 8312 CD9481       562+            CALL     PSHT
                   563             PLL      FVO
 8315 113930       564+            LXI      D,FVO
 8318 CDAE81       565+            CALL     PLLT
 831B 3A4830       566             LDA      BPOF
 831E 324030       567             STA      POF
 8321 3A4A30       568             LDA      BNOF
 LOC  OBJ         LINE        SOURCE STATEMENT

 8324 324130       569         STA     NOF
 8327 3A4930       570         LDA     BPMAX
 832A 324230       571         STA     PMAX
 832D 3A4B30       572         LDA     BNMAX
 8330 324330       573         STA     NMAX
 8333 CDAB83       574         CALL    VLIN
 8336 323730       575         STA     VR
 8339 D321         576         OUT     21H
                   577 L54:    IFF     VVBKT,EQUALS,ZERO,L55    ;SET BUCKET SWITCH
                   578+        PSH     VVBKT
 833B 113130       579+        LXI     D,VVBKT
 833E CD9481       580+        CALL    PSHT
                   581+        PLL     V1
 8341 111D30       582+        LXI     D,V1
 8344 CDAE81       583+        CALL    PLLT
                   584+        PSH     ZERO
 8347 111C80       585+        LXI     D,ZERO
 834A CD9481       586+        CALL    PSHT
                   587+        PLL     V2
 834D 112130       588+        LXI     D,V2
 8350 CDAE81       589+        CALL    PLLT
 8353 CD0882       590+        CALL    EQUALS
 8356 E601         591+        ANI     01H
 8358 C27E83       592+        JNZ     L55
                   593         IFF     VVBKT,GTHAN,ZERO,L56
                   594+        PSH     VVBKT
 835B 113130       595+        LXI     D,VVBKT
 835E CD9481       596+        CALL    PSHT
                   597+        PLL     V1
 8361 111D30       598+        LXI     D,V1
 8364 CDAE81       599+        CALL    PLLT
                   600+        PSH     ZERO
 8367 111C80       601+        LXI     D,ZERO
 836A CD9481       602+        CALL    PSHT
                   603+        PLL     V2
 836D 112130       604+        LXI     D,V2
 8370 CDAE81       605+        CALL    PLLT
 8373 CDCB81       606+        CALL    GTHAN
 8376 E601         607+        ANI     01H
 8378 C28683       608+        JNZ     L56
 837B C38E83       609         JMP     L57
 837E 3EC0         610 L55:    MVI     A,0C0H                    ;SEGMENT FOR STATIC BUCKET
 8380 323830       611         STA     VB
 8383 D322         612         OUT     22H
 8385 C9           613         RET
 8386 3E80         614 L56:    MVI     A,80H                     ;SEGMENT FOR OPENING BUCKET
 8388 323830       615         STA     VB
 838B D322         616         OUT     22H
 838D C9           617         RET
 838E 3E40         618 L57:    MVI     A,40H                     ;SEGMENT FOR CLOSING BUCKET
 8390 323830       619         STA     VB
 8393 D322         620         OUT     22H
 8395 C9           621         RET
                   622                                           ;
                   623                                           ;
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  LOC  OBJ          LINE        SOURCE STATEMENT

                     624                                         ;** SUBROUTINE FLOAT **
                     625                                         ;
                     626                                         ;PUTS CONTENTS OF A REGISTER
                     627                                         ; ON TOP OF APU STACK
                     628                                         ; .
                     629                                         ;REGISTERS AFFECTED: A
                     630                                         ;
  8396 320010        631 FLOAT:  STA     1000H
  8399 AF            632         XRA     A
  839A 320010        633         STA     1000H
  839D CDA984        634         CALL    FLTS
  83A0 C9            635         RET
                     636                                         ;
                     637                                         ;
                     638                                         ;** SUBROUTINE FIX **
                     639                                         ;
                     640                                         ;PUTS 32-BIT TOS OF APU
                     641                                         ; IN THE A REGISTER
                     642                                         ;
                     643                                         ;REGISTERS AFFECTED: A
                     644                                         ;
  83A1 CDCD84        645 FIX:    CALL    FIXS
  83A4 3A0010        646         LDA     1000H
  83A7 3A0010        647         LDA     1000H
  83AA C9            648         RET
                     649                                         ;
                     650                                         ;
                     651                                         ;** SUBROUTINE VLIN **
                     652                                         ;
                     653                                         ;VALVE OPENING IN NOMINAL RANGE -1 TO
                     654                                         ; +1 IS PASSED IN FVO.
                     655                                         ; SUBROUTINE CALCULATES BYTE TO
                     656                                         ; BE OUTPUT TO THE DRIVER CIRCUIT
                     657                                         ; USING DATA POS, PMAX, NOS, & NMAX.
                     658                                         ;
                     659                                         ;REGISTERS AFFECTED: A,D,E,STATUS
                     660                                         ;
                     661 VLIN:   IFF     FVO,GTHAN,ZERO,L61
                     662+        PSH     FVO
  83AB 113930        663+        LXI     D,FVO
  83AE CD9481        664+        CALL    PSHT
                     665+        PLL     V1
  83B1 111D30        666+        LXI     D,V1
  83B4 CDAE81        667+        CALL    PLLT
                     668+        PSH     ZERO
  83B7 111C80        669+        LXI     D,ZERO
  83BA CD9481        670+        CALL    PSHT
                     671+        PLL     V2
  83BD 112130        672+        LXI     D,V2
  83C0 CDAE81        673+        CALL    PLLT
  83C3 CDCB81        674+        CALL    GTHAN
  83C6 E601          675+        ANI     01H
  83C8 C2ED83        676+        JNZ     L61
                     677         IFF     FVO,LTHAN,ZERO,L62
                     678+        PSH     FVO
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 LOC  OBJ          LINE        SOURCE STATEMENT

 83CB 113930        679+        LXI     D,FVO
 83CE CD9481        680+        CALL    PSHT
                    681+        PLL     V1
 83D1 111D30        682+        LXI     D,V1
 83D4 CDAE81        683+        CALL    PLLT
                    684+        PSH     ZERO
 83D7 111C80        685+        LXI     D,ZERO
 83DA CD9481        686+        CALL    PSHT
                    687+        PLL     V2
 83DD 112130        688+        LXI     D,V2
 83E0 CDAE81        689+        CALL    PLLT
 83E3 CDE281        690+        CALL    LTHAN
 83E6 E601          691+        ANI     01H
 83E8 C22184        692+        JNZ     L62
 83EB AF            693         XRA     A                        ;SEGMENT FOR FVO=0
 83EC C9            694         RET
                    695 L61:    IFF     FVO,LTHAN,ONE,L63
                    696+        PSH     FVO
 83ED 113930        697+        LXI     D,FVO
 83F0 CD9481        698+        CALL    PSHT
                    699+        PLL     V1
 83F3 111D30        700+        LXI     D,V1
 83F6 CDAE81        701+        CALL    PLLT
                    702+        PSH     ONE
 83F9 112080        703+        LXI     D,ONE
 83FC CD9481        704+        CALL    PSHT
                    705+        PLL     V2
 83FF 112130        706+        LXI     D,V2
 8402 CDAE81        707+        CALL    PLLT
 8405 CDE281        708+        CALL    LTHAN
 8408 E601          709+        ANI     01H
 840A C21184        710+        JNZ     L63
 840D 3A4230        711         LDA     PMAX                     ;SEGMENT FOR FVO>PMAX
 8410 C9            712         RET
 8411 3A4030        713 L63:    LDA     POF                      ;SEGMENT FOR 0<FVO<1
 8414 323E30        714         STA     OFFSET
 8417 3A4230        715         LDA     PMAX
 841A 323F30        716         STA     MAX
 841D C36084        717         JMP     L64
 8420 C9            718         RET
                    719 L62:    IFF     FVO,GTHAN,MINONE,L65
                    720+        PSH     FVO
 8421 113930        721+        LXI     D,FVO
 8424 CD9481        722+        CALL    PSHT
                    723+        PLL     V1
 8427 111D30        724+        LXI     D,V1
 842A CDAE81        725+        CALL    PLLT
                    726+        PSH     MINONE
 842D 112880        727+        LXI     D,MINONE
 8430 CD9481        728+        CALL    PSHT
                    729+        PLL     V2
 8433 112130        730+        LXI     D,V2
 8436 CDAE81        731+        CALL    PLLT
 8439 CDCB81        732+        CALL    GTHAN
 843C E601          733+        ANI     01H
 LOC  OBJ         LINE        SOURCE STATEMENT

 843E C24584       734+         JNZ     L65
 8441 3A4330       735          LDA     NMAX                         ;SEGMENT FOR FVO<=-1
 8444 C9           736          RET
 8445 3A4130       737 L65:     LDA     NOF                          ;SEGMENT FOR -1<FVO<0
 8448 323E30       738          STA     OFFSET
 844B 3A4330       739          LDA     NMAX
 844E 323F30       740          STA     MAX
                   741          PSH     FVO
 8451 113930       742+         LXI     D,FVO
 8454 CD9481       743+         CALL    PSHT
 8457 CD9D84       744          CALL    CHSF
                   745          PLL     FVO
 845A 113930       746+         LXI     D,FVO
 845D CDAE81       747+         CALL    PLLT
 8460 3A3E30       748 L64:     LDA     OFFSET                       ;COMMON SEGMENT FOR INTERMEDIATE
 8463 CD9683       749          CALL    FLOAT                        ; VALVE OPENING
 8466 CDE584       750          CALL    PTOF
 8469 3A3F30       751          LDA     MAX
 846C CD9683       752          CALL    FLOAT
 846F CD3985       753          CALL    XCHF
 8472 CDB584       754          CALL    FSUB
                   755          PSH     FVO
 8475 113930       756+         LXI     D,FVO
 8478 CD9481       757+         CALL    PSHT
 847B CD9184       758          CALL    FMUL
 847E CD8584       759          CALL    FADD
 8481 CDA183       760          CALL    FIX
 8484 C9           761          RET
                   762                                               ;
                   763                                               ;
                   764                                               ;** MATHS SUBROUTINES MACRO **
                   765                                               ;
                   766                                               ;REGISTERS AFFECTED: NONE
                   767                                               ;
                   768 MATHS    MACRO   FNCTN,CODE
 -                 769 FNCTN:   STA     ASTR
 -                 770          MVI     A,CODE
 -                 771          STA     1100H
 -                 772          LDA     ASTR
 -                 773          RET
                   774          ENDM
                   775                                               ;
                   776                                               ;
                   777                                               ;MATHS MACRO CALLS
                   778                                               ;
                   779                                               ;ALL OPERANDS ARE 32 BIT FLOATING POINT
                   780                                               ; UNLESS OTHERWISE SPECIFIED
                   781                                               ;
                   782          MATHS   FADD,10H                     ;TOS=TOS+NOS
 8485 323D30       783+FADD:    STA     ASTR
 8488 3E10         784+         MVI     A,10H
 848A 320011       785+         STA     1100H
 848D 3A3D30       786+         LDA     ASTR
 8490 C9           787+         RET
                   788          MATHS   FMUL,12H                     ;TOS=TOS*NOS
 LOC  OBJ          LINE        SOURCE STATEMENT

 8491 323D30        789+FMUL:   STA     ASTR
 8494 3E12          790+        MVI     A,12H
 8496 320011        791+        STA     1100H
 8499 3A3D30        792+        LDA     ASTR
 849C C9            793+        RET
                    794         MATHS   CHSF,15H               ;TOS=-TOS
 849D 323D30        795+CHSF:   STA     ASTR
 84A0 3E15          796+        MVI     A,15H
 84A2 320011        797+        STA     1100H
 84A5 3A3D30        798+        LDA     ASTR
 84A8 C9            799+        RET
                    800         MATHS   FLTS,1DH               ;CONVERT 16 BIT TOS TO 32 BIT FL. PT.
 84A9 323D30        801+FLTS:   STA     ASTR
 84AC 3E1D          802+        MVI     A,1DH
 84AE 320011        803+        STA     1100H
 84B1 3A3D30        804+        LDA     ASTR
 84B4 C9            805+        RET
                    806         MATHS   FSUB,11H               ;TOS=NOS-TOS
 84B5 323D30        807+FSUB:   STA     ASTR
 84B8 3E11          808+        MVI     A,11H
 84BA 320011        809+        STA     1100H
 84BD 3A3D30        810+        LDA     ASTR
 84C0 C9            811+        RET
                    812         MATHS   FDIV,13H               ;TOS=NOS/TOS
 84C1 323D30        813+FDIV:   STA     ASTR
 84C4 3E13          814+        MVI     A,13H
 84C6 320011        815+        STA     1100H
 84C9 3A3D30        816+        LDA     ASTR
 84CC C9            817+        RET
                    818         MATHS   FIXS,1FH               ;CONVERT 32 BIT FL. PT. TOS TO 16 BIT
 84CD 323D30        819+FIXS:   STA     ASTR
 84D0 3E1F          820+        MVI     A,1FH
 84D2 320011        821+        STA     1100H
 84D5 3A3D30        822+        LDA     ASTR
 84D8 C9            823+        RET
                    824         MATHS   PTOS,77H               ;COPY 16 BIT TOS ONTO STACK
 84D9 323D30        825+PTOS:   STA     ASTR
 84DC 3E77          826+        MVI     A,77H
 84DE 320011        827+        STA     1100H
 84E1 3A3D30        828+        LDA     ASTR
 84E4 C9            829+        RET
                    830         MATHS   PTOF,17H               ;COPY 32 BIT TOS ONTO STACK
 84E5 323D30        831+PTOF:   STA     ASTR
 84E8 3E17          832+        MVI     A,17H
 84EA 320011        833+        STA     1100H
 84ED 3A3D30        834+        LDA     ASTR
 84F0 C9            835+        RET
                    836         MATHS   POPF,18H               ;ROTATE TOS TO BOTTOM OF STACK
 84F1 323D30        837+POPF:   STA     ASTR
 84F4 3E18          838+        MVI     A,18H
 84F6 320011        839+        STA     1100H
 84F9 3A3D30        840+        LDA     ASTR
 84FC C9            841+        RET
                    842         MATHS   PUPI,1AH               ;PUSH PI ONTO TOS
 84FD 323D30        843+PUPI:   STA     ASTR
 LOC  OBJ          LINE        SOURCE STATEMENT

 8500 3E1A          844+         MVI     A,1AH
 8502 320011        845+         STA     1100H
 8505 3A3D30        846+         LDA     ASTR
 8508 C9            847+         RET
                    848          MATHS   SIN,02H                 ;TOS=SIN(TOS)
 8509 323D30        849+SIN:     STA     ASTR
 850C 3E02          850+         MVI     A,02H
 850E 320011        851+         STA     1100H
 8511 3A3D30        852+         LDA     ASTR
 8514 C9            853+         RET
                    854          MATHS   ASIN,05H                ;TOS=ASIN(TOS)
 8515 323D30        855+ASIN:    STA     ASTR
 8518 3E05          856+         MVI     A,05H
 851A 320011        857+         STA     1100H
 851D 3A3D30        858+         LDA     ASTR
 8520 C9            859+         RET
                    860          MATHS   COS,03H                 ;TOS=COS(TOS)
 8521 323D30        861+COS:     STA     ASTR
 8524 3E03          862+         MVI     A,03H
 8526 320011        863+         STA     1100H
 8529 3A3D30        864+         LDA     ASTR
 852C C9            865+         RET
                    866          MATHS   ACOS,06H                ;TOS=ACOS(TOS)
 852D 323D30        867+ACOS:    STA     ASTR
 8530 3E06          868+         MVI     A,06H
 8532 320011        869+         STA     1100H
 8535 3A3D30        870+         LDA     ASTR
 8538 C9            871+         RET
                    872          MATHS   XCHF,19H                ;EXCHANGE TOS AND NOS
 8539 323D30        873+XCHF:    STA     ASTR
 853C 3E19          874+         MVI     A,19H
 853E 320011        875+         STA     1100H
 8541 3A3D30        876+         LDA     ASTR
 8544 C9            877+         RET
                    878          MATHS   SQRT,01H                ;TOS=SQRT(TOS)
 8545 323D30        879+SQRT:    STA     ASTR
 8548 3E01          880+         MVI     A,01H
 854A 320011        881+         STA     1100H
 854D 3A3D30        882+         LDA     ASTR
 8550 C9            883+         RET
                    884  END


PUBLIC SYMBOLS


EXTERNAL SYMBOLS


USER SYMBOLS
ACOS   A 852D   ADCON  A 8173   ANMAX  A 3047   ANOF   A 3046   APMAX  A 3045   APOF   A 3044   ASIN   A 8515
ASTR   A 303D   BNMAX  A 304B   BNOF   A 304A   BPMAX  A 3049   BPOF   A 3048   CHSF   A 849D   CNST20 A 8030
CNST21 A 8034   CONV   A 813A   COS    A 8521   D14    A 802C   DLOOP  A 80D8   EQUALS A 8208   FADD   A 8485
FDIV   A 84C1   FIX    A 83A1   FIXS   A 84CD   FLOAT  A 8396   FLTS   A 84A9   FMUL   A 8491   FSUB   A 84B5
FVO    A 3039   GEDUAL A 81F9   GTHAN  A 81CB   H255   A 8038   H79    A 8018   H87    A 8014   HALF   A 8024
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I1      A 3010   I2      A 3014   IFF     + 0002   INIT    A 812B   JBKT    A 300C   JOYSTK  A 822E   JSLEW   A 3008
JXDOT   A 3000   JYDOT   A 3004   L2      A 81D5   L3      A 81DF   L4      A 81EC   L5      A 81F6   L50     A 8285
L51     A 829E   L52     A 82E3   L53     A 830F   L54     A 833B   L55     A 837E   L56     A 8386   L57     A 838E
L6      A 8217   L61     A 83ED   L62     A 8421   L63     A 8411   L64     A 8460   L65     A 8445   L7      A 822B
LEQUAL  A 81FE   LOOP    A 80EF   LTHAN   A 81E2   MATHS   + 0003   MAX     A 303F   MINONE  A 8028   NEQUAL  A 8203
NMAX    A 3043   NOF     A 3041   OFFSET  A 303E   ONE     A 8020   OUTPUT  A 82B7   PAUSE   A 818D   PLL     + 0001
PLLT    A 81AE   PMAX    A 3042   POF     A 3040   POPF    A 84F1   PSH     + 0000   PSHT    A 8194   PTOF    A 84E5
PTOS    A 84D9   PUPI    A 84FD   S       A 3019   SIN     A 8509   SNMAX   A 304F   SNOF    A 304E   SPMAX   A 304D
SPOF    A 304C   SQRT    A 8545   STATUS  A 3018   TEN     A 800C   TWO     A 8010   V1      A 301D   V2      A 3021
VB      A 3038   VL      A 3036   VLIN    A 83AB   VR      A 3037   VS      A 3035   VVALFA  A 3029   VVBETA  A 302D
VVBKT   A 3031   VVSLEW  A 3025   XANMAX  A 8003   XANOF   A 8002   XAPMAX  A 8001   XAPOF   A 8000   XBNMAX  A 8007
XBNOF   A 8006   XBPMAX  A 8005   XBPOF   A 8004   XCHF    A 8539   XSNMAX  A 800B   XSNOF   A 800A   XSPMAX  A 8009
XSPOF   A 8008   ZERO    A 801C

ASSEMBLY COMPLETE,   NO ERRORS
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APPENDIX B

PROGRAM DIG

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ASM80 :F1:DIG.SRC


ISIS-II 8080/8085 MACRO ASSEMBLER, V4.0          MODULE    PAGE     1

  LOC  OBJ         LINE        SOURCE STATEMENT

                      1 $MOD85 MACROFILE
 3000                 2         ORG      3000H                          ;UNIVERSITY OF LIVERPOOL
                      3                                                 ;DEPARTMENT OF ELECTRICAL ENGINEERING
                      4                                                 ; AND ELECTRONICS
                      5                                                 ;
                      6                                                 ;E.R.I. DEANE
                      7                                                 ;
                      8                                                 ;THIS IS AN ASSEMBLY LANGUAGE PROGRAM
                      9                                                 ; FOR "X-Y" CONTROL OF A PA6 DIGGER
                     10                                                 ; WITH A LEARN AND REPEAT FACILITY
                     11                                                 ;
                     12                                                 ;CODE EDITED 1600 5TH JANUARY 1983
                     13                                                 ; DISK: NO. 4  VER 5.33
                     14                                                 ;
                     15                                                 ;
                     16                                                 ;** RAM LOCATIONS FOR PROGRAM VARIABLES **
                     17                                                 ;
  3000               18 MODFLG: DS       1                              ;BYTE TO REGISTER MODE
  3001               19 DX:     DS       4                              ;DISTANCE FROM ALPHA PIVOT TO BUCKET PIVOT
  3005               20 AI:     DS       4                              ;INPUT TO ALPHA CONTROL LOOP
  3009               21 BI:     DS       4                              ;INPUT TO BETA CONTROL LOOP
  300D               22 AA:     DS       4                              ;INTERMEDIATE RESULT IN CALCULATING AI
  3011               23 AB:     DS       4                              ;INTERMEDIATE RESULT IN CALCULATING AI
  3015               24 XOF:    DS       4                              ;X OFFSET USED IN REPEAT MODE
  3019               25 YOF:    DS       4                              ;Y OFFSET USED IN REPEAT MODE
  301D               26 MODE:   DS       1                              ;IMAGE OF DATA FROM MODE SWITCHES
  301E               27 PPOINT: DS       2                              ;PATH STACK POINTER
  3020               28 XP:     DS       4                              ;VARIABLE FOR LEARN ROUTINE
  3024               29 YP:     DS       4                              ;   "       "    "      "
  3028               30 PSIP:   DS       4                              ;   "       "    "      "
  302C               31 DIST:   DS       4                              ;   "       "    "      "
  3030               32 DPSI:   DS       4                              ;   "       "    "      "
  3034               33 PCOUNT: DS       1                              ;PATH POINT COUNTER FOR LEARN
  3035               34 RCOUNT: DS       1                              ;COUNTS PATH POINTS FOR REPEAT
  3036               35 NCOUNT: DS       1                              ;COUNTS CONTROL ROUTINE CALLS FOR REPEAT
  3037               36 TFLAG:  DS       1                              ;IMAGE OF DATA SENT TO PORT 2A FOR
                     37                                                 ; MEASURING LOOP EXECUTION TIME
  3038               38 JXDOT:  DS       4                              ;JOYSTICK INPUT XDOT IN USER CO-ORDS
  303C               39 JYDOT:  DS       4                              ;   "        "   YDOT  "  "       "
  3040               40 JSLEW:  DS       4                              ;   "        "   SLEW RATE
  3044               41 JBKT:   DS       4                              ;   "        "   BUCKET MOVEMENT
  3048               42 I1:     DS       4                              ;INTERMEDIATE RESULT LOCATION
  304C               43 I2:     DS       4                              ;INTERMEDIATE RESULT LOCATION
  3050               44 CXDOT:  DS       4                              ;XDOT INPUT TO CONTROL LOOP
  3054               45 CYDOT:  DS       4                              ;YDOT INPUT TO CONTROL LOOP
  3058               46 XI:     DS       4                              ;X INPUT TO CONTROL LOOP
  305C               47 YI:     DS       4                              ;Y INPUT TO CONTROL LOOP
  3060               48 PSII:   DS       4                              ;PSI INPUT TO CONTROL LOOP
  3064               49 XO:     DS       4                              ;X OUTPUT POSITION
  3068               50 YO:     DS       4                              ;Y OUTPUT POSITION
  306C               51 PSIO:   DS       4                              ;PSI OUTPUT VALUE
  3070               52 EX:     DS       4                              ;X POSITIONAL ERROR = XI-XO
  3074               53 EY:     DS       4                              ;Y POSITIONAL ERROR = YI-YO
  3078               54 EPSI:   DS       4                              ;PSI POSITIONAL ERROR = PSII-PSIO
 LOC  OBJ         LINE        SOURCE STATEMENT

 307C               55 ETA:     DS      4                       ;SQRT(EX**2+EY**2)
 3080               56 MCALFA:  DS      4                       ;ANGLE OF LIFT ARM ON MACHINE
 3084               57 ALPHA:   DS      4                       ;ANGLE ALPHA
 3088               58 BETA:    DS      4                       ;ANGLE BETA
 308C               59 DELTA:   DS      4                       ;ANGLE DELTA
 3090               60 STATUS:  DS      1                       ;STATUS OF APU
 3091               61 S:       DS      4                       ;INTERMEDIATE RESULT LOCATION
 3095               62 V1:      DS      4                       ;LOCATION FOR IFF DATA TRANSFER
 3099               63 V2:      DS      4                       ;LOCATION FOR IFF DATA TRANSFER
 309D               64 PITCH:   DS      4                       ;PITCH ANGLE SELECTED BY OPERATOR
 30A1               65 EALPHA:  DS      4                       ;ALPHA ERROR
 30A5               66 EBETA:   DS      4                       ;BETA ERROR
 30A9               67 VVSLEW:  DS      4                       ;SLEW VALVE SETTING (32 BIT FORMAT)
 30AD               68 VVALFA:  DS      4                       ;ALPHA VALVE SETTING (32 BIT FORMAT)
 30B1               69 VVBETA:  DS      4                       ;BETA VALVE SETTING (32 BIT FORMAT)
 30B5               70 VVBKT:   DS      4                       ;BUCKET VALVE SETTING (32 BIT FORMAT)
 30B9               71 VS:      DS      1                       ;SLEW VALVE SETTING (8 BIT FORMAT)
 30BA               72 VL:      DS      1                       ;LIFT VALVE SETTING (8 BIT FORMAT)
 30BB               73 VR:      DS      1                       ;REACH VALVE SETTING (8 BIT FORMAT)
 30BC               74 VB:      DS      1                       ;BUCKET VALVE SETTING (8 BIT FORMAT)
 30BD               75 FCOUNT:  DS      1                       ;NO. OF CONTROL ROUTINE CALLS/POINT IN REPEAT MODE
 30BE               76 ECRIT:   DS      4                       ;CRITICAL X OR Y ERROR
 30C2               77 FVO:     DS      4                       ;FRACTIONAL VALVE OPENING
 30C6               78 ASTR:    DS      1                       ;STORAGE LOCATION FOR A REG
 30C7               79 OFFSET:  DS      1                       ;INPUT PARAMETERS FOR SUBROUTINE VLIN
 30C8               80 MAX:     DS      1                       ; "        "        "       "       "
 30C9               81 POF:     DS      1                       ; "        "        "       "       "
 30CA               82 NOF:     DS      1                       ; "        "        "       "       "
 30CB               83 PMAX:    DS      1                       ; "        "        "       "       "
 30CC               84 NMAX:    DS      1                       ; "        "        "       "       "
 30CD               85 APOF:    DS      1                       ;ALPHA +VE OFFSET
 30CE               86 APMAX:   DS      1                       ;ALPHA +VE SATN. O/P
 30CF               87 ANOF:    DS      1                       ;ALPHA -VE OFFSET
 30D0               88 ANMAX:   DS      1                       ;ALPHA -VE SATN. O/P
 30D1               89 BPOF:    DS      1                       ;BETA +VE OFFSET
 30D2               90 BPMAX:   DS      1                       ;BETA +VE SATN. O/P
 30D3               91 BNOF:    DS      1                       ;BETA -VE OFFSET
 30D4               92 BNMAX:   DS      1                       ;BETA -VE SATN. O/P
 30D5               93 SPOF:    DS      1                       ;SLEW +VE OFFSET
 30D6               94 SPMAX:   DS      1                       ;SLEW +VE SATN. O/P
 30D7               95 SNOF:    DS      1                       ;SLEW -VE OFFSET
 30D8               96 SNMAX:   DS      1                       ;SLEW -VE SATN. O/P
 30D9               97 A1A:     DS      4                       ;ALPHA FEEDFORWARD GAIN = 20
 30DD               98 A1B:     DS      4                       ;BETA FEEDFORWARD GAIN = 5
 30E1               99 PCRIT:   DS      4                       ;PCRIT=BUCKET ERROR MARGIN=0.07 RAD
 30E5              100 NCRIT:   DS      4                       ;NCRIT=-BUCKET ERROR MARGIN=-0.07 RAD
 30E9              101 ECMIN:   DS      4                       ;MIN. CRIT. X OR Y ERROR = 0.1m
 30ED              102 CNST10:  DS      4                       ;CRIT. CHANGE IN JOYSTK READING = 0.167
 30F1              103 CNST11:  DS      4                       ;TARGET COORDINATE INCREMENT FACTOR = 0.04m
 30F5              104 DCRIT:   DS      4                       ;SPACING OF PATH POINTS
 30F9              105 DPCRIT:  DS      4                       ;BUCKET ANGLE BETWEEN POINTS
 30FD              106 FFAST:   DS      1                       ;CONTROL CALLS PER POINT FOR
 30FE              107 FSLOW:   DS      1                       ; FAST AND SLOW REPEAT
 30FF              108 DELAY:   DS      2                       ;VALUE OF DELAY IN CONTROL LOOP
 3101              109 AMIN:    DS      4                       ;MINIMUM ALPHA VALUE
 LOC  OBJ         LINE        SOURCE STATEMENT

 3105              110 AMAX:   DS      4                          ;MAXIMUM ALPHA VALUE
 3109              111 BMIN:   DS      4                          ;MINIMUM BETA VALUE
 310D              112 BMAX:   DS      4                          ;MAXIMUM BETA VALUE
 3111              113 BASE:   DS      1                          ;BASE LOCATION OF RAM FOR PATH STORAGE
                   114                                            ;
                   115                                            ;** ROM LOCATIONS CONTAINING DEFAULT
                   116                                            ;          VALUES OF PROGRAM CONSTANTS **
                   117                                            ;
 8000              118 ORG     8000H
 8000 C0           119 XAPOF:  DB      0C0H                       ;ALPHA +VE OFFSET
 8001 FF           120 XAPMAX: DB      0FFH                       ;ALPHA +VE SATN. O/P
 8002 40           121 XANOF:  DB      40H                        ;ALPHA -VE OFFSET
 8003 7F           122 XANMAX: DB      7FH                        ;ALPHA -VE SATN. O/P
 8004 40           123 XBPOF:  DB      40H                        ;BETA +VE OFFSET
 8005 7F           124 XBPMAX: DB      7FH                        ;BETA +VE SATN. O/P
 8006 C0           125 XBNOF:  DB      0C0H                       ;BETA -VE OFFSET
 8007 FF           126 XBNMAX: DB      0FFH                       ;BETA -VE SATN. O/P
 8008 C0           127 XSPOF:  DB      0C0H                       ;SLEW +VE OFFSET
 8009 FF           128 XSPMAX: DB      0FFH                       ;SLEW +VE SATN. O/P
 800A 40           129 XSNOF:  DB      40H                        ;SLEW -VE OFFSET
 800B 7F           130 XSNMAX: DB      7FH                        ;SLEW -VE SATN. O/P
 800C 00           131 XA1A:   DB      00H,00H,0A0H,05H           ;ALPHA FEEDFORWARD GAIN = 20
 800D 00
 800E A0
 800F 05
 8010 00           132 XA1B:   DB      00H,00H,0A0H,03H           ;BETA FEEDFORWARD GAIN = 5
 8011 00
 8012 A0
 8013 03
 8014 4A           133 XPCRIT: DB      4AH,0F3H,8EH,7DH           ;PCRIT = BKT ERROR MARGIN = 0.07
 8015 F3
 8016 8E
 8017 7D
 8018 4A           134 XNCRIT: DB      4AH,0F3H,8EH,0FDH          ;NCRIT = -BKT ERROR MARGIN = -0.07
 8019 F3
 801A 8E
 801B FD
 801C CC           135 XEMIN:  DB      0CCH,0CCH,0CCH,7DH         ;CRITICAL X OR Y ERROR = 0.1m
 801D CC
 801E CC
 801F 7D
 8020 02           136 XEACRT: DB      02H,42H,0B2H,78H           ;CRIT. ALPHA ERROR = 0.00272
 8021 42
 8022 B2
 8023 78
 8024 C2           137 XEBCRT: DB      0C2H,16H,82H,79H           ;CRIT. BETA ERROR = 0.00397
 8025 16
 8026 82
 8027 79
 8028 00           138 XCST10: DB      00H,00H,80H,7FH            ;CRIT. CHANGE IN JOYSTK READING = 0.25
 8029 00
 802A 80
 802B 7F
 802C 06           139 XCST11: DB      06H,0D7H,0A3H,7BH          ;TARGET COORD INCREMENT FACTOR = 0.02
 802D D7
 LOC  OBJ         LINE        SOURCE STATEMENT

 802E A3
 802F 7B
 8030 CC           140 XDCRIT: DB      0CCH,0CCH,0CCH,7DH       ;PATH POINT SPACING = 0.1m
 8031 CC
 8032 CC
 8033 7D
 8034 4A           141 XDPCRT: DB      4AH,0F3H,8EH,7EH         ;ANGULAR PATH POINT SPACING = 0.140 RAD
 8035 F3
 8036 8E
 8037 7E
 8038 01           142 XFFAST: DB      01H                      ;NO. OF CONTROL CALLS BETWEEN PATH POINTS
                   143                                          ; FOR REPEAT FAST
 8039 0C           144 XFSLOW: DB      0CH                      ;NO. OF CONTROL CALLS BETWEEN PATH POINTS
                   145                                          ; FOR REPEAT SLOW
 803A 01           146 XDELAY: DB      01H,00H
 803B 00
 803C 40           147 XAMIN:  DB      40H,3EH,98H,01H          ;MIN ALPHA VALUE = 1.19 rad
 803D 3E
 803E 98
 803F 01
 8040 A8           148 XAMAX:  DB      0A8H,0F1H,0A2H,02H       ;MAX ALPHA VALUE = 2.55 rad
 8041 F1
 8042 A2
 8043 02
 8044 C2           149 XBMIN:  DB      0C2H,0FEH,92H,00H        ;MIN BETA VALUE = 0.574 rad
 8045 FE
 8046 92
 8047 00
 8048 F2           150 XBMAX:  DB      0F2H,0FDH,9CH,02H        ;MAX BETA VALUE = 2.45 rad
 8049 FD
 804A 9C
 804B 02
 804C FF           151 MAXPTS: DB      0FFH                     ;MAXIMUM NUMBER OF POINTS IN STORED TRAJECTORY
 804D 00           152 TEN:    DB      00H,00H,0A0H,04H         ;10D
 804E 00
 804F A0
 8050 04
 8051 00           153 TWO:    DB      00H,00H,80H,02H          ;2D
 8052 00
 8053 80
 8054 02
 8055 A2           154 MA:     DB      0A2H,30H,0B6H,79H        ;VALPHA SCALE FACTOR = 0.00556 rad/bit
 8056 30
 8057 B6
 8058 79
 8059 CC           155 CA:     DB      0CCH,0F7H,93H,01H        ;VALPHA OFFSET = 1.16 rad
 805A F7
 805B 93
 805C 01
 805D 40           156 MB:     DB      40H,50H,0FCH,79H         ;VBETA SCALE FACTOR = 0.0077 rad/bit
 805E 50
 805F FC
 8060 79
 8061 00           157 CB:     DB      00H,2BH,87H,00H          ;VBETA OFFSET = 0.528 rad
 8062 2B
 LOC  OBJ         LINE        SOURCE STATEMENT

 8063 87
 8064 00
 8065 32           158 MD:      DB      32H,15H,0A9H,79H        ;VDELTA SCALE FACTOR = 0.00516 rad/bit
 8066 15
 8067 A9
 8068 79
 8069 EA           159 CD:      DB      0EAH,051H,0F8H,7FH      ;VDELTA OFFSET = 0.485 rad
 806A 51
 806B F8
 806C 7F
 806D 84           160 LA:      DB      84H,0EBH,91H,02H        ;LENGTH OF LIFT ARM = 2.28m
 806E EB
 806F 91
 8070 02
 8071 C0           161 RA:      DB      0C0H,0F5H,0C8H,01H      ;LENGTH OF REACH ARM = 1.57m
 8072 F5
 8073 C8
 8074 01
 8075 00           162 H87:     DB      00H,00H,087H,08H        ;87H = 135D
 8076 00
 8077 87
 8078 08
 8079 00           163 H79:     DB      00H,00H,0F2H,07H        ;79H = 121D
 807A 00
 807B F2
 807C 07
 807D 00           164 ZERO:    DB      00H,00H,00H,00H         ;0D
 807E 00
 807F 00
 8080 00
 8081 00           165 ONE:     DB      00H,00H,80H,01H         ;1D
 8082 00
 8083 80
 8084 01
 8085 FE           166 HALF:    DB      0FEH,0FFH,0FFH,7FH      ;0.5D
 8086 FF
 8087 FF
 8088 7F
 8089 00           167 MINONE:  DB      00H,00H,80H,81H         ;-1D
 808A 00
 808B 80
 808C 81
 808D 14           168 MU:      DB      14H,0AEH,97H,02H        ; = 2.37 rad
 808E AE
 808F 97
 8090 02
 8091 CA           169 ZETA:    DB      0CAH,0CCH,0CCH,7CH      ; = 0.05 rad
 8092 CC
 8093 CC
 8094 7C
 8095 0E           170 GC0:     DB      0EH,58H,0E9H,02H        ;COEFFICIENTS FOR GAMMA(DELTA)
 8096 58
 8097 E9
 8098 02
 8099 F2           171 GC1:     DB      0F2H,0B9H,0DAH,0FFH
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  LOC  OBJ         LINE        SOURCE STATEMENT

 809A B9
 809B DA
 809C FF
 809D 44             172 GC2:     DB      44H,50H,8CH,80H
 809E 50
 809F 8C
 80A0 80
 80A1 C0             173 CNST1:   DB      0C0H,39H,0F5H,03H       ;LA**2+RA**2 = 7.66 m**2
 80A2 39
 80A3 F5
 80A4 03
 80A5 28             174 CNST2:   DB      28H,18H,0E5H,03H        ;2*LA*RA = 7.16 m**2
 80A6 18
 80A7 E5
 80A8 03
 80A9 A8             175 CNST3:   DB      0A8H,0F1H,0AEH,02H      ;LA**2-RA**2 = 2.73 m**2
 80AA F1
 80AB AE
 80AC 02
 80AD 84             176 CNST4:   DB      84H,0EBH,91H,03H        ;2*LA = 4.56m
 80AE EB
 80AF 91
 80B0 03
 80B1 0C             177 CNST9:   DB      0CH,0C7H,0BAH,7CH       ;k*1 = 0.0456 m**2
 80B2 C7
 80B3 BA
 80B4 7C
 80B5 CE             178 CNST13:  DB      0CEH,0D9H,0C9H,79H      ;SLOPE SCALE FACTOR = 0.00616 rad/bit
 80B6 D9
 80B7 C9
 80B8 79
 80B9 F6             179 CNST14:  DB      0F6H,0FH,0C9H,80H       ;SLOPE OFFSET = -0.785 rad
 80BA 0F
 80BB C9
 80BC 80
 80BD 00             180 CNST20:  DB      00H,00H,0F0H,06H        ;3CH = 60D
 80BE 00
 80BF F0
 80C0 06
 80C1 00             181 CNST21:  DB      00H,00H,98H,07H         ;4CH = 76D
 80C2 00
 80C3 98
 80C4 07
 80C5 00             182 D14:     DB      00H,00H,0E0H,04H        ;14D
 80C6 00
 80C7 E0
 80C8 04
 80C9 00             183 H255:    DB      00H,00H,0FFH,08H        ;FFH = 255D
 80CA 00
 80CB FF
 80CC 08
                     184                                          ;
                     185                                          ;** MAIN PROGRAM **
                     186                                          ;
                     187                                          ;INITIALISE SYSTEM
 LOC  OBJ         LINE        SOURCE STATEMENT

                   188                                              ;
 80D0              189          ORG     80D0H
 80D0 0644         190          MVI     B,68D                       ;SET UP DEFAULT CONSTANTS IN RAM
 80D2 110080       191          LXI     D,XAPOF
 80D5 21CD30       192          LXI     H,APOF
 80D8 1A           193 DLOOP:   LDAX    D                           ;LOOP TO TRANSFER DATA FROM ROM INTO RAM
 80D9 77           194          MOV     M,A
 80DA 13           195          INX     D
 80DB 23           196          INX     H
 80DC 05           197          DCR     B
 80DD C2D880       198          JNZ     DLOOP
                   199                                              ;
                   200                                              ;
 80E0 3EF8         201          MVI     A,0F8H                      ;UNMASK AND DISABLE INTERRUPTS
 80E2 30           202          SIM
 80E3 F3           203          DI
 80E4 3ECF         204          MVI     A,0CFH                      ;LOAD LOCATION 20CE WITH 0CFH
 80E6 32CE20       205          STA     20CEH                       ; FOR VECTORED INTERRUPT HANDLING
                   206                                              ;
                   207                                              ;
 80E9 31C220       208          LXI     SP,20C2H                    ;SET STACK POINTER
 80EC CDFE83       209          CALL    INIT                        ;CALL ROUTINE FOR SETTING UP
                   210                                              ; I/O PORT DATA DIRECTION REGISTERS
                   211                                              ;
                   212                                              ;
                   213                                              ;
                   214                                              ;SEGMENT FOR MODE SELECTION
 80EF AF           215          XRA     A
 80F0 320030       216          STA     MODFLG
 80F3 D300         217 MLOOP:   OUT     00H                         ;TURN OFF VALVES
 80F5 D301         218          OUT     01H
 80F7 D321         219          OUT     21H
 80F9 2F           220          CMA
 80FA D322         221          OUT     22H
 80FC DB2A         222 L100:    IN      2AH                         ;READ SWITCHES FOR MODE SELECTION
 80FE 47           223          MOV     B,A
 80FF C5           224          PUSH    B                           ;PUT INPUT ON TOS
 8100 21FF00       225          LXI     H,00FFH                     ;CALL DELAY ROUTINE
 8103 CD9787       226          CALL    PAUSE
 8106 DB2A         227          IN      2AH                         ;READ SWITCHES
 8108 C1           228          POP     B                           ;COMPARE WITH PREVIOUS INPUT
 8109 B8           229          CMP     B
 810A C2FC80       230          JNZ     L100
 810D 321D30       231          STA     MODE
 8110 21FF00       232 L101:    LXI     H,00FFH                     ;WAIT FOR SWITCH TO BE RELEASED
 8113 CD9787       233          CALL    PAUSE
 8116 DB2A         234          IN      2AH
 8118 FE00         235          CPI     00H
 811A C21081       236          JNZ     L101
 811D 21FF00       237          LXI     H,00FFH
 8120 CD9787       238          CALL    PAUSE
 8123 DB2A         239          IN      2AH
 8125 FE00         240          CPI     00H
 8127 C21081       241          JNZ     L101
 812A 3A1D30       242          LDA     MODE                        ;CALL ROUTINE ACCORDING TO MODE &
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  LOC  OBJ         LINE        SOURCE STATEMENT

  812D E606         243         ANI     06H                       ; JUMP ON RETURN TO START OF LOOP
  812F FE06         244         CPI     06H
  8131 C24881       245         JNZ     L102
  8134 3A0030       246         LDA     MODFLG                    ;IF MODFLG = REPEAT SLOW THEN CALL RFCON
  8137 FE01         247         CPI     01H                       ; ELSE CALL RFAST
  8139 CA4281       248         JZ      L108
  813C CDC083       249         CALL    RFAST
  813F C3F380       250         JMP     MLOOP
  8142 CDCA83       251 L108:   CALL    RFCON
  8145 C3F380       252         JMP     MLOOP
  8148 3A1D30       253 L102:   LDA     MODE
  814B E605         254         ANI     05H
  814D FE05         255         CPI     05H
  814F C26681       256         JNZ     L103
  8152 3A0030       257         LDA     MODFLG                    ;IF MODFLG = REPEAT FAST CALL RSCON
  8155 FE01         258         CPI     01H                       ; ELSE CALL RSLOW
  8157 CA6081       259         JZ      L109
  815A CDE183       260         CALL    RSLOW
  815D C3F380       261         JMP     MLOOP
  8160 CDEB83       262 L109:   CALL    RSCON
  8163 C3F380       263         JMP     MLOOP
  8166 3A1D30       264 L103:   LDA     MODE
  8169 E602         265         ANI     02H
  816B FE02         266         CPI     02H
  816D C27681       267         JNZ     L104
  8170 CDE681       268         CALL    LEARN
  8173 C3F380       269         JMP     MLOOP
  8176 CD7C81       270 L104:   CALL    MANUAL
  8179 C3F380       271         JMP     MLOOP
                    272                                           ;
                    273                                           ;
                    274                                           ;** SUBROUTINE MANUAL **
                    275                                           ;
                    276                                           ;SUBROUTINE FOR MANUAL MODE OPERATION
                    277                                           ;
                    278                                           ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                    279                                           ;
  817C AF           280 MANUAL: XRA     A                         ;INDICATE MODE
  817D 320030       281         STA     MODFLG
  8180 D323         282         OUT     23H
  8182 CD9081       283 LOOP1:  CALL    XY                        ;CALL ROUTINE FOR XY CONTROL
  8185 DB2A         284         IN      2AH                       ;CHECK MODE SWITCHES
  8187 FE00         285         CPI     00H
  8189 C0           286         RNZ
  818A FB           287         EI                                ;ALLOW INTERRUPT
  818B 00           288         NOP
  818C F3           289         DI
  818D C38281       290         JMP     LOOP1
                    291                                           ;
                    292                                           ;
                    293                                           ;** SUBROUTINE XY **
                    294                                           ;
                    295                                           ;THIS SUBROUTINE IS THE MAIN
                    296                                           ; CONTROL ROUTINE FOR LINEAR X-Y
                    297                                           ; MOVEMENT OF THE BUCKET BLADE AND
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 LOC  OBJ         LINE        SOURCE STATEMENT

                   298                                         ; IS USED IN MANUAL AND LEARN MODES
                   299                                         ;
                   300                                         ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                   301                                         ;
                   302                                         ;
 8190 CD1384       303 XY:     CALL    CONV                    ;READS IN CONTROL SETTINGS AND
                   304                                         ; OUTPUT POSITIONS
 8193 CD3F86       305         CALL    COORD                   ;CALCULATES OUTPUT POSITIONS IN
                   306                                         ; USER COORDINATES
 8196 CDD587       307         CALL    IP1                     ;CALCULATES CHANGES IN CONTROL
                   308                                         ; SETTINGS AND DEFINES CONTROL LOOP
                   309                                         ; INPUT VELOCITIES
 8199 CD2487       310         CALL    EPOS                    ;CALCULATES POSITIONAL ERRORS
                   311                                         ; IN X AND Y, AND TOTAL ERROR MAGNITUDE ETA
 819C CD9E87       312         CALL    SETEC                   ;SET ECRIT ACCORDING TO INPUT VELOCITIES
 819F CD0289       313         CALL    IP2                     ;IF ETA IS GREATER THAN ECRIT THEN
                   314                                         ; FREEZE TARGET POSITION ELSE ASSIGN
                   315                                         ; NEW TARGET POSITION ACCORDING TO
                   316                                         ; INPUT VELOCITIES
 81A2 CD5F89       317         CALL    FFD                     ;CALCULATE VALVE SETTINGS
 81A5 CD968C       318         CALL    OUTPUT                  ;OUTPUT VALVE CONTROL BYTES
 81A8 C9           319         RET
                   320                                         ;
                   321                                         ;
                   322                                         ;
                   323                                         ;** APU STACK PUSH MACRO **
                   324                                         ;
                   325                                         ;THIS MACRO GENERATES CODE FOR
                   326                                         ; PUSHING A 32 BIT OPERAND FROM
                   327                                         ; MEMORY ONTO THE APU STACK
                   328                                         ;
                   329                                         ;REGISTERS AFFECTED: D,E
                   330                                         ;
                   331 PSH     MACRO   XYZ
 -                 332         LXI     D,XYZ
 -                 333         CALL    PSHT
                   334         ENDM
                   335                                         ;
                   336                                         ;
                   337                                         ;** APU STACK POP MACRO **
                   338                                         ;
                   339                                         ;MACRO FOR POPPING A 32 BIT
                   340                                         ; OPERAND FROM THE APU STACK
                   341                                         ; INTO MEMORY
                   342                                         ;
                   343                                         ;REGISTERS AFFECTED: D,E
                   344                                         ;
                   345 PLL     MACRO   POR
 -                 346         LXI     D,POR
 -                 347         CALL    PLLT
                   348         ENDM
                   349                                         ;
                   350                                         ;
                   351                                         ;
                   352                                         ;** MACRO FOR CONDITIONAL JUMPS **
 LOC  OBJ         LINE        SOURCE STATEMENT

                   353                                          ;
                   354                                          ;THIS MACRO GENERATES CODE FOR MAKING
                   355                                          ; CONDITIONAL JUMPS DEPENDING ON THE
                   356                                          ; VALUES OF TWO 32 BIT FLOATING POINT
                   357                                          ; VARIABLES ID1 AND ID2
                   358                                          ;
                   359                                          ;IF ID1 GTHAN:GEQUAL:EQUALS:NEQUAL:
                   360                                          ;       LEQUAL:LTHAN ID2
                   361                                          ; THEN GOTO LABL
                   362                                          ; ELSE CONTINUE
                   363                                          ;
                   364                                          ;REGISTERS AFFECTED: A,D,E,STATUS
                   365                                          ;
                   366                                          ; DATA IS PASSED TO SUBROUTINE OP IN
                   367                                          ; TEMPORARY VARIABLES V1 AND V2.  THE
                   368                                          ; RESULT IS RETURNED IN THE A REGISTER:
                   369                                          ; 1=TRUE, 0=FALSE. THE RESULT OF OP IS
                   370                                          ; CHECKED AND CONTROL JUMPS OR CONTINUES
                   371                                          ; ACCORDINGLY
                   372                                          ;
                   373 IFF     MACRO   ID1,OP,ID2,LABL
 -                 374         PSH     ID1
 -                 375         PLL     V1
 -                 376         PSH     ID2
 -                 377         PLL     V2
 -                 378         CALL    OP
 -                 379         ANI     01H
 -                 380         JNZ     LABL
                   381         ENDM
                   382                                          ;
                   383                                          ;
                   384                                          ;
                   385                                          ;** ROUTINES FOR LEARN AND REPEAT FUNCTIONS **
                   386                                          ;
                   387                                          ;** SUBROUTINE XPXO **
                   388                                          ;
                   389                                          ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                   390                                          ;
 81A9 216430       391 XPXO:   LXI     H,XO                     ;THIS ROUTINE COPIES THE CURRENT OUTPUT
 81AC 112030       392         LXI     D,XP                     ; COORDINATES XO, YO & PSIO TO XP, YP
 81AF 060C         393         MVI     B,0CH                    ; AND PSIP RESPECTIVELY
 81B1 7E           394 L201:   MOV     A,M
 81B2 12           395         STAX    D
 81B3 23           396         INX     H
 81B4 13           397         INX     D
 81B5 05           398         DCR     B
 81B6 C2B181       399         JNZ     L201
 81B9 C9           400         RET
                   401                                          ;
                   402                                          ;
                   403                                          ;** SUBROUTINE TPULL **
                   404                                          ;
                   405                                          ;THIS ROUTINE PULLS A CO-ORDINATE
                   406                                          ; FROM THE PATH STACK USING POINTER PPOINT.
                   407                                          ; 12 BYTES ARE PULLED, REGISTER B ACTING AS
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  LOC  OBJ         LINE        SOURCE STATEMENT

                    408                                         ; THE BYTE COUNTER.  HL POINTS TO THE
                    409                                         ; DESTINATION ADDRESS AND DE TO THE SOURCE
                    410                                         ; ADDRESS.
                    411                                         ;
                    412                                         ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                    413                                         ;
 81BA 2A1E30        414 TPULL:  LHLD    PPOINT
 81BD EB            415         XCHG
 81BE 060C          416         MVI     B,0CH
 81C0 215830        417         LXI     H,XI
 81C3 1A            418 LOOP3:  LDAX    D
 81C4 77            419         MOV     M,A
 81C5 23            420         INX     H
 81C6 13            421         INX     D
 81C7 05            422         DCR     B
 81C8 C2C381        423         JNZ     LOOP3
 81CB EB            424         XCHG
 81CC 221E30        425         SHLD    PPOINT
 81CF C9            426         RET
                    427                                         ;
                    428                                         ;
                    429                                         ;
                    430                                         ;** SUBROUTINE TPUSH **
                    431                                         ;
                    432                                         ;THIS ROUTINE PUSHES X0, Y0, AND PSI0
                    433                                         ; ONTO THE PATH STACK USING DATA
                    434                                         ; POINTER PPOINT.  12 BYTES ARE TO BE
                    435                                         ; TRANSFERRED, REGISTER B IS THE BYTE
                    436                                         ; COUNTER.  HL POINTS TO THE SOURCE ADD-
                    437                                         ; RESS AND DE TO THE DESTINATION ADDRESS.
                    438                                         ;
                    439                                         ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                    440                                         ;
                    441                                         ;
 81D0 2A1E30        442 TPUSH:  LHLD    PPOINT                  ;LOAD DE WITH CONTENTS OF PPOINT
 81D3 EB            443         XCHG
 81D4 060C          444         MVI     B,0CH                   ;B=12D
 81D6 216430        445         LXI     H,X0
 81D9 7E            446 LOOP:   MOV     A,M
 81DA 12            447         STAX    D
 81DB 23            448         INX     H
 81DC 13            449         INX     D
 81DD 05            450         DCR     B
 81DE C2D981        451         JNZ     LOOP
 81E1 EB            452         XCHG                            ;LOAD PPOINT WITH CONTENTS OF DE
 81E2 221E30        453         SHLD    PPOINT
 81E5 C9            454         RET
                    455                                         ;
                    456                                         ;
                    457                                         ;** SUBROUTINE LEARN **
                    458                                         ;
                    459                                         ;ROUTINE FOR LEARNING A PATH
                    460                                         ;
                    461                                         ;REGISTERS AFFECTED: A,H,L,D,E,STATUS
                    462                                         ;
  LOC  OBJ          LINE        SOURCE STATEMENT

 81E6 3E01           463 LEARN:  MVI     A,01H                          ;INDICATE MODE
 81E8 D323           464         OUT     23H
 81EA AF             465         XRA     A                              ;ZERO PATH POINT COUNTER PCOUNT
 81EB 323430         466         STA     PCOUNT
 81EE 211131         467         LXI     H,BASE                         ;INITIALISE PPOINT TO BASE ADDRESS
 81F1 221E30         468         SHLD    PPOINT                         ; OF PATH STORAGE AREA
 81F4 CDA981         469         CALL    XPXO                           ;SET XP = XO ETC.
 81F7 CDD081         470         CALL    TPUSH                          ;PUSH CURRENT OUTPUT POSITION ON STACK
 81FA CD9081         471 L206:   CALL    XY                             ;CALL XY ROUTINE
                     472         PSH     YO                             ;IF CURRENT XY COORDINATE >= DCRIT
 81FD 116830         473+        LXI     D,YO
 8200 CD0185         474+        CALL    PSHT
                     475         PSH     YP                             ; FROM LAST XY COORDINATE JMP L202
 8203 112430         476+        LXI     D,YP
 8206 CD0185         477+        CALL    PSHT
 8209 CD948E         478         CALL    FSUB                           ;DIST=SQRT((YO-YP)**2+(XO-XP)**2)
 820C CDC48E         479         CALL    PTOF
 820F CD708E         480         CALL    FMUL
                     481         PSH     XO
 8212 116430         482+        LXI     D,XO
 8215 CD0185         483+        CALL    PSHT
                     484         PSH     XP
 8218 112030         485+        LXI     D,XP
 821B CD0185         486+        CALL    PSHT
 821E CD948E         487         CALL    FSUB
 8221 CDC48E         488         CALL    PTOF
 8224 CD708E         489         CALL    FMUL
 8227 CD648E         490         CALL    FADD
 822A CD248F         491         CALL    SQRT
                     492         PLL     DIST
 822D 112C30         493+        LXI     D,DIST
 8230 CD1785         494+        CALL    PLLT
                     495         IFF     DIST,GEQUAL,DCRIT,L202
                     496+        PSH     DIST
 8233 112C30         497+        LXI     D,DIST
 8236 CD0185         498+        CALL    PSHT
                     499+        PLL     V1
 8239 119530         500+        LXI     D,V1
 823C CD1785         501+        CALL    PLLT
                     502+        PSH     DCRIT
 823F 11F530         503+        LXI     D,DCRIT
 8242 CD0185         504+        CALL    PSHT
                     505+        PLL     V2
 8245 119930         506+        LXI     D,V2
 8248 CD1785         507+        CALL    PLLT
 824B CD5E85         508+        CALL    GEQUAL
 824E E601           509+        ANI     01H
 8250 C29182         510+        JNZ     L202
                     511         PSH     PSIO                           ;IF CURRENT PSIO VALUE >= DPCRIT
 8253 116C30         512+        LXI     D,PSIO
 8256 CD0185         513+        CALL    PSHT
                     514         PSH     PSIP                           ; RECORD NEW PATH POINT ELSE JMP L205
 8259 112830         515+        LXI     D,PSIP
 825C CD0185         516+        CALL    PSHT
 825F CD948E         517         CALL    FSUB
 LOC  OBJ         LINE        SOURCE STATEMENT

 8262 CDC48E       518          CALL    PTOF
 8265 CD708E       519          CALL    FMUL
 8268 CD248F       520          CALL    SQRT
                   521          PLL     DPSI
 826B 113030       522+         LXI     D,DPSI
 826E CD1785       523+         CALL    PLLT
                   524          IFF     DPSI,LTHAN,DPCRIT,L205  ;(DPCRIT = 5 DEG. = 0.0873 RAD)
                   525+         PSH     DPSI
 8271 113030       526+         LXI     D,DPSI
 8274 CD0185       527+         CALL    PSHT
                   528+         PLL     V1
 8277 119530       529+         LXI     D,V1
 827A CD1785       530+         CALL    PLLT
                   531+         PSH     DPCRIT
 827D 11F930       532+         LXI     D,DPCRIT
 8280 CD0185       533+         CALL    PSHT
                   534+         PLL     V2
 8283 119930       535+         LXI     D,V2
 8286 CD1785       536+         CALL    PLLT
 8289 CD4785       537+         CALL    LTHAN
 828C E601         538+         ANI     01H
 828E C2A482       539+         JNZ     L205
 8291 CDA981       540 L202:    CALL    XPXO                        ;XP = XO ETC.
 8294 CDD081       541          CALL    TPUSH                       ;PUT CURRENT O/P POSN ON PATH STACK
 8297 3A3430       542          LDA     PCOUNT                      ;INCREMENT PATH POINT COUNTER PCOUNT
 829A 3C           543          INR     A                           ; & TEST FOR FULL MEMORY
 829B 323430       544          STA     PCOUNT
 829E 47           545          MOV     B,A
 829F 3A4C80       546          LDA     MAXPTS
 82A2 B8           547          CMP     B
 82A3 C8           548          RZ
 82A4 DB2A         549 L205:    IN      2AH                         ;IF INPUT FROM MODE SELECT SWITCHES # 0
 82A6 FE00         550          CPI     00H                         ; THEN RETURN   ELSE JUMP TO L206
 82A8 CAFA81       551          JZ      L206
 82AB C9           552          RET
                   553                                              ;
                   554                                              ;
                   555                                              ;** SEGMENTS FOR REPEATING A STORED
                   556                                              ;                                PATH **
                   557                                              ;
                   558                                              ;
                   559                                              ;** SUBROUTINE RSETUP **
                   560                                              ;
                   561                                              ;THIS ROUTINE INITIALISES THE
                   562                                              ; COUNTERS, THE DATA POINTER,
                   563                                              ; AND OFFSETS. IT THEN READS THE
                   564                                              ; FIRST PATH POINT FOR REPEATING
                   565                                              ; THE STORED PATH AND CALCULATES
                   566                                              ; THE OFFSETS XOF AND YOF. IT ALSO
                   567                                              ; ASSIGNS XI=XO AND YI=YO
                   568                                              ;
 82AC AF           569 RSETUP: XRA      A                           ;ZERO NCOUNT AND RCOUNT
 82AD 323630       570          STA     NCOUNT                      ; WHICH COUNT CONTROL ROUTINE CALLS
 82B0 323530       571          STA     RCOUNT                      ; AND PATH POINTS RESPECTIVELY
 82B3 211131       572          LXI     H,BASE                      ;INITIALISE DATA POINTER
 LOC  OBJ          LINE        SOURCE STATEMENT

 82B6 221E30        573          SHLD     PPOINT
 82B9 CDBA81        574          CALL     TPULL                        ;READ 1ST PATH POINT, CALCULATE
                    575          PSH      XO                           ; OFFSET, SET XI=XO & YI=YO
 82BC 116430        576+         LXI      D,XO
 82BF CD0185        577+         CALL     PSHT
 82C2 CDC48E        578          CALL     PTOF
                    579          PSH      XI
 82C5 115830        580+         LXI      D,XI
 82C8 CD0185        581+         CALL     PSHT
 82CB CD948E        582          CALL     FSUB
                    583          PLL      XOF
 82CE 111530        584+         LXI      D,XOF
 82D1 CD1785        585+         CALL     PLLT
                    586          PLL      XI
 82D4 115830        587+         LXI      D,XI
 82D7 CD1785        588+         CALL     PLLT
                    589          PSH      YO
 82DA 116830        590+         LXI      D,YO
 82DD CD0185        591+         CALL     PSHT
 82E0 CDC48E        592          CALL     PTOF
                    593          PSH      YI
 82E3 115C30        594+         LXI      D,YI
 82E6 CD0185        595+         CALL     PSHT
 82E9 CD948E        596          CALL     FSUB
                    597          PLL      YOF
 82EC 111930        598+         LXI      D,YOF
 82EF CD1785        599+         CALL     PLLT
                    600          PLL      YI
 82F2 115C30        601+         LXI      D,YI
 82F5 CD1785        602+         CALL     PLLT
 82F8 CD2487        603          CALL     EPOS
 82FB C9            604          RET
                    605                                                 ;
                    606                                                 ;
                    607                                                 ;** SUBROUTINE REPEAT **
                    608                                                 ;
                    609                                                 ;THIS ROUTINE PULLS SUCCESSIVE
                    610                                                 ; POINTS FROM THE PATH STACK AND
                    611                                                 ; CALLS THE CONTROL ROUTINES TO
                    612                                                 ; MAKE THE MACHINE FOLLOW THE
                    613                                                 ; STORED PATH.
                    614                                                 ;
                    615                                                 ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                    616                                                 ;
                    617 REPEAT: IFF      ETA,GTHAN,ECRIT,L301          ;IF ERROR)ECRIT OR :EPSI:)PCRIT
                    618+         PSH      ETA
 82FC 117C30        619+         LXI      D,ETA
 82FF CD0185        620+         CALL     PSHT
                    621+         PLL      V1
 8302 119530        622+         LXI      D,V1
 8305 CD1785        623+         CALL     PLLT
                    624+         PSH      ECRIT
 8308 11BE30        625+         LXI      D,ECRIT
 830B CD0185        626+         CALL     PSHT
                    627+         PLL      V2
 LOC  OBJ          LINE        SOURCE STATEMENT

 830E 119930        628+        LXI     D,V2
 8311 CD1785        629+        CALL    PLLT
 8314 CD3085        630+        CALL    GTHAN
 8317 E601          631+        ANI     01H
 8319 C2A583        632+        JNZ     L301
                    633                                              ; OR (NCOUNT+1)<FCOUNT THEN JMP L301
                    634         PSH     EPSI                         ;FIND :EPSI:
 831C 117830        635+        LXI     D,EPSI
 831F CD0185        636+        CALL    PSHT
 8322 CDC48E        637         CALL    PTOF
 8325 CD708E        638         CALL    FMUL
 8328 CD248F        639         CALL    SQRT
                    640         PLL     I1
 832B 114830        641+        LXI     D,I1
 832E CD1785        642+        CALL    PLLT
                    643         IFF     I1,GTHAN,PCRIT,L301
                    644+        PSH     I1
 8331 114830        645+        LXI     D,I1
 8334 CD0185        646+        CALL    PSHT
                    647+        PLL     V1
 8337 119530        648+        LXI     D,V1
 833A CD1785        649+        CALL    PLLT
                    650+        PSH     PCRIT
 833D 11E130        651+        LXI     D,PCRIT
 8340 CD0185        652+        CALL    PSHT
                    653+        PLL     V2
 8343 119930        654+        LXI     D,V2
 8346 CD1785        655+        CALL    PLLT
 8349 CD3085        656+        CALL    GTHAN
 834C E601          657+        ANI     01H
 834E C2A583        658+        JNZ     L301
 8351 3A3630        659         LDA     NCOUNT                       ;INCREMENT NCOUNT & COMPARE WITH FCOUNT
 8354 3C            660         INR     A
 8355 323630        661         STA     NCOUNT
 8358 47            662         MOV     B,A
 8359 3ABD30        663         LDA     FCOUNT
 835C B8            664         CMP     B
 835D C2A583        665         JNZ     L301
 8360 3A3430        666         LDA     PCOUNT                       ;IF END OF PATH CLEAR MODFLG
 8363 47            667         MOV     B,A                          ; AND RETURN
 8364 3A3530        668         LDA     RCOUNT
 8367 B8            669         CMP     B
 8368 C27083        670         JNZ     L308
 836B AF            671         XRA     A
 836C 320030        672         STA     MODFLG
 836F C9            673         RET
 8370 3C            674 L308:   INR     A                            ;ELSE INCREMENT RCOUNT & RESET
 8371 323530        675         STA     RCOUNT                       ; NCOUNT
 8374 AF            676         XRA     A
 8375 323630        677         STA     NCOUNT
 8378 CDBA81        678         CALL    TPULL                        ;READ PATH POINT AND
                    679         PSH     XI                           ;ADD OFFSET
 837B 115830        680+        LXI     D,XI
 837E CD0185        681+        CALL    PSHT
                    682         PSH     XOF
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  LOC  OBJ          LINE        SOURCE STATEMENT

 8381 111530         683+        LXI     D,XOF
 8384 CD0185         684+        CALL    PSHT
 8387 CD648E         685         CALL    FADD
                     686         PLL     XI
 838A 115830         687+        LXI     D,XI
 838D CD1785         688+        CALL    PLLT
                     689         PSH     YI
 8390 115C30         690+        LXI     D,YI
 8393 CD0185         691+        CALL    PSHT
                     692         PSH     YOF
 8396 111930         693+        LXI     D,YOF
 8399 CD0185         694+        CALL    PSHT
 839C CD648E         695         CALL    FADD
                     696         PLL     YI
 839F 115C30         697+        LXI     D,YI
 83A2 CD1785         698+        CALL    PLLT
 83A5 CD1384         699 L301:   CALL    CONV                           ;CALL CONTROL ROUTINES
 83A8 CD3F86         700         CALL    COORD
 83AB CD2487         701         CALL    EPOS
 83AE CD5F89         702         CALL    FFD
 83B1 CD968C         703         CALL    OUTPUT
 83B4 DB2A           704         IN      2AH                            ;CHECK MODE SWITCH INPUTS
 83B6 FE00           705         CPI     00H
 83B8 C0             706         RNZ
                     707                                                ;
 83B9 FB             708         EI                                     ;ALLOW INTERRUPT
 83BA 00             709         NOP
 83BB F3             710         DI
                     711                                                ;
 83BC C3FC82         712         JMP     REPEAT
 83BF C9             713         RET
                     714                                                ;
                     715                                                ;
                     716                                                ;
                     717                                                ;** SUBROUTINE RFAST **
                     718                                                ;
                     719                                                ;SEGMENT FOR REPEAT FAST MODE.
                     720                                                ; CONTROL NORMALLY ENTERS AT LABEL
                     721                                                ; RFAST.  HOWEVER IF THE MACHINE IS
                     722                                                ; ALREADY IN REPEAT SLOW MODE CONTROL
                     723                                                ; ENTERS AT RFCON.  THIS ALLOWS THE
                     724                                                ; REPEAT SPEED TO BE CHANGED WITHOUT
                     725                                                ; RESTARTING THE TRAJECTORY.
                     726                                                ;
                     727                                                ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                     728                                                ;
 83C0 3A3430         729 RFAST:  LDA     PCOUNT                         ;RETURN IF NO PATH IN MEMORY
 83C3 47             730         MOV     B,A
 83C4 AF             731         XRA     A
 83C5 B8             732         CMP     B
 83C6 C8             733         RZ
 83C7 CDAC82         734         CALL    RSETUP
 83CA 3E03           735 RFCON:  MVI     A,03H                          ;INDICATE MODE
 83CC D323           736         OUT     23H
 83CE 3E02           737         MVI     A,02H
 LOC  OBJ          LINE        SOURCE STATEMENT

 83D0 320030        738          STA     MODFLG
 83D3 3AFD30        739          LDA     FFAST                               ;SET UP NO. OF CONTROL ROUTINE
 83D6 32BD30        740          STA     FCOUNT                              ; CALLS BETWEEN POINTS
 83D9 AF            741          XRA     A                                   ;CLEAR NCOUNT
 83DA 323630        742          STA     NCOUNT
 83DD CDFC82        743          CALL    REPEAT
 83E0 C9            744          RET
                    745                                                      ;
                    746                                                      ;
                    747                                                      ;** SUBROUTINE RSLOW **
                    748                                                      ;
                    749                                                      ;SEGMENT FOR REPEAT SLOW MODE
                    750                                                      ;
                    751                                                      ;CONTROL NORMALLY ENTERS THE
                    752                                                      ; ROUTINE AT LABEL RSLOW. HOWEVER
                    753                                                      ; IF THE SYSTEM IS ALREADY IN
                    754                                                      ; REPEAT FAST MODE THEN CONTROL
                    755                                                      ; ENTERS AT LABEL RSCON.  THIS
                    756                                                      ; ALLOWS THE REPEAT SPEED TO BE
                    757                                                      ; CHANGED WITHOUT RESTARTING THE
                    758                                                      ; TRAJECTORY.
                    759                                                      ;
                    760                                                      ;REGISTERS AFFECTED: A,B,D,E,H,L,STATUS
                    761                                                      ;
 83E1 3A3430        762 RSLOW:   LDA     PCOUNT                              ;RETURN IF NO PATH IN MEMORY
 83E4 47            763          MOV     B,A
 83E5 AF            764          XRA     A
 83E6 B8            765          CMP     B
 83E7 C8            766          RZ
 83E8 CDAC82        767          CALL    RSETUP
 83EB 3E02          768 RSCON:   MVI     A,02H                               ;INDICATE MODE
 83ED D323          769          OUT     23H
 83EF 3E01          770          MVI     A,01H
 83F1 320030        771          STA     MODFLG
 83F4 3AFE30        772          LDA     FSLOW
 83F7 32BD30        773          STA     FCOUNT
 83FA CDFC82        774          CALL    REPEAT
 83FD C9            775          RET
                    776                                                      ;
                    777                                                      ;
                    778                                                      ;
                    779                                                      ;** SUBROUTINE INIT **
                    780                                                      ;
                    781                                                      ;THIS ROUTINE SETS UP THE I/O
                    782                                                      ; PORT DATA DIRECTION REGISTERS
                    783                                                      ;
                    784                                                      ;REGISTERS AFFECTED: A
                    785                                                      ;
 83FE 3E0F          786 INIT:    MVI     A,0FH                               ;SET PORTS 21,22,23 FOR OUTPUT
 8400 D320          787          OUT     20H
 8402 3EFF          788          MVI     A,0FFH
 8404 D302          789          OUT     02H
 8406 D303          790          OUT     03H
 8408 D30A          791          OUT     0AH
 840A 3E0C          792          MVI     A,0CH
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  LOC  OBJ          LINE        SOURCE STATEMENT

  840C D328          793          OUT     28H
  840E AF            794          XRA     A                        ;ZERO PATH POINT COUNTER
  840F 323430        795          STA     PCOUNT
  8412 C9            796          RET
                     797                                           ;
                     798                                           ;
                     799                                           ;
                     800                                           ;** SUBROUTINE CONV **
                     801                                           ;
                     802                                           ;THIS SUBROUTINE READS IN THE JOYSTICK
                     803                                           ; AND PITCH CONTROL SETTINGS AND THE
                     804                                           ; MACHINE POSITION
                     805                                           ;
                     806                                           ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                     807                                           ;
  8413 3E03          808 CONV:    MVI     A,03H                    ;LOAD A WITH JOYSTICK SLEW CONTROL
                     809                                           ;CHANNEL NUMBER
  8415 CDE784        810          CALL    ADCON
  8418 CD9385        811          CALL    JOYSTK                   ;TRANSFORMS JOYSTICK VOLTAGE
                     812                                           ; TO RANGE -1 TO +1 (RESULT ON TOS)
                     813          PLL     JSLEW
  841B 114030        814+         LXI     D,JSLEW
  841E CD1785        815+         CALL    PLLT
  8421 3E04          816          MVI     A,04H                    ;READ YDOT INPUT FROM JOYSTICK
  8423 CDE784        817          CALL    ADCON
  8426 CD9385        818          CALL    JOYSTK
                     819          PLL     JYDOT
  8429 113C30        820+         LXI     D,JYDOT
  842C CD1785        821+         CALL    PLLT
  842F 3E05          822          MVI     A,05H                    ;READ XDOT INPUT FROM JOYSTICK
  8431 CDE784        823          CALL    ADCON
  8434 CD9385        824          CALL    JOYSTK
                     825          PLL     JXDOT
  8437 113830        826+         LXI     D,JXDOT
  843A CD1785        827+         CALL    PLLT
  843D 3E06          828          MVI     A,06H                    ;READ BUCKET VELOCITY INPUT FROM
  843F CDE784        829          CALL    ADCON                    ; JOYSTICK
  8442 CD9385        830          CALL    JOYSTK
                     831          PLL     JBKT
  8445 114430        832+         LXI     D,JBKT
  8448 CD1785        833+         CALL    PLLT
  844B 3E07          834          MVI     A,07H                    ;PITCH
  844D CDE784        835          CALL    ADCON
  8450 CD1C86        836          CALL    SLOPE                    ;CALCULATE INPUT PITCH ANGLE
                     837                                           ; FROM CONTROL KNOB VOLTAGE
                     838                                           ;
                     839                                           ;READ IN VOLTAGES FROM POTENTIOMETERS
                     840                                           ; ON MACHINE PIVOTS AND CALCULATE ARM
                     841                                           ; ANGLES
  8453 CD5D84        842          CALL    ALFIP                    ;INPUT ALPHA AND SUBTRACT PITCH
  8456 CD9784        843          CALL    BETIP                    ;INPUT BETA
  8459 CDBF84        844          CALL    DELTIP                   ;INPUT DELTA
  845C C9            845          RET
                     846                                           ;
                     847                                           ;
  LOC  OBJ          LINE        SOURCE STATEMENT

                     848                                     ;** SUBROUTINE ALFIP **
                     849                                     ;
                     850                                     ;INPUTS ALPHA VOLTAGE, SCALES IT,
                     851                                     ; ADDS OFFSET, AND SUBTRACTS PITCH
                     852                                     ;
                     853                                     ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                     854                                     ;
  845D 3E00          855 ALFIP:  MVI     A,00H               ;A=ALPHA CHANNEL NUMBER
  845F CDE784        856         CALL    ADCON
  8462 320010        857         STA     1000H               ;PUSH VALPHA ONTO APU STACK
  8465 AF            858         XRA     A
  8466 320010        859         STA     1000H
  8469 CD888E        860         CALL    FLTS                ;CONVERT RESULT TO 32-BIT FL. PT. FORMAT
                     861         PSH     MA                  ;PUSH SCALE FAC & MPY
  846C 115580        862+        LXI     D,MA
  846F CD0185        863+        CALL    PSHT
  8472 CD708E        864         CALL    FMUL
                     865         PSH     CA                  ;PUSH OFFSET AND ADD
  8475 115980        866+        LXI     D,CA
  8478 CD0185        867+        CALL    PSHT
  847B CD648E        868         CALL    FADD
  847E CDC48E        869         CALL    PTOF                ;PULL LIFT ARM ANGLE
                     870         PLL     MCALFA
  8481 118030        871+        LXI     D,MCALFA
  8484 CD1785        872+        CALL    PLLT
                     873         PSH     PITCH               ;SUBTRACT PITCH
  8487 119D30        874+        LXI     D,PITCH
  848A CD0185        875+        CALL    PSHT
  848D CD948E        876         CALL    FSUB
                     877         PLL     ALPHA
  8490 118430        878+        LXI     D,ALPHA
  8493 CD1785        879+        CALL    PLLT
  8496 C9            880         RET
                     881                                     ;
                     882                                     ;
                     883                                     ;** SUBROUTINE BETIP **
                     884                                     ;
                     885                                     ;INPUTS VBETA, SCALES IT, AND ADDS
                     886                                     ;        OFFSET
                     887                                     ;
                     888                                     ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                     889                                     ;
  8497 3E01          890 BETIP:  MVI     A,01H               ;A=BETA CHANNEL NUMBER
  8499 CDE784        891         CALL    ADCON
  849C 320010        892         STA     1000H               ;CONVERT TO 32-BIT FL. PT. FORMAT
  849F AF            893         XRA     A
  84A0 320010        894         STA     1000H
  84A3 CD888E        895         CALL    FLTS
                     896         PSH     MB                  ;MPY BY SCALE FAC
  84A6 115D80        897+        LXI     D,MB
  84A9 CD0185        898+        CALL    PSHT
  84AC CD708E        899         CALL    FMUL
                     900         PSH     CB                  ;PUSH OFFSET AND ADD
  84AF 116180        901+        LXI     D,CB
  84B2 CD0185        902+        CALL    PSHT
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 LOC  OBJ         LINE        SOURCE STATEMENT

 84B5 CD648E       903         CALL    FADD
                   904         PLL     BETA
 84B8 118830       905+        LXI     D,BETA
 84BB CD1785       906+        CALL    PLLT
 84BE C9           907         RET
                   908
                   909                                      ;
                   910                                      ;
                   911                                      ;** SUBROUTINE DELTIP **
                   912                                      ;
                   913                                      ;INPUTS VDELTA, SCALES IT, AND
                   914                                      ; ADDS OFFSET
                   915                                      ;
                   916                                      ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                   917                                      ;
 84BF 3E02         918 DELTIP: MVI     A,02H
 84C1 CDE784       919         CALL    ADCON
 84C4 320010       920         STA     1000H                ;CONVERT INPUT TO 32-BIT FL. PT.
 84C7 AF           921         XRA     A
 84C8 320010       922         STA     1000H
 84CB CD888E       923         CALL    FLTS
                   924         PSH     MD                   ;MULTIPLY BY SCALE FACTOR
 84CE 116580       925+        LXI     D,MD
 84D1 CD0185       926+        CALL    PSHT
 84D4 CD708E       927         CALL    FMUL
                   928         PSH     CD                   ;ADD OFFSET
 84D7 116980       929+        LXI     D,CD
 84DA CD0185       930+        CALL    PSHT
 84DD CD648E       931         CALL    FADD
                   932         PLL     DELTA
 84E0 118C30       933+        LXI     D,DELTA
 84E3 CD1785       934+        CALL    PLLT
 84E6 C9           935         RET
                   936                                      ;
                   937                                      ;
                   938                                      ;** SUBROUTINE ADCON **
                   939                                      ;
                   940                                      ;THIS ROUTINE OPERATES THE
                   941                                      ; ANALOGUE TO DIGITAL CONVERTER.
                   942                                      ; THE CHANNEL NUMBER IS IN THE
                   943                                      ; A REGISTER ON CALLING AND
                   944                                      ; THE RESULT AT RETURN
                   945                                      ;
                   946                                      ;REGISTERS AFFECTED: A,H,L,STATUS
                   947                                      ;
 84E7 D32B         948 ADCON:  OUT     2BH                  ;OUTPUT CHANNEL NUMBER
 84E9 C608         949         ADI     08H
 84EB D32B         950         OUT     2BH                  ;LATCH CHANNEL NUMBER
 84ED AF           951         XRA     A                    ;CLEAR CONTROL WORD
 84EE D32B         952         OUT     2BH
 84F0 211100       953         LXI     H,0011H              ;SET DELAY
 84F3 CD9787       954         CALL    PAUSE                ;CALL DELAY ROUTINE
 84F6 3E10         955         MVI     A,10H                ;SET TRISTATE OUTPUT
 84F8 D32B         956         OUT     2BH
 84FA 00           957         NOP
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  LOC  OBJ          LINE        SOURCE STATEMENT

  84FB 00            958         NOP
  84FC 00            959         NOP
  84FD 00            960         NOP
  84FE DB29          961         IN      29H                      ;READ RESULT
  8500 C9            962         RET
                     963                                          ;
                     964                                          ;
                     965                                          ;** SUBROUTINE PSHT **
                     966                                          ;
                     967                                          ;PUSHES A 32-BIT FL. PT. VARIABLE
                     968                                          ; ONTO THE APU STACK.
                     969                                          ; DE CONTAINS THE ADDRESS
                     970                                          ; OF THE LS BYTE OF THE
                     971                                          ; OPERAND ON CALLING
                     972                                          ; AND OF THE MS BYTE AT
                     973                                          ; RETURN
                     974                                          ;
                     975                                          ;REGISTERS AFFECTED: D,E
                     976                                          ;
  8501 F5            977 PSHT:   PUSH    PSW
  8502 1A            978         LDAX    D                        ;LD ACC WITH LS BYTE
  8503 320010        979         STA     1000H                    ;PUSH ACC TO APU
  8506 13            980         INX     D                        ;INCREMENT DATA POINTER
  8507 1A            981         LDAX    D
  8508 320010        982         STA     1000H
  850B 13            983         INX     D
  850C 1A            984         LDAX    D
  850D 320010        985         STA     1000H
  8510 13            986         INX     D
  8511 1A            987         LDAX    D
  8512 320010        988         STA     1000H
  8515 F1            989         POP     PSW
  8516 C9            990         RET
                     991                                          ;
                     992                                          ;
                     993                                          ;** SUBROUTINE PLLT **
                     994                                          ;
                     995                                          ;PULLS A 32-BIT FL. PT. VARIABLE
                     996                                          ; FROM THE APU STACK
                     997                                          ; DE CONTAINS ADDRESS OF LS
                     998                                          ; BYTE ON CALLING AND MS
                     999                                          ; BYTE AT RETURN
                    1000                                          ;
                    1001                                          ;REGISTERS AFFECTED: D,E
  8517 F5           1002 PLLT:   PUSH    PSW
  8518 13           1003         INX     D
  8519 13           1004         INX     D
  851A 13           1005         INX     D
  851B 3A0010       1006         LDA     1000H
  851E 12           1007         STAX    D
  851F 1B           1008         DCX     D
  8520 3A0010       1009         LDA     1000H
  8523 12           1010         STAX    D
  8524 1B           1011         DCX     D
  8525 3A0010       1012         LDA     1000H
  LOC  OBJ         LINE        SOURCE STATEMENT

 8528 12           1013         STAX    D
 8529 1B           1014         DCX     D
 852A 3A0010       1015         LDA     1000H
 852D 12           1016         STAX    D
 852E F1           1017         POP     PSW
 852F C9           1018         RET ;
                   1019                                           ;
                   1020                                           ;
                   1021                                           ;** SET OF SUBROUTINES FOR EVALUATING
                   1022                                           ; OPERATORS IN CONDITIONAL JUMPS **
                   1023                                           ;
                   1024                                           ;EACH SUBROUTINE RETURNS 01H IN THE
                   1025                                           ; ACCUMULATOR IF THE CONDITION IS VALID
                   1026                                           ;
                   1027                                           ;REGISTERS AFFECTED: A,D,E,STATUS
                   1028                                           ;
  8530 CD6D85      1029 GTHAN:  CALL    EQUALS                    ;CALL EQUALS TO CHECK FOR EQUALITY AND
                   1030                                           ; SET SIGN BIT OF THE APU FOR THE RESULT
                   1031                                           ; OF THE SUBTRACTION V1-V2
  8533 E601        1032         ANI     01H                       ;IF VARAIBLES ARE NOT EQUAL THEN L2 ELSE
  8535 CA3A85      1033         JZ      L2                        ; CLEAR ACCUMULATOR AND RETURN
  8538 AF          1034         XRA     A
  8539 C9          1035         RET
  853A 3A9030      1036 L2:     LDA     STATUS                    ;CHECK SIGN OF RESULT V1-V2
  853D E640        1037         ANI     40H
  853F CA4485      1038         JZ      L3
  8542 AF          1039         XRA     A                         ;NEGATIVE RESULT SIGN: CLR ACC & RETURN
  8543 C9          1040         RET
  8544 3E01        1041 L3:     MVI     A,01H                     ;POSITIVE RESULT SIGN: SET ACC TO 01 & RET
  8546 C9          1042         RET
                   1043                                           ;
                   1044                                           ;
  8547 CD6D85      1045 LTHAN:  CALL    EQUALS                    ;CALL EQ TO CHECK FOR EQUALITY AND SET
  854A E601        1046         ANI     01H                       ; SIGN BIT OF APU FOR THE SUBTRACTION V1-V2
  854C CA5185      1047         JZ      L4                        ;IF VARIABLES ARE NOT EQUAL THEN L4 ELSE
  854F AF          1048         XRA     A                         ; CLEAR ACC & RETURN
  8550 C9          1049         RET
  8551 3A9030      1050 L4:     LDA     STATUS                    ;CHECK SIGN OF RESULT OF SUBTRACTION V1-V2
  8554 E640        1051         ANI     40H
  8556 C25B85      1052         JNZ     L5
  8559 AF          1053         XRA     A                         ;POSITIVE SIGN: CLR ACC AND RETURN
  855A C9          1054         RET
  855B 3E01        1055 L5:     MVI     A,01H                     ;NEGATIVE SIGN: SET ACC TO 01 AND RET
  855D C9          1056         RET
                   1057                                           ;
                   1058                                           ;
  855E CD4785      1059 GEQUAL: CALL    LTHAN                     ;CALL LT AND INVERT RESULT
  8561 2F          1060         CMA
  8562 C9          1061         RET
                   1062                                           ;
                   1063                                           ;
  8563 CD3085      1064 LEQUAL: CALL    GTHAN                     ;CALL GT AND INVERT RESULT
  8566 2F          1065         CMA
  8567 C9          1066         RET
                   1067                                           ;
 LOC  OBJ         LINE        SOURCE STATEMENT

 8568 CD6D85      1068 NEQUAL: CALL EQUALS
 856B 2F          1069         CMA
 856C C9          1070         RET
                  1071                                          ;
                  1072                                          ;
                  1073 EQUALS: PSH     V1                       ;SUBTRACT V2 FROM V1
 856D 119530      1074+        LXI     D,V1
 8570 CD0185      1075+        CALL    PSHT
                  1076         PSH     V2
 8573 119930      1077+        LXI     D,V2
 8576 CD0185      1078+        CALL    PSHT
 8579 CD948E      1079         CALL    FSUB
 857C 3A0011      1080 L6:     LDA     1100H                    ;WAIT TILL APU NOT BUSY
 857F E680        1081         ANI     80H
 8581 C27C85      1082         JNZ     L6
 8584 3A0011      1083         LDA     1100H
 8587 329030      1084         STA     STATUS                   ;TRANSFER APU STATUS TO CORE
 858A E620        1085         ANI     20H                      ;CHECK ZERO BIT
 858C C29085      1086         JNZ     L7
 858F C9          1087         RET                              ;RETURN 00 IN A REG INDICATING INEQUALTY
                  1088                                          ;
 8590 3E01        1089 L7:     MVI     A,01H                    ;RETURN 01 IN A REG INDICATING EQUALITY
 8592 C9          1090         RET
                  1091                                          ;
                  1092                                          ;
                  1093                                          ;
                  1094                                          ;
                  1095                                          ;** SUBROUTINE JOYSTK **
                  1096                                          ;
                  1097                                          ;JOYSTICK VOLTAGE IS IN 'A' REGISTER
                  1098                                          ; ON CALLING. THE SUBROUTINE TRANS-
                  1099                                          ; FORMS IT TO THE RANGE -1 TO +1 AND
                  1100                                          ; LEAVES THE RESULT ON THE TOS
                  1101                                          ;
                  1102                                          ;REGISTERS AFFECTED A,D,E,STATUS
                  1103                                          ;
 8593 320010      1104 JOYSTK: STA     1000H                    ;CONVERT JOYSTICK VOLTAGE TO 32 BIT
 8596 AF          1105         XRA     A                        ; FORMAT
 8597 320010      1106         STA     1000H
 859A CD888E      1107         CALL    FLTS
                  1108         PLL     I1
 859D 114830      1109+        LXI     D,I1
 85A0 CD1785      1110+        CALL    PLLT
                  1111         IFF     I1,GTHAN,H87,L50         ;IF JOYSTICK VOLTAGE)87H THEN L50
                  1112+        PSH     I1
 85A3 114830      1113+        LXI     D,I1
 85A6 CD0185      1114+        CALL    PSHT
                  1115+        PLL     V1
 85A9 119530      1116+        LXI     D,V1
 85AC CD1785      1117+        CALL    PLLT
                  1118+        PSH     H87
 85AF 117580      1119+        LXI     D,H87
 85B2 CD0185      1120+        CALL    PSHT
                  1121+        PLL     V2
 85B5 119930      1122+        LXI     D,V2
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  LOC  OBJ         LINE        SOURCE STATEMENT

  85B8 CD1785      1123+        CALL     PLLT
  85BB CD3085      1124+        CALL     GTHAN
  85BE E601        1125+        ANI      01H
  85C0 C2EA85      1126+        JNZ      L50
                   1127         IFF      I1,LTHAN,H79,L51         ;IF JOYSTICK VOLTAGE<79H THEN L51
                   1128+        PSH      I1
  85C3 114830      1129+        LXI      D,I1
  85C6 CD0185      1130+        CALL     PSHT
                   1131+        PLL      V1
  85C9 119530      1132+        LXI      D,V1
  85CC CD1785      1133+        CALL     PLLT
                   1134+        PSH      H79
  85CF 117980      1135+        LXI      D,H79
  85D2 CD0185      1136+        CALL     PSHT
                   1137+        PLL      V2
  85D5 119930      1138+        LXI      D,V2
  85D8 CD1785      1139+        CALL     PLLT
  85DB CD4785      1140+        CALL     LTHAN
  85DE E601        1141+        ANI      01H
  85E0 C20386      1142+        JNZ      L51
                   1143         PSH      ZERO                     ;JOYSTICK IN CENTRAL DEAD BAND:
  85E3 117D80      1144+        LXI      D,ZERO
  85E6 CD0185      1145+        CALL     PSHT
  85E9 C9          1146         RET                               ; RETURN ZERO RESULT
                   1147 L50:    PSH      I1                       ;OFFSET AND SCALE JOYSTICK VOLTAGE
  85EA 114830      1148+        LXI      D,I1
  85ED CD0185      1149+        CALL     PSHT
                   1150         PSH      H87                      ; FOR POSITIVE DEFLECTION
  85F0 117580      1151+        LXI      D,H87
  85F3 CD0185      1152+        CALL     PSHT
  85F6 CD948E      1153         CALL     FSUB
                   1154         PSH      D14                      ;PUSH 14 BASE 10
  85F9 11C580      1155+        LXI      D,D14
  85FC CD0185      1156+        CALL     PSHT
  85FF CDA08E      1157         CALL     FDIV
  8602 C9          1158         RET
                   1159 L51:    PSH      I1                       ;OFFSET AND SCALE JOYSTICK VOLTAGE
  8603 114830      1160+        LXI      D,I1
  8606 CD0185      1161+        CALL     PSHT
                   1162         PSH      H79                      ; FOR NEGATIVE DEFLECTION
  8609 117980      1163+        LXI      D,H79
  860C CD0185      1164+        CALL     PSHT
  860F CD948E      1165         CALL     FSUB
                   1166         PSH      D14
  8612 11C580      1167+        LXI      D,D14
  8615 CD0185      1168+        CALL     PSHT
  8618 CDA08E      1169         CALL     FDIV
  861B C9          1170         RET
                   1171                                           ;
                   1172                                           ;
                   1173                                           ;** SUBROUTINE SLOPE **
                   1174                                           ;
                   1175                                           ;THIS ROUTINE CALCULATES THE
                   1176                                           ; PITCH ANGLE FROM THE PITCH
                   1177                                           ; CONTROL VOLTAGE.  THE VOLTAGE
  LOC  OBJ         LINE        SOURCE STATEMENT

                   1178                                                ; IS IN THE 'A' REGISTER ON CALLING
                   1179                                                ; AND THE RESULT ON THE TOS AT RETURN
                   1180                                                ;
                   1181                                                ;REGISTERS AFFECTED: A,D,E
                   1182                                                ;
 861C 320010       1183 SLOPE:  STA     1000H                          ;CONVERT VOLTAGE TO 32 BIT FORMAT
 861F AF           1184         XRA A
 8620 320010       1185         STA     1000H
 8623 CD888E       1186         CALL    FLTS
                   1187         PSH     CNST13                         ;PSH 8.18 E-03
 8626 11B580       1188+        LXI     D,CNST13
 8629 CD0185       1189+        CALL    PSHT
 862C CD708E       1190         CALL    FMUL
                   1191         PSH     CNST14                         ;PSH -1.047
 862F 11B980       1192+        LXI     D,CNST14
 8632 CD0185       1193+        CALL    PSHT
 8635 CD648E       1194         CALL    FADD
                   1195         PLL     PITCH
 8638 119D30       1196+        LXI     D,PITCH
 863B CD1785       1197+        CALL    PLLT
 863E C9           1198         RET
                   1199                                                ;
                   1200                                                ;
                   1201                                                ;** SUBROUTINE COORD **
                   1202                                                ;
                   1203                                                ;CALCULATES OUTPUT COORDINATES XO,
                   1204                                                ; YO, AND PSIO, FROM ALPHA, BETA,
                   1205                                                ; AND DELTA
                   1206                                                ;
                   1207                                                ;REGISTERS AFFECTED: D,E
                   1208                                                ;
                   1209 COORD:  PSH     ALPHA                          ;CALCULATE X-COORDINATE OF BUCKET PIVOT
 863F 118430       1210+        LXI     D,ALPHA
 8642 CD0185       1211+        CALL    PSHT
 8645 CDE88E       1212         CALL    SIN                            ; IN USER DEFINED AXES
                   1213         PSH     LA                             ;XO=L*SIN(ALPHA)+R*SIN(ALPHA+BETA-PI)
 8648 116D80       1214+        LXI     D,LA
 864B CD0185       1215+        CALL    PSHT
 864E CD708E       1216         CALL    FMUL
                   1217         PLL     I1
 8651 114630       1218+        LXI     D,I1
 8654 CD1785       1219+        CALL    PLLT
                   1220         PSH     ALPHA
 8657 118430       1221+        LXI     D,ALPHA
 865A CD0185       1222+        CALL    PSHT
                   1223         PSH     BETA
 865D 118830       1224+        LXI     D,BETA
 8660 CD0185       1225+        CALL    PSHT
 8663 CD648E       1226         CALL    FADD
 8666 CDDC8E       1227         CALL    PUPI
 8669 CD948E       1228         CALL    FSUB
 866C CDE88E       1229         CALL    SIN
                   1230         PSH     RA
 866F 117180       1231+        LXI     D,RA
 8672 CD0185       1232+        CALL    PSHT
 LOC  OBJ         LINE        SOURCE STATEMENT

 8675 CD708E       1233         CALL     FMUL
                   1234         PSH      I1
 8678 114830       1235+        LXI      D,I1
 867B CD0185       1236+        CALL     PSHT
 867E CD648E       1237         CALL     FADD
                   1238         PLL      X0
 8681 116430       1239+        LXI      D,X0
 8684 CD1785       1240+        CALL     PLLT
                   1241         PSH      ALPHA                     ;CALCULATE Y COORDINATE
 8687 118430       1242+        LXI      D,ALPHA
 868A CD0185       1243+        CALL     PSHT
 868D CD008F       1244         CALL     COS                       ;Y0=-L*COS(ALPHA)-R*COS(ALPHA+BETA-PI)
 8690 CD7C8E       1245         CALL     CHSF
                   1246         PSH      LA
 8693 116D80       1247+        LXI      D,LA
 8696 CD0185       1248+        CALL     PSHT
 8699 CD708E       1249         CALL     FMUL
                   1250         PLL      I1
 869C 114830       1251+        LXI      D,I1
 869F CD1785       1252+        CALL     PLLT
                   1253         PSH      ALPHA
 86A2 118430       1254+        LXI      D,ALPHA
 86A5 CD0185       1255+        CALL     PSHT
                   1256         PSH      BETA
 86A8 118830       1257+        LXI      D,BETA
 86AB CD0185       1258+        CALL     PSHT
 86AE CD648E       1259         CALL     FADD
 86B1 CDDC8E       1260         CALL     PUPI
 86B4 CD948E       1261         CALL     FSUB
 86B7 CD008F       1262         CALL     COS
                   1263         PSH      RA
 86BA 117180       1264+        LXI      D,RA
 86BD CD0185       1265+        CALL     PSHT
 86C0 CD708E       1266         CALL     FMUL
                   1267         PSH      I1
 86C3 114830       1268+        LXI      D,I1
 86C6 CD0185       1269+        CALL     PSHT
 86C9 CD188F       1270         CALL     XCHF
 86CC CD948E       1271         CALL     FSUB
                   1272         PLL      Y0
 86CF 116830       1273+        LXI      D,Y0
 86D2 CD1785       1274+        CALL     PLLT
                   1275         PSH      DELTA                     ;CALCULATE PSI
 86D5 118C30       1276+        LXI      D,DELTA
 86D8 CD0185       1277+        CALL     PSHT
 86DB CDC48E       1278         CALL     PTOF                      ;CALCULATE GAMMA
 86DE CDC48E       1279         CALL     PTOF                      ; X=DELTA
 86E1 CD708E       1280         CALL     FMUL                      ; GAMMA=GC0+(GC1*X)+(GC2*X*X)
                   1281         PSH      GC2
 86E4 119D80       1282+        LXI      D,GC2
 86E7 CD0185       1283+        CALL     PSHT
 86EA CD708E       1284         CALL     FMUL
 86ED CD188F       1285         CALL     XCHF
                   1286         PSH      GC1
 86F0 119980       1287+        LXI      D,GC1
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  LOC  OBJ          LINE        SOURCE STATEMENT

 86F3 CD0185        1288+        CALL    PSHT
 86F6 CD708E        1289         CALL    FMUL
 86F9 CD648E        1290         CALL    FADD
                    1291         PSH     GCO
 86FC 119580        1292+        LXI     D,GCO
 86FF CD0185        1293+        CALL    PSHT
 8702 CD648E        1294         CALL    FADD                              ;LEAVES GAMMA ON TOS
                    1295         PSH     BETA                              ;CALCULATE PSI=GAMMA+BETA+ALPHA-PI
 8705 118830        1296+        LXI     D,BETA
 8708 CD0185        1297+        CALL    PSHT
 870B CD648E        1298         CALL    FADD
                    1299         PSH     ALPHA
 870E 118430        1300+        LXI     D,ALPHA
 8711 CD0185        1301+        CALL    PSHT
 8714 CD648E        1302         CALL    FADD
 8717 CDDC8E        1303         CALL    PUPI
 871A CD948E        1304         CALL    FSUB
                    1305         PLL     PSIO
 871D 116C30        1306+        LXI     D,PSIO
 8720 CD1785        1307+        CALL    PLLT
 8723 C9            1308         RET
                    1309                                                   ;
                    1310                                                   ;
                    1311                                                   ;** SUBROUTINE EPOS **
                    1312                                                   ;
                    1313                                                   ;CALCULATES POSITIONAL ERRORS
                    1314                                                   ; EX, EY, EPSI AND ETA.  THE
                    1315                                                   ; ROUTINE ALSO CONTAINS A DELAY
                    1316                                                   ; SEGMENT TO VARY THE LOOP EXECUTION
                    1317                                                   ; TIME FOR EXPERIMENTAL PURPOSES
                    1318                                                   ;
                    1319                                                   ;REGISTERS AFFECTED: A,D,E,H,L,STATUS
                    1320                                                   ;
                    1321 EPOS:   PSH     XI
 8724 115830        1322+        LXI     D,XI
 8727 CD0185        1323+        CALL    PSHT
                    1324         PSH     XO
 872A 116430        1325+        LXI     D,XO
 872D CD0185        1326+        CALL    PSHT
 8730 CD948E        1327         CALL    FSUB
                    1328         PLL     EX
 8733 117030        1329+        LXI     D,EX
 8736 CD1785        1330+        CALL    PLLT
                    1331         PSH     YI
 8739 115C30        1332+        LXI     D,YI
 873C CD0185        1333+        CALL    PSHT
                    1334         PSH     YO
 873F 116830        1335+        LXI     D,YO
 8742 CD0185        1336+        CALL    PSHT
 8745 CD948E        1337         CALL    FSUB
                    1338         PLL     EY
 8748 117430        1339+        LXI     D,EY
 874B CD1785        1340+        CALL    PLLT
                    1341         PSH     PSII
 874E 116030        1342+        LXI     D,PSII
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  LOC  OBJ          LINE        SOURCE STATEMENT

  8751 CD0185       1343+         CALL    PSHT
                    1344          PSH     PSIO
  8754 116C30       1345+         LXI     D,PSIO
  8757 CD0185       1346+         CALL    PSHT
  875A CD948E       1347          CALL    FSUB
                    1348          PLL     EPSI
  875D 117830       1349+         LXI     D,EPSI
  8760 CD1785       1350+         CALL    PLLT
                    1351          PSH     EX                        ;CALCULATE ETA=SQRT(EX**2+EY**2)
  8763 117030       1352+         LXI     D,EX
  8766 CD0185       1353+         CALL    PSHT
  8769 CDC48E       1354          CALL    PTOF
  876C CD708E       1355          CALL    FMUL
                    1356          PSH     EY
  876F 117430       1357+         LXI     D,EY
  8772 CD0185       1358+         CALL    PSHT
  8775 CDC48E       1359          CALL    PTOF
  8778 CD708E       1360          CALL    FMUL
  877B CD648E       1361          CALL    FADD
  877E CD248F       1362          CALL    SQRT
                    1363          PLL     ETA
  8781 117C30       1364+         LXI     D,ETA
  8784 CD1785       1365+         CALL    PLLT
                    1366                                            ;TIMING SEGMENT
  8787 3A3730       1367          LDA     TFLAG                     ;COMPLEMENT AND OUTPUT TFLAG
  878A 2F           1368          CMA
  878B D308         1369          OUT     08H
  878D 323730       1370          STA     TFLAG
  8790 2AFF30       1371          LHLD    DELAY
  8793 CD9787       1372          CALL    PAUSE
  8796 C9           1373          RET
                    1374                                            ;
                    1375                                            ;
                    1376                                            ;
                    1377                                            ;** SUBROUTINE PAUSE **
                    1378                                            ;
                    1379                                            ;SUBROUTINE FOR DELAY DECREMENTS
                    1380                                            ; INPUT IN HL REGISTER UNTIL ZERO
                    1381                                            ;
                    1382                                            ;REGISTERS AFFECTED: A,H,L,STATUS
                    1383                                            ;
  8797 2B           1384 PAUSE:   DCX     H
  8798 7C           1385          MOV     A,H
  8799 B5           1386          ORA     L
  879A C29787       1387          JNZ     PAUSE
  879D C9           1388          RET
                    1389                                            ;
                    1390                                            ;
                    1391                                            ;
                    1392                                            ;** SUBROUTINE SETEC **
                    1393                                            ;
                    1394                                            ;CALCULATES ECRIT =
                    1395                                            ; ECMIN*(1+SQRT(CXDOT**2+CYDOT**2))
                    1396                                            ;
                    1397                                            ;REGISTERS AFFECTED: D,E
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 LOC  OBJ          LINE        SOURCE STATEMENT

                   1398                                                    ;
                   1399 SETEC:  PSH     CXDOT
 879E 115030       1400+        LXI     D,CXDOT
 87A1 CD0185       1401+        CALL    PSHT
 87A4 CD248E       1402         CALL    PTOF
 87A7 CD708E       1403         CALL    FMUL
                   1404         PSH     CYDOT
 87AA 115430       1405+        LXI     D,CYDOT
 87AD CD0185       1406+        CALL    PSHT
 87B0 CD248E       1407         CALL    PTOF
 87B3 CD708E       1408         CALL    FMUL
 87B6 CD648E       1409         CALL    FADD
 87B9 CD248F       1410         CALL    SQRT
                   1411         PSH     ONE
 87BC 118180       1412+        LXI     D,ONE
 87BF CD0185       1413+        CALL    PSHT
 87C2 CD648E       1414         CALL    FADD
                   1415         PSH     ECMIN
 87C5 11E930       1416+        LXI     D,ECMIN
 87C8 CD0185       1417+        CALL    PSHT
 87CB CD708E       1418         CALL    FMUL
                   1419         PLL     ECRIT
 87CE 11E530       1420+        LXI     D,ECRIT
 87D1 CD1785       1421+        CALL    PLLT
 87D4 C9           1422         RET
                   1423                                                    ;
                   1424                                                    ;
                   1425                                                    ;
                   1426                                                    ;** SUBROUTINE IP1 **
                   1427                                                    ;
                   1428                                                    ;IF INPUT BUCKET VELOCITY IS NON-ZERO
                   1429                                                    ; THEN PSII=PSIO
                   1430                                                    ; IF JXDOT OR JYDOT HAS CHANGED SIGNIF-
                   1431                                                    ; ICANTLY OR BOTH ARE EQUAL TO ZERO
                   1432                                                    ; THEN UPDATE CXDOT AND CYDOT AND SET
                   1433                                                    ; TARGET POSITION TO CURRENT OUTPUT
                   1434                                                    ; POSITION
                   1435                                                    ;
                   1436                                                    ;REGISTERS AFFECTED: A,D,E,STATUS
                   1437                                                    ;
                   1438 IP1:    IFF     JBKT,EQUALS,ZERO,L21
                   1439+        PSH     JBKT
 87D5 114430       1440+        LXI     D,JBKT
 87D8 CD0185       1441+        CALL    PSHT
                   1442+        PLL     V1
 87DB 119530       1443+        LXI     D,V1
 87DE CD1785       1444+        CALL    PLLT
                   1445+        PSH     ZERO
 87E1 117D80       1446+        LXI     D,ZERO
 87E4 CD0185       1447+        CALL    PSHT
                   1448+        PLL     V2
 87E7 119930       1449+        LXI     D,V2
 87EA CD1785       1450+        CALL    PLLT
 87ED CD6D85       1451+        CALL    EQUALS
 87F0 E601         1452+        ANI     01H
 LOC  OBJ         LINE        SOURCE STATEMENT

 87F2 C20188       1453+        JNZ     L21
                   1454         PSH     PSI0                    ;SET PSII=PSI0
 87F5 116C30       1455+        LXI     D,PSI0
 87F8 CD0185       1456+        CALL    PSHT
                   1457         PLL     PSII
 87FB 116030       1458+        LXI     D,PSII
 87FE CD1785       1459+        CALL    PLLT
                   1460 L21:    PSH     JXDOT                   ;CALCULATE DIFFERENCE BETWEEN JXDOT
 8801 113830       1461+        LXI     D,JXDOT
 8804 CD0185       1462+        CALL    PSHT
                   1463         PSH     CXDOT                   ; AND CXDOT
 8807 115030       1464+        LXI     D,CXDOT
 880A CD0185       1465+        CALL    PSHT
 880D CD948E       1466         CALL    FSUB
 8810 CDC48E       1467         CALL    PTOF
 8813 CD708E       1468         CALL    FMUL
 8816 CD248F       1469         CALL    SQRT
                   1470         PLL     I1
 8819 114830       1471+        LXI     D,I1
 881C CD1785       1472+        CALL    PLLT
                   1473         IFF     I1,LEQUAL,CNST10,L22    ;(CNST10=CRITICAL VALUE OF DIFFERENCE)
                   1474+        PSH     I1
 881F 114830       1475+        LXI     D,I1
 8822 CD0185       1476+        CALL    PSHT
                   1477+        PLL     V1
 8825 119530       1478+        LXI     D,V1
 8828 CD1785       1479+        CALL    PLLT
                   1480+        PSH     CNST10
 882B 11ED30       1481+        LXI     D,CNST10
 882E CD0185       1482+        CALL    PSHT
                   1483+        PLL     V2
 8831 119930       1484+        LXI     D,V2
 8834 CD1785       1485+        CALL    PLLT
 8837 CD6385       1486+        CALL    LEQUAL
 883A E601         1487+        ANI     01H
 883C C24288       1488+        JNZ     L22
 883F C3C588       1489         JMP     L26
                   1490 L22:    PSH     JYDOT                   ;CALCULATE DIFFERENCE BETWEEN JYDOT
 8842 113C30       1491+        LXI     D,JYDOT
 8845 CD0185       1492+        CALL    PSHT
                   1493         PSH     CYDOT                   ; AND CYDOT
 8848 115430       1494+        LXI     D,CYDOT
 884B CD0185       1495+        CALL    PSHT
 884E CD948E       1496         CALL    FSUB
 8851 CDC48E       1497         CALL    PTOF
 8854 CD708E       1498         CALL    FMUL
 8857 CD248F       1499         CALL    SQRT
                   1500         PLL     I1
 885A 114830       1501+        LXI     D,I1
 885D CD1785       1502+        CALL    PLLT
                   1503         IFF     I1,LEQUAL,CNST10,L23
                   1504+        PSH     I1
 8860 114830       1505+        LXI     D,I1
 8863 CD0185       1506+        CALL    PSHT
                   1507+        PLL     V1
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  LOC  OBJ         LINE        SOURCE STATEMENT

  8866 119530       1508+        LXI     D,V1
  8869 CD1785       1509+        CALL    PLLT
                    1510+        PSH     CNST10
  886C 11ED30       1511+        LXI     D,CNST10
  886F CD0185       1512+        CALL    PSHT
                    1513+        PLL     V2
  8872 119930       1514+        LXI     D,V2
  8875 CD1785       1515+        CALL    PLLT
  8878 CD6385       1516+        CALL    LEQUAL
  887B E601         1517+        ANI     01H
  887D C28388       1518+        JNZ     L23
  8880 C3C588       1519         JMP     L26
                    1520 L23:    IFF     JYDOT,EQUALS,ZERO,L24
                    1521+        PSH     JYDOT
  8883 113C30       1522+        LXI     D,JYDOT
  8886 CD0185       1523+        CALL    PSHT
                    1524+        PLL     V1
  8889 119530       1525+        LXI     D,V1
  888C CD1785       1526+        CALL    PLLT
                    1527+        PSH     ZERO
  888F 117D80       1528+        LXI     D,ZERO
  8892 CD0185       1529+        CALL    PSHT
                    1530+        PLL     V2
  8895 119930       1531+        LXI     D,V2
  8898 CD1785       1532+        CALL    PLLT
  889B CD6D85       1533+        CALL    EQUALS
  889E E601         1534+        ANI     01H
  88A0 C2A488       1535+        JNZ     L24
  88A3 C9           1536         RET
                    1537 L24:    IFF     JXDOT,EQUALS,ZERO,L26
                    1538+        PSH     JXDOT
  88A4 113830       1539+        LXI     D,JXDOT
  88A7 CD0185       1540+        CALL    PSHT
                    1541+        PLL     V1
  88AA 119530       1542+        LXI     D,V1
  88AD CD1785       1543+        CALL    PLLT
                    1544+        PSH     ZERO
  88B0 117D80       1545+        LXI     D,ZERO
  88B3 CD0185       1546+        CALL    PSHT
                    1547+        PLL     V2
  88B6 119930       1548+        LXI     D,V2
  88B9 CD1785       1549+        CALL    PLLT
  88BC CD6D85       1550+        CALL    EQUALS
  88BF E601         1551+        ANI     01H
  88C1 C2C588       1552+        JNZ     L26
  88C4 C9           1553         RET
                    1554 L26:    PSH     XO
  88C5 116430       1555+        LXI     D,XO
  88C8 CD0185       1556+        CALL    PSHT
                    1557         PLL     XI
  88CB 115830       1558+        LXI     D,XI
  88CE CD1785       1559+        CALL    PLLT
                    1560         PSH     YO
  88D1 116830       1561+        LXI     D,YO
  88D4 CD0185       1562+        CALL    PSHT
  LOC  OBJ          LINE        SOURCE STATEMENT

                    1563         PLL      YI
 88D7 115C30        1564+        LXI      D,YI
 88DA CD1785        1565+        CALL     PLLT
                    1566         PSH      PSIO
 88DD 116C30        1567+        LXI      D,PSIO
 88E0 CD0185        1568+        CALL     PSHT
                    1569         PLL      PSII
 88E3 116030        1570+        LXI      D,PSII
 88E6 CD1785        1571+        CALL     PLLT
                    1572         PSH      JXDOT
 88E9 113830        1573+        LXI      D,JXDOT
 88EC CD0185        1574+        CALL     PSHT
                    1575         PLL      CXDOT
 88EF 115030        1576+        LXI      D,CXDOT
 88F2 CD1785        1577+        CALL     PLLT
                    1578         PSH      JYDOT
 88F5 113C30        1579+        LXI      D,JYDOT
 88F8 CD0185        1580+        CALL     PSHT
                    1581         PLL      CYDOT
 88FB 115430        1582+        LXI      D,CYDOT
 88FE CD1785        1583+        CALL     PLLT
 8901 C9            1584         RET
                    1585                                                   ;
                    1586                                                   ;
                    1587                                                   ;** SUBROUTINE IP2 **
                    1588                                                   ;
                    1589                                                   ;IF POSITION ERROR IS BELOW THRESHOLD
                    1590                                                   ; VALUE ECRIT  THEN UPDATE XI AND YI
                    1591                                                   ;              ELSE RETURN
                    1592                                                   ;
                    1593                                                   ;REGISTERS AFFECTED: A,D,E,S
                    1594                                                   ;
                    1595 IP2:        IFF      ETA,GTHAN,ECRIT,L32          ;IF ETA>ECRIT   THEN CONTINUE ELSE
                    1596+        PSH      ETA
 8902 117C30        1597+        LXI      D,ETA
 8905 CD0185        1598+        CALL     PSHT
                    1599+        PLL      V1
 8908 119530        1600+        LXI      D,V1
 890B CD1785        1601+        CALL     PLLT
                    1602+        PSH      ECRIT
 890E 11BE30        1603+        LXI      D,ECRIT
 8911 CD0185        1604+        CALL     PSHT
                    1605+        PLL      V2
 8914 119930        1606+        LXI      D,V2
 8917 CD1785        1607+        CALL     PLLT
 891A CD3085        1608+        CALL     GTHAN
 891D E601          1609+        ANI      01H
 891F C25E89        1610+        JNZ      L32
                    1611         PSH      CXDOT                    ; XI=XI+CNST11*CXDOT
 8922 115030        1612+        LXI      D,CXDOT
 8925 CD0185        1613+        CALL     PSHT
                    1614         PSH      CNST11                   ; YI=YI+CNST11*CYDOT
 8928 11F130        1615+        LXI      D,CNST11
 892B CD0185        1616+        CALL     PSHT
 892E CD708E        1617         CALL     FMUL
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  LOC  OBJ          LINE        SOURCE STATEMENT

                    1618          PSH      XI
  8931 115830       1619+         LXI      D,XI
  8934 CD0185       1620+         CALL     PSHT
  8937 CD648E       1621          CALL     FADD
                    1622          PLL      XI
  893A 115830       1623+         LXI      D,XI
  893D CD1785       1624+         CALL     PLLT
                    1625          PSH      CYDOT
  8940 115430       1626+         LXI      D,CYDOT
  8943 CD0185       1627+         CALL     PSHT
                    1628          PSH      CNST11
  8946 11F130       1629+         LXI      D,CNST11
  8949 CD0185       1630+         CALL     PSHT
  894C CD708E       1631          CALL     FMUL
                    1632          PSH      YI
  894F 115C30       1633+         LXI      D,YI
  8952 CD0185       1634+         CALL     PSHT
  8955 CD648E       1635.         CALL     FADD
                    1636          PLL      YI
  8958 115C30       1637+         LXI      D,YI
  895B CD1785       1638+         CALL     PLLT
  895E C9           1639 L32:     RET
                    1640                                                   ;
                    1641                                                   ;
                    1642                                                   ;** SUBROUTINE FFD **
                    1643                                                   ;
                    1644                                                   ;CALCULATES VALVE OPENINGS,
                    1645                                                   ; RESULTS IN RANGE -1 TO +1
                    1646                                                   ;
                    1647                                                   ;REGISTERS AFFECTED: A,D,E,STATUS
                    1648                                                   ;
                    1649 FFD:     PSH      JSLEW                           ;SET SLEW VOLTAGE
  895F 114030       1650+         LXI      D,JSLEW
  8962 CD0185       1651+         CALL     PSHT
                    1652          PLL      VVSLEW
  8965 11A930       1653+         LXI      D,VVSLEW
  8968 CD1785       1654+         CALL     PLLT
                    1655                                                   ;
  896B 3A0030       1656          LDA      MODFLG                          ;DISREGARD JOYSTICK INPUTS IF IN
  896E FE00         1657          CPI      00H                             ; REPEAT MODE
  8970 C2BF89       1658          JNZ      L43
                    1659                                                   ;IF JXDOT AND JYDOT BOTH = 0 THEN
                    1660                                                   ; SET VVALFA AND VVBETA TO ZERO
                    1661          IFF      JXDOT,EQUALS,ZERO,L44
                    1662+         PSH      JXDOT
  8973 113830       1663+         LXI      D,JXDOT
  8976 CD0185       1664+         CALL     PSHT
                    1665+         PLL      V1
  8979 119530       1666+         LXI      D,V1
  897C CD1785       1667+         CALL     PLLT
                    1668+         PSH      ZERO
  897F 117D80       1669+         LXI      D,ZERO
  8982 CD0185       1670+         CALL     PSHT
                    1671+         PLL      V2
  8985 119930       1672+         LXI      D,V2
  LOC  OBJ          LINE        SOURCE STATEMENT

  8988 CD1785       1673+        CALL     PLLT
  898B CD6D85       1674+        CALL     EQUALS
  898E E601         1675+        ANI      01H
  8990 C29689       1676+        JNZ      L44
  8993 C3BF89       1677         JMP      L43
                    1678 L44:    IFF      JYDOT,EQUALS,ZERO,L46
                    1679+        PSH      JYDOT
  8996 113C30       1680+        LXI      D,JYDOT
  8999 CD0185       1681+        CALL     PSHT
                    1682+        PLL      V1
  899C 119530       1683+        LXI      D,V1
  899F CD1785       1684+        CALL     PLLT
                    1685+        PSH      ZERO
  89A2 117D80       1686+        LXI      D,ZERO
  89A5 CD0185       1687+        CALL     PSHT
                    1688+        PLL      V2
  89A8 119930       1689+        LXI      D,V2
  89AB CD1785       1690+        CALL     PLLT
  89AE CD6D85       1691+        CALL     EQUALS
  89B1 E601         1692+        ANI      01H
  89B3 C2B989       1693+        JNZ      L46
  89B6 C3BF89       1694         JMP      L43
  89B9 CD808C       1695 L46:    CALL     FREEZE
  89BC C3BB8A       1696         JMP      L47
                    1697 L43:    PSH      XI
  89BF 115830       1698+        LXI      D,XI
  89C2 CD0185       1699+        CALL     PSHT
  89C5 CDC48E       1700         CALL     PTOF
  89C8 CD708E       1701         CALL     FMUL
                    1702         PSH      YI
  89CB 115C30       1703+        LXI      D,YI
  89CE CD0185       1704+        CALL     PSHT
  89D1 CDC48E       1705         CALL     PTOF
  89D4 CD708E       1706         CALL     FMUL
  89D7 CD648E       1707         CALL     FADD
  89DA CD248F       1708         CALL     SQRT
                    1709         PLL      DX
  89DD 110130       1710+        LXI      D,DX
  89E0 CD1785       1711+        CALL     PLLT
                    1712                                                 ;
                    1713         PSH      CNST1                          ;BI=ACOS((LA**2+RA**2-DX**2)/
  89E3 11A180       1714+        LXI      D,CNST1
  89E6 CD0185       1715+        CALL     PSHT
                    1716         PSH      DX                             ; (2*LA*RA))
  89E9 110130       1717+        LXI      D,DX
  89EC CD0185       1718+        CALL     PSHT
  89EF CDC48E       1719         CALL     PTOF
  89F2 CD708E       1720         CALL     FMUL
  89F5 CD948E       1721         CALL     FSUB
                    1722         PSH      CNST2
  89F8 11A580       1723+        LXI      D,CNST2
  89FB CD0185       1724+        CALL     PSHT
  89FE CDA08E       1725         CALL     FDIV
  8A01 CD0C8F       1726         CALL     ACOS
                    1727         PLL      BI
  LOC  OBJ          LINE        SOURCE STATEMENT

  8A04 110930       1728+        LXI     D,BI
  8A07 CD1785       1729+        CALL    PLLT
                    1730                                             ;
                    1731         PSH     CNST3                       ;AA=ACOS((LA**2+DX**2-RA**2)/
  8A0A 11A980       1732+        LXI     D,CNST3
  8A0D CD0185       1733+        CALL    PSHT
                    1734         PSH     DX                          ; (2*LA*DX))
  8A10 110130       1735+        LXI     D,DX
  8A13 CD0185       1736+        CALL    PSHT
  8A16 CDC48E       1737         CALL    PTOF
  8A19 CD708E       1738         CALL    FMUL
  8A1C CD648E       1739         CALL    FADD
                    1740         PSH     DX
  8A1F 110130       1741+        LXI     D,DX
  8A22 CD0185       1742+        CALL    PSHT
                    1743         PSH     CNST4
  8A25 11AD80       1744+        LXI     D,CNST4
  8A28 CD0185       1745+        CALL    PSHT
  8A2B CD708E       1746         CALL    FMUL
  8A2E CDA08E       1747         CALL    FDIV
  8A31 CD0C8F       1748         CALL    ACOS
                    1749         PLL     AA
  8A34 110D30       1750+        LXI     D,AA
  8A37 CD1785       1751+        CALL    PLLT
                    1752                                             ;
                    1753         PSH     YI                          ;AB=ACOS(-YI/DX)
  8A3A 115C30       1754+        LXI     D,YI
  8A3D CD0185       1755+        CALL    PSHT
  8A40 CD7C8E       1756         CALL    CHSF
                    1757         PSH     DX
  8A43 110130       1758+        LXI     D,DX
  8A46 CD0185       1759+        CALL    PSHT
  8A49 CDA08E       1760         CALL    FDIV
  8A4C CD0C8F       1761         CALL    ACOS
                    1762         PLL     AB
  8A4F 111130       1763+        LXI     D,AB
  8A52 CD1785       1764+        CALL    PLLT
                    1765         PSH     AB                          ;AI=AA+AB
  8A55 111130       1766+        LXI     D,AB
  8A58 CD0185       1767+        CALL    PSHT
                    1768         PSH     AA
  8A5B 110D30       1769+        LXI     D,AA
  8A5E CD0185       1770+        CALL    PSHT
  8A61 CD648E       1771         CALL    FADD
                    1772         PLL     AI
  8A64 110530       1773+        LXI     D,AI
  8A67 CD1785       1774+        CALL    PLLT
                    1775         PSH     AI                          ;EALPHA=AI-ALPHA
  8A6A 110530       1776+        LXI     D,AI
  8A6D CD0185       1777+        CALL    PSHT
                    1778         PSH     ALPHA
  8A70 118430       1779+        LXI     D,ALPHA
  8A73 CD0185       1780+        CALL    PSHT
  8A76 CD948E       1781         CALL    FSUB
  8A79 CDC48E       1782         CALL    PTOF
  LOC  OBJ          LINE        SOURCE STATEMENT

                    1783          PLL      EALPHA                     ;VVALFA=A1A*EALPHA
  8A7C 11A130       1784+         LXI      D,EALPHA
  8A7F CD1785       1785+         CALL     PLLT
                    1786          PSH      A1A
  8A82 11D930       1787+         LXI      D,A1A
  8A85 CD0185       1788+         CALL     PSHT
  8A88 CD708E       1789          CALL     FMUL
                    1790          PLL      VVALFA
  8A8B 11AD30       1791+         LXI      D,VVALFA
  8A8E CD1785       1792+         CALL     PLLT
                    1793          PSH      BI                         ;EBETA=BI-BETA
  8A91 110930       1794+         LXI      D,BI
  8A94 CD0185       1795+         CALL     PSHT
                    1796          PSH      BETA
  8A97 118830       1797+         LXI      D,BETA
  8A9A CD0185       1798+         CALL     PSHT
  8A9D CD948E       1799          CALL     FSUB
  8AA0 CDC48E       1800          CALL     PTOF
                    1801          PLL      EBETA                      ;VVBETA=A1B*EBETA
  8AA3 11A530       1802+         LXI      D,EBETA
  8AA6 CD1785       1803+         CALL     PLLT
                    1804          PSH      A1B
  8AA9 11DD30       1805+         LXI      D,A1B
  8AAC CD0185       1806+         CALL     PSHT
  8AAF CD708E       1807          CALL     FMUL
                    1808          PLL      VVBETA
  8AB2 11B130       1809+         LXI      D,VVBETA
  8AB5 CD1785       1810+         CALL     PLLT
  8AB8 CD6D8B       1811          CALL     CHKLMT
  8ABB 3A0030       1812 L47:     LDA      MODFLG                     ;DISREGARD JOYSTICK INPUTS IF IN
  8ABE FE00         1813          CPI      00H                        ; REPEAT MODE
  8AC0 C2038B       1814          JNZ      L49
                    1815                                              ;CALCULATE VVBKT
                    1816                                              ; IF JBKT=0 THEN VVBKT=SGN(EPSI)
                    1817                                              ;  ELSE VVBKT=SGN(JBKT)
                    1818          IFF      JBKT,GTHAN,ZERO,L41
                    1819+         PSH      JBKT
  8AC3 114430       1820+         LXI      D,JBKT
  8AC6 CD0185       1821+         CALL     PSHT
                    1822+         PLL      V1
  8AC9 119530       1823+         LXI      D,V1
  8ACC CD1785       1824+         CALL     PLLT
                    1825+         PSH      ZERO
  8ACF 117D80       1826+         LXI      D,ZERO
  8AD2 CD0185       1827+         CALL     PSHT
                    1828+         PLL      V2
  8AD5 119930       1829+         LXI      D,V2
  8AD8 CD1785       1830+         CALL     PLLT
  8ADB CD3085       1831+         CALL     GTHAN
  8ADE E601         1832+         ANI      01H
  8AE0 C2508B       1833+         JNZ      L41
                    1834          IFF      JBKT,LTHAN,ZERO,L42
                    1835+         PSH      JBKT
  8AE3 114430       1836+         LXI      D,JBKT
  8AE6 CD0185       1837+         CALL     PSHT
  LOC  OBJ          LINE        SOURCE STATEMENT

                    1838+        PLL      V1
 8AE9 119530        1839+        LXI      D,V1
 8AEC CD1785        1840+        CALL     PLLT
                    1841+        PSH      ZERO
 8AEF 117D80        1842+        LXI      D,ZERO
 8AF2 CD0185        1843+        CALL     PSHT
                    1844+        PLL      V2
 8AF5 119930        1845+        LXI      D,V2
 8AF8 CD1785        1846+        CALL     PLLT
 8AFB CD4785        1847+        CALL     LTHAN
 8AFE E601          1848+        ANI      01H
 8B00 C25D8B        1849+        JNZ      L42
                    1850 L49:    IFF      EPSI,GTHAN,PCRIT,L41
                    1851+        PSH      EPSI
 8B03 117830        1852+        LXI      D,EPSI
 8B06 CD0185        1853+        CALL     PSHT
                    1854+        PLL      V1
 8B09 119530        1855+        LXI      D,V1
 8B0C CD1785        1856+        CALL     PLLT
                    1857+        PSH      PCRIT
 8B0F 11E130        1858+        LXI      D,PCRIT
 8B12 CD0185        1859+        CALL     PSHT
                    1860+        PLL      V2
 8B15 119930        1861+        LXI      D,V2
 8B18 CD1785        1862+        CALL     PLLT
 8B1B CD3085        1863+        CALL     GTHAN
 8B1E E601          1864+        ANI      01H
 8B20 C2508B        1865+        JNZ      L41
                    1866         IFF      EPSI,LTHAN,NCRIT,L42
                    1867+        PSH      EPSI
 8B23 117830        1868+        LXI      D,EPSI
 8B26 CD0185        1869+        CALL     PSHT
                    1870+        PLL      V1
 8B29 119530        1871+        LXI      D,V1
 8B2C CD1785        1872+        CALL     PLLT
                    1873+        PSH      NCRIT
 8B2F 11E530        1874+        LXI      D,NCRIT
 8B32 CD0185        1875+        CALL     PSHT
                    1876+        PLL      V2
 8B35 119930        1877+        LXI      D,V2
 8B38 CD1785        1878+        CALL     PLLT
 8B3B CD4785        1879+        CALL     LTHAN
 8B3E E601          1880+        ANI      01H
 8B40 C25D8B        1881+        JNZ      L42
                    1882         PSH      ZERO                        ;EPSI=0: VVBKT=0
 8B43 117D80        1883+        LXI      D,ZERO
 8B46 CD0185        1884+        CALL     PSHT
                    1885         PLL      VVBKT
 8B49 11B530        1886+        LXI      D,VVBKT
 8B4C CD1785        1887+        CALL     PLLT
 8B4F C9            1888         RET
                    1889 L41:    PSH      ONE
 8B50 118180        1890+        LXI      D,ONE
 8B53 CD0185        1891+        CALL     PSHT
                    1892         PLL      VVBKT
 LOC  OBJ          LINE        SOURCE STATEMENT

8B56 11B530        1893+        LXI      D,VVBKT
8B59 CD1785        1894+        CALL     PLLT
8B5C C9            1895         RET
                   1896 L42:    PSH      ONE
8B5D 118180        1897+        LXI      D,ONE
8B60 CD0185        1898+        CALL     PSHT
8B63 CD7C8E        1899         CALL     CHSF
                   1900         PLL      VVBKT
8B66 11B530        1901+        LXI      D,VVBKT
8B69 CD1785        1902+        CALL     PLLT
8B6C C9            1903         RET
                   1904                                             ;
                   1905                                             ;
                   1906                                             ;** SUBROUTINE CHKLMT **
                   1907                                             ;
                   1908                                             ;FREEZES LIFT AND REACH ARM
                   1909                                             ; MOVEMENT IF ATTEMPT IS MADE TO
                   1910                                             ; EXCEED THE LIMIT OF RAM TRAVEL
                   1911                                             ;
                   1912                                             ;REGISTERS AFFECTED: A,D,E,STATUS
                   1913                                             ;
                   1914 CHKLMT: IFF      MCALFA,GEQUAL,AMAX,L80
                   1915+        PSH      MCALFA
8B6D 118030        1916+        LXI      D,MCALFA
8B70 CD0185        1917+        CALL     PSHT
                   1918+        PLL      V1
8B73 119530        1919+        LXI      D,V1
8B76 CD1785        1920+        CALL     PLLT
                   1921+        PSH      AMAX
8B79 110531        1922+        LXI      D,AMAX
8B7C CD0185        1923+        CALL     PSHT
                   1924+        PLL      V2
8B7F 119930        1925+        LXI      D,V2
8B82 CD1785        1926+        CALL     PLLT
8B85 CD5E85        1927+        CALL     GEQUAL
8B88 E601          1928+        ANI      01H
8B8A C2908B        1929+        JNZ      L80
8B8D C3B08B        1930         JMP      L81
                   1931 L80:    IFF      VVALFA,GEQUAL,ZERO,L87
                   1932+        PSH      VVALFA
8B90 11AD30        1933+        LXI      D,VVALFA
8B93 CD0185        1934+        CALL     PSHT
                   1935+        PLL      V1
8B96 119530        1936+        LXI      D,V1
8B99 CD1785        1937+        CALL     PLLT
                   1938+        PSH      ZERO
8B9C 117D80        1939+        LXI      D,ZERO
8B9F CD0185        1940+        CALL     PSHT
                   1941+        PLL      V2
8BA2 119930        1942+        LXI      D,V2
8BA5 CD1785        1943+        CALL     PLLT
8BA8 CD5E85        1944+        CALL     GEQUAL
8BAB E601          1945+        ANI      01H
8BAD C27C8C        1946+        JNZ      L87
                   1947 L81:    IFF      MCALFA,LEQUAL,AMIN,L82
 LOC  OBJ         LINE        SOURCE STATEMENT

                  1948+         PSH     MCALFA
 8BB0 118030      1949+         LXI     D,MCALFA
 8BB3 CD0185      1950+         CALL    PSHT
                  1951+         PLL     V1
 8BB6 119530      1952+         LXI     D,V1
 8BB9 CD1785      1953+         CALL    PLLT
                  1954+         PSH     AMIN
 8BBC 110131      1955+         LXI     D,AMIN
 8BBF CD0185      1956+         CALL    PSHT
                  1957+         PLL     V2
 8BC2 119930      1958+         LXI     D,V2
 8BC5 CD1785      1959+         CALL    PLLT
 8BC8 CD6385      1960+         CALL    LEQUAL
 8BCB E601        1961+         ANI     01H
 8BCD C2D38B      1962+         JNZ     L82
 8BD0 C3F38B      1963          JMP     L83
                  1964 L82:     IFF     VVALFA,LEQUAL,ZERO,L87
                  1965+         PSH     VVALFA
 8BD3 11AD30      1966+         LXI     D,VVALFA
 8BD6 CD0185      1967+         CALL    PSHT
                  1968+         PLL     V1
 8BD9 119530      1969+         LXI     D,V1
 8BDC CD1785      1970+         CALL    PLLT
                  1971+         PSH     ZERO
 8BDF 117D80      1972+         LXI     D,ZERO
 8BE2 CD0185      1973+         CALL    PSHT
                  1974+         PLL     V2
 8BE5 119930      1975+         LXI     D,V2
 8BE8 CD1785      1976+         CALL    PLLT
 8BEB CD6385      1977+         CALL    LEQUAL
 8BEE E601        1978+         ANI     01H
 8BF0 C27C8C      1979+         JNZ     L87
                  1980 L83:     IFF     BETA,GEQUAL,BMAX,L84
                  1981+         PSH     BETA
 8BF3 118830      1982+         LXI     D,BETA
 8BF6 CD0185      1983+         CALL    PSHT
                  1984+         PLL     V1
 8BF9 119530      1985+         LXI     D,V1
 8BFC CD1785      1986+         CALL    PLLT
                  1987+         PSH     BMAX
 8BFF 110D31      1988+         LXI     D,BMAX
 8C02 CD0185      1989+         CALL    PSHT
                  1990+         PLL     V2
 8C05 119930      1991+         LXI     D,V2
 8C08 CD1785      1992+         CALL    PLLT
 8C0B CD5E85      1993+         CALL    GEQUAL
 8C0E E601        1994+         ANI     01H
 8C10 C2168C      1995+         JNZ     L84
 8C13 C3368C      1996          JMP     L85
                  1997 L84:     IFF     VVBETA,GEQUAL,ZERO,L87
                  1998+         PSH     VVBETA
 8C16 11B130      1999+         LXI     D,VVBETA
 8C19 CD0185      2000+         CALL    PSHT
                  2001+         PLL     V1
 8C1C 119530      2002+         LXI     D,V1
 LOC  OBJ         LINE        SOURCE STATEMENT

 8C1F CD1785      2003+        CALL    PLLT
                  2004+        PSH     ZERO
 8C22 117D80      2005+        LXI     D,ZERO
 8C25 CD0185      2006+        CALL    PSHT
                  2007+        PLL     V2
 8C28 119930      2008+        LXI     D,V2
 8C2B CD1785      2009+        CALL    PLLT
 8C2E CD5E85      2010+        CALL    GEQUAL
 8C31 E601        2011+        ANI     01H
 8C33 C27C8C      2012+        JNZ     L87
                  2013 L85:    IFF     BETA,LEQUAL,BMIN,L86
                  2014+        PSH     BETA
 8C36 118830      2015+        LXI     D,BETA
 8C39 CD0185      2016+        CALL    PSHT
                  2017+        PLL     V1
 8C3C 119530      2018+        LXI     D,V1
 8C3F CD1785      2019+        CALL    PLLT
                  2020+        PSH     BMIN
 8C42 110931      2021+        LXI     D,BMIN
 8C45 CD0185      2022+        CALL    PSHT
                  2023+        PLL     V2
 8C48 119930      2024+        LXI     D,V2
 8C4B CD1785      2025+        CALL    PLLT
 8C4E CD6385      2026+        CALL    LEQUAL
 8C51 E601        2027+        ANI     01H
 8C53 C2598C      2028+        JNZ     L86
 8C56 C37F8C      2029         JMP     L88
                  2030 L86:    IFF     VVBETA,LEQUAL,ZERO,L87
                  2031+        PSH     VVBETA
 8C59 11B130      2032+        LXI     D,VVBETA
 8C5C CD0185      2033+        CALL    PSHT
                  2034+        PLL     V1
 8C5F 119530      2035+        LXI     D,V1
 8C62 CD1785      2036+        CALL    PLLT
                  2037+        PSH     ZERO
 8C65 117D80      2038+        LXI     D,ZERO
 8C68 CD0185      2039+        CALL    PSHT
                  2040+        PLL     V2
 8C6B 119930      2041+        LXI     D,V2
 8C6E CD1785      2042+        CALL    PLLT
 8C71 CD6385      2043+        CALL    LEQUAL
 8C74 E601        2044+        ANI     01H
 8C76 C27C8C      2045+        JNZ     L87
 8C79 C37F8C      2046         JMP     L88
 8C7C CD808C      2047 L87:    CALL    FREEZE
 8C7F C9          2048 L88:    RET
                  2049                                     ;
                  2050                                     ;
                  2051                                     ;** SUBROUTINE FREEZE **
                  2052                                     ;
                  2053                                     ;ASSIONS VALUE ZERO TO ALPHA
                  2054                                     ; AND BETA VALVE SETTINGS
                  2055                                     ;
                  2056                                     ;REGISTERS AFFECTED: D,E
                  2057                                     ;
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  LOC  OBJ         LINE        SOURCE STATEMENT

                   2058 FREEZE: PSH     ZERO
 8C80 117D80       2059+        LXI     D,ZERO
 8C83 CD0185       2060+        CALL    PSHT
 8C86 CDC48E       2061         CALL    PTOF
                   2062         PLL     VVALFA
 8C89 11AD30       2063+        LXI     D,VVALFA
 8C8C CD1785       2064+        CALL    PLLT
                   2065         PLL     VVBETA
 8C8F 11B130       2066+        LXI     D,VVBETA
 8C92 CD1785       2067+        CALL    PLLT
 8C95 C9           2068         RET
                   2069                                        ;
                   2070                                        ;
                   2071                                        ;** SUBROUTINE OUTPUT **
                   2072                                        ;
                   2073                                        ; OPERATES CUT-OFF, OFFSETS
                   2074                                        ; AND OUTPUTS SIGNAL TO
                   2075                                        ; VALVE DRIVERS
                   2076                                        ;
                   2077                                        ;REGISTERS AFFECTED: A,D,E,S
                   2078                                        ;
                   2079 OUTPUT: PSH     VVSLEW                 ;SET SLEW VALVE
 8C96 11A930       2080+        LXI     D,VVSLEW
 8C99 CD0185       2081+        CALL    PSHT
                   2082         PLL     FVO
 8C9C 11C230       2083+        LXI     D,FVO
 8C9F CD1785       2084+        CALL    PLLT
 8CA2 3AD530       2085         LDA     SPOF
 8CA5 32C930       2086         STA     POF
 8CA8 3AD730       2087         LDA     SNOF
 8CAB 32CA30       2088         STA     NOF
 8CAE 3AD630       2089         LDA     SPMAX
 8CB1 32CB30       2090         STA     PMAX
 8CB4 3AD830       2091         LDA     SNMAX
 8CB7 32CC30       2092         STA     NMAX
 8CBA CD8A8D       2093         CALL    VLIN
 8CBD 32B930       2094         STA     VS
 8CC0 D300         2095         OUT     00H
                   2096 L52:    PSH     VVALFA                 ;SET LIFT VALVE
 8CC2 11AD30       2097+        LXI     D,VVALFA
 8CC5 CD0185       2098+        CALL    PSHT
                   2099         PLL     FVO
 8CC8 11C230       2100+        LXI     D,FVO
 8CCB CD1785       2101+        CALL    PLLT
 8CCE 3ACD30       2102         LDA     APOF
 8CD1 32C930       2103         STA     POF
 8CD4 3ACF30       2104         LDA     ANOF
 8CD7 32CA30       2105         STA     NOF
 8CDA 3ACE30       2106         LDA     APMAX
 8CDD 32CB30       2107         STA     PMAX
 8CE0 3AD030       2108         LDA     ANMAX
 8CE3 32CC30       2109         STA     NMAX
 8CE6 CD8A8D       2110         CALL    VLIN
 8CE9 32BA30       2111         STA     VL
 8CEC D301         2112         OUT     01H
 LOC  OBJ         LINE        SOURCE STATEMENT

                  2113 L53:    PSH     VVBETA                        ;SET REACH VALVE
 8CEE 11B130      2114+        LXI     D,VVBETA
 8CF1 CD0185      2115+        CALL    PSHT
                  2116         PLL     FVO
 8CF4 11C230      2117+        LXI     D,FVO
 8CF7 CD1785      2118+        CALL    PLLT
 8CFA 3AD130      2119         LDA     BPOF
 8CFD 32C930      2120         STA     POF
 8D00 3AD330      2121         LDA     BNOF
 8D03 32CA30      2122         STA     NOF
 8D06 3AD230      2123         LDA     BPMAX
 8D09 32CB30      2124         STA     PMAX
 8D0C 3AD430      2125         LDA     BNMAX
 8D0F 32CC30      2126         STA     NMAX
 8D12 CD8A8D      2127         CALL    VLIN
 8D15 32BB30      2128         STA     VR
 8D18 D321        2129         OUT     21H
                  2130 L54:    IFF     VVBKT,EQUALS,ZERO,L55   ;SET BUCKET SWITCH
                  2131+        PSH     VVBKT
 8D1A 11B530      2132+        LXI     D,VVBKT
 8D1D CD0185      2133+        CALL    PSHT
                  2134+        PLL     V1
 8D20 119530      2135+        LXI     D,V1
 8D23 CD1785      2136+        CALL    PLLT
                  2137+        PSH     ZERO
 8D26 117D80      2138+        LXI     D,ZERO
 8D29 CD0185      2139+        CALL    PSHT
                  2140+        PLL     V2
 8D2C 119930      2141+        LXI     D,V2
 8D2F CD1785      2142+        CALL    PLLT
 8D32 CD6D85      2143+        CALL    EQUALS
 8D35 E601        2144+        ANI     01H
 8D37 C25D8D      2145+        JNZ     L55
                  2146         IFF     VVBKT,GTHAN,ZERO,L56
                  2147+        PSH     VVBKT
 8D3A 11B530      2148+        LXI     D,VVBKT
 8D3D CD0185      2149+        CALL    PSHT
                  2150+        PLL     V1
 8D40 119530      2151+        LXI     D,V1
 8D43 CD1785      2152+        CALL    PLLT
                  2153+        PSH     ZERO
 8D46 117D80      2154+        LXI     D,ZERO
 8D49 CD0185      2155+        CALL    PSHT
                  2156+        PLL     V2
 8D4C 119930      2157+        LXI     D,V2
 8D4F CD1785      2158+        CALL    PLLT
 8D52 CD3085      2159+        CALL    GTHAN
 8D55 E601        2160+        ANI     01H
 8D57 C2658D      2161+        JNZ     L56
 8D5A C36D8D      2162         JMP     L57
 8D5D 3EC0        2163 L55:    MVI     A,0C0H                        ;SEGMENT FOR STATIC BUCKET
 8D5F 32BC30      2164         STA     VB
 8D62 D322        2165         OUT     22H
 8D64 C9          2166         RET
 8D65 3E80        2167 L56:    MVI     A,80H                         ;SEGMENT FOR OPENING BUCKET
 LOC  OBJ          LINE        SOURCE STATEMENT

 8D67 32BC30       2168          STA     VB
 8D6A D322         2169          OUT     22H
 8D6C C9           2170          RET
 8D6D 3E40         2171 L57:     MVI     A,40H                    ;SEGMENT FOR CLOSING BUCKET
 8D6F 32BC30       2172          STA     VB
 8D72 D322         2173          OUT     22H
 8D74 C9           2174          RET
                   2175                                           ;
                   2176                                           ;
                   2177                                           ;** SUBROUTINE FLOAT **
                   2178                                           ;
                   2179                                           ;PUTS CONTENTS OF 'A' REGISTER
                   2180                                           ; ON TOP OF APU STACK
                   2181                                           ;
                   2182                                           ;REGISTERS AFFECTED: A
                   2183                                           ;
 8D75 320010       2184 FLOAT:   STA     1000H
 8D78 AF           2185          XRA     A
 8D79 320010       2186          STA     1000H
 8D7C CD888E       2187          CALL    FLTS
 8D7F C9           2188          RET
                   2189                                           ;
                   2190                                           ;
                   2191                                           ;** SUBROUTINE FIX **
                   2192                                           ;
                   2193                                           ;PUTS 32-BIT TOS OF APU
                   2194                                           ; IN THE A REGISTER
                   2195                                           ;
                   2196                                           ;REGISTERS AFFECTED: A
                   2197                                           ;
 8D80 CDAC8E       2198 FIX:     CALL    FIXS
 8D83 3A0010       2199          LDA     1000H
 8D86 3A0010       2200          LDA     1000H
 8D89 C9           2201          RET
                   2202                                           ;
                   2203                                           ;
                   2204                                           ;** SUBROUTINE VLIN **
                   2205                                           ;
                   2206                                           ;VALVE OPENING IN NOMINAL RANGE -1 TO
                   2207                                           ; +1 IS PASSED IN FVO.
                   2208                                           ; SUBROUTINE CALCUALATES BYTE OP TO
                   2209                                           ; BE OUTPUT TO THE DRIVER CIRCUIT
                   2210                                           ; USING DATA POS, PMAX, NOS, & NMAX.
                   2211                                           ;
                   2212                                           ;REGISTERS AFFECTED: A,D,E,STATUS
                   2213                                           ;
                   2214 VLIN:    IFF     FVO,GTHAN,ZERO,L61
                   2215+         PSH     FVO
 8D8A 11C230       2216+         LXI     D,FVO
 8D8D CD0185       2217+         CALL    PSHT
                   2218+         PLL     V1
 8D90 119530       2219+         LXI     D,V1
 8D93 CD1785       2220+         CALL    PLLT
                   2221+         PSH     ZERO
 8D96 117D80       2222+         LXI     D,ZERO
 LOC  OBJ          LINE         SOURCE STATEMENT

 8D99 CD0185        2223+        CALL     PSHT
                    2224+        PLL      V2
 8D9C 119930        2225+        LXI      D,V2
 8D9F CD1785        2226+        CALL     PLLT
 8DA2 CD3085        2227+        CALL     GTHAN
 8DA5 E601          2228+        ANI      01H
 8DA7 C2CC8D        2229+        JNZ      L61
                    2230         IFF      FVO,LTHAN,ZERO,L62
                    2231+        PSH      FVO
 8DAA 11C230        2232+        LXI      D,FVO
 8DAD CD0185        2233+        CALL     PSHT
                    2234+        PLL      V1
 8DB0 119530        2235+        LXI      D,V1
 8DB3 CD1785        2236+        CALL     PLLT
                    2237+        PSH      ZERO
 8DB6 117D80        2238+        LXI      D,ZERO
 8DB9 CD0185        2239+        CALL     PSHT
                    2240+        PLL      V2
 8DBC 119930        2241+        LXI      D,V2
 8DBF CD1785        2242+        CALL     PLLT
 8DC2 CD4785        2243+        CALL     LTHAN
 8DC5 E601          2244+        ANI      01H
 8DC7 C2008E        2245+        JNZ      L62
 8DCA AF            2246         XRA      A                             ;SEGMENT FOR FVO=0
 8DCB C9            2247         RET
                    2248 L61:    IFF      FVO,LTHAN,ONE,L63
                    2249+        PSH      FVO
 8DCC 11C230        2250+        LXI      D,FVO
 8DCF CD0185        2251+        CALL     PSHT
                    2252+        PLL      V1
 8DD2 119530        2253+        LXI      D,V1
 8DD5 CD1785        2254+        CALL     PLLT
                    2255+        PSH      ONE
 8DD8 118180        2256+        LXI      D,ONE
 8DDB CD0185        2257+        CALL     PSHT
                    2258+        PLL      V2
 8DDE 119930        2259+        LXI      D,V2
 8DE1 CD1785        2260+        CALL     PLLT
 8DE4 CD4785        2261+        CALL     LTHAN
 8DE7 E601          2262+        ANI      01H
 8DE9 C2F08D        2263+        JNZ      L63
 8DEC 3ACB30        2264         LDA      PMAX                          ;SEGMENT FOR FVO)PMAX
 8DEF C9            2265         RET
 8DF0 3AC930        2266 L63:    LDA      POF                           ;SEGMENT FOR 0(FVO(1
 8DF3 32C730        2267         STA      OFFSET
 8DF6 3ACB30        2268         LDA      PMAX
 8DF9 32C830        2269         STA      MAX
 8DFC C33F8E        2270         JMP      L64
 8DFF C9            2271         RET
                    2272 L62:    IFF      FVO,GTHAN,MINONE,L65
                    2273+        PSH      FVO
 8E00 11C230        2274+        LXI      D,FVO
 8E03 CD0185        2275+        CALL     PSHT
                    2276+        PLL      V1
 8E06 119530        2277+        LXI      D,V1
 LOC  OBJ         LINE        SOURCE STATEMENT

 8E09 CD1785      2278+         CALL    PLLT
                  2279+         PSH     MINONE
 8E0C 118980      2280+         LXI     D,MINONE
 8E0F CD0185      2281+         CALL    PSHT
                  2282+         PLL     V2
 8E12 119930      2283+         LXI     D,V2
 8E15 CD1785      2284+         CALL    PLLT
 8E18 CD3085      2285+         CALL    GTHAN
 8E1B E601        2286+         ANI     01H
 8E1D C2248E      2287+         JNZ     L65
 8E20 3ACC30      2288          LDA     NMAX                    ;SEGMENT FOR FVO<=-1
 8E23 C9          2289          RET
 8E24 3ACA30      2290 L65:     LDA     NOF                     ;SEGMENT FOR -1<FVO<0
 8E27 32C730      2291          STA     OFFSET
 8E2A 3ACC30      2292          LDA     NMAX
 8E2D 32C830      2293          STA     MAX
                  2294          PSH     FVO
 8E30 11C230      2295+         LXI     D,FVO
 8E33 CD0185      2296+         CALL    PSHT
 8E36 CD7C8E      2297          CALL    CHSF
                  2298          PLL     FVO
 8E39 11C230      2299+         LXI     D,FVO
 8E3C CD1785      2300+         CALL    PLLT
 8E3F 3AC730      2301 L64:     LDA     OFFSET                  ;COMMON SEGMENT FOR INTERMEDIATE
 8E42 CD758D      2302          CALL    FLOAT                   ; VALVE OPENING
 8E45 CDC48E      2303          CALL    PTOF
 8E48 3AC830      2304          LDA     MAX
 8E4B CD758D      2305          CALL    FLOAT
 8E4E CD188F      2306          CALL    XCHF
 8E51 CD948E      2307          CALL    FSUB
                  2308          PSH     FVO
 8E54 11C230      2309+         LXI     D,FVO
 8E57 CD0185      2310+         CALL    PSHT
 8E5A CD708E      2311          CALL    FMUL
 8E5D CD648E      2312          CALL    FADD
 8E60 CD808D      2313          CALL    FIX
 8E63 C9          2314          RET
                  2315                                          ;
                  2316                                          ;
                  2317                                          ;** MATHS SUBROUTINES MACRO **
                  2318                                          ;
                  2319                                          ;THIS MACRO GENERATES THE SUBROUTINES
                  2320                                          ; FOR OPERATING THE APU.  THE PARAMETERS
                  2321                                          ; ARE THE FUNCTION NAME 'FNCTN' AND THE
                  2322                                          ; AND THE CONTROL BYTE 'CODE' TO BE SENT
                  2323                                          ; TO THE APU COMMAND REGISTER.
                  2324                                          ;
                  2325                                          ;REGISTERS AFFECTED: NONE
                  2326                                          ;
                  2327                                          ;
                  2328 MATHS    MACRO   FNCTN,CODE
 -                2329 FNCTN:   STA     ASTR
 -                2330          MVI     A,CODE
 -                2331          STA     1100H
 -                2332          LDA     ASTR
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  LOC  OBJ          LINE         SOURCE STATEMENT

 -                  2333          RET
                    2334          ENDM
                    2335                                                   ;
                    2336                                                   ;
                    2337                                                   ;** MATHS MACRO CALLS **
                    2338                                                   ;
                    2339                                                   ;ALL OPERANDS ARE 32 BIT FLOATING
                    2340                                                   ; POINT UNLESS OTHERWISE INDICATED
                    2341                                                   ;
                    2342          MATHS    FADD,10H                        ;ADD TOS TO NOS, RESULT ON TOS
  8E64 32C630       2343+FADD:    STA      ASTR
  8E67 3E10         2344+         MVI      A,10H
  8E69 320011       2345+         STA      1100H
  8E6C 3AC630       2346+         LDA      ASTR
  8E6F C9           2347+         RET
                    2348          MATHS    FMUL,12H                        ;MULTIPLY TOS AND NOS, RESULT ON TOS
  8E70 32C630       2349+FMUL:    STA      ASTR
  8E73 3E12         2350+         MVI      A,12H
  8E75 320011       2351+         STA      1100H
  8E78 3AC630       2352+         LDA      ASTR
  8E7B C9           2353+         RET
                    2354          MATHS    CHSF,15H                        ;CHANGE SIGN OF TOS
  8E7C 32C630       2355+CHSF:    STA      ASTR
  8E7F 3E15         2356+         MVI      A,15H
  8E81 320011       2357+         STA      1100H
  8E84 3AC630       2358+         LDA      ASTR
  8E87 C9           2359+         RET
                    2360          MATHS    FLTS,1DH                        ;CONVERTS 16 BIT TOS TO 32 BIT FL. PT.
  8E88 32C630       2361+FLTS:    STA      ASTR
  8E8B 3E1D         2362+         MVI      A,1DH
  8E8D 320011       2363+         STA      1100H
  8E90 3AC630       2364+         LDA      ASTR
  8E93 C9           2365+         RET
                    2366          MATHS    FSUB,11H                        ;TOS=NOS-TOS
  8E94 32C630       2367+FSUB:    STA      ASTR
  8E97 3E11         2368+         MVI      A,11H
  8E99 320011       2369+         STA      1100H
  8E9C 3AC630       2370+         LDA      ASTR
  8E9F C9           2371+         RET
                    2372          MATHS    FDIV,13H                        ;TOS=NOS/TOS
  8EA0 32C630       2373+FDIV:    STA      ASTR
  8EA3 3E13         2374+         MVI      A,13H
  8EA5 320011       2375+         STA      1100H
  8EA8 3AC630       2376+         LDA      ASTR
  8EAB C9           2377+         RET
                    2378          MATHS    FIXS,1FH                        ;CONVERTS TOS TO 16 BIT FIXED PT
  8EAC 32C630       2379+FIXS:    STA      ASTR
  8EAF 3E1F         2380+         MVI      A,1FH
  8EB1 320011       2381+         STA      1100H
  8EB4 3AC630       2382+         LDA      ASTR
  8EB7 C9           2383+         RET
                    2384          MATHS    PTOS,77H                        ;COPY 16 BIT TOS ONTO STACK
  8EB8 32C630       2385+PTOS:    STA      ASTR
  8EBB 3E77         2386+         MVI      A,77H
  8EBD 320011       2387+         STA      1100H
 LOC  OBJ          LINE        SOURCE STATEMENT

 8EC0 3AC630       2388+        LDA     ASTR
 8EC3 C9           2389+        RET
                   2390         MATHS   PTOF,17H               ;COPY 32 BIT TOS ONTO STACK
 8EC4 32C630       2391+PTOF:   STA     ASTR
 8EC7 3E17         2392+        MVI     A,17H
 8EC9 320011       2393+        STA     1100H
 8ECC 3AC630       2394+        LDA     ASTR
 8ECF C9           2395+        RET
                   2396         MATHS   POPF,18H               ;ROTATE TOS TO BOTTOM OF STACK
 8ED0 32C630       2397+POPF:   STA     ASTR
 8ED3 3E18         2398+        MVI     A,18H
 8ED5 320011       2399+        STA     1100H
 8ED8 3AC630       2400+        LDA     ASTR
 8EDB C9           2401+        RET
                   2402         MATHS   PUPI,1AH               ;PUSH PI ONTO TOS
 8EDC 32C630       2403+PUPI:   STA     ASTR
 8EDF 3E1A         2404+        MVI     A,1AH
 8EE1 320011       2405+        STA     1100H
 8EE4 3AC630       2406+        LDA     ASTR
 8EE7 C9           2407+        RET
                   2408         MATHS   SIN,02H                ;TOS=SIN(TOS)
 8EE8 32C630       2409+SIN:    STA     ASTR
 8EEB 3E02         2410+        MVI     A,02H
 8EED 320011       2411+        STA     1100H
 8EF0 3AC630       2412+        LDA     ASTR
 8EF3 C9           2413+        RET
                   2414         MATHS   ASIN,05H               ;TOS=ASIN(TOS)
 8EF4 32C630       2415+ASIN:   STA     ASTR
 8EF7 3E05         2416+        MVI     A,05H
 8EF9 320011       2417+        STA     1100H
 8EFC 3AC630       2418+        LDA     ASTR
 8EFF C9           2419+        RET
                   2420         MATHS   COS,03H                ;TOS=COS(TOS)
 8F00 32C630       2421+COS:    STA     ASTR
 8F03 3E03         2422+        MVI     A,03H
 8F05 320011       2423+        STA     1100H
 8F08 3AC630       2424+        LDA     ASTR
 8F0B C9           2425+        RET
                   2426         MATHS   ACOS,06H               ;TOS=ACOS(TOS)
 8F0C 32C630       2427+ACOS:   STA     ASTR
 8F0F 3E06         2428+        MVI     A,06H
 8F11 320011       2429+        STA     1100H
 8F14 3AC630       2430+        LDA     ASTR
 8F17 C9           2431+        RET
                   2432         MATHS   XCHF,19H               ;EXCHANGE TOS AND NOS
 8F18 32C630       2433+XCHF:   STA     ASTR
 8F1B 3E19         2434+        MVI     A,19H
 8F1D 320011       2435+        STA     1100H
 8F20 3AC630       2436+        LDA     ASTR
 8F23 C9           2437+        RET
                   2438         MATHS   SQRT,01H               ;TOS=SQRT TOS
 8F24 32C630       2439+SQRT:   STA     ASTR
 8F27 3E01         2440+        MVI     A,01H
 8F29 320011       2441+        STA     1100H
 8F2C 3AC630       2442+        LDA     ASTR
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  LOC  OBJ          LINE        SOURCE STATEMENT

  8F2F C9           2443+         RET
                    2444 END

PUBLIC SYMBOLS

EXTERNAL SYMBOLS

USER SYMBOLS
A1A     A 30D9   A1B     A 30DD   AA      A 300D   AB      A 3011   ACOS    A 8F0C   ADCON   A 84E7   AI      A 3005
ALFIP   A 845D   ALPHA   A 3084   AMAX    A 3105   AMIN    A 3101   ANMAX   A 30D0   ANOF    A 30CF   APMAX   A 30CE
APOF    A 30CD   ASIN    A 8EF4   ASTR    A 30C6   BASE    A 3111   BETA    A 3088   BETIP   A 8497   BI      A 3009
BMAX    A 310D   BMIN    A 3109   BNMAX   A 30D4   BNOF    A 30D3   BPMAX   A 30D2   BPOF    A 30D1   CA      A 8059
CB      A 8061   CD      A 8069   CHKLMT  A 8B6D   CHSF    A 8E7C   CNST1   A 80A1   CNST10  A 30ED   CNST11  A 30F1
CNST13  A 80B5   CNST14  A 80B9   CNST2   A 80A5   CNST20  A 80BD   CNST21  A 80C1   CNST3   A 80A9   CNST4   A 80AD
CNST9   A 80B1   CONV    A 8413   COORD   A 863F   COS     A 8F00   CXDOT   A 3050   CYDOT   A 3054   D14     A 80C5
DCRIT   A 30F5   DELAY   A 30FF   DELTA   A 308C   DELTIP  A 84BF   DIST    A 302C   DLOOP   A 80D8   DPCRIT  A 30F9
DPSI    A 3030   DX      A 3001   EALPHA  A 30A1   EBETA   A 30A5   ECMIN   A 30E9   ECRIT   A 30BE   EPOS    A 8724
EPSI    A 3078   EQUALS  A 856D   ETA     A 307C   EX      A 3070   EY      A 3074   FADD    A 8E64   FCOUNT  A 30BD
FDIV    A 8EA0   FFAST   A 30FD   FFD     A 895F   FIX     A 8D80   FIXS    A 8EAC   FLOAT   A 8D75   FLTS    A 8E88
FMUL    A 8E70   FREEZE  A 8C80   FSLOW   A 30FE   FSUB    A 8E94   FVO     A 30C2   GCO     A 8095   GC1     A 8099
GC2     A 809D   GEQUAL  A 855E   GTHAN   A 8530   H255    A 80C9   H79     A 8079   H87     A 8075   HALF    A 8085
I1      A 3048   I2      A 304C   IFF     + 0002   INIT    A 83FE   IP1     A 87D5   IP2     A 8902   JBKT    A 3044
JOYSTK  A 8593   JSLEW   A 3040   JXDOT   A 3038   JYDOT   A 303C   L100    A 80FC   L101    A 8110   L102    A 8148
L103    A 8166   L104    A 8176   L108    A 8142   L109    A 8160   L2      A 853A   L201    A 81B1   L202    A 8291
L205    A 82A4   L206    A 81FA   L21     A 8801   L22     A 8842   L23     A 8883   L24     A 88A4   L26     A 88C5
L3      A 8544   L301    A 83A5   L308    A 8370   L32     A 895E   L4      A 8551   L41     A 8B50   L42     A 8B5D
L43     A 89BF   L44     A 8996   L46     A 89B9   L47     A 8AB8   L49     A 8B03   L5      A 855B   L50     A 85EA
L51     A 8603   L52     A 8CC2   L53     A 8CEE   L54     A 8D1A   L55     A 8D5D   L56     A 8D65   L57     A 8D6D
L6      A 857C   L61     A 8DCC   L62     A 8E00   L63     A 8DF0   L64     A 8E3F   L65     A 8E24   L7      A 8590
L80     A 8B90   L81     A 8BB0   L82     A 8BD3   L83     A 8BF3   L84     A 8C16   L85     A 8C36   L86     A 8C59
L87     A 8C7C   L88     A 8C7F   LA      A 806D   LEARN   A 81E6   LEQUAL  A 8563   LOOP    A 81D9   LOOP1   A 8182
LOOP3   A 81C3   LTHAN   A 8547   MA      A 8055   MANUAL  A 817C   MATHS   + 0003   MAX     A 30C8   MAXPTS  A 804C
MB      A 805D   MCALFA  A 3080   MD      A 8065   MINONE  A 8089   MLOOP   A 80F3   MODE    A 301D   MODFLG  A 3000
MU      A 808D   NCOUNT  A 3036   NCRIT   A 30E5   NEQUAL  A 8568   NMAX    A 30CC   NOF     A 30CA   OFFSET  A 30C7
ONE     A 8081   OUTPUT  A 8C96   PAUSE   A 8797   PCOUNT  A 3034   PCRIT   A 30E1   PITCH   A 309D   PLL     + 0001
PLLT    A 8517   PMAX    A 30CB   POF     A 30C9   POPF    A 8ED0   PPOINT  A 301E   PSH     + 0000   PSHT    A 8501
PSII    A 3060   PSIO    A 306C   PSIP    A 3028   PTOF    A 8EC4   PTOS    A 8EB8   PUPI    A 8EDC   RA      A 8071
RCOUNT  A 3035   REPEAT  A 82FC   RFAST   A 83C0   RFCON   A 83CA   RSCON   A 83EB   RSETUP  A 82AC   RSLOW   A 83E1
S       A 3091   SETEC   A 879E   SIN     A 8EE8   SLOPE   A 861C   SNMAX   A 30D8   SNOF    A 30D7   SPMAX   A 30D6
SPOF    A 30D5   SQRT    A 8F24   STATUS  A 3090   TEN     A 804D   TFLAG   A 3037   TPULL   A 81BA   TPUSH   A 81D0
TWO     A 8051   V1      A 3095   V2      A 3099   VB      A 30BC   VL      A 30BA   VLIN    A 8D8A   VR      A 30BB
VS      A 30B9   VVALFA  A 30AD   VVBETA  A 30B1   VVBKT   A 30B5   VVSLEW  A 30A9   XA1A    A 800C   XA1B    A 8010
XAMAX   A 8040   XAMIN   A 803C   XANMAX  A 8003   XANOF   A 8002   XAPMAX  A 8001   XAPOF   A 8000   XBMAX   A 8048
XBMIN   A 8044   XBNMAX  A 8007   XBNOF   A 8006   XBPMAX  A 8005   XBPOF   A 8004   XCHF    A 8F18   XCST10  A 8028
XCST11  A 802C   XDCRIT  A 8030   XDELAY  A 803A   XDPCRT  A 8034   XEACRT  A 8020   XEBCRT  A 8024   XEMIN   A 801C
XFFAST  A 8038   XFSLOW  A 8039   XI      A 3058   XNCRIT  A 8018   XO      A 3064   XOF     A 3015   XP      A 3020
XPCRIT  A 8014   XPXO    A 81A9   XSNMAX  A 800B   XSNOF   A 800A   XSPMAX  A 8009   XSPOF   A 8008   XY      A 8190
YI      A 305C   YO      A 3068   YOF     A 3019   YP      A 3024   ZERO    A 807D   ZETA    A 8091

ASSEMBLY COMPLETE,    NO ERRORS
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