THREE DIMENSIONAL CONTROL OF MACHINE TOOLS BY USING MICROCOMPUTER

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Approval of the Graduate School of Natural and Applied Sciences.

for Prof.Dr.Bilgin Kaftanoğlu

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Electrical and Electronic Engineering.

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ABSTRACT

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In this thesis, three dimensional control of a machine tool by using microprocessor is designed and constructed. In this system, an important part can be observed as drive circuits. These circuits are designed and fitted to other devices. The microcomputer that is used in this system is also designed and constructed. In a Computerized Numerical Control, (CNC) machine tool, tables should be able to follow any arbitrary path for shaping the workpiece in any form. In this work, linear motion is selected. Linear motion has a great importance in the path following ability of the cutting tool. This is the basic of the other motions. The main purpose here is to design a control unit which controls the tables of the machine tool. There are three tables, two of them are dependent each other, and one of them is independent from the others. After the testing of the system, satisfactory operation in open loop on no load conditions is obtained up to 1300 mm/min. feedrate in 0.05mm steps. In closed loop operation, due to damped oscillation of the motor's rotor the desired operation is not obtained.

Key words: Computerized Numerical Control, Linear motion,
microprocessor , machine tool, drive circuit.

ÖZET

TAKIM TEZGAHLARININ ÜÇ BOYUTTA MİKROBİLGİSAYAR İLE KONTROLU

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Bu tez çalışmasında, bir takım tezgahının üç boyutta mikroişlemci ile kontrolu dizayn edildi ve gerçekleştirildi. Sistemde önemli kısım olarak sürücü devreler göz önüne alınabilir. Bu devreler dizayn edilerek diğer cihazlarla uyumu sağlandı. Sistemde kullanılan mikrobilgisayarda bu çalışma içerisinde dizayn edildi ve gerçekleştirildi. Bilgisayarlı Nümerik Kontrollu bir takım tezgahında tablalar işlenecek parçayı herhangi bir şekilde işleyebilmek için değişik hareket yolları takip ederler. Bu çalışmada, lineer hareket seçilmiştir. Lineer hareket kesici tezgahlarda, önemli bir özelliğe haizdir. Bu hareket diğer hareketlerin temelidir. Burada temel gaye takım tezgahının tablalarını kontrol eden kontrol birimini dizayn etmektir. İkisi birbirine bağımlı, diğeri ise bağımsız olmak üzere üç tabla vardır. Sistemin test edilmesi neticesinde açık çevrim yüksüz şartlarda 0,05 mm lik adımlarla 1300 mm/dak. besleme hızına kadar arzu edilen çalışma gerçekleştirildi. Kapalı çevrim çalıştırmada motorların rotorlarındaki salınımlardan dolayı arzu edilen işlem elde edilemedi.

Anahtar sözcükler: Bilgisayarlı Numerik Kontrol, Lineer hareket, mikroişlemci, takım tezgahı, sürücü devre.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

1.1. General Information About Computerized Numerical Control (CNC) Systems

There is no doubt that Numerical Control (NC) of Machine Tools has been the mostly spoken objective in the Production Field, in the last 35 years. A gradual, disciplined approach to the design of NC of machine tools, coupled with intensified support from organized research, particularly with the rapid progress in integrated circuit technology has improved the quality of design in this field. The concept of numerical control ultimately extends far beyond the individual machine tool; it is a comprehensive form of organisation of internal data transmission and processing. The application of numerical control to machine tools has increased the speed and repetitive accuracy in production considerably, and the potential consequences of this to the world's productivity and economy are enormous [I] .

The rapidly progressing development of electronic components has, as in other areas of automation, strongly influenced the design of control systems. Thus new developments in CNC are determined extensively by the availability of new, very large scale integrated components such as microprocessors and semiconductor memories. The influence of the new technology is reflected in the scope of functions available, as well as in volume and price of the controls. Between the years 1966 and 1976 the scope of functions in NC's was approximately doubled, the volume has been reduced to, a twentieth and the price to a quarter[SP].

1.2. Historical Background of CNC Systems

The first attempts to control machine tools numerically were initiated in 1950's and since then, it has been considerably developed. Today, there is a more general use of numerically controlled machine tool and a rapid increase can be expected as many more alternatives, in both price and facilities, are offered.

In a machine tool, when the relative positions of the workpiece and cutting tool are determined by the information derived from numerical values, it is said to be under numerical control. The information which is called program is suitably coded for storing on cards, paper or magnetic tape and once provided to the system, it is carried out automatically, in a predetermined sequence.

While making a workpiece on a machine tool, several judgements of speeds, feeds, mathematics and sometimes, even tool configuration, were machine tool operator's own responsibility. Moreover he had to manufacture the part by making intermittent measurements to ensure that he did not remove too much metal. With the introduction of numerical control, all or part of these features are performed, by the coded instructions, much more accurately, quickly and less scrap and rejects[I].

As with most technological advances, the sizes of control units decrease due to the evolutions in semiconductor field. Also tapes and tape readers are gradually phased out as interfaces connected directly from computers by pass them.

Since Computer Aided Manufacturing (CAM) has gained considerable importance, the manufacturing control system makes use of a special NC machine (CNC) which receives its intsructions directly from a computer. Because a conventional NC equipment is incapable of performing these tasks, a modified NC system is required. A CNC system uses a digital computer to replace some or all of the logical functions performed by the conventional machine control unit.

Since the development of the first mumerically controlled machine tools in the early fifties, the inner structure and the outside appearance of numerical controls have changed decisively. Whereas, the first numerical controls were based on relays as the logic components, soon afterwards transistors, and some years late integrated circuits were employed to cope with the ever extending control functions. From 1972 onwards minicomputers were available which were suitable for use in NC. Today, new developments of numerical controls are being determined by the availability of inexpensive highly integrated components, such as microprocessors |HU|.

1.2.1 Computer Control Types of Machine Tools

There are mainly two types of computer control of machine tools.

The first one is the Computerized Numerical Control, CNC, which is an NC system where the dedicated computer is used to perform some or all of the basic NC functions for a single machine tool (or a number of machine tools if the total number of controlled axes is small) in accordance with control programs stored in the read-write memory of the computer.

Generally, the control and operating programs are read int the computer via the tape reader and held in the memory. The operating program is the logic of the control system which defines the features of the control, whereas the NC program is the set of cycle instructions which define the movements of the machine tool [RA], [WE].

First CNC Systems were equipped with minicomputers and core memories. Today's CNC systems employ a microcomputer and semiconductor memories as the central controlling unit. This CNC, which is often termed as a "microprocessor CNC", offers the manufacturer the opportunity to produce the hardware at a reasonable price independently the machine aplication such as turning, boring, milling or punching. When the functions of the control are divided over several microprocessors, the term "multi-microprocessor control" is employed [SP].

The second type of computer control of machine tools is Direct Numerical Control, DNC, which is the use of a computer to distribute data to machine tool controllers in a multiple machine tool arrangement. The important difference between DNC and CNC is the replacement of a dedicated computer by a larger computer that manages many machines on a time-shared basis [SP], [MI].

1.3. Design Problem of CNC Systems

The purpose in the design is the microcomputer control of a machine tool table in a closed-loop system. In a CNC machine tool, tables should be able to follow any arbitrary path for shaping the workpiece in any form. Generally in practical situations, these paths consist of some combinations of linear, circular, elliptical, hyperbolic, segments or they are approximated to these forms [BR], [I].

Linear motion has a great importance in the path following ability of the cutting tool. This is the basic of the circular, elliptical, hyperbolic, etc. motions. It is possible to obtain these motions with a predetermined accuracy using piecewise linear motion approximations [DAN] , [SO] , [CH] .

In this work, the main purpose is to design a control unit which controls the tables of a machine tool. There are three tables, two of them are dependent each other, and one of them is independent from the others. The general block diagram of the system is shown in Fig 1.1.

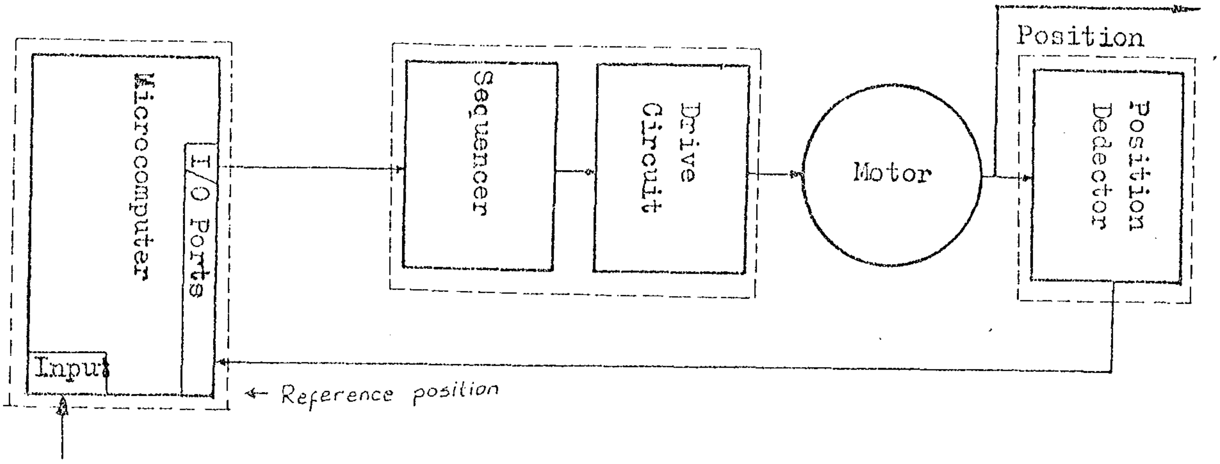


Fig 1.1. General block diagram of computer control

Microcomputer, that is used in this work is also designed and constructed. More detailed information about the microcomputer is given in Chapter II. The informations about hardware of the designed system are given in Chapter III. In Chapter IV, the software of the system is discussed. In Chapter V, results, discussions and recommendations are expressed.

This work was initiated in the Electrical and Electronic Engineering Department of METU, it is also supported by Electrical and Electronic Engineering Department of Erciyes University.

CHAPTER II

MICROCOMPUTER - ALP 85

2.1. General

Microcomputer is making an impact on every aspect of our lives; and soon it will play a significant role in the daily functioning of all industrialized societies. The basic structure of the microcomputer is no different from any other computer. In the 1960's, computers were accessible and affordable only to large corporations, big universities, and goverment agencies. Because of advances in semiconductor technology, the million-dollar computing capacity of the 1960's is now available for less than ten dollars in an integrated circuit called microprocessor. A computer which is designed by using a microprocessor is called a microcomputer[GA]. The special microcomputer designed in this thesis work is called ALP 85.

2.1.1 Computer Technology

In the last twenty-five years, semiconductor technology has undergone unprecedented changes. Integrated circuits (ICs) appeared on the scene at the end of the 1950's following the invention of the transistor. In an integrated circuit, an entire circuit consisting of several transistors, diodes, and resistors is contained on a single chip. In the early 1960's, logic gates known as the 7400 series were commonly available as ICs, and the technology of integrating the circuits of a logic gate on a single chip became known as Small-Scale- Integration (SSI). As semiconductor technology advanced, more than a hundred gates were fabricated on one chip; this was called Medium-Scale Integration (MSI). A typical example of MSI is a decade counter (7490). Within a few years, it was possible to fabricate more than a thousand gates on a single chip; this came to be known as Large-Scale Integration (LSI). Now we are in the era of Very-Large-Scale Integration (VLSI) and Super-Large-Scale Integration (SLSI). The lines of demarcation between these different scales of integration are ill-defined and arbitrary.

As the technology moved from SSI to SLSI, the face of computer changed. Initially, computers were built with discrete logic gates (SSI). As more and more logic circuits were built on one chip using LSI technology, it became possible to build the whole central processing unit,(CPU), with its related timing function on a single chip. This came to be known as the microprocessor, and a computer built with a microprocessor is known as a microcomputer. This distinction may soon disappear, however, as the computing power of the microprocessor approaches that of the CPUs of the traditional large computers. Early microcomputers were built with a 4 -bit microprocessor. Now a 64-bit microprocessor is being used in some prototype computers. Even if they are built with a microprocessor, it is meaningless to classify them as microcomputers [GA].

2.1.2 Microcomputer Organization

Figure 2.1 shows a simplified but formal structure of a microcomputer. It includes four components: microprocessor, input, output, and memory(read/write memory and read only memory) units. These components are organised around a common communication path called a bus. The entire group of components is called a system or a microcomputer system, while the components are called subsystems.

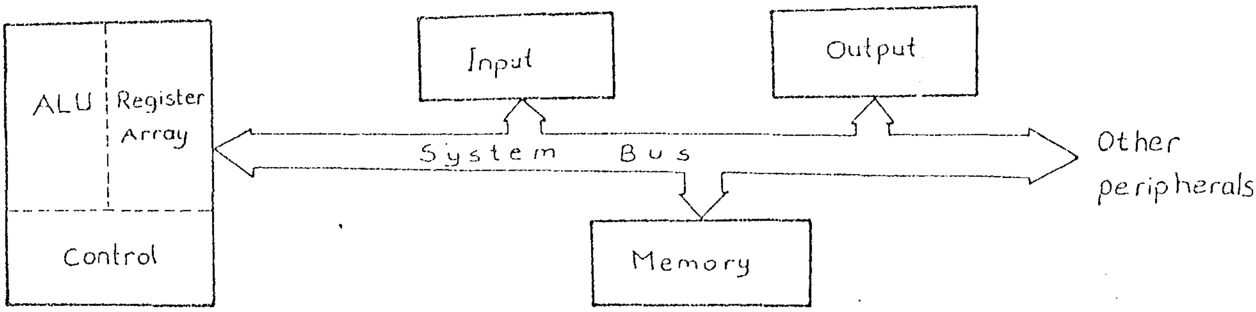


Fig. 2.1. Block diagram of a microcomputer.

At the outset, we will differentiate between the terms microprocessor and microcomputer because of the common misuse of these terms in popular literature. The microprocessor is one component of the microcomputer. On the other hand, the microcomputer is a complete computer similar to any other computer, except that the CPU functions of the microcomputer are performed by the microprocessor. Similarly, the term peripheral is used for input/output devices; however, occasionally memory is also included in this term [GA], [BR].

2.2. Designed Microcomputer - ALP 85

The designed microcomputer is constructed on Euro-card format in which the dimensions are 100mmx160mm. It is an 8-bit microcomputer based on the Intel 8085 microprocessor chip. It has 2K bytes monitor stored in EPROM. 4K bytes RAM and 2K bytes EPROM are available for the user programs. The microcomputer uses Intel 8155 as input/output ports. Intel 8155 has 3 ports; 2 programmable 8-bit I/O ports and 1 programmable 6-bit I/O port. The microcomputer has also a keyboard and 8 seven-segment displays. The communications between keyboard and displays are achieved by using Intel 8279 keyboard and display controller chip. An EPROM programmer and a magnetic tape interface are available on CPU card.

The block diagram of the designed microcomputer is given in Figure 2.2 [ECB].

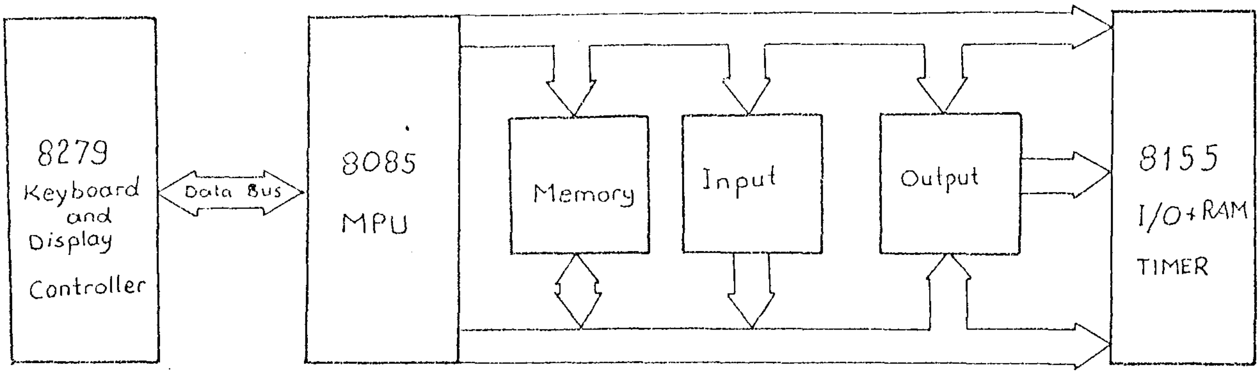


Fig. 2.2. Block diagram of the ALP 85 microcomputer.

2.3. Components of ALP 85

The various components of the microcomputer shown in Figure 2.2 and their functions are described in the following paragraphs.

2.3.1. 8085 MPU

The term Micro-Processing Unit (MPU) is similar to the term Central Processing Unit (CPU) used in traditional computers. We define the MPU as a device or a group of devices that can communicate with peripherals, provide timing signals, direct data flow, and perform computing tasks as specified by the instructions in memory. The unit will have the necessary lines for the address bus, the data bus, and perform computing tasks as specified by the instructions in the memory. The unit will have the necessary lines for the address bus, data bus, and the control signals, and would require only a power supply and a crystal to be completely functional.

Using this description, the 8085 microprocessor can almost qualify as an MPU, but with the following two limitations:

1. The low-order address bus of the 8085 microprocessor is

multiplexed (time-shared) with the data bus. The buses need to be demultiplexed.

2. Appropriate control signals neeed to be generated to interface memory and I/O with the 8085 [IN] ,[LE].

The 8085 is an 8-bit general purpose microprocessor capable of addressing 64Kbytes of memory. The device has forty pins, requires a +5V single power supply, and can operate with a 3-MHz sigle-phase clock. The 8085 is an enhanced version of its predecessar, the 8080A; its instruction set is upward-compatible with that of the 8080A, meaning that the 8085 instruction set includes all the 8080A instructions plus some additional ones. Programs written for the 8080A will be executed by the 8085, but the 8085 and the 8080A are not pin compatible.

Figure 2.3 shows the logic pinout of the 8085 microprocessor. All the signals or signal ports can be classified into six groups: (1) address bus, (2) data bus, (3) control and status signals, (4) power supply and frequency signal, (5) interrupts and peripheral initiated signals, and (6) serial I/O ports.

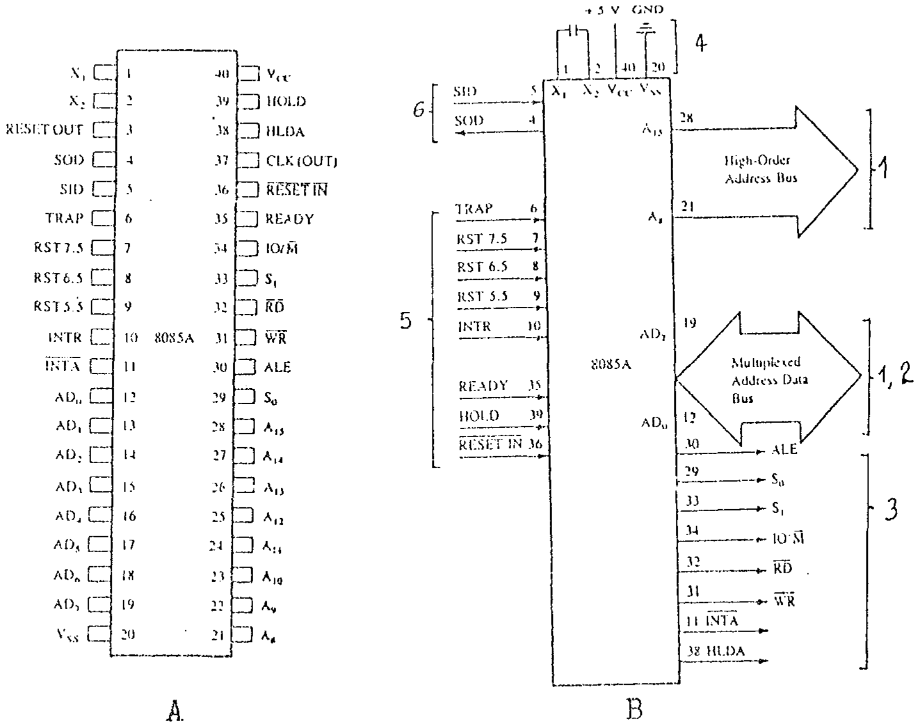


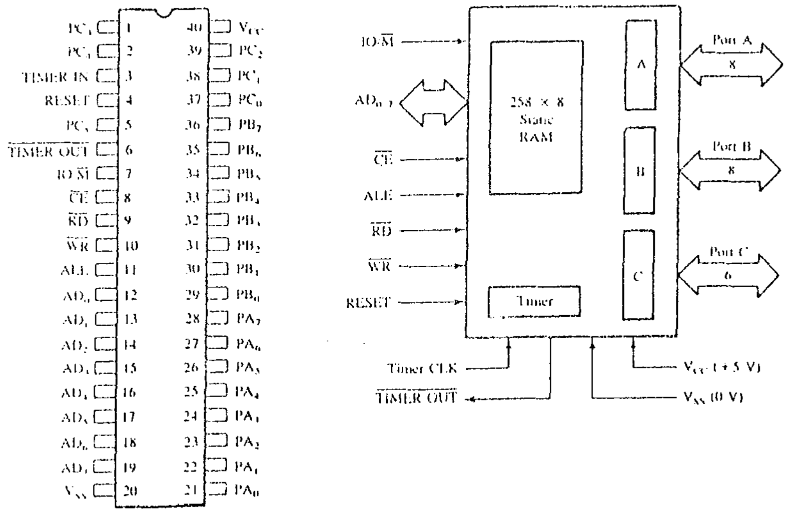
Figure 2.3. Microprocessor pinout and signals.

2.3.2. 8155 I/O Ports-RAM-TIMER

The Intel 8155H are RAM and I/O chips implemented in N-channel, depletion load, silicon gate technology (HMOS), to be used in the 8085A microprocessor system. The RAM portion is designed with 2048 static cells organized as 256x8. They have a maximum access time of 400 ns to permit use with states in 8085A CPU. The 8155A has maximum access times of 330 ns for use with the 8085A CPU.

The I/O portion consists of three general purpose I/O ports. One of the three ports can be programmed to be status pins, thus allowing the other two ports to operate in handshake mode.

A 14-bit programmable counter/timer is also included on the chip to provide either a square wave or terminal count pulse for the CPU system depending on timer mode. The functional block diagram and pin configuration of 8155 is shown in Figure 2.4.



(a) (b)

Figure 2.4. Pin configuration and functional block diagram of 8155

a) Pin configuration,

b) Block diagram.

The 8155 contains the followings:

- 2K Bit Static RAM organized as 256x8,
- Two 8-bit I/O ports (PA and PB) and one 6-bit I/O port (PC),
- 14-bit timer-counter.

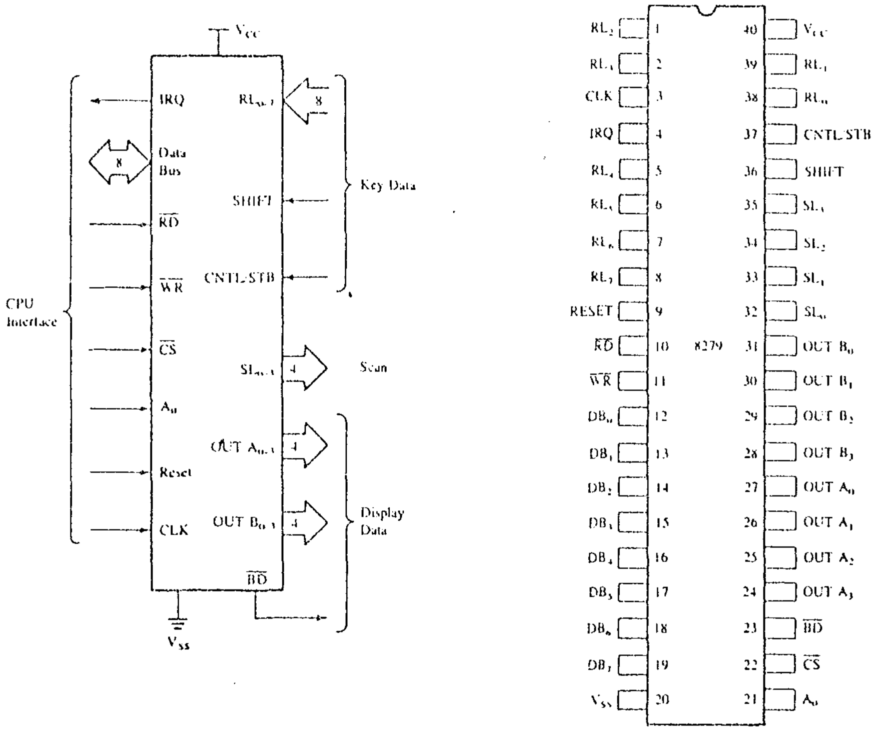
The IO/$\overline{M}$ (IO/Memory Select) pin selects either the five registers (Command, Status, PA_{0-7}, PB_{0-7}, PC_{0-5}) or the memory (RAM) portion.

The 8-bit address on the Address/Data lines, Chip Enable input $\overline{CE}$, and IO/ $\overline{M}$ are all latched on-chip at the falling edge of ALE [IN].

2.3.3. 8279 Programmable Keyboard/Display Controller

The Intel 8279 is a general programmable keyboard and display I/O interface device designed for use with Intel microprocessors. The keyboard portion can provide a scanned interface to a 64-contact key matrix. The keyboard portion will also interface to an array of sensors or a strobed interface keyboard, such as the hall effect and ferrite variety, Key depressions can be 2- key lockout or N-key rollover. Keyboard entries are debounced and strobed in an 8-charecter FIFO. If more than 8 characters are entered, overrun status is set. Key entries set the interrupt output line to the CPU.

The display portion provides a scanned display interface for LED, incandescent, and other popular display technologies. Both numeric and alphanumeric segment displays may be used as well as simple indicators. The 8279 has 16x8 display RAM which can be organized into dual 16x4. The RAM can be loaded or interrogated by the CPU. Both right entry, calculator and left entry typewriter display formats are possible. Both read and write of the display RAM can be done with auto-increment of the display RAM address. Logic symbol and pin configuration of 8279 is shown in Figure 2.5.



(a) (b)

Figure 2.5. a) Logic symbol and b) Pin configuration of 8279

Since the main purpose is not to design and the construction of microcomputer, these explanations about the components are enough. More detailed information about these components can be obtained in the references [IN], [BR], [GA].

The printed circuit board, components, and a photograf of CPU card are shown in Appendix A.

CHAPTER III

HARDWARE OF THE DESIGNED SYSTEM

3.1. Purpose and Design Problem

Purpose of the design problem is the closed loop control of machine tool tables in three dimensional linear motion with a microcomputer. There are three axis in the machine tool. In the scope of controlling the machine tool, the x and y axes are dependend on each other while z axis is independent from x and y axis. If the system is started to work, firstly z-axis value is given to the microcomputer and then the other values are given to the microcomputer.

In the designed system, the maximum dimensions of the workpiece is taken as 100mmx200mmx1500mm in view of the available machine tool. The software can easily be modified for other dimensions.

Machining the workpieces made of different materials requires different feedrates. It is reported and found that practically possible feedrate range is between 0 and 1500mm/min. Therefore, in the designed system, a performance in this range is sought [OR].

In the designed system, it is assumed that the smallest linear movement (one step) will be equal to the accuracy tolerance. This accuracy tolerance is taken as 0.05 mm. In the system, stepping motors are used to give the movements to tables, a lead screw should be used to translate the rotational movement of the motors to linear movement of the tables. Stepping motors have quantized angular movement characteristics. The smallest rotation is the step angle of this motor. Gear boxes will be employed to obtain smaller step sizes. It is decided that the gear ratio must be such that the tables make a 0.05 mm linear motion(accurracy tolerance) corresponding to each step angle of the motors.

CNC machine tools can be controlled into two ways; (i) Point to Point Control and (ii) Continous Path Control.

In point to point control, there is no functional relationship between the movements along the different coordinates. This group includes drilling machines, boring machines, milling machines etc. It is further, divided into two sub-groups: Positioning control and Straight-line control. In positioning control, the tool is never in contact with the workpiece while the control moves the slide to individual discrete points such as from A to B in Figure 3.1. A most typical example is the coordinate drilling machine. In straight-line control, the tool is in contact with the workpiece while the slide is moved along the coordinates. The motion is however always parallel to one of the axes of the machine tool. An example to this type of control is milling machine with traverse tables which is shown in Figure 3.2.

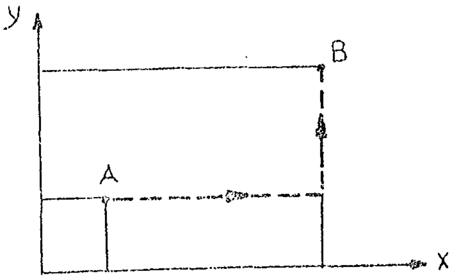


Figure 3.1. Positioning control

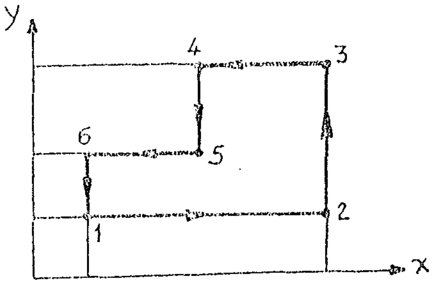


Figure 3.2. Straight-line control

In continous path control, there is a functional relationship between the movements along different coordinates. Hence the tool can be guided along a path of any desired shape as shown in Figure 3.3. A typical example is the profile milling machine[I].

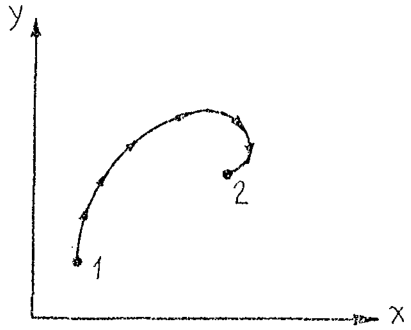


Figure 3.3. Continous path control

To achive this type of motion, continous control of the slide positions is required. Moreover an interpolator or a curve generator is included, which has two main functions to perform:

1. To interpolate between fixed data points or generate a particular type of curve,
2. To resolve the feedrate into the component velocities of the slides.

3.2. Principles of the Solution and Available Choices

3.2.1. Stepping Motor

The characterictic property of stepping motors is the stepwise rotation of the motor shaft. One revolution of the shaft is composed of an exactly defined number of angle steps, which is dependent upon the design of the motor. The step is the process involving a rotation of the motor shaft by the step angle. Stepping motors are used chiefly in the area of control technology which includes e.g. also office machines. For this reason, it only makes sense to compare motors designed for the same tasks. This comprises small rotating field motors, asynchronous motors, and DC motors.

In the course of the development of digital systems, step motors came into increasing use. They are preferred because they exhibit the following combination of the following characteristics:

1. Positioning accurate to one step without feedback, by imposition of a definete number of control pulses,

2. High torque at small angular velocities,
3. In the stationary state with excitation, a high holding torque which causes self brake action.

In most cases, problems incurred in the use of step motors have been of dynamic nature. A step motor may be described with good appoximation as a linear system of second order with oscillatory behavior. This system is modified by the coupling of external inertial and load moments. As for all drive types, this gives rise to three essential problem areas [BER]:

1. Start problems,
2. Brake problems,
3. Oscillation problems.

The stepping motors can be classified in three cathegories: Permanent Magnet Stepping Motors, Variable Reluctance Stepping Motors and Hybrid Stepping Motors. In general, hybrid stepping motors are more efficient and are available in higher power models. Also they have longer detend torque (the maximum steady torque that can be applied to the shaft of an unenergized stepping motor without causing continous rotation) than the others.

A hybrid stepping motor has a permanent magnet mounted on the rotor. The main flux path for the magnet flux, shown in Figure 3.4., lies from the magnet N-pole, into a soft-iron end cap, radially through the end-cap, across the air-gap, through the stator poles of section X, axially along the stator back-iron, through the stator poles of section Y, accross the air-gap and back to the magnet S-pole via the end-cap.

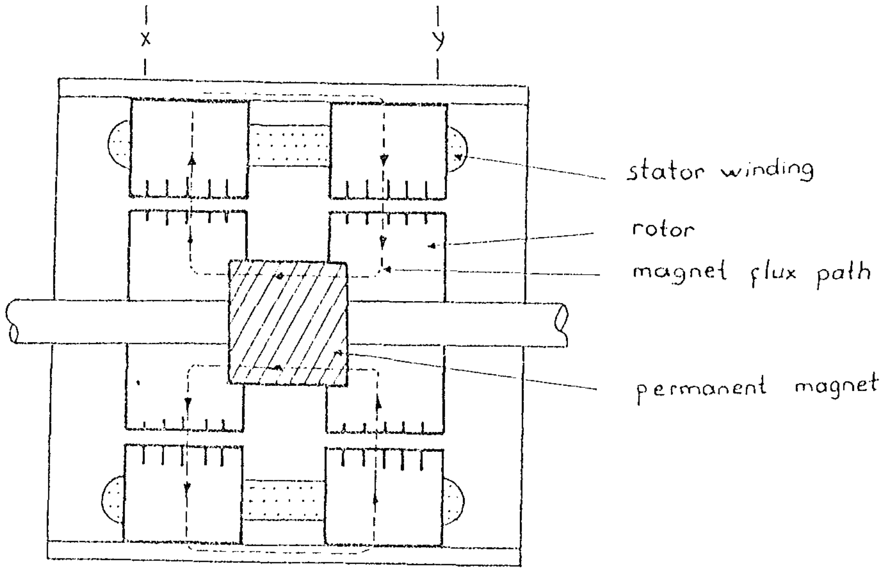


Figure 3.4. Cross-section of a hybrid motor parallel to the shaft.

There are typically eight stator poles, as in Figure 3.5, and each pole has between two and six teeth. The stator poles are also provided with windings which are used to encourage or discourage the flow of magnet flux through certain poles according to the rotor position required. Two windings are provided and

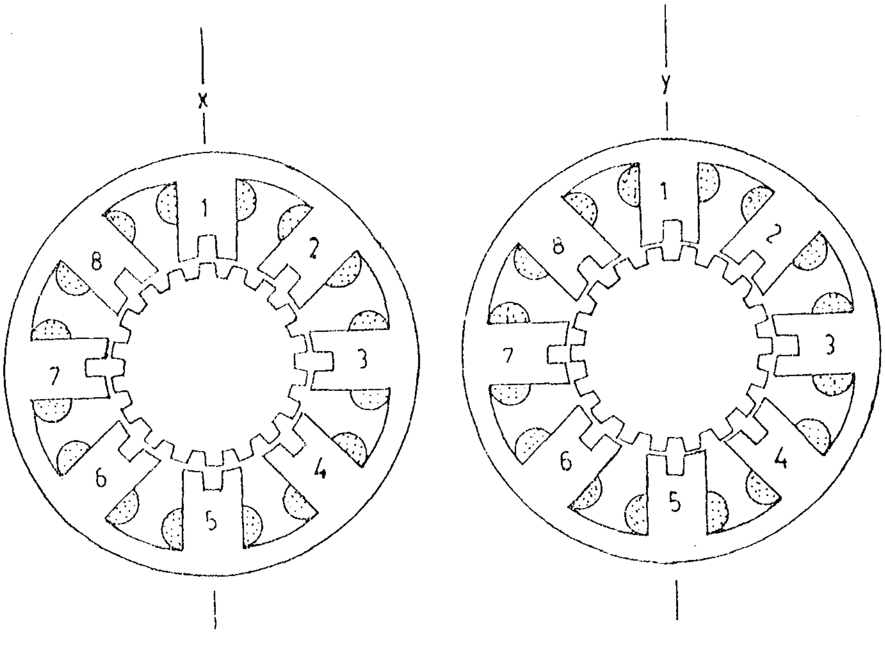


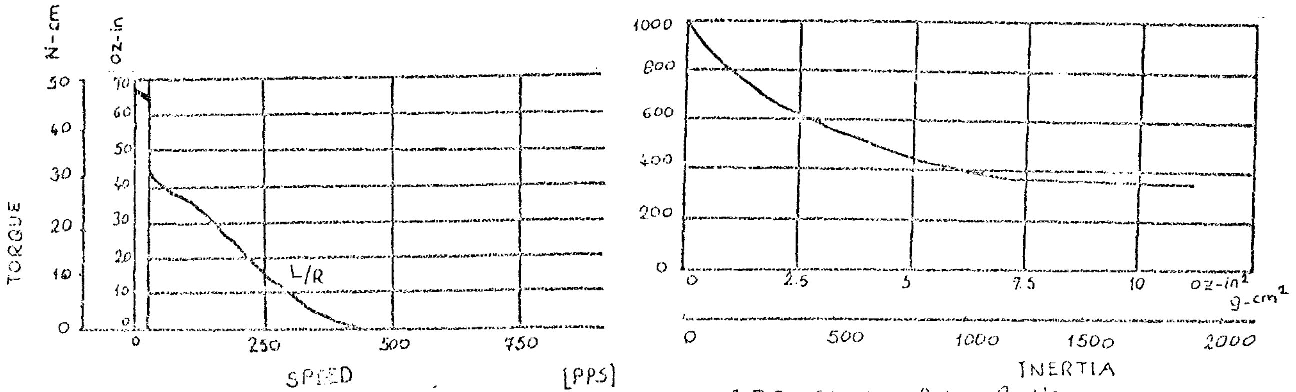
Figure 3.5. Cross-section of a hybrid motor perpendicular to the shaft.

each winding (phase) is situated on four of the eight stator poles; winding A is placed on poles 1,3,5,7 and winding B is on poles 2,4,6,8. Succesive poles of each phase are wound in the opposite sense, e.g. if winding A is excited by positive current the resultant magnetic field is directed radially outward in poles 3 and 7, but radially inward in poles 1 and 5. A similar scheme is used for phase B and the situation for the whole machine is summarized in Table 3.1.

Winding	Current Direction	Direction of pole Radially outward	magnetic field Radially inward
A	Positive	3,7	1,5
A	Negative	1,5	3,7
B	Positive	4,8	2,6
B	Negative	2,6	4,8

TABLE 3.1. Position pole magnetic field.

Hybrid motor is a natural choice for applications requiring a small step length and high torque in a restricted working space. Therefore, in the designed system, hybrid stepping motor is selected. The step angle of the selected hybrid motor is 1.8^{o} and it is 2-phase full-step hybrid motor. Characteristics curves of the hybrid motor are shown in Figure 3.6, and some specifications are given in Table 3.2 [AC], [OR].



S.P.R.: Starting Pulse Ratio.

Figure 3.6. Characteristics curves of PH 265-03 hybrid motor;
a) Speed v.s.Torque char. b) Inertia v.s.S.P.R. char.

Motor Type	Voltage	Current per phase	Holding Torque		Resistance per phase	Inductance per phase
Single shaft	V	A/phase	oz-in	N-cm	ohm/phase	mH/phase
PH265-03	24	0.21	58.3	41.2	114	14.4
Rotor inertia : 0.6 oz-in^2 (110 g-cm^2), Weight : 1.2 lbs (0.54 kg)						

Table 3.2. Specifications of PH 265-03 stepping motor.

3.2.2. Drive Circuit

The control signals for a stepping motor system are invariably low power, e.g. TTL digital integrated circuits provide 5V at 18 mA, whereas a typical variable-reluctance stepping motor giving a torque of 1.2 Nm has a rated winding excitation of 5V and 3A. Therefore if the drive circuit is based on conventional bipolar junction transistor switches, the controller must be interfaced to the motor via several stages of switching amplification [AC].
There are two types of drive circuits:
(i) Unipolar Drive Circuit and (ii) Bipolar Drive Circuit.

3.2.2.1 Unipolar Drive Circuit

A simple unipolar drive circuit suitable for use with a three-phase variable-reluctance stepping motor is shown in Figure 3.7. Each phase winding is excited by a separate drive circuit, which is controlled by a low-power phase control signal.

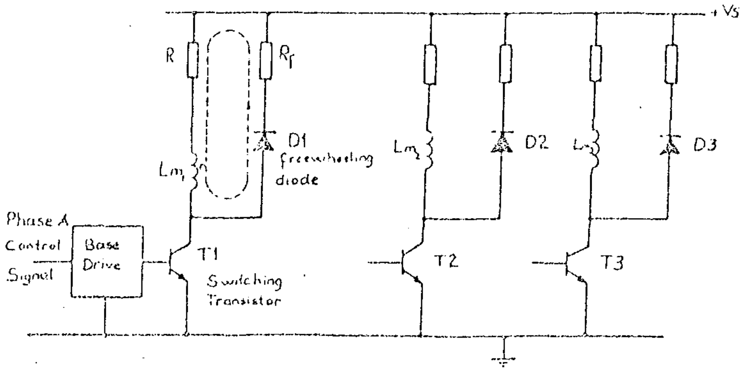


Figure 3.7. Three-phase unipolar drive circuit.
(---------freewheeling current path).

This control signal may require several stages of switched amplification before it attains the power level required at the base of the phase transistor.

The phase winding is excited whenever its switching transistor is saturated by a suffeciently high base current. Under these conditions the full d.c. supply voltage is applied accross the series combination of phase winding and forcing resistance, since the voltage drop across the saturated transistor is small (typically o.1 V). The d.c. supply voltage (V_S) is chosen so that it produces the rated winding current (I) when applied to the total phase circuit resistance, which is equal to the sum of the phase winding (r) and forcing (R) resistances:

$$V_S = I(r+R) \qquad (3.1)$$

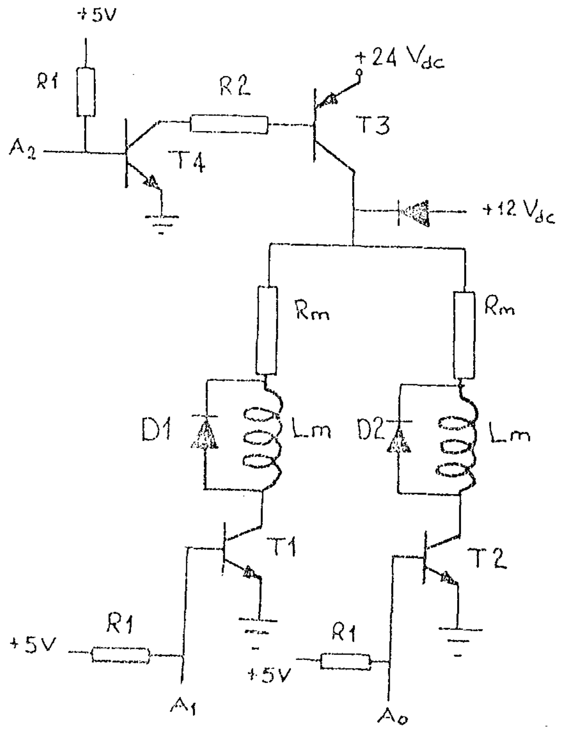
In general the phase winding has a considerable inductance, so its natural electrical time constant (L/R) is long. The build-up of phase current to its rated value would be too slow for satisfactory operation of the motor at high speeds. By adding the forcing resistance, with a proportional increase in supply voltage, the phase electrical time constant can be reduced, enabling operation over a wider speed range.

Another consequence of the finite phase winding inductance is that the phase current cannot be switched off instantaneously. If the base drive of the switching transistor was suddenly removed a large induced voltage would appear between the transistor collector and emitter, causing permanent damage to the drive circuit. This possibility is avoided by providing an alternative current path-known as the freewheeling circuit--for the phase current. When the switching transistor is turned off the phase current can continue to flow through the path provided by the freewheeling diode and freewheeling resistance.

delivered to the load. Stepping motor drive circuit accepts sequence signals from sequencer and converts them to the proper format for driving the motor windings.

Since the motor rotates in response to a changing pattern of interactions between the rotor magnetic field and the stator magnetic field, a sequencer which creates the proper sequence should be designed. The outputs of the sequencer will be the inputs of the drive circuit. The sequencer is explained in th following section.

In the designed system, a maximum of 1500 mm/min feedrate is desired. This corresponds to 500 steps/sec or 150 rev/min or 2.5 rev/sec. The stepping motors used in the system have 1.8^0 step angle. This means 200 steps per revolution. That is, one revolution of the motor will create 200x0.05 mm(=10 mm) linear motion. The designed drive circuit is shown in Figure 3.9 satisfy the system torque and speed requirements [BRE].



R1=450 Ω
R2=110 Ω
Rm=8 Ω
T1,T2=MJE 3055
T3=MJE 2955
T4=BC 237
D1,D2,D3=MR 1386

Figure 3.9. Designed drive circuit for steping motor

The phase current if is established at its rated value then the maximum voltage ($V_{ce\,max}$) across the switching transistor occurs in the instant after the transistor switch is opened. The current (I) has not started to decay and flows through the freewheeling resistance (R_f), so the maximum collector-emitter voltage (neglecting the forward voltage drep across the frewheeling diode) is:

$$V_{ce\,max} \approx V_s + R_f I \quad (3.2)$$

The phase current therefore decays in the freewheeling circuit and the magnetic energy stored in the phase inductance at turn-off is dissipited in the freewheeling circuit resistance (winding+forcing+freewheeling) resistances [AC], [OZ], [OR].

3.2.2.2. Bipolar Drive Circuit

One phase of a transistor bridge bipolar drive circuit, suitable for use with a hybrid or permanent-magnet stepping motor, is shown in Figure 3.8. The transistors are switched in pairs according to the current polarity required. For positive excitation of the phase winding transistors T1 and T4 are turned on, so that the current path is from the supply, through transistor T1 to the phase winding and forcing resistance, then through transistor T4 back to the supply. In the opposite case the transistors T2 and T3 are turned on so that the current direction in the phase winding is reversed.

The four switching transistors in the bridge require separate base drives to amplify the two (positive and negative) phase control signals. In the case of the 'upper' transistors (T1 and T2) the base drive must be referred to the positive supply rail, which may be at a variable potential. For this reason the phase control signals to these upper base drives are often transmitted via a stage of optical isolation.

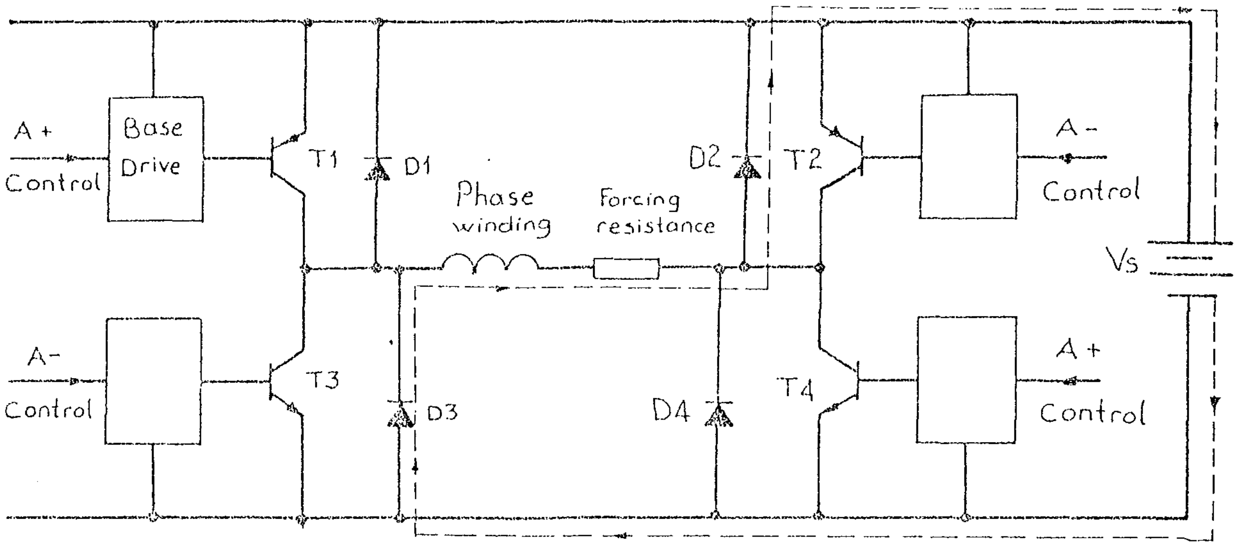


Figure 3.8. One phase of a transistor bridge bipolar drive circuit (-------- freewheeling current path after T1 and T4 turn off).

A bridge of four diodes, connected in reverse parallel with the switching transistors, provides the path for freewheeling currents. In the illustration of Figure 3.8. the freewheeling current path, via diodes D2 and D3, corresponds to the situation immediately after turn-off of transistors T1 and T4. The freewheeling path includes the d.c. supply and therefore some of the energy stored in the phase winding inductance at turn-off is returned to the supply. The consequent improvement in overall system efficiency represents a significant advantage of the bipolar bridge drive over the unipolar drive and for this reason most large (greater than 1KW) stepping motors, including variable-reluctance types, are operated from bipolar drive [NG] ;[AC].

In the designed system, unipolar voltage drive circuit is selected. This is a simple method of driving stepping motors. However, this type of driver with selected component values can give the required torque and the speed of the designed system.

Drive circuit design is one of the most important aspects of a stepping motor system. The overall system performance is heavily dependent upon the drive system, not only on the power

3.2.3. Sequencer

The sequencer creates the proper sequence and pattern of states in response to a serial pulse train. Microcomputer generates this serial pulse train and this created proper sequence (by the sequencer) is fed to the drive circuit to make the motor rotate.

A sequencer has two inputs and four outputs. Its inputs are the direction and the pulse inputs. 0V or 5V is given to the direction input to determine the direction of the motor rotation. Each pulse given to the pulse input makes the motor rotate one step in the determined direction. The outputs of the sequencer are used in switching of the drive circuit to energize the windings in proper sequence. The designed sequencer circuit and its output waveform are shown in Figure 3.10 [MA].

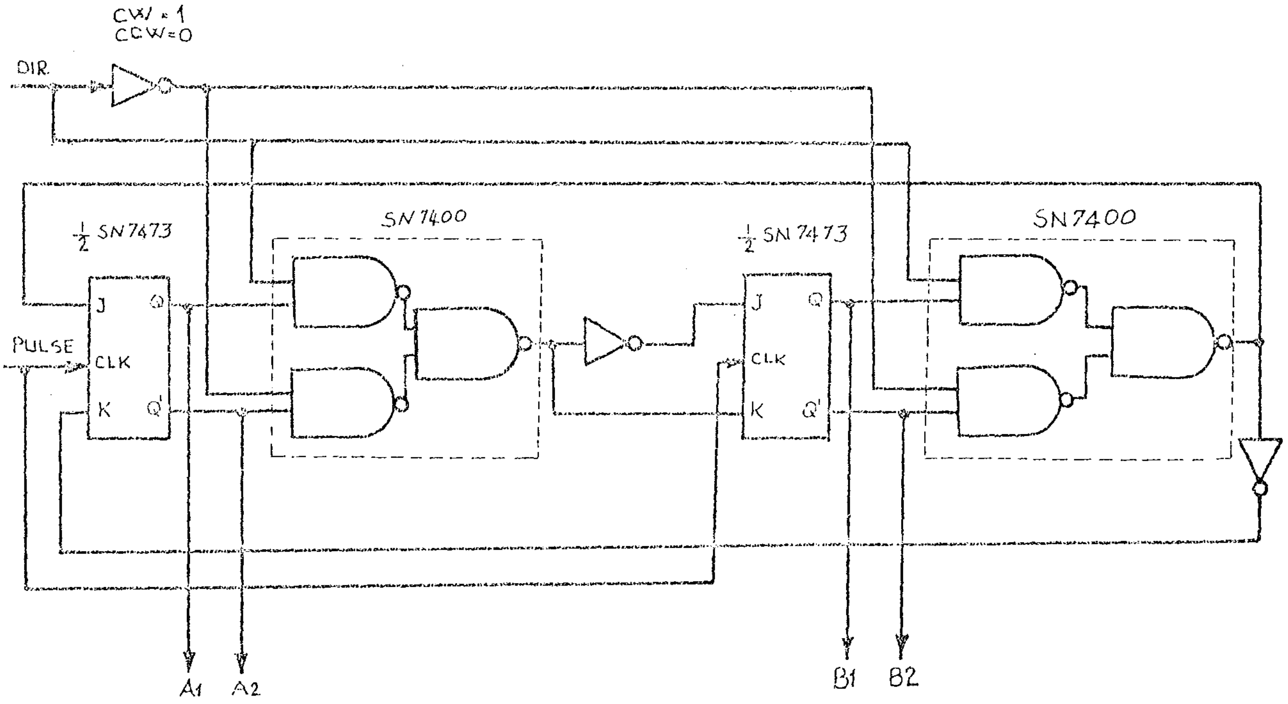


Figure 3.10. a) Sequencer.

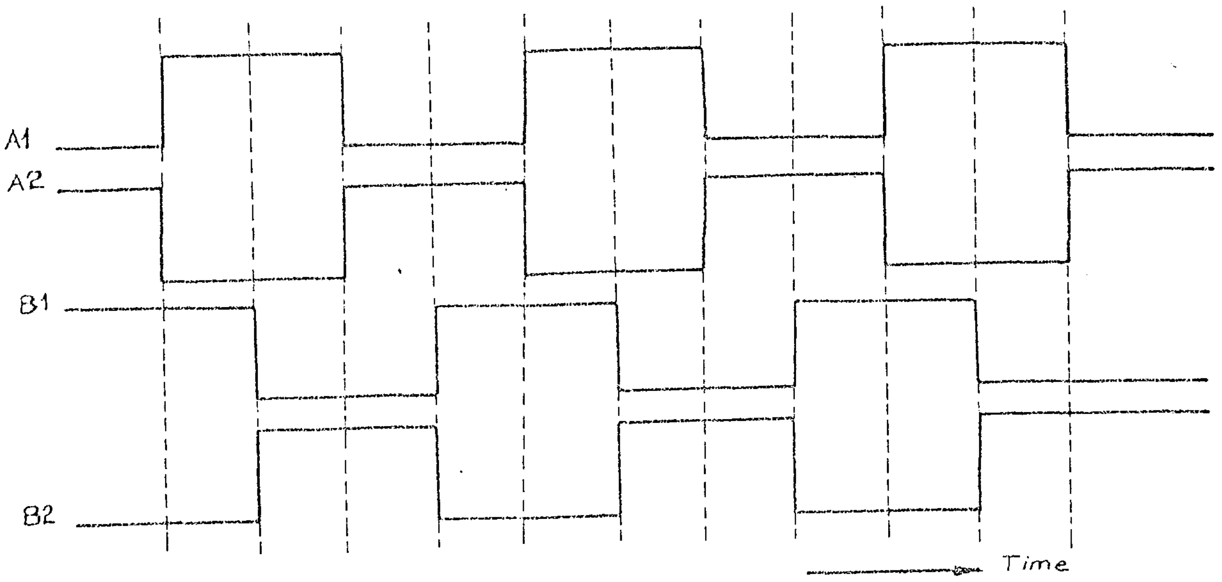


Figure 3.10. b) Output of sequencer

3.2.4 Position Transducer

Position transducers are explained as incremental and absolute devices separately.

3.2.4.1 Digital Incremental Position Transducers

The digital methods of controlling machine tools depend upon the generation of a series of pulses by the motion of the table. These pulses are generated either by rotary or linear position transducers.

In Incremental Rotary Devices, electromechanical methods, using springs or brushes to sweep the conducting and nonconducting areas on a disc, for scanning are rarely used nowadays because of their tendency to faulty operation. The most common method of generating electrical pulses is by the variation of the intensity of light falling on a photocell. A disc called digitizer, having equally spaced, alternate opaque and transparent segments suits for this purpose as shown in Figure 3.11a. The digitizer is placed between a light source and a photocell in which a flow of current is induced, as shown in Figure 3.11b.

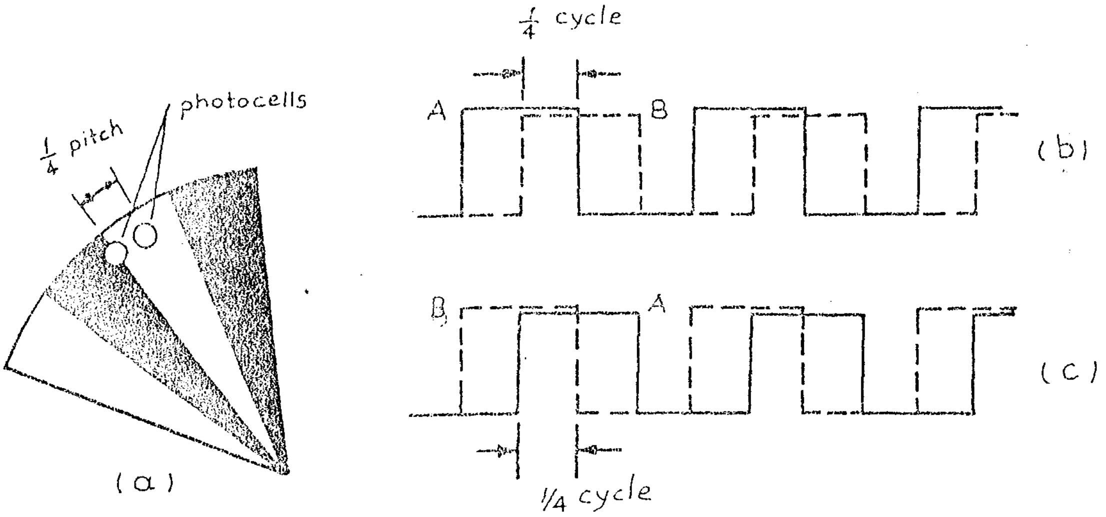


Figure 3.12. Photocells and their outputs;

a) Positioning of two photocells,

b) Outputs of photocells A and B in clockwise rotation.

c) Outputs of A and B in counter clock wise rotation.

Another way to determine the direction of rotation would be to code the digitizer specially and place the photocells as shown in Figure 3.13. In clockwise rotation after they are both illuminated, A will close while B receives light, whereas in opposite direction both will be dark, as illustrated in Table 3.3.

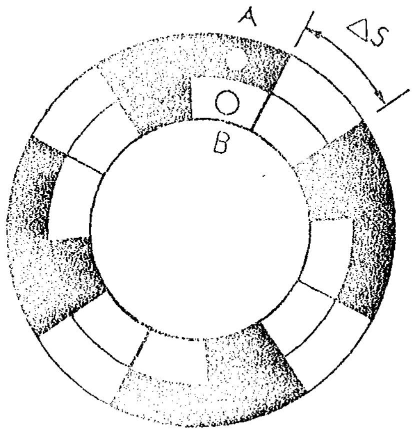


Figure 3.13. Coded digitizer.

Thus a logic circuit may easily detect the direction of rotation.

Clockwise rotation		Counterclockwise rotation	
A	B	A	B
1	1	1	1
0	1	0	0
0	0	0	1
1	1	1	1

1:Illuminated
0:dark

Table 3.3. Photocells according to direction of rotation.

In incremantal Linear Devices, it is again not practical to use electromechanical (by brushes and segments) or inductive scanning for small displacement elements "ΔS", which is the case in machine tool practice. Therefore uncoded linear scales are best scanned by photoelectric means either by transmitted light method or reflected light method.

In the first method a linear scale, consisting of a glass plate upon which a number of equispaced lines are engraved, is fixed to the slide with a light source and a photocell on either side. The number of lines determines the accuracy obtainable and the process is similar to that of a rotary system. Another possibility is to introduce an auxiliary grating and making use of Moire Fringes to determine the passage of lines more easily.

As illustrated in Figure 3.14, the lines on both gratings are spaced by ΔS, and rotation of the auxiliary grating by "S" produces a Moire Fringe Pattern. One of the gratings is fixed while the other is connected to the slide. Depending on the direction of motion of the machine slide, the fringes will appear

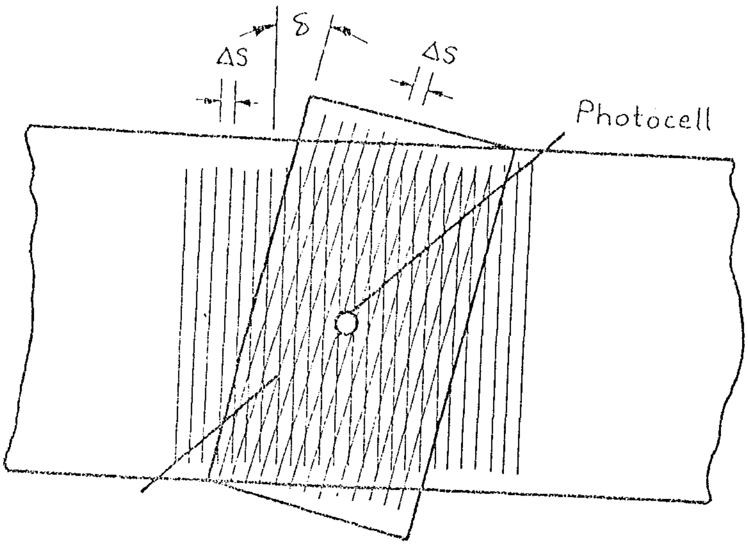


Figure 3.14. Moire Fringes with an auxiliary grating.

to move either upward or downward. The intensity of light seen by the photocell will vary sinusoidally, as the gratings are moved relative to each other. The sinusoidal output of the photocell is either counted directly or a phase comparison method may be used to determine the distance travelled.

The reflected light method bears the same principle, with the difference that instead of a glass scale it utilizes polished stainless steel scale on which the light is reflected. Though this method has the advantage that the easily broken, dirt attracting glass scale is avoided, it requires a complicated optical system. In addition to that it has a less optical resolution, due to the increased spacing of the graduations for reliable operation[I].

3.2.4.2 Digital Absolute Position Transducers

To measure the position absolutely relative to a predetermined datum, in addition to the incremental grating track with the $2^0 x\Delta S$ grating, further tracks with binary gratings $2^1 x\Delta S$, $2^2 x\Delta S$, $2^3 x\Delta S$ etc. are introduced. However, each track is considered separately and scanned by different scanners. Again photoelectric scanning is found to be more suitable due to the previously stated reasons.

In absolute rotary devices, the digitizer disc may be constructed to give a binary output. It is then said to be encoded. Figure 3.15 shows segments that will give the decimal digits 0 to 9 in the binary code. The subdivision ΔS of the disc determines the resolution obtainable. Errors in the scanning of the encoded disc are possible due to slight misalignment or to the ambiguity of signal when the disc comes to rest, with the scanner on an edge potition . An alternative scan may be used with two sets of photocells displaced on the disc, the two outputs being sorted out by logic circuitry. Several alternative codes may also be used, of which the Gray Code is popular as shown in Figure 3.15b. In this code there is only one transition point for each change of digit.

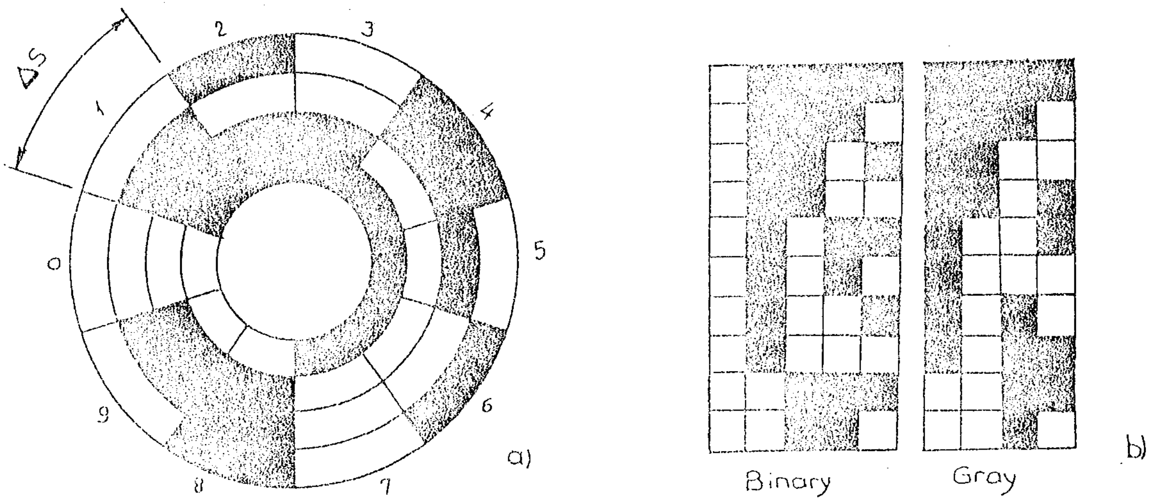


Figure 3.15. a) Absolute digitizer and b)Codes.

Rotary discs are either made by increasing the number of tracks and employing precision gearing in their connection to the appropriate elements (however scanning becomes more complex and expensive) or connected to each other by gearing as shown in Figure 3.16 and zonal scanning is used[I].

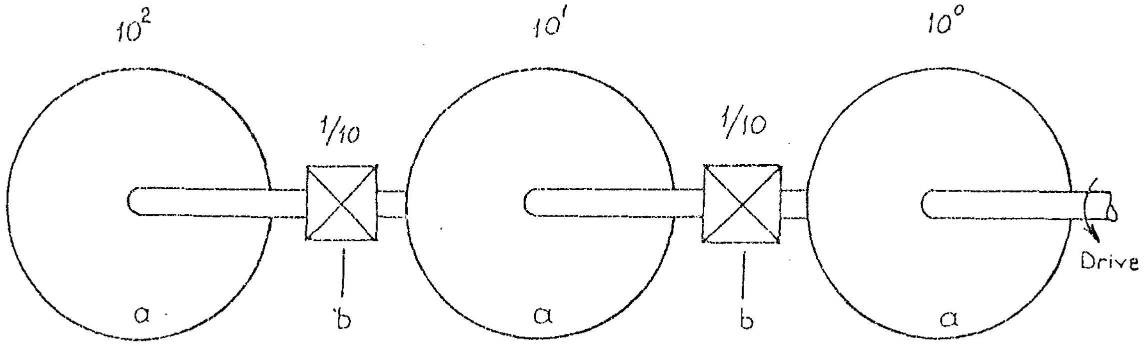


Figure 3.16. Zonal scanning of binary coded discs;
a : Code discs as in figure 3.15a,
b : Gearing with 1:10 ratio.

In the abolute linear devices, to determine the position of the machine slide directly, coded linear scales are desirable. However the cost of producing these scales is very high due to the following reasons:

a) displacement elements "ΔS" are very small,
b) large number of tracks are required,
c) precautions are needed to ensure accurate scanning, etc.

In the designed system, because of accuracy the linear incremental digital position transducers are used.

3.3. Interfacing of the system with the Microcomputer.

As previously explained, the microcomputer will generate two signals (one direction and one pulse signal) for each motor sequencer. It should also take the positional feedback information from position transducers. There are three positional information, they are taken from x,y, and z axes. Microcomputer should be informed about whether the table is going in the positive or in the negative direction in any axis. It takes totally 2 bits feedback signal.

The position transducers which convert the positional information into voltage form using only the logic levels 0 and

1(OV and 5V). It is an incremental transducer. It also gives the direction of the movement. The physical position values are determined by software counts of taken incremental values.

In general, the winding of stepping motors may be adjusted to different impedance levels to trade voltage for current. Rising rate of current in a winding is proportional to V/Lm, so that higher voltages will yield better high-speed performance generally. It is not unusual for the source voltage for pulse initiation and termination to be 10,20 or 30 times the steady state motor voltage. There are some methods for control of this 'overdrive' voltage so as to limit steady state current to correct value[OZ].

As mentioned earlier, the control system is designed for linear motion in three dimensions. The system programs are written for this purpose. Motion along any counter can be traced by suitably dividing it into linear sections and a master program can be written to do this. Note that such a master program will require additional memory space and care must be taken so that the additional calculations can be done in the available interval.

The linear motion between the given two points can be traced in different manners. The point to point control method is selected. This is one of the reliable and simple methods.

In this method, at the beginning point of the motion, one step is taken in the x direction, then the calculation is done to find the corresponding y coordinate and this y coordinate is reached by taken steps in y direction. When this y coordinate for the physical (actual) x coordinate is obtained, one more step is taken in x direction. This continues until the destination point is reached. As it is noticed, only one directional motion is done at a time.

Movement in x direction is always one step. This corresponds to the accuracy tolerance as explained earlier. If the calculated y coordinate for the physical x coordinate is not a multiple of 0.05 mm(one step), then the largest of the multiples of 0.05 mm which is smaller then this y value is taken.

CHAPTER IV

SOFTWARE OF THE SYSTEM

4.1. Software Specifications

Logic of the system software is as fallows:

The coordinates and feedrate are entered from keyboard by the operator in the decimal form which are converted to the hexadecimal form and so, all the operations and calculations are done in this form. The entered data, coordinate or feedrate, which is not permissible for the system is not accepted by the software. The coordinates of the line between the given two points is determined, its parameters are calculated. The delay routines are adjusted by the entered feedrate to make it possible to achieve the required pulse frequency which is given to the control circuits of the motors. This pulse frequency determines the speed of the motors and, indirectly, the feedrate. Therefore, this pulse frequency is obtained by adjusting the delay duration through which microcomputer passes in the loop. The microcomputer takes the physical (actual) positional data from position transducers and compare them with the ideal ones which are calculated from the line equation and determines the control signals for the rotations of the motors [DA].

4.2. Basic Functions

The four basic arithmetic operations, addition, subtraction, multiplication and division are used in the system software.

Since they are used many times in the system program, they are developed and organized as subroutines. Three subroutines are written for these four basic arithmetic operations. These are:

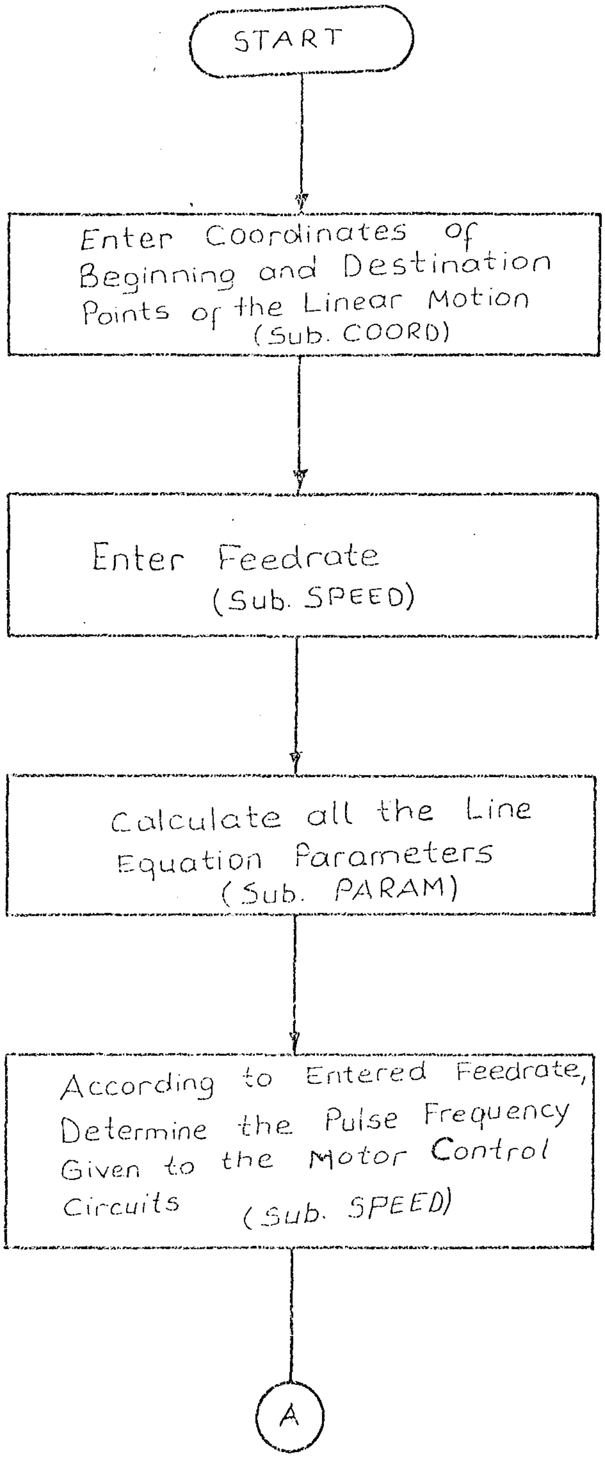
ADDSUB: This subroutine performs the addition of two 3 byte length signed binary numbers to give a result of 3 byte length signed binary number. If the second number has a minus sign then the operation will be the subtraction.

MULT: This subroutine multiplies the two 4 byte length signed binary numbers. As a result it gives a 4 byte length signed binary number.

DIVI : This subroutine divides a 2 byte length binary number to another 2 byte length binary number. The result of the division consists of 4 bytes. Right most 2 bytes give the fractional part of the result[F].

4.3. Main Program

Since the programs related to some system functions are written as subroutines, the main program generally is constituted of calling some subroutines. As it is seen from Figure 4.1, at the beginning, the main program calls COORD subroutine for accepting the beginning and destination point coordinates. Calling the subroutine SPEED makes the enterence of feedrate possible. The subroutine PARAM calculates the line equation parameters. Ideal Y- coordinate is calculated by calling the subroutine YID using the line equation parameters. The output from microcomputer to the control circuits of the motors is done by calling the subroutine OUT. Transferring the positional information from potision transducers to microcomputer is done by the subroutine INPUT. The determination of whether the entered destination point is reached or not is done by the subroutine OKEY.


START
Enter Coordinates of Beginning and Destination Points of the Linear Motion (Sub. COORD)
Enter Feedrate (Sub. SPEED)
Calculate all the Line Equation Parameters (Sub. PARAM)
According to Entered Feedrate, Determine the Pulse Frequency Given to the Motor Control Circuits (Sub. SPEED)
A

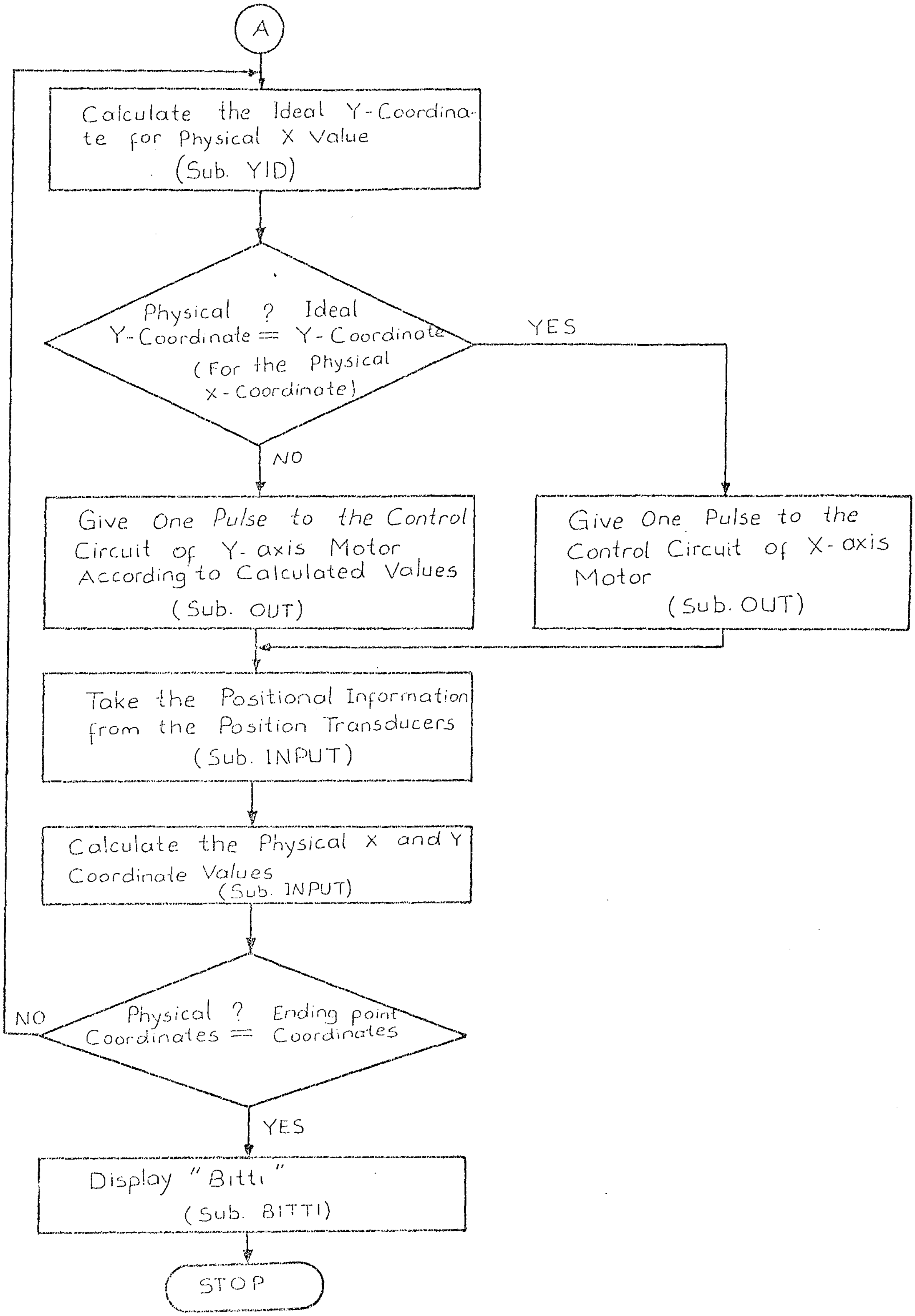


Figure 4.1. Flowchart of main program.

If the destination point is reached then the subroutine BITTI indicates this by displaying "Bitti" on seven segment displays. Otherwise, the main program calls the subroutine YID once more and goes on as it is seen from the flowchart in Figure 4.1. In the following sections, brief flowcharts and explanations of these subroutines are given. The main program and these subroutines written in Assembly Language are given in Appendix B.

4.4. Subroutines

In this section the subroutines called by the main program will be considered one by one. Their logic and flowcharts will be given in the simplified form [DA].

These subroutines are: COORD, SPEED, PARAM, YID, OUT, INPUT, OKEY, BITTI.

4.4.1. COORD Subroutine

This subroutine makes possible the enterence of the beginning and destination point coordinates of the linear motion, (X1,Y1) and (X2,Y2), respectively, from the keyboard. First "HI=" is displayed on the seven segment displays which is corresponded about Z axis. Z-axis is independent of X and Y axes. The data is entered to microcomputer in decimal form. After enterence of data in decimal form, microcomputer converts this into hexadecimal form. The flowchart about this subroutine is shown in Figure 4.2.

4.4.2 SPEED Subroutine

Like the subroutine COORD, this subroutine makes the enterence of feedrate from the keyboard possible. As explained before, it does not accept the feedrate values which are out of the range of the system. If the entered feedrate value is in the permissible range, i.e. valid data, then this entered decimal data value is converted into the hexadecimal form as shown in Figure 4.3. This subroutine also adjusts the variables of delay routines. These routines are adjusted according to the entered feedrate value. They adjust time delays between the pulses given to the motor control circuits to get the desired speed of the motor.

4.4.3 PARAM Subroutine

This subroutine calculates and finds the slope and constant term of the line equation on which the ideal motion takes place. These two calculated values are used in the subroutine YID. Its flowchart is given in Figure 4.4.

4.4.4. YID Subroutine

Since the system is a closed loop control system, a feedback is taken from the position of the table and according to this feedback new decisions are done. In system, for the physical (actual) x coordinate, the desired y coordinate should be known. Subroutine YID calculates ideal y coordinate (YID) for any x coordinate value It uses the slope (M) and constant term ($Y1-M\times X1$) of the line, on which the ideal motion takes place, which is calculated in subroutine PARAM. The flowchart of YID is given in Figure 4.5.

4.4.5. OUT Subroutine

At the control of the motion, after the comparison between the physical and ideal coordinates, some pulses should be produced to the motor control circuits. The main aim of this subroutine is to produce these pulses. Each pulse given to the pulse input of the sequencer makes the motor take one

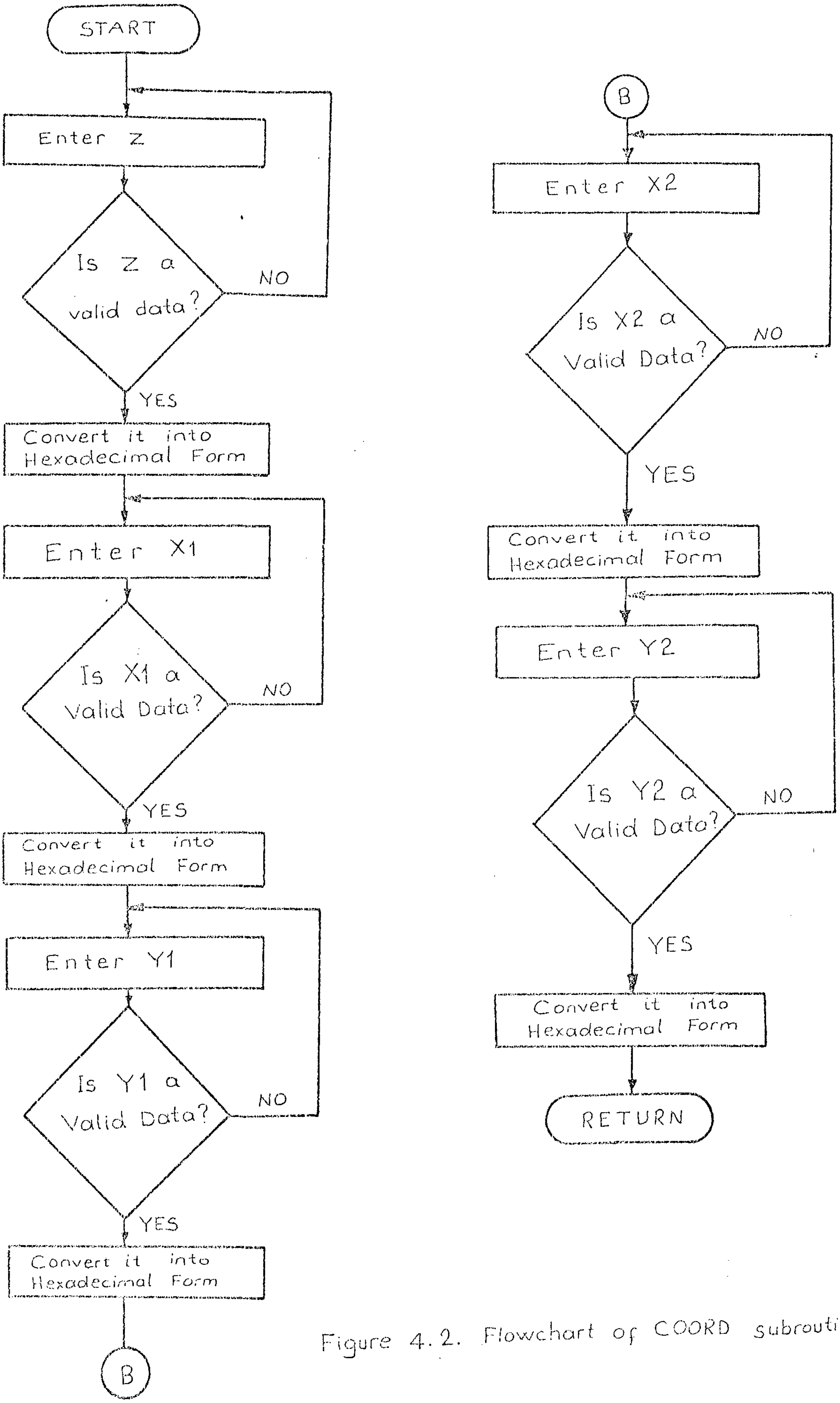


Figure 4.2. Flowchart of COORD subroutine.

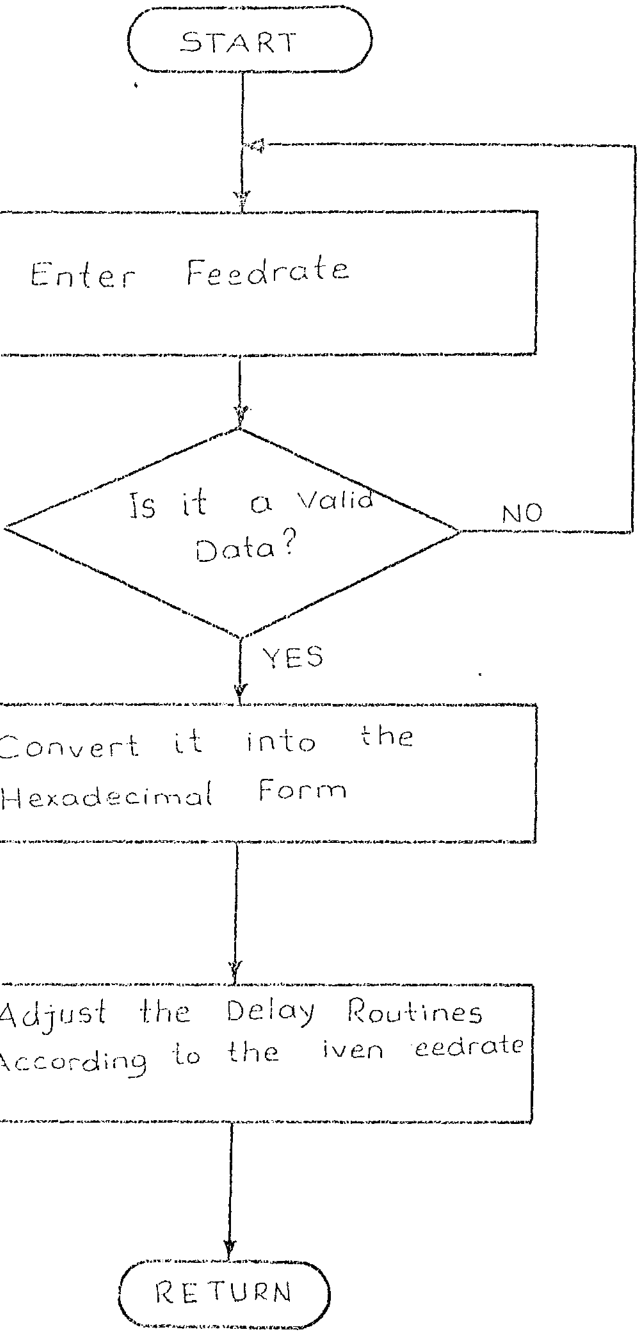


Figure 4.4. Flowchart of SPEED subroutine.

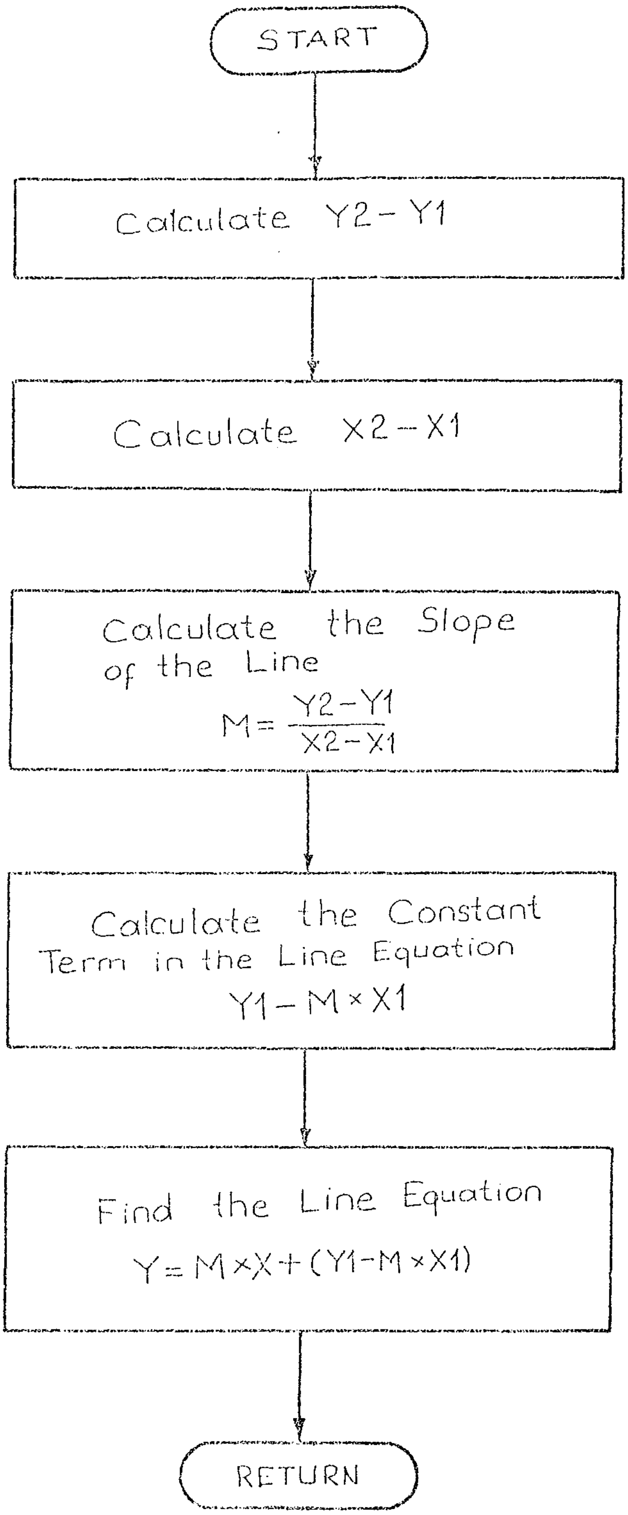


Figure 4.3. Flowchart of PARAM subroutine.

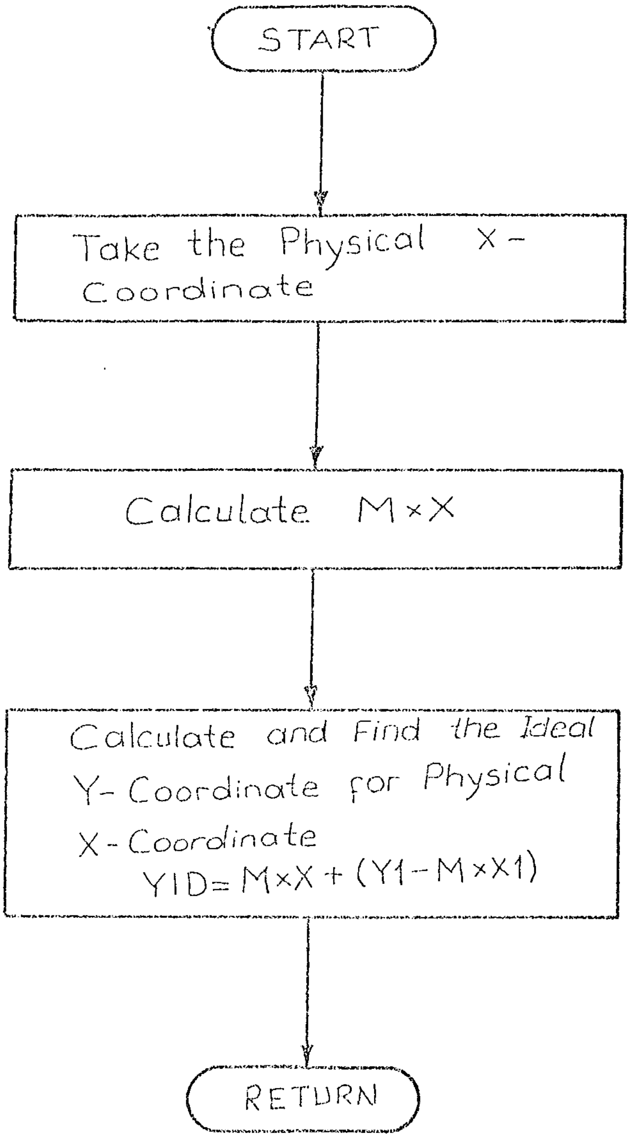


Figure 4.5. Flowchart of YID subroutine.

step in the determined direction by the sequencer direction input. For a given x coordinate, this subroutine compares physical (YAC) and ideal (YID) y coordinates. As a result of this comparision, it generates the required pulses to the motor control circuit to make the physical y coordinate equals to the ideal y coordinate. If they are equal, then it brings the x coordinate to its next value. The flowchart of this subroutine is shown in Figure 4.5.

4.4.6 INPUT Subroutine

In the closed loop control system, a feedback always exists. The purpose of this subroutine is to produce this feedback so that the ideal position of the table could be continuously checked with the current position defined by subroutine OUT. It takes positional data input from position transducers and determines which data is from which transducer. By the use of this obtained incremental positional data, absolute physical x-coordinate (XAC) and y coordinate (YAC) are obtained as shown in Figure 4.7.

4.4.7 OKEY Subroutine

This subroutine determines whether the destination point of the motion is reached or not. It sets the variable OOKEY to 1 if it is reached, to 0 if not reached. This variable is checked in the main program to see whether the destination point is reached or not. Its flowchart is given Figure 4.8.

4.4.8. BITTI Subroutine

This subroutine displays "Bitti" on the seven segment displays to show that destination point of the motion is reached. Its flowchart is shown in Figure 4.9.

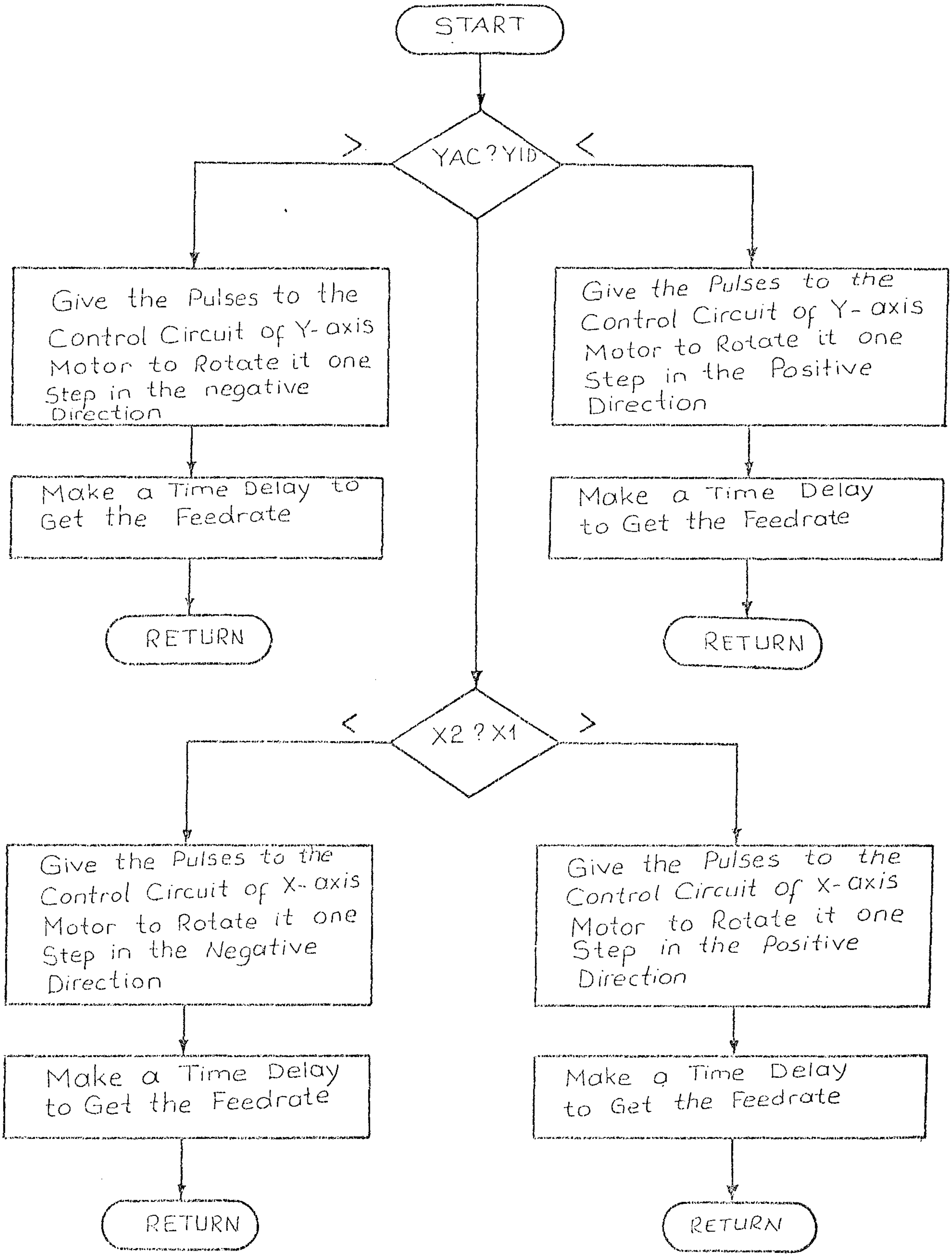


Figure 4.6 Flowchart of OUT subroutine.

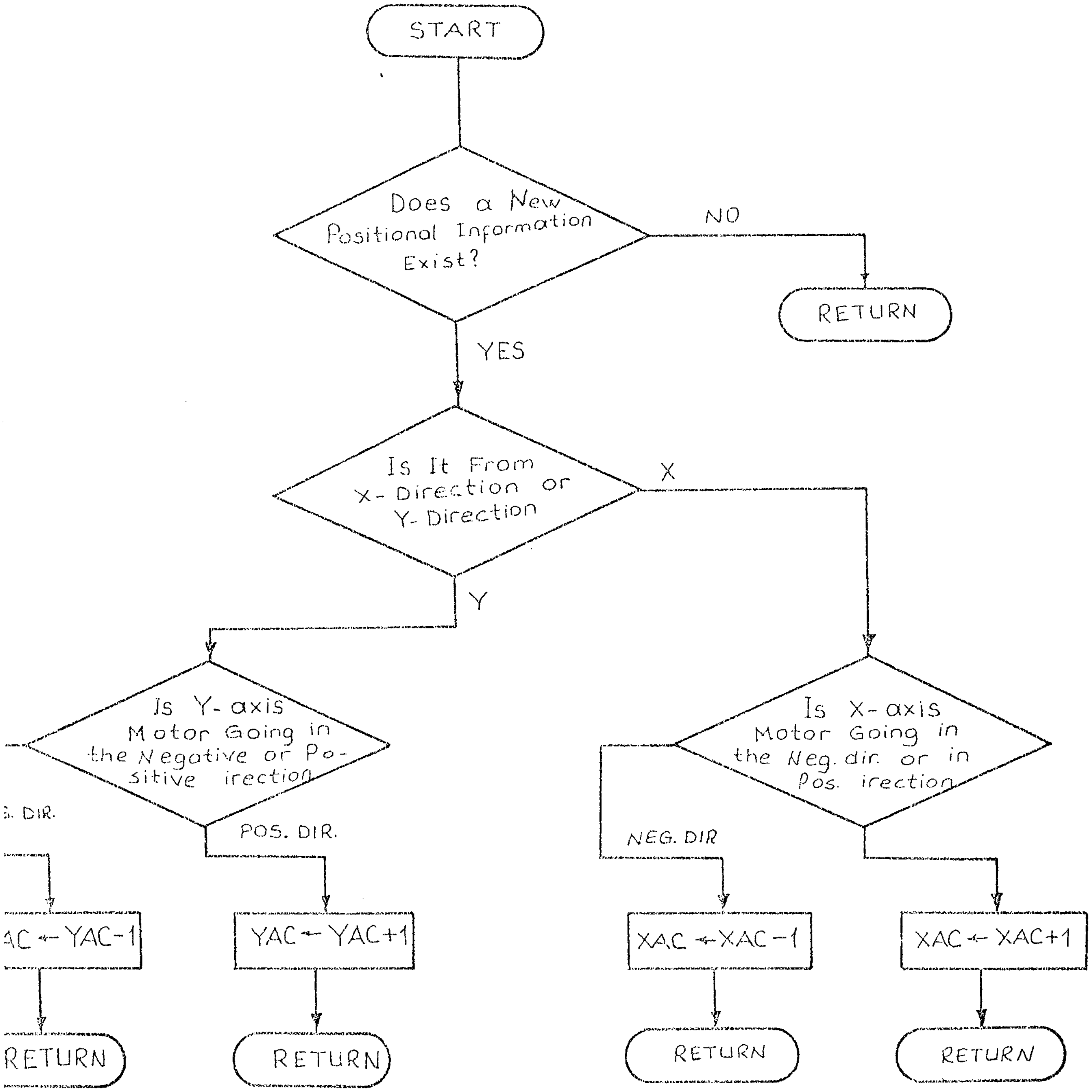


Figure 4.7. Flowchart of INPUT subroutine.

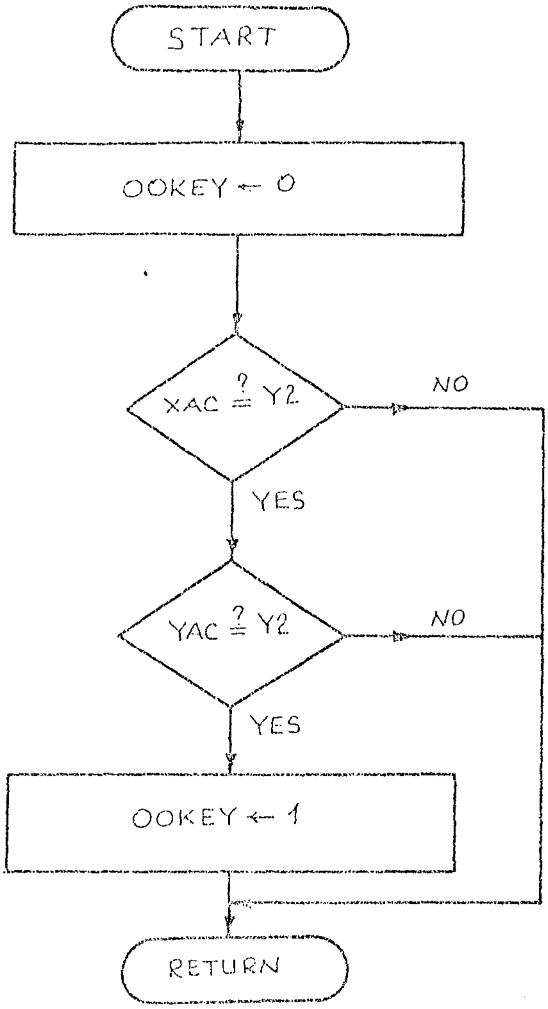


Figure 4.8 Flowchart of OKEY subroutine.

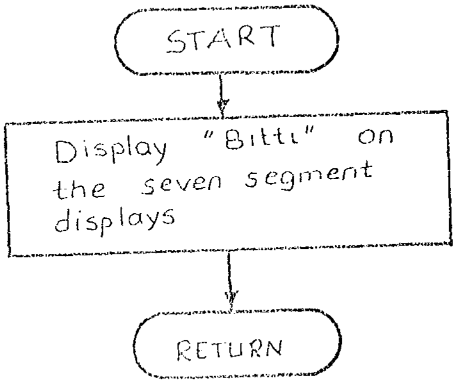


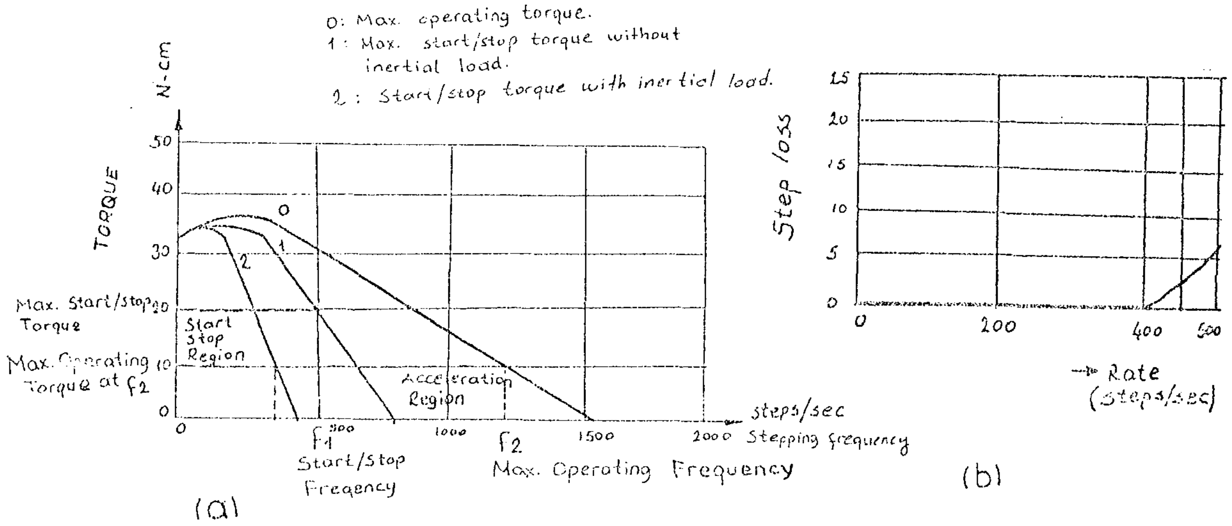
Figure 4.9. Flowchart of BITTI subroutine.

CHAPTER V

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

5.1. Testing of Motor Operations

Sequencer and drive circuits are connected to the stepping motor to test the motor operation. A square wave genarator is then used to get different rotational speeds. This is achieved by changing the frequency of the applied signal. It is observed that any rotational speed between 0 and 500 steps/sec can be reached. After this, starting and stopping performances of the motor at these speed values are also observed as shown in Figure 5.1a. In order to find out whether the motor loses any step or not, the sequencer is excited by different number of pulses at a predetermined frequency and corresponding rotation of the motor is observed. From these tests, it is seen that for the speed values up to 400 steps/sec the motor does not lose any step as shown in Figure 5.1b.



(a) (b)

Figure 5.1 Starting and Stopping Performace of Motor

However, for higher rotational speed values the motor may lose some steps while starting or stopping it. It should also be pointed out that these tests are carried out with an insufficient voltage and current values so that the drive cicuit is operated under its nominal current and voltage ratings. Its reason was the nonexistence of a well regulated dc power supply.

It is expected that the higher start-stop speed rates can be attained without losing any step if the drive circuit could be fed at its nominal ratings. On the other hand, it would be better to use higher voltage and current rating switching transistors to improve the performance, or the VMOS power field-effect transistors.

During the operation of the motor, its winding voltage and current waveforms are observed as shown in Figure 5.2.

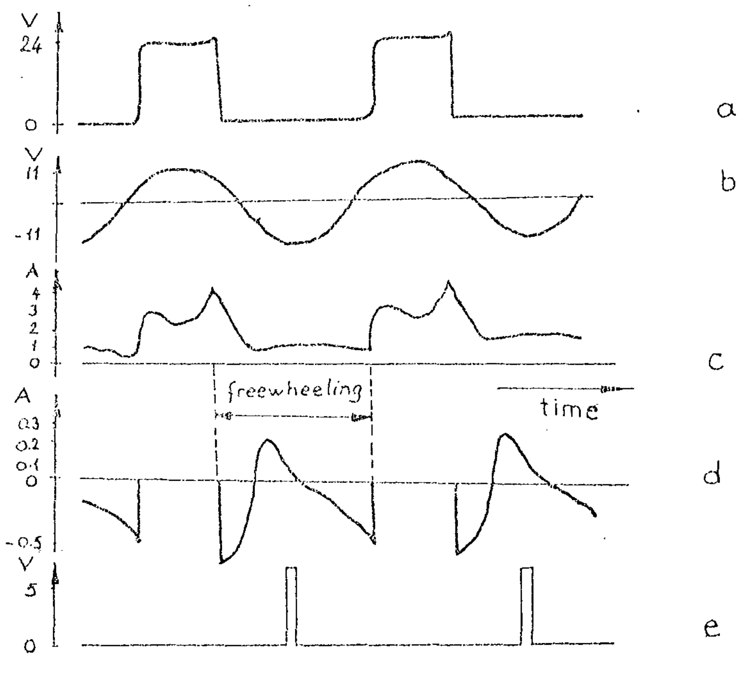


Figure 5.2. Waveforms of Phase-A Winding;

a) applied phase voltage,

b) motional voltage,

c) current waveform,

d) rate of change of freewheeling current

e) position detector pulse.

At the beginning of each pulse, there is a damped oscillation in the winding voltage. This shows that, at these points there is a mechanical damped oscillation in settling of the rotors, which is a known problem of stepping motors [AC], [FI]. These tests are done on no load conditions. When it is operated on load conditions, these oscillations would be more dominant. In future work, to reach higher speed values this fact should be taken into account. This will require a more sophisticated drive circuit.

5.2. Testing of the Linear Motion

When the beginning and destination point coordinates and feedrate are entered to the microcomputer, it generates control pulses to the sequencers for x, y, z directions. In the first stage of the test procedure, the motor is connected to the system to control the motion in x direction and x component of the linear motion is observed. For the second stage, the above procedure is repeated for y direction and y component of the linear motion is obtained.

5.3. Conclusions and Recommendations

In this thesis work, microcomputer control of linear motion of the table of a machine tool is designed, constructed and tested with the available facilities.

In tests, satisfactory operation in open loop on no load conditions is obtained up to 1300 mm/min feedrate in 0.05 mm. steps. In closed loop operation, due to damped oscillation of the motor's rotor the desired operation is not obtained.

From the above discussions it is clear that by carrying out some modifications, the closed loop performance of the system can be improved.

This work shows that such a control system can be designed and implemented to satisfy the design specifications. However, improvements in the drive circuit is essential. The software of the system, on the other hand is quite flexible therefore is suitable to be used as a building block in a more sophisticated control environments.

A master program which converts any given path into linear segments can also be written. Once the path is subdivided into linear segments, the software developed here can be used to follow these linear contour segments and thereby permitting complex contours to be followed. ALP 85 microcomputer EPROM memory region can be expanded with ease to store this master program.

The followings are recommended for future work on this topic:

- Oscillations of the rotor should be either electronically or mechanically damped for a reliable operation.
- A master program which converts any given motion path into linear segments should be written.
- EPROM memory region of the ALP 85 microcomputer should be expanded to store master program.
- Switching transistors can be replaced with VMOS field-effect transistor to improve the reliability of drive circuit.
- This work should be completed by fitting the system developed here to a proper machine tool. Some electrical and mechanical problems probably will arise when the overall system is operated with closed loop control strategy. These problems may be solved within the scope of another research work.

Operating instructions of the system are listed in Appendix C. A photograf of the system set is given in Appendix D.

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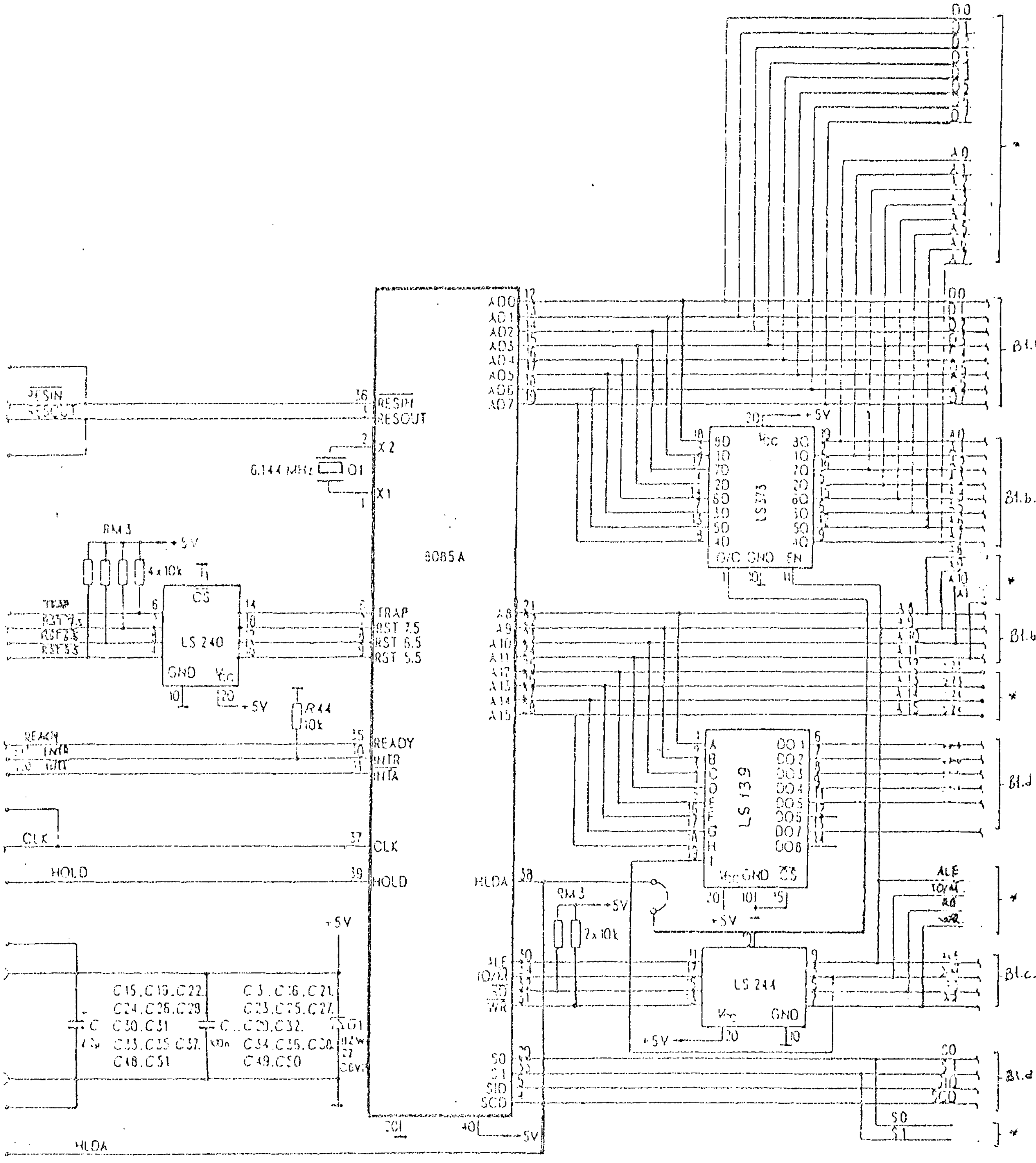
APPENDIX A

MICROCOMPUTER CIRCUITS



* connections of the user interface.

Figure A-1. Circuit diagram of ALP 85 microcomputer

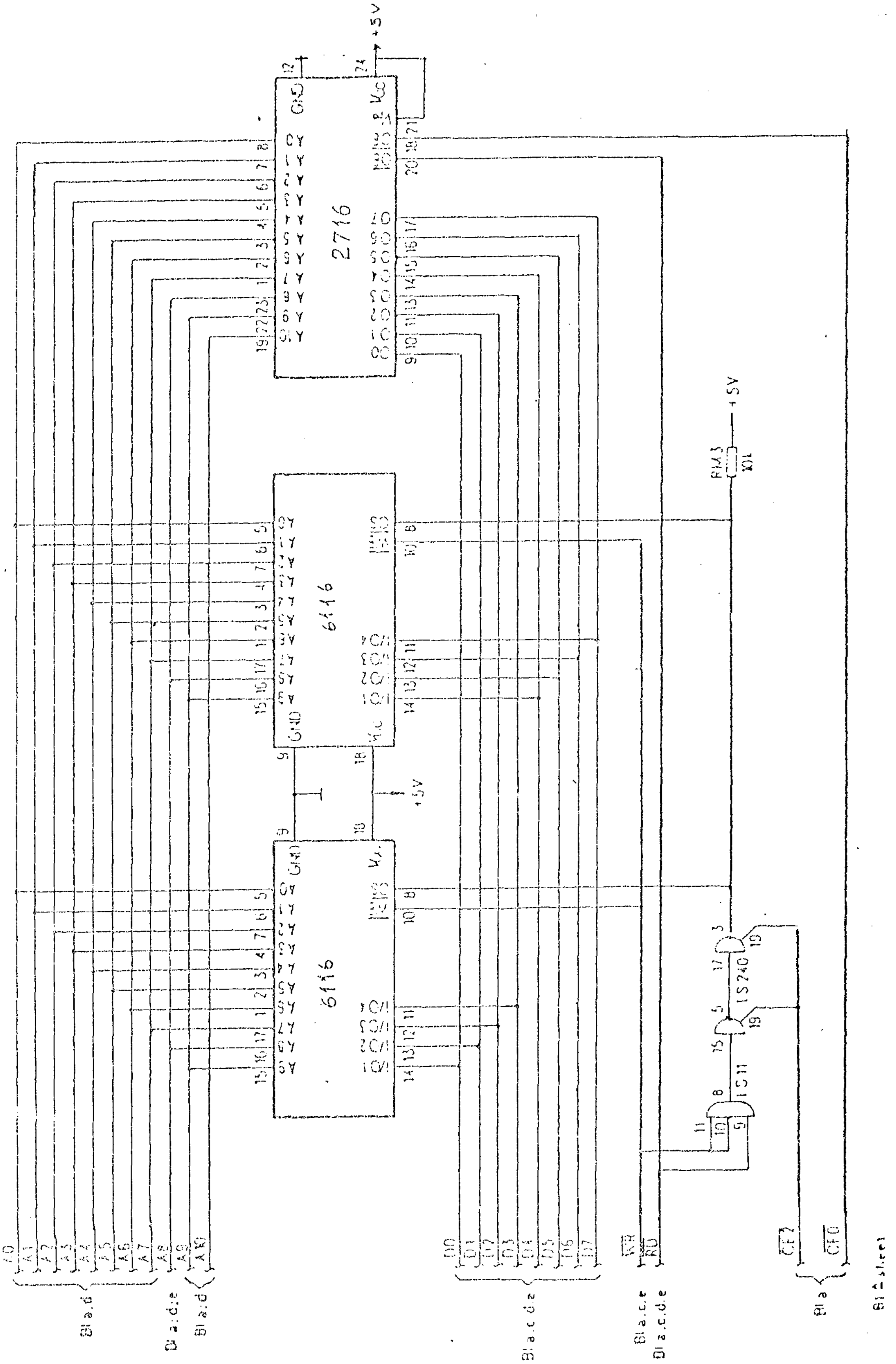


Figure A-1. Continued.

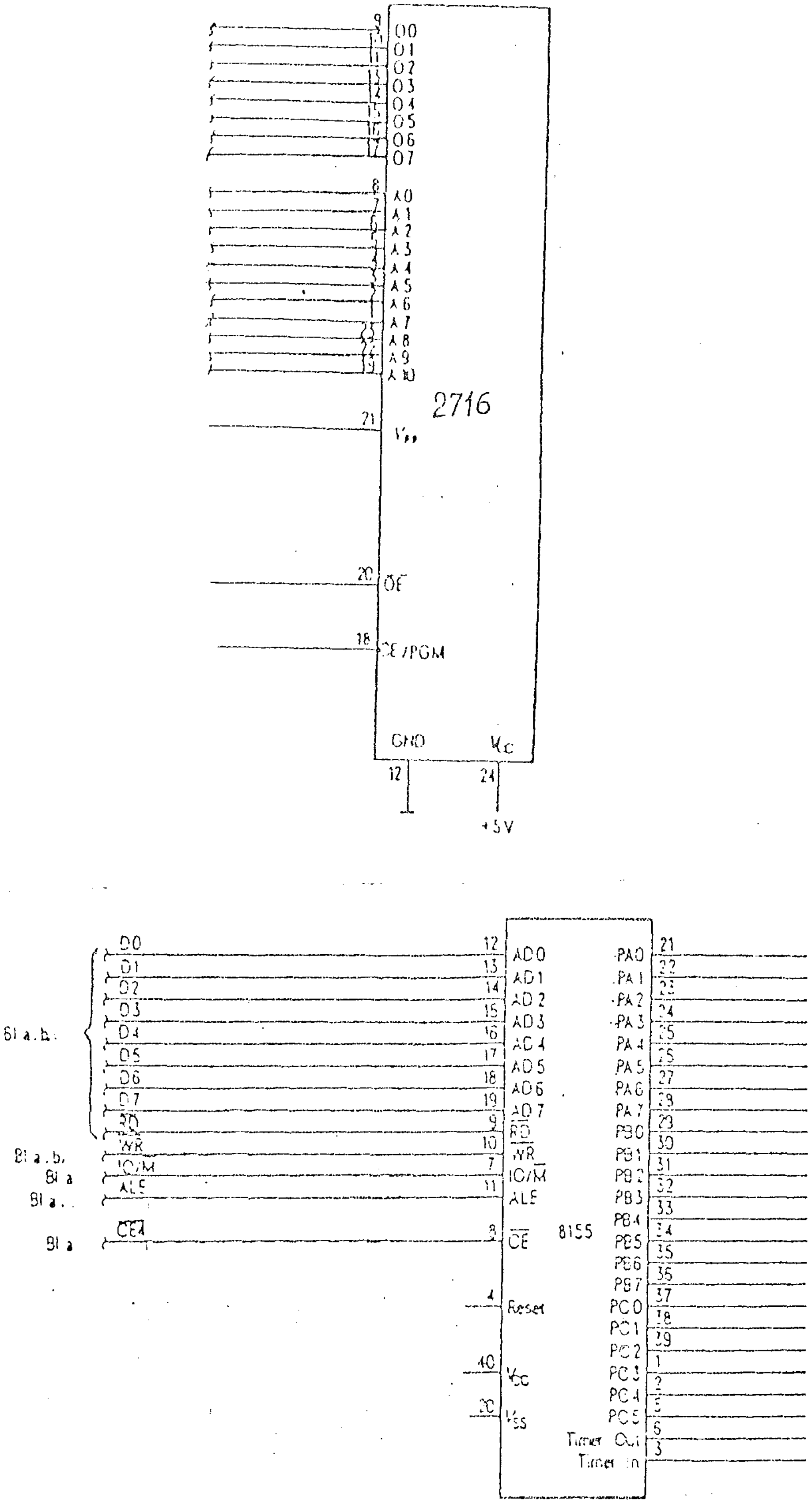


Figure A-1. Continued.

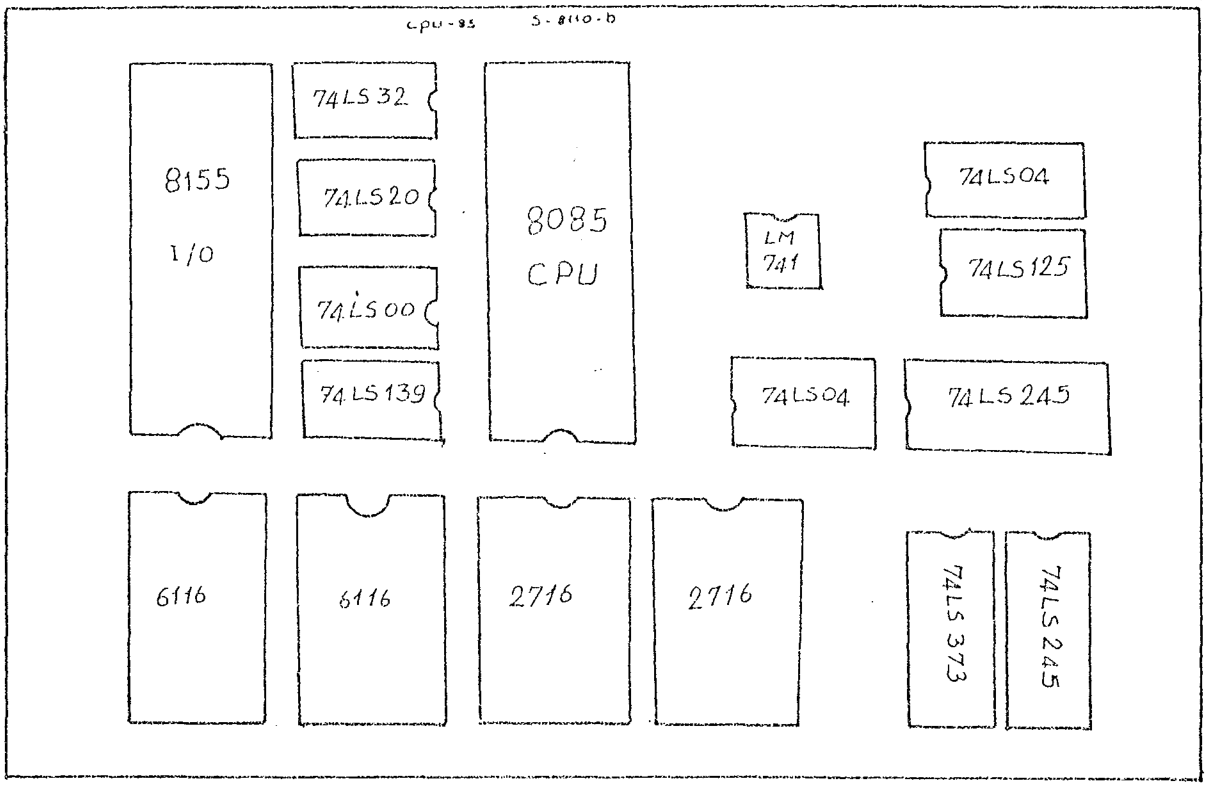


Figure A-2. Placement of Components on B- Side.

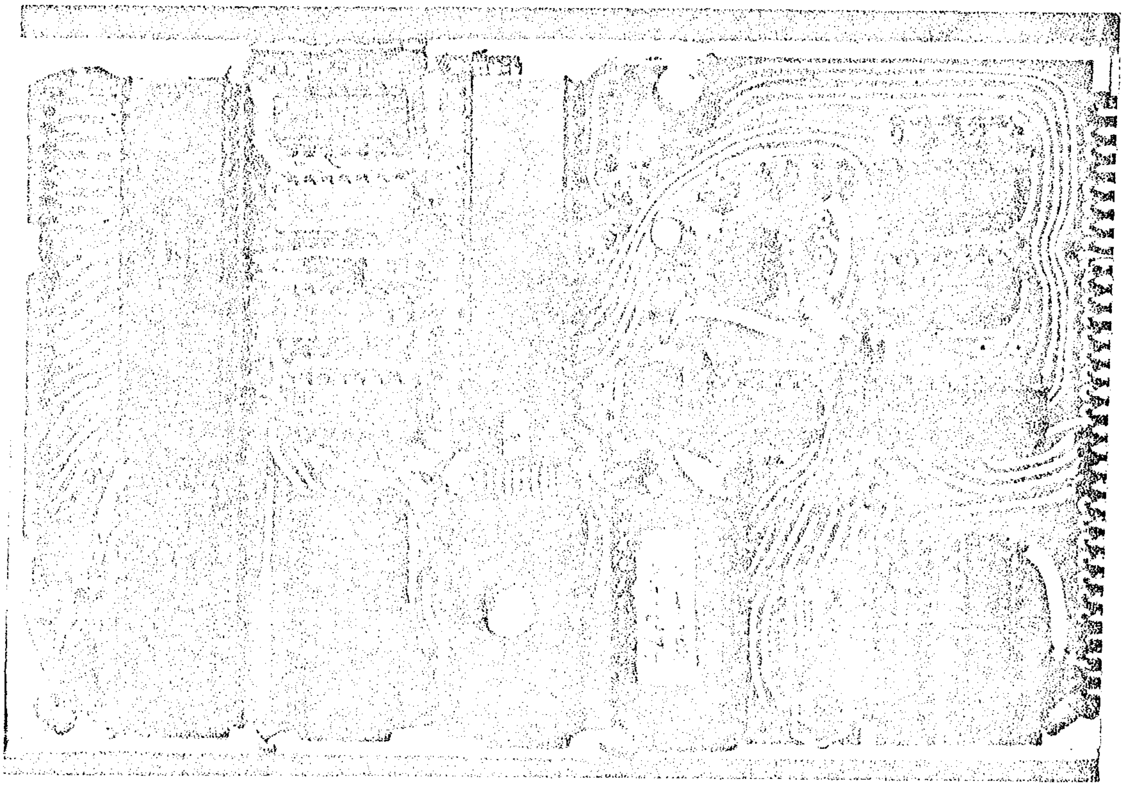
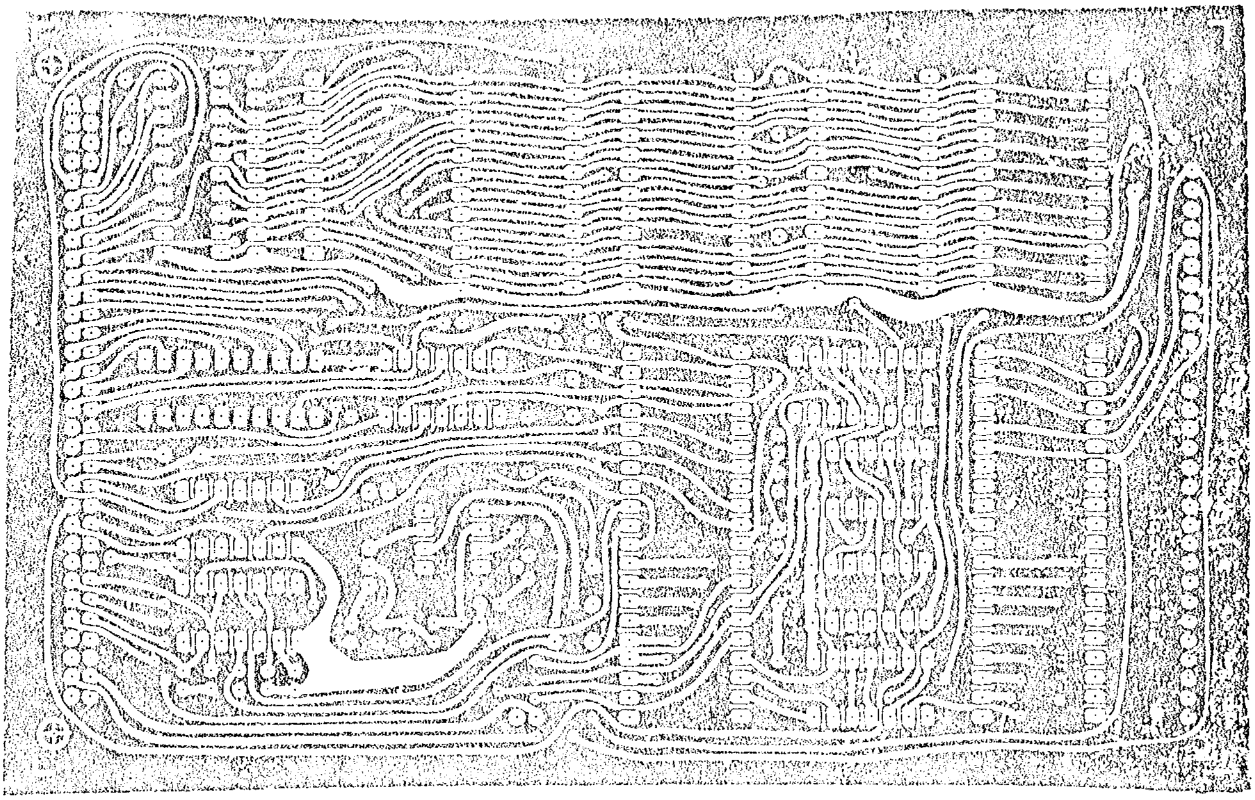
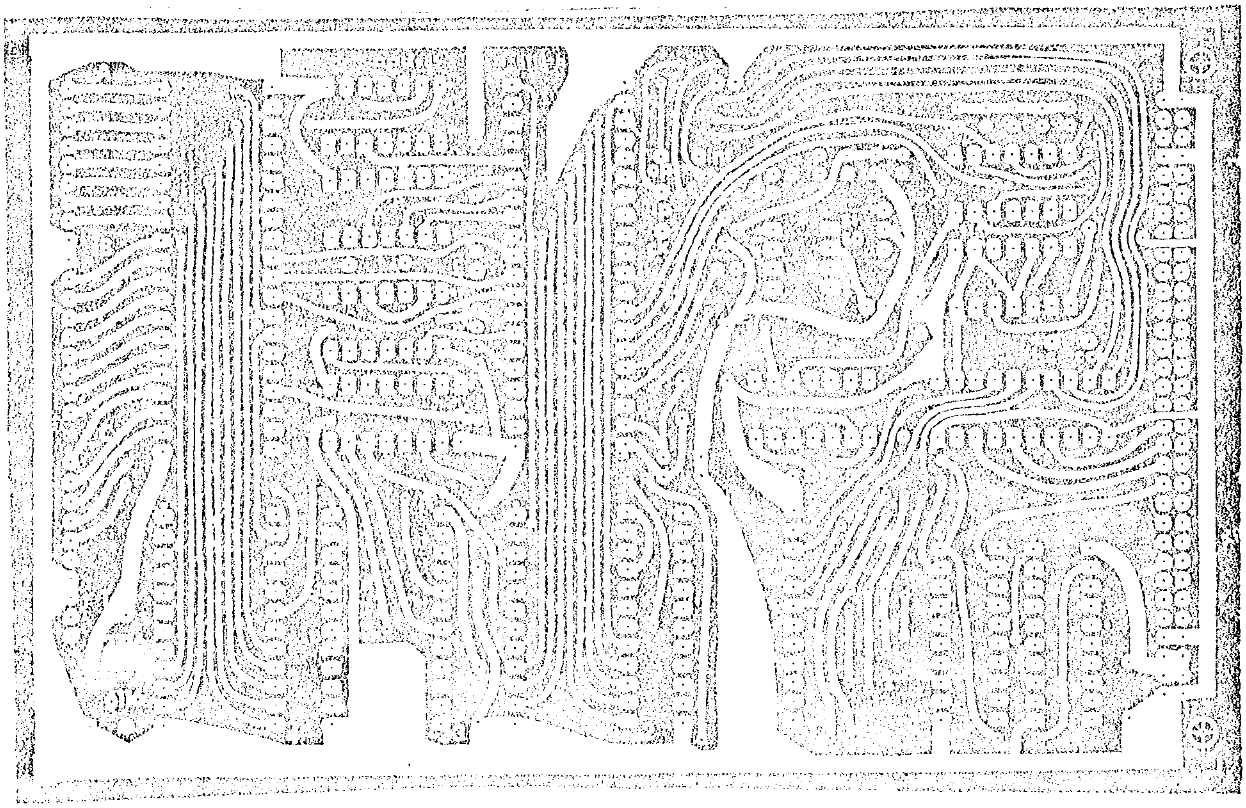


Figure A-3. Photograph of CPU Card.



(a)



(b)

Figure A-4 Printed Circuit Layout of ALP 85.

a: A-Side

b: B-Side

APPENDIX B : SYSTEM PROGRAM

```
8080/8085  MACRO ASSEMBLER                                    MODULE PAGE 1

LINE                              SOURCE STATEMENT

  1 ;                  MAIN MACHINE TOOL CONTROL
  2 ;                PROGRAM IN THREE DIMENSIONS
  3 ;
  4  ......................  ORG   0800H
  5  AUS ..................  EQU   05A8H
  6  ANWEIN  ..............  EQU   0701H
  7  ANWAZL  ..............  EGU   07BCH
  8  UMW  .................  EQU   05C9H
  9  ANWAUS   .............  EQU   07C7H
 10  MAIN : ...............  LXI   SP, E0B0H
 11  ......................  MVI   A,F1H
 12  ......................  OUT   E1H
 13  ......................  CALL  COORD
 14  ......................  CALL  SPEED
 15  ......................  CALL  BASLA
 16  ......................  MOV   A,E
 17  ......................  CPI   0FH
 18  ......................  J2    SPEED1
 19   .....................  JMP   ANA
 20  CMAIN : ..............  CALL  PARAM
 21 .......................  IN    FAH
 22  ......................  ANI   0FH
 23  ......................  STA   1B36H
 24  ......................  LHLD  1B00H
 25  ......................  SHLD  1B34H
 26  ......................  LHLD  1B03H
 27  ......................  SHLD  1B32H
 28  LOOP : ...............  CALL  YID
 29  ......................  CALL  OKEY
 30  ......................  J2    SOBE
 31  ......................  CALL  OUT
 32  ......................  CALL  INPUT
 33  ......................  JMP   LOOP
 34  SOBE : ...............  CALL  BITTI
 35  ......................  HLT
 36  ;
 37  ; END OF MAIN PROGRAM
 38  ;
 39  ;  ADDSUB SUBROUTINE
 40  ;
 41  ADDSUB :                CALL CHECK
 42  ......................  LXI  H,1B0EH
 43  ......................  MOV  A.M
 44  ......................  ANI  80H
 45  ......................  JNZ  COMP
 46  ......................  LXI H,1B11H
 47  ......................  MOV  A,M
 48  ......................  ANI  80H
 49  ......................  JNZ  COMP
 50  ......................  PUSH B

LINE                              SOURCE STATEMENT

 51  ......................  PUSH D
 52  ......................  PUSH H
 53  ......................  LHLD 1B0FH
 54  ......................  LDA  1B0EH
 55  ......................  MOV  B,A
 56  ......................  LDA  1B11H
 57  ......................  DAD  D
 58  ......................  SHLD  1B12H
 59  ......................  ADC   B
 60  ......................  STA   1B14H
 61  ......................  ANI  80H
 62  ......................  J2  LEAVE
 63  ......................  LXI  H,1B14H
 64  ......................  CALL  COMP
 65  LEAVE :...............  POP   H
 66  ......................  POP   D
 67  ......................  POP   B
 68  COMP :................  DCX   H
 69  ......................  DCX   H
 70  ......................  MOV   A,M
 71  ......................  CMA
 72  ......................  ADI   01H
 73  ......................  MOV   M,A
 74  ......................  INX   H
 75  ......................  MOV   A,M
 76  ......................  CMA
 77  ......................  ACI   00H
 78  ......................  MOV   M,A
 79  ......................  INX   H
 80  ......................  MOV   A,M
 81  ......................  CMA
 82  ......................  ACI  00H
 83  ......................  ORI  80H
 84  ......................  MOV  M,A
 85  ......................  RET
 86  CHECK : ..............  LXI  H,1B0CH
 87  ......................  CALL SS
 88  ......................  LXI  H,1B0FH
 89  ......................  CALL SS
 90  ......................  RET
 91  SS : .................  MOV  A,M
 92  ......................  ANA  A
 93  ......................  RNZ
 94  ......................  INX  H
 95  ......................  MOV  A,M
 96  ......................  ANA  A
 97  ......................  RNZ
 98  ......................  INX  H
 99  ......................  SUB  A
100  ......................  MOV  M,A
```

```
LINE                              SOURCE STATEMENT

101 ...................... RET
102 ;
103 ;  END OF ADDSUB
104 ;
105 ;  MULT SUBROUTINE
106 ;
107 MULT  :                 LDA  1B43H
108 ......................  ANI  80H
109 ...................... MOV  C,A
110 ...................... LDA  1B47H
111 ...................... ANI  80H
112 ...................... XRA  C
113 ...................... MOV  C,A
114 ...................... LDA  1B43H
115 ...................... ANI  7FH
116 ...................... STA  1B43H
117 ...................... LDA  1B47H
118 ...................... ANI  7FH
119 ...................... STA  1B47H
120 ...................... LXI  H,1B48H
121 ...................... SUB  A
122 ...................... MOV  M,A
123 ...................... INX  H
124 ...................... MOV  M,A
125 ...................... INX  H
126 ...................... MOV  M,A
127 ...................... INX  H
128 ...................... MOV  M,A
129 ...................... MVI  B,20H
130 STAR:                  LXI   H,1B48H
131 ...................... CALL SHIFT
132 ...................... LXI H,1B44H
133 ...................... CALL SHIFT
134 ...................... JNC CONT
135 ...................... CALL SUM
136 CONT :                 DCR  B
137 ...................... JNZ  STAR
138 ...................... LDA  1B4BH
139 ...................... ORA C
140 ...................... STA  1B4BH
141 ...................... RET
142 SHIFT :                MOV  A,M
143  ..................... ANA A
144 ......................  RAL
145 .......................  MOV M,A
146 .......................  INX H
147  SHIFT1 :               MOV A,M
148 ...................... RAL
149 ...................... MOV M,A
150 ......................INX H

LINE                              SOURCE STATEMENT

151  SHIFT 2 :             MOV  A,M
152  ...................... RAL
153  ...................... NOP
154  ...................... MOV  M,A
155  ...................... INX  H
156  ...................... MOV  A,M
157  ...................... RAL
158  ...................... MOV  M,A
159  ...................... RET
160  SUM : ................ PUSH  B
161  ...................... LHLD  1B40H
162  ...................... XCHG
163  ...................... LHLD  1B48H
164  ...................... DAD   D
165  ...................... SHLD  1B48H
166  ...................... JC    CAR
167  ...................... CALL  REPEAT
168  ...................... SHLD  1B4AH
169  ...................... POP   B
170  ...................... RET
171  CAR :                  CALL REPEAT
172  ......................  INX  H
173  ......................  SHLD 1B4AH
174  ......................  POP   B
175  ......................  RET
176  REPEAT :                LHLD   1B42H
177  ......................  XCHG
178  ......................  LHLD  1B4AH
179  ......................  DAD    D
180 .......................  RET
181 ;
182 ;END OF MULT
183 ;
184; DIVI SUBROUTINE
185;
186 DIVI :                   LHLD    1B18H
187 ......................   XCHG
188 ......................   LHLD    1B1CH
189 .......................  MOV C,L
190 .......................  MOV B,H
191 ......................   LXI H,0000H
192 ......................   CALL DIV
193 ......................   XCHG
194 ......................   SHLD 1B2AH
195 ......................   LHLD 1B1CH
196 .........................MOV C,L
197 ......................   MOV B,H
198 .........................LXI H,0000H
199 ......................   XCHG
200 ......................   CALL DIV
```

```
LINE                              SOURCE STATEMENT

 201 ........................ XCHG
 202 ........................ SHLD 1B28H
 203 .........................RET
 204  DIV:                    MOV A,B
 205 .........................CMA
 206 ........................ MOV B,A
 207 ........................ MOV A,C
 208 ........................ CMA
 209 ........................ MOV C,A
 210 .........................INX B
 211 ........................ CALL LOOP1
 212  LOOP1:                  MOV A,D
 213 .........................MOV D,E
 214 ........................ MVI E,08H
 215  LOOP11 :                DAD H
 216 ........................ JC OVER
 217 ........................ ADD A
 218 ........................ JNC SUB1
 219 ........................ INX H
 220  SUB1:                   PUSH H
 221........................  DAD B
 222 ........................ JC OK
 223 ........................ POP H
 224 ......................   DCR E
 225 ........................ JNZ  LOOP11
 226 ........................ MOV E,A
 227 ........................ STC
 228 ........................ RET
 229   OK:                    INX  SP
  230 .......................INX SP
  231 ..................... . INR A
  232 ....................... DCR A
  233 ......................  JNZ LOOP11
  234 ......................  MOV E,A
  235 .......................  STC
  236 ......................  RET
  237  OVER:                  ADC A
  238 ....................... JNC OSU
  239 ....................... INX H
  240 ....................... DAD B
  241 ......................  DCR E
  242  .....................  JNZ  LOOP1
  243 ....................... MOV E,A
  244  ...................... STC
  245 .......................  RET
  246 ;
  247 ;  END OF DIV
  248 ;
  249 ;  COORD SUBROUTINE
  250 ;

LINE                              SOURCE STATEMENT

 251  COORD:                  CALL  SIFIR
 252                          CALL  Z
 253 ........................ CALL X
 254 ........................ CALL ONEE
 255 ........................ CALL XX122
 256 .......................  LXI H,0000H
 257 .......................  CALL CEVIR
 258 .......................  SHLD 1B00H
 259 .......................  CALL BASLA
 260 .......................  MOV A,E
 261    ....................  CPI 0FH
 262 .......................  JZ COORD
 263  SHOWY1:                 CALL Y
 264 .........................CALL ONLE1
 265 .......................  CALL YY12
 266 .......................  CALL CEVIR1
 267  .....................   SHLD 1B03H
 268 ......................   CALL BASLA
 269  ....................    MOV A,E
 270  .....................   CPI 0FH
 271 .....................    JZ SHOWY1
 272   SHOWX1:                CALL X
 273  .....................   CALL TWOE
 274  ....................... CALL XX12
 275  ......................  LXI H,0000H
 276  ......................  CALL CEVIR2
 277   ....................   SHLD 1B06H
 278  .....................   CALL BASLA
 279   .....................MOV A,E
 280   ...................... CPI 0FH
 281   ...................... JZ SHOW X1
 282   SHOWY2:                CALLY
 283   ....................   CALL ONLE2
 284  ....................    CALL YY12
 285   ...................    CALL CEVIR
 286  ....................    SHLD 1B09H
 287  ........................RET
 288  BASLA:                  CALL ANWEIN
 289   ....................   JZ BASLA
 290  ....................    ANI 0FH
 291    ..................... MOV E,A
 292 SIFIR:                   CALL ANWAZL
 293   ....................   MVI B,80H
 294    ..................... RET
 295   Z:                     MVI A,8FH
 296     .....................RET
 297   X:                     MVI A,76H
 298   ...................... CALL AUS
 299   ...................... RET
 300  Y:                       MVI A,6EH
```

```
        MVI   A,80H
        LHLD 1B09H
        LHLD 1B09H
        SHLD 1B0FH
        SUB A
        STA 1B11H
        LDA 1B14H
        LDA 1B14H
        STA 1B39H
        LHLD 1B12H
        SHLD 1B18H
        LHLD 1B00H
        SHLD 1B0CH
        MVI A,80H
        STA 1B0EH
        LHLD 1B06H
        SHLD 1B0FH
        SUB A
        STA 1B11H
        CALL ADDSUB
        LDA 1B14H
        LXI H,1B3AH
        MOV M,A
        DCX H
        XRA M
        MOV M,A
        LHLD 1B12H
        XCHG
        LHLD 1B18H
        DAD D
        SHLD 1B2EH
        LHLD 1B18H
        SHLD 1B50H
        LHLD 1B1CH
        SHLD 1B52H
        CALL DIVI
        LHLD 1B28
        SHLD 1B40H
        LHLD 1B2AH
        SHLD 1B42H
        LXI H,0000H
        SHLD 1B46H
        LHLD 1B00H
        SHLD 1B44H
        CALL MULT
        LHLD 1B4AH
        SHLD 1B0CH
        LDA  1B39H
        XRI  80H
        STA  1B0EH
        LHLD    1B03H
        SHLD 1B0FH
        SUB A
        STA 1B11H
        CALL ADDSUB
        LHLD 1B12H
        SHLD 1B0CH
        LDA 1B14H
        STA 1B0EH
        LHLD 1B40H
        SHLD 1B4CH
        LHLD 1B42H
        SHLD 1B4EH
        RET
        ;
        ;END OF PARAM
        ;
        ; YID SUBROUTINE
        ;
YID:    LHLD 1B34H
        SHLD 1B44H
        LXI H,0000H
        SHLD 1B46H
        CALL MULT
        LDA 1B4BH
        ANI 80H
        STA 1B11H
        LHLD 1B4AH
        SHLD 1B0FH
        CALL ADDSUB
        LHLD 1B12H
        SHLD 1B30H
        RET
        ;
        ;END OF YID
        ;
        ;BITTI SUBROUTINE
        ;
BITTI:  CALL ANWAZL
        MVI B,20H
        MVI A,7F
        CALL AUS
        MVI A,78H
        CALL AUS
        MVI A,78H
        CALL AUS
        MVI A,78H
        CALL AUS
        MVI A,04H
        RET
```

```
LINE         SOURCE STATEMENT   LINE         SOURCE STATEMENT
601          RET                651          OUT     0F9H
602          ;                  652          CALL    DELAY
603          ; END OF BITTI     653          CALL    INPUT
604          ;                  654          RET
605          ; OKEY SUBROUTINE  655   031:   MVI     A,08H
606          ;                  656          OUT     0F9H
607         OKEY:LDA 1B06 H     657          MVI     A,0CH
608         LXI H,1B34 H        658          MOV     E,A
608         LXI H,1B34 H        658          OUT     0F9H
609         XRA M               659          CALL    DELAM
610         RNZ                 660          CALL    INPUT
611         LDA 1B07 H          661          RET
612         INX H               662   000:   CALL    COMPAR
613         XRA M               663   000:   JNZ     041
614         RNZ                 664   042:   MVI     A,02H
615         DCX H               665          OUT     DF9H
616         DCX H               666          MVI     A,03H
617         LDA 1B31H           667          MOV     E,A
618         XRA M               668          OUT     0F9H
619         RNZ                 669          CALL    DELAM
620         DCX H               670          CALL    INPUT
621         LDA 1B30H           671          RET
622         XRA M               672   041:   MVI     A,08H
623         RET                 673          OUT     0F9H
624         ;                   674          MVI     A,0CH
625         ;END OF OKEY        675          MOV     E,A
626         ;                   676          OUT     0F9H
627         ;OUT SUBROUTINE     677          CALL    DELAY
628         ;                   678          CALL    INPUT
629  OUT:   LXI H,1B39H         679          RET
630         MOV A,M             680   001:   CALL    COMPAR
631         RLC                 681          JNZ     011
632         MOV B,A             682   012:   MVI     A,02H
633         INX H               683          OUT     0F9H
634         MOV A,M             684          MVI     A,03H
635         RLC                 685          MOV     E,A
636         RLC                 686          OUT     0F9H
637         ORA B               687          CALL    DELAY
638         STA 1B54H           688          CALL    INPUT
639         ANA A               689          RET
640         JZ 000              690   011:   MVI     A,00H
641         CPI 01H             691          OUT     0F9H
642         JZ 001              692          MVI     A,04H
643         CPI 02H             693          MOV     E,A
644         JZ 002              694          OUT     0F9H
645  003:   CALL COMPAR         695          CALL    DELAY
646         JNZ 031             696          CALL    INPUT
647  032:   MVI A,00H           697          RET
648         OUT 0F9H            698   002:   CALL    COMPAR
649         MVI A,01H           699          JNZ     021
650         MOV E,A             700   022:   MVI     A,00H
```

```
LINE          SOURCE STATEMENT
701           OUT    0F9H
702           MVI    A,01H
703           MOV    E,A
704           OUT    0F9H
705           CALL   DELAY
706           CALL   INPUT
707           RET
708     021:  MVI    A,08H
709           OUT    0F9H
710           MVI    A,0CH
711           MOV    E,A
712           OUT    0F9H
713           CALL   DELAY
714           CALL   INPUT
715           RET
716     COMPAR:LHLD  1B30H
717           XCHG
718           LHLD   1B32H
719           MOV    A,L
720           SUB    E
721           RNZ
722           MOV    A,H
723           SBB    D
724           RET
725     DELAY: LDA   1B38H
726           ANA    A
727           MOV    C,A
728           CALL   DL
729           MOV    A,E
730           ANI    0AH
731           OUT    0F9H
732           MOV    A,C
733           CALL   DL
734           RET
735     DL:   MVI    B,0DAH
736     ID1:  DCR    B
737           JNZ    ID1
738           DCR    A
739           JNZ    DL
740           RET
741     ;
742     ;END OF OUT
743     ;
744     ;INPUT SUBROUTINE
745     ;
746     INPUT: CALL INPUT1
747           CPI    02H
748           JZ     STEST
749           CPI    08H
750           JZ     YDEC
```

```
LINE          SOURCE STATEMENT
751 YINCE :   LHLD   1B32H
752           INX    H
753           SHLD   1B32H
754           RET
755 YDEC:     LHLD   1B32H
756           DCX    H
757           SHLD   1B32H
758           RET
759 STEST:    CPI    01H
760           RZ
761           ANI    04H
762           JZ     XDEC
763 XINCE     LHLD   1B34H
764           INX    H
765           SHLD   1B34H
766           RET
767 XDEC:     LHLD   1B34H
768           DCX    H
769           SHLD   1B34H
770           RET
771 INPUT1:   IN     0FAH
772           ANI    0FH
773           MOV    D,A
774           ANI    0CH
775           MOV    B,A
776           LXI    H,1B36H
777           MOV    A,D
778           XRA    M
779           ANI    03H
780           ORA    B
781           MOV    M,D
782           RET
783 ;
784 ;END OF INPUT
785 ;
786 ANA:      LDA    1B03H
787           MOV    B,A
788           LDA    1B09H
789           ORA    B
790           JNZ    CMAIN
791           LDA    1B00H
792           MOV    B,A
793           LDA    1B06H
794           ORA    B
795           JZ     CMAIN
796           LHLD   1B03H
797           XCHG
798           LHLD   1B09H
799           MOV    A,L
800           SUB    E
```

```
LINE          SOURCE STATEMENT
801           MOV   A,H
802           SBB   D
803           JNC   ONYP
804 ONYN:     CALL  OKEY
805           JZ    SOEEN
806           MVI   A,00H
807           OUT   0F9H
808           MVI   A,04H
809           OUT   0F9H
810           CALL  DELAY
811           MVI   A,00H
812           OUT   0F9H
813           CALL  DELAY
814           LHLD  1B32H
815           DCX   H
816           SHLD  1B32H
817           JMP   ONYN
818 ONYP:     CALL  OKEY
819           JZ    SOEEN
820           MVI   A,08H
821           OUT   0F9H
822           CALL  DELAY
823           MVI   A,08H
824           OUT   0F9H
825           LHLD  1B32H
826           INX   H
827           SHLD  1B32H
828           JMP   ONYP
829 SPED:     LHLD  1B50H
830           XCHG
831           LHLD  1B52H
832           MOV   A,L
833           SUB   E
834           MOV   A,H
835           SBB   D
836           JNC   BOL1
837           SHLD  1B18H
838           XCHG
839           SHLD  1B1CH
840           CALL  DIV1
841           JMP   CBOL1
842 BOL 1:    SHLD  1B1CH
843           XCHG
844           SHLD  1B18H
845           CALL  DIV1
846 CBOL1:    LDA   1B29H
847           CPI   80H
848           RC
849           CPI   0C8H
850           JNC   BBOL2
```

```
LINE          SOURCE STATEMENT
851           LDA   1B39H
852           MOV   B,A
853           ANA   A
854           RAR
855           ANA   A
856           RAR
857           ANA   A
858           RAR
859           MOV   C,A
860           ANA   A
861           RAR
862           ADD   C
863           ADD   B
864           STA   1B38H
865           RET
866 BBOL2:    CPI   0E8H
867           JNC   BBOL3
868           LDA   1B38H
869           MOV   B,A
870           ANA   A
871           RAR
872           ANA   A
873           RAR
874           ADD
875           STA   1B38H
876           RET
877 BBOL3:    LDA   1B38H
878           MOV   B,A
879           ANA   A
880           RAR
881           MOV   C,A
882           ANA   A
883           RAR
884           ADD   C
885           ADD   B
886           STA   1B38H
887           RET
888           END
```

APPENDIX C : OPERATING INSTRUCTIONS OF SYSTEM

S.1 Turn on the supply voltages.

S.2 Start the execution of the system program:

S.2.1 Press the "R" key and enter Command 7. Give the beginning address (0800H) of the system program and start the execution by pressing on the terminal key, ([↓] or [↑]) [ECB].

S.2.2 "H1 =———.———" will be displayed on the seven segment displays of the microcomputer.

S.3 Enter the z coordinate (Z) of the beginning point of the motion.

S.4 Enter the x coordinate (X1) of the beginning point of the motion.

S.4.1 If the entered value of X1 is desired to be changed, press the key "F". This will bring the software to step S.2.2. In other words "H1 =———.———" will appear again on the seven segment displays and a new X1 value is expected ones more.

S.4.2. After pressing the termination key, the entered value of X1 is stored and "Y=———.———" is displayed on the seven segment displays.

S.5 Enter the y coordinate (Y1) of the beginning point of the motion:

S.5.1 Press the "F" key if you want to change the entered Y1 value as in step S.4.1.

S.5.2 Press the termination key and obtain "H2=———.———" on the displays.

S.6 Enter the x coordinate (X2) of the destination point of the motion:

S.6.1 "F" key is used, if necessary, for changing the entered X2 value.

S.6.2 Pressing the termination key displays "Y=———.———"

S.7 Enter the y coordinate (Y2) of the destination point of the motion.

S.7.1 Press the key "F" if Y2 value is desired to be changed.

S.7.2 Press the termination key. Then, "H=———·———" will appear on the displays.

S.8 Enter the feedrate.

S.9 Start the motion.

S.10 End of motion.

S.10.1 A "Bıttı" message on the seven segment displays will indicate that the motion is completed.

S.11 Go to step S.2 if cutting is to be proceeeded between new coordinates.

APPENDIX D : PHOTOGRAPH OF SYSTEM SET