AUTOMATION
OF
SOME ASPECTS
OF
TIG WELDING

Automation of some aspects of TIG Welding

by

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ABSTRACT

The objective of this project was an investigation into the feasibility of automating the TIG (Tungsten-inert-gas) welding of aluminium, under the severe transient electric noise interference conditions which prevail. The principles of TIG welding, both d.c. and a.c., and the requirements for automating the welding process were studied, resulting in the design of a single-axis system which was used for the control of aluminium welding. A systematic approach to transient noise suppression was followed in the design.

For effective control of the TIG welding process, it is necessary not only to carry out welding using robotic and microcomputer techniques, but also to perform feedback control by using sensors in order to ensure high precision and hence high quality welds. This led to the design and development of two low cost sensors. Both sensors are suitable for seam tracking.

The developed systems have been implemented and tested successfully. Details are given of each system's operating features and the hardware and software necessary to achieve the designs. Computer simulations are carried out for comparison with experimental results. Experimental results are presented demonstrating the capabilities of these designs.

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CHAPTER 1 INTRODUCTION

1.1 AUTOMATED WELDING

In a rapidly developing welding industry, there is a constant demand for modern welding systems capable of producing high quality welds with improved production rate and lower cost. The wide range of modern welding makes it necessary for research on the automation of welding to be carried out for individual needs. In particular, Tungsten Inert Gas (TIG) welding is still widely used as a manual welding process in industry, including the joining of aluminium alloy parts.

For several years a group has been carrying out research at The University of Liverpool into the requirements for fully automating the TIG welding process [1-3]. The aspects reported so far include, pulsed and d.c. TIG welding of stainless steel, the design and construction of a five-axis robot, and the development of vision-based systems for seam tracking and weld inspection. These were all concerned with the welding of stainless steel.

Manual welding of aluminium is an unhealthy job. The smoke and fumes can cause many respiratory problems. Some of the fumes are toxic or carcinogenic. Precautions are also necessary in welding aluminium alloys which contain small amount of magnesium, because magnesium radiates harmful ultraviolet light when heated. Generally, it is difficult to achieve the high quality standards together with a reasonable production rate by manual welding. In the past few years, industrial robots have become available for automating the welding process, mostly these are dedicated to a specific type of welding, such as the spot welding of car bodies or the MIG welding of pipe lines. TIG welding is used mainly for the joining of accurately made metal components, and it is the most commonly used method of welding aluminium today. The shortcoming of TIG welding process include low efficiency, high cost and intensive use of highly skilled labour. This has led to the need for the automation of aluminium welding, using robotic techniques.

1.2 ROBOTS FOR WELDING

The main reasons for converting a manual welding operation to a robotic welding system include safety, quality, and productivity. One benefit is the removal of the welder from the immediate vicinity of the arc. The environmental conditions resulting from the welding process are hazardous to the welder. When the robot is applied to do a certain weld job, it continues to reproduce the programmed instructions independent of the environmental conditions. Smoke and harmful ultraviolet radiation from the arc are no longer a constraint on the welding process. In addition, a programmable welding operation provides higher accuracy and greater flexibility. The use of a robotic welding system results in higher arc-on time, hence higher productivity and lower production cost than for manual welding.

A robotic welding system also allows better process control. The optimisation of welding parameters can be determined in advance by the operator and stored in the welding software in the robot's controller. The repeatable position and speed of the robot coupled with the proper weld parameters allow for more consistent and higher quality welds than are possible with manual welding. A desirable feature of robotic welding is the control of the weld parameters by the robot, using feedback techniques. Repeatable results can then be produced.

The type of welding robot available may be classified according to the methode of positioning the torch:

(a) systems based on cartesian coordinates x, y, z, which describe a cube situated on one side of the robot.

(b) systems based on cylindrical coordinates, i.e. the linear axes x, and y are constructed using cartisian coordinates and the rotary axis z using polar coordinates.

(c) systems based on spherical coordinates, i.e. the linear x axis is constructed using cartesian coordinates and the rotary axis y and z using polar coordinates.

(d) systems based on polar coordinates using a radial or articulated arm. The working area is all around the robot.

The number of movements possible in a given system is known as the number of degrees of freedom, and the mechanical devices causing these movements are called axes. Each axis does not necessarily correspond to a degree of freedom, and so the degree of freedom is a nominal quantity which has a maximum value of six, and the axes of a system determine the size and configuration of the working area.

1.3 REQUIREMENTS OF ROBOTIC WELDING

It is now an accepted fact that a computer controlled robot has the manipulation and logic capabilities for automating the welding process, but other factors which were non-existent with manual welding must now be taken into consideration. Some problems relate to interfacing the robot with peripheral welding equipment such as the weld power supply and the workpiece positioner. Software must also be written specifically for the control of the welding process.

TIG welding process can be carried out by either d.c. or a.c. welding power sources. Different types of welding require different approaches to system design and construction. In d.c. welding the current flows continuously in one direction without changing the polarity of the tungsten electrode, and is useful for welding alloy steels, such as stainless steel, which requires deep penetrations. However, in a.c. welding the current alternates its direction of flow (100 times per second for a 50Hz supply). This means that the arc is extinguished each half cycle as the current approaches to zero. To ensure the re-ignition of the arc a high frequency, high voltage signal is injected every half cycle. This type of welding is particularly useful for metals having refractory surface oxides, e.g. aluminium and its alloys, which requires an a.c. arc to break the oxide layer. The major problem involved in a.c. welding is the high frequency re-ignition unit which produces transient interference in electronic equipment, thus a systematic approach to electrical noise reduction is required when designing robotic systems for a.c. TIG welding.

1.4 SENSORS IN AUTOMATIC WELDING

In many cases the automation of TIG welding process cannot be realised because the permissible workpiece tolerances are exceeded. The workpiece may be distorted during welding, and as the torch is preprogrammed to follow a set path, the torch may deviate from the metal joint. To achieve the optimum results in automated welding, the weld seam must be followed by the torch. i.e. the robot must work under conditions that cannot be exactly given before welding. It is widely accepted that many potential robot applications for welding require some level of positional adaptation. The robot must be equipped with a sensor for measuring the actual position of a welding seam in relation to the welding torch. According to this sensory information, the control system needs to correct the robot position.

1.5 PROJECT ASPECTS

The objective of research covered in this thesis is to investigate the possibility of automating the welding of aluminium and to design sensors for TIG welding. As a first stage, straight line welding was considered, leading to the development of a linear welding system. It was decided to first use the system to weld stainless steel, in order to test its capabilities without having transient interference. Once this was proved to be working satisfactorily it would then be converted for welding aluminium. When the welding process for aluminium was successively controlled by microcomputer, the second stage would be to develop sensors to ensure quality welds for TIG welding. In this project, two low cost sensor systems were developed, namely, the Infra-red and Ultrasonic seam trackers. Both sensors were tested in conjunction with a three-axis cartesian robot.

1.6 OVERVIEW OF THE THESIS

This thesis consists of nine chapters and five appendices.

The principles of TIG welding and the requirements for automating the welding process are described in Chapter 2. Also in that chapter a possible method of constructing an automatic welding system using microcomputer is described. Experimental tests indicate that the use of a microcomputer can greatly reduce the system cost and provide greater flexibility. Chapter 3 outlines the problems of transient interference which is encountered in the development of the aluminium welding system. A systematic approach to the suppression of transient interference becomes essential in the design. An experimental system for aluminium welding is described in Chapter 4. Chapter 5 reviews the application of sensors in automated welding. This leads to the design and development of two low cost sensors. Hardware and software development of both sensors is presented in Chapters 6 and 7 . Chapter 8 describes the experimental robot controller. The robot position control algorithms are described using computer models in comparison with experimental results. The concluding section includes recommendations for future work.

The appendices contain detailed information such as the program listings and essential technical data.

CHAPTER 2 TIG WELDING AND AUTOMATION

2.1 INTRODUCTION

Arc welding is a term applied to a group of welding methods in which an electric arc is formed and maintained between the work surface and an electrode held by a torch. The heat resulting from the arc created between the work surface and the electrode may be effectively concentrated on the area to be welded.

There are several different types of arc welding process [4]. TIG welding is an arc welding process using a fixed tungsten electrode and an argon gas shield.

The practical operation of TIG welding can be divided into two main parts:

(a) The control of welding conditions, particularly the arc length.

(b) The movement and guiding of the torch along the weld seam.

In the automation of TIG welding, (a) and (b) can be controlled by means of a welding robot.

This chapter outlines the principles of TIG welding and describes a method of constructing a single axis welding robot. This is based on a microcomputer controlling a linear traverse and a welding power supply.

2.2 PRINCIPLES OF TIG WELDING

In TIG welding the arc is sustained between a tungsten electrode and the workpiece within a shield of the inert gas. The gas shield excludes atmospheric oxygen and nitrogen and prevents contamination of electrode and molten metal. The shielding gas is supplied through the welding torch. The tungsten electrode serves only as a focal point for the arc and is not intended to furnish any material to the weld pool. On joints where filler metal is required, a welding rod or filler wire is fed into the weld zone and melted with the base metal. Fig.2.1(a) illustrates the inert gas shield of TIG welding and (b) shows the cross section of a finished weld sample.

TIG welding can be carried out using either d.c. or a.c. welding sources. The characteristics of the arc are changed considerably with change of direction of flow of current, that is with electrode polarity

2.2.1 DC TIG WELDING

When d.c. is used, the polarity of the electrode can be set to positive or negative depending upon applications as summarised in fig.2.2.

With a positive electrode, the electron stream is from workpiece to electrode while the positive ions travel from electrode to workpiece. The electrons streaming to the tungsten electrode generate greater heat, which can cause overheating, with the consequent vaporisation of the tungsten and the possibility of tungsten being transferred to the molten pool and contaminating it. Thus electrodes with large diameters and hemispherical tips are used. Very much less heat is generated at the molten pool and it is therefore wide and shallow. For this reason TIG welding with a positive electrode is seldom used.

For a negative electrode the electron stream is from electrode to the workpiece with the zone of greatest heat concentrated in the workpiece, thus penetration is deep and the weld pool is narrower. The electrode is near the zone of lesser heat and may be of reduced diameter and use a conical tip.

2.2.2 AC TIG WELDING

When a.c. is used on a 50Hz supply, voltage and current reverse direction 100 times a second which produces welding conditions between those of the electrode being positive and electrode being negative, the heat being fairly evenly distributed between electrode and workpiece. Depth of penetration is between that of electrode positive and electrode negative modes and the electrode tip shape is between the previous diameters. This type of welding is particularly useful for the welding of aluminium alloys where a thin layer of refractory oxide with a melting point around 2000°C is present over the surface. During the positive half-cycle, the positive ions in the TIG arc bombard this oxide and this, together with the electron emission from the plate, break up and disperse the oxide film. During the negative half-cycle weld penetration takes place.

In a.c. welding the reversals of voltage and current introduce the problem of arc re-ignition as the arc is extinguished twice in every cycle. When the electrode is negative the arc requires a low voltage for re-ignition due to the greater electron emission from the tungsten, but when the voltage is reversed so that the electrode becomes positive the arc will not re-ignite unless there is a sufficient voltage available at the arc gap.

One way to ensure re-ignition of the arc is to inject high frequency, high voltage between the electrode and workpiece on both positive and negative half-cycles when the current approaches to zero. The injected signals are generated by a spark gap oscillator, which can give rise to considerable transient interference on electronic devices. Adequate suppression and screening must be provided to eliminate this interference in automated welding.

The choice of either a.c. or d.c. welding depends on the metal to be welded. For metals having refractory surface oxides, a.c. is used while d.c. is used for carbon and alloy steels, heat-resistant and stainless steels, copper and its alloys, nickel and its alloys, titanium, zirconium and silver.

2.3 APPLICATIONS OF TIG WELDING

In any type of welding, the quality of a weld is determined by the surface contaminants, particularly oxides, which should be prevented from accumulating on the metal surface. The cleaner the surface, the better the weld. To obtain such conditions, the molten weld metal must be protected from the atmosphere during the welding operation. Otherwise, atmospheric oxygen and nitrogen, or other contaminants, will combine readily with the molten weld metal and result in a weak porous weld. The basic principle of TIG welding process provides an ideal solution, ensuring quality welding.

The TIG welding process is used with welding currents normally from 5A up to 800A and is one of the most versatile methods of welding. The process is most suitable for welding single-pass or double-sided close butt joints, edge joints or outside corner joints. It is less suitable for fillet welds in which care must be taken to obtain good fusion into the root. Because it can be easily mechanised and gives high quality welds, the process is greatly favoured for precision welding.

2.4 TIG WELDING SYSTEM

The basic features of a TIG welding system is shown in Fig. 2.3. The major equipment components required for TIG welding are:

(a) the welding torch.

(b) the shielding gas.

(c) the welding power supply.

2.4.1 WELDING TORCH

A TIG welding torch is designed to deliver both the electric current and the shielding gas to the point of welding as well as providing passages within the torch for cooling purposes. The tungsten electrode is firmly held in the torch by a collet holder. At the end of the torch there is a shielding gas nozzle which controls the direction and amount of inert gas covering the weld. The nozzles are made of ceramic and easily removable for cleaning and replacement. Because of the intensive heat of the arc, cooling by water or air is required to protect the torch body and power cables.

The arc temperature is dependent on the amount of current applied, as the thickness of the workpiece increases the size of the electrode diameter must also increase to deal with the larger welding currents required. The electrode may be of pure tungsten but more generally it is alloyed with thorium oxide (up to 2.2%) or zirconium oxide (up to 0.4%) Tungsten has a melting point of 3380°C. In comparison with the melting points of the base metal, e.g., 658°C for aluminium and up to 1420°C for steel, there is very little tungsten vaporisation in the welding arc and the tungsten retains its hardness when red hot [5].

Pure tungsten electrodes are generally used for ordinary quality welds. The thoriated tungsten electrodes give easier starting, a more stable arc and a smaller possibility of weld contamination, and in addition they have a greater current carrying capacity for a given diameter than pure tungsten. However, it is difficult to maintain a hemispherical end when they are used for a.c., as a result zirconiated electrodes are often selected for a.c. welding because of the high resistance to tungsten contamination and good arc starting characteristics. They are used therefore for high quality welds in aluminium, and like pure tungsten they produce a hemispherical end.

TIG welding torches are available in a variety of sizes based on their amperage rated capacity. Table 2.1 shows the electrode current ratings.

2.4.2 SHIELDING GAS

Shielding gas for TIG welding can be argon, helium, or a mixture of both. Argon is used more extensively because it is less expensive than helium. Since argon is heavier than air it provides a better shield for the weld. Moreover, there is less fume during the welding process with argon and consequently it permits better control of the weld pool and arc.

Argon normally produces a better cleaning action especially in welding aluminium with alternating current. With argon there is a smoother and quieter arc action. The lower arc voltage characteristics of argon are particularly advantageous in welding thin material because there is less tendency for the arc to burn through the metal.

2.4.3 WELDING POWER SUPPLY

Welding power supplies can be chosen to give d.c. or a.c. or both d.c. and a.c. from one unit.

A d.c. power supply consists of a step-down transformer and a bridge rectifier. The principle feature of this type of power supply is the rectification of the transformer output to d.c. welding power. Two types of transformers are normally used, single-phase and three-phase transformers. The smaller welding units can be used on single-phase supplies and the larger ones require a three-phase supply.

An a.c. power supply usually consists of a transformer that takes the single- or three-phase mains and transforms the voltage to about 80V for open circuit outputs. Current control is by tapped inductor and the auxiliary devices include the high frequency oscillator.

A d.c. and a.c. power supply can be used for either d.c. or a.c. welding. It is connected to the single- or three-phase 50Hz mains, fed into a step-down transformer and then into a controlled rectifier which may also act as a contactor. The rectifier can be switched under load. Current can be supplied for TIG welding and output switched for electrode positive or negative or a.c. by means of the controlling circuit.

2.5 WELD JOINT PREPARATIONS

The quality of the weld deposit is heavily dependent on the consistency of many factors, including: torch speed, welding current, joint preparations etc.

For maximum joint strengths, the full thickness of the metal must be fused together. This often requires some method of joint preparations.

The joint should be formed by compatible materials. If filler metal is needed for weld reinforcement, it must be compatible with the base materials. A good joint design provides for easy cleaning. A small amount of oil, grease, moisture, or other foreign matter between two accurately placed parts can cause weld metal porosity.

2.6 OPERATION PROCESS AND AUTOMATION REQUIREMENTS

The practical operations in making a weld can be considered as following this sequence:

1. Assemble parts. Tack, jig or mount parts in a fixture.
2. Present the workpiece to the welding torch.
3. Initiate welding.
4. Create relative movement between the welding source and the workpiece.
5. Control the welding variables.
6. Stop welding.
7. Remove work.
8. Re-position welding source ready for the next weld.

The process can be performed either manually or automatically. Manual welding is understood to be that in which the welding variables are continuously controlled by the operator and the means for welding are held in the operator's hand. With automatic welding the welding parameters and the movement of the workpiece need to be maintained by the control system.

To convert a manual TIG welding operation into an automatic welding system, a robotic system suitable for TIG welding is required. In some situations sophisticated robotic systems can be economically justified but in many cases such expense would be inappropriate.

Currently, computing systems have become widely available at reasonable cost because of the advent of microcomputers. Such microcomputers not only have considerable computing power, but are simple to use. It is possible to use a low cost microcomputer to facilitate parameter setting and control of mechanised TIG welding equipment for the support of welding process.

The following section will describe the development of a linear (single axis) welding system which is based on microcomputer control of the weld parameters and workpiece movements.

2.7 PRELIMINARY EXPERIMENTS

In preliminary experiments it was decided to construct a microcomputer controlled welding system using a linear axis together with sensors for simple weld tests, such as the straight line welds. It was shown in section 2.2.2 that a.c. welding needs a high frequency re-ignition voltage at each half cycle of the welding current, and this is likely to produce spurious signals which could affect the microcomputer. For this reason, preliminary tests carried out for welding of stainless steel using d.c. TIG welding without the danger of transient interference which occurs in welding of aluminium. The purpose was to investigate the feasibility of using microcomputer applications in TIG welding in order to gain basic knowledge in welding automation, and more importantly, to consider possible solutions in reducing the system cost for suitable welding application. If the main aspects of the automation of TIG welding was accomplished using a d.c. power source, then the automation of the welding of aluminium using a.c. power source could be considered, and this will be discussed in chapter 3 and 4.

A block diagram of the d.c. welding system is shown in fig.2.4. It consists of three units:

(a) Welding Power Supply.

(b) Linear Traverse with Motor Drives.

(c) Microcomputer Controller.

The three units are linked to provide control of welding current, speed, and direction of a simple straight line weld.

2.7.1 THE DC WELDING MACHINE

Preliminary experiments were conducted on the project requirement of welding 0.7 mm - 3 mm thick metal plates. Tests on welding stainless steel plates were carried out using the Welding Institute Polypack d.c. Welding Supply which is outlined in fig.2.5. This power supply is transistor controlled with 50A current rating. The transistor bank consists of fifty bipolar transistors in parallel and the base of this transistor bank is driven by an differential amplifier. The output current can be controlled by varying the reference voltage which is input to the error amplifier. Although a 300A version is also available, the 50A power supply was considered to be suitable for the experiment.

The power supply can be easily interfaced to the microcomputer using an 8-bit digital-to-analogue converter (DAC) which translates a digital current demand into an analogue signal for the power source error amplifier. This allows current levels to be set between 0 and 50A as shown in Table 2.2.

The sequence control unit provides a convenient means of initiating and terminating the welding current. When the START/STOP signal is activated, a preset argon gas purge is carried out and the pilot arc supply is enabled. Once the arc is established the arc ignition unit and the pilot supply unit is disabled, and the main current supply enabled. If the START/STOP signal is deactivated the arc supply is cut off and the argon gas post-purge will be carried out for a preset time.

2.7.2 THE LINEAR TRAVERSE

The TIG welding process requires the robot to accurately position and orientate the workpiece in relation to the welding torch. Then, while maintaining these coordinate relationships, the robot must control the desired welding speed of the workpiece. A single-dimensional robot which provides a linear movement for the workpiece may be used for preliminary straight line welds.

An experimental system which is equivalent to a one-degree of freedom robot consisting of a linear traverse, which moves the position of the workpiece in a forward or backward direction, a fixed position vertical micrometer, which supports the torch and may be adjusted to set the arc length between the torch and the workpiece, and a stepping motor drive unit, which is interfaced to a BBC microcomputer for software control.

The traverse has an eleven inches square metal table mounted on to parallel steel rods by four brass bushes.It is driven by a shaft screw which goes through a tapped bush under the centre of the table. The supporting rods are mounted in two steel end plates. The shaft screw has a bearing at one end and the other end is fixed directly on the driving shaft of the stepping motor which is mounted on the end plate at that end.

Down the centre of the table there is a slot into which a perforated copper bar can be fitted for distributing the backing gas if required.

On each side of the slot there is a plate fixed by four screws. These plates are used to clamp the workpiece into position and also to restrict warping during the welding process. On the same side as the stepping motor there is a connector block for wiring extensions from the stepping motor drive unit. On each side of the table there is a push button switch clamped on the steel rod. It is used to stop the movement when the table hits the switch.

The stepping motor drive unit consists of a Unimatic UDB-053/1 drive card, a power supply (12V, 8A) and source current limiting resistors. An internal wiring diagram is shown in fig.2.6. The stepping motor used is a Sigma 20-2220D200-E033 motor [6]. Each pulse to the drive unit is translated to a change of current in the motor windings and produces a 1.8° movement of the rotor. The drive unit is designed to be operated either manually or controlled by the BBC microcomputer. The unit has several useful features including acceleration and deceleration modes. The front panel of the unit is shown in fig.2.7. On the front panel there are seven switches and a DIN socket; one of these switches (S6) is for power on/off. The HALF/FULL STEP switch (S1) determines the mode of operation of the stepping motor. In the half step mode all the motor speeds, whether driven by fast, slow or by the microcomputer are halved. Half step operation was found to be effective in eliminating resonance and reducing acoustic noise on the motor shaft. When running, the operation is smoother. Half step performance can be equivalent to the full step operation by doubling the input pulse rate. Two of the switches marked FAST (S4) and SLOW (S5), when turned on will move the traverse at speeds preset on the drive board. The FAST control can be used for coarse position of the traverse and the SLOW can be used for the fine position. Both the FAST and SLOW modes are used only for manual settings. In automatic control operations, the speeds are controlled by the pulses sent from the microcomputer. The DIRECTION (S3) control determines whether the traverse table moves from right to left or vice versa. The direction of motion can also be controlled by the microcomputer. If the microcomputer is used, the DIRECTION switch should be on the LEFT (off state) mode, and the MANUAL/MICROCOMPUTER switch (S2) to the MICROCOMPUTER mode. In this case the DIN socket is connected to the external pulse input of the drive board, and this allows communication with the Microcomputer console. This input has an active pull up resistor and is driven by an open collector opto-isolator.

The traverse speed is proportional to the input frequency. The AUTO_STOP/CONTINUE control (S7+S8) is mainly designed for manual operations. If it is set to AUTO-STOP, the traverse table will stop automatically when it hits the push button switch which can be adjusted to provide the required travel distance. The CONTINUE mode is used for the reverse movement after the traverse is stopped.

At the rear panel of this unit there is a D-type socket which allows extension to the terminal block on the traverse. The connections from the terminal block to the motor is shown in fig.2.8.

2.7.3 THE MICROCOMPUTER CONTROLLER

The controller used is based on the BBC model B microcomputer [7]. It has a four channel 12-bit analogue-to-digital converter, serial and parallel printer interface, an 8-bit user port, and the 1MHz bus which allows additional input and output ports to be added. It has also a fast version of BASIC plus a built in 6502 assembler which makes it easy to use machine code when high speed operation is essential. The user port and the 1MHz bus are selected for circuit interface.

Both the parallel printer and the user port provided by a 6522 Versatile Interface Adapter (VIA). This is a very flexible I/O control device. It contains a pair of 16-bit interval timers, a serial-to-parallel/parallel-to-serial shift register and input data latching on the peripheral ports.

The user port consists of eight lines which can be individually programmed to act as inputs or outputs under the control of a Data Direction Register. The polarity of the output pins are controlled by an output register and input data may be latched into an internal register under the control of the handshake control line (CB1). Besides, the MSB of output pins (PB7) can be controlled by one of the interval timers for generating programmable frequency square waves. This is particularly useful for the speed control of a stepping motor.

An 8-bit user port is obviously very useful, but it was found that more inputs or outputs were required. The simple solution to this problem is to use the 1MHz Bus port as it offered a greater scope for expansion.

For peripheral interfacing the user port was chosen to control the linear traverse and the 1MHz bus port to provide the required 8-bit current command to the digital-to-analogue converter in order to control the welding power supply. The hardware design is shown in fig.2.9.

The direction and speed of the linear traverse are determined by the outputs of the user port, PB1 and PB7 respectively. Since the stepping motor drive card has active pull-up resistor inputs, it must be driven by open collector logic gates. In the design, opto-isolators were used to provide grounding isolation and the open collector logic gates.

The microcomputer input/output signals are configured as inputs after reset with the quiescent condition being high. Inverters connected directly to the user port ensures no signal goes into the peripheral circuits at rest condition. Only if a particular line is programmed to low, the corresponding inverter output will become high which activates the appropriate control line.

The outputs from D0 to D7 of the 1MHz bus port provide an 8-bit current command which is latched by the 74LS273 and converted into an analogue form by the ZN425E DAC. The DAC output gives a reference voltage from 0-2.5V. This provides full control of the welding current from 0-50A with a resolution of 195mA.

Accesses through the 1MHz bus are performed within the address range &FC00-&FCFF. &FC00 is the address which is decoded by the 74LS138 to enable an 8-bit command accessing to the DAC. When an access is made to &FC00 the NPGFC control line will become active low and the appropriate address will appear on the eight address lines.

On the BBC microcomputer the 6502 CPU normally operates with a 2MHz clock for the synchronisation of signals throughout the computer system. As most processing is carried out at the maximum clock speed the processor must slow down when accessing the 1MHz extension bus. When addresses on the bus change, the 2MHz clock will be low but there is no guarantee that the 1MHz signal on the bus will also be low. This may result in rogue glitches on the NPGFC control line. This problem can be obviated by using a clean up circuit as shown in fig.2.10 so that when an appropriate address decode signal indicates that the 1MHz extension bus has been accessed the microcomputer clock signal will coincide with the extension bus clock.

Prior to starting operation, the system must be programmed by software. Detail of software is shown in Appendix I. This program is written in BASIC. For system initialisation all data lines of the user port are set as outputs and the speed and direction control lines are reset to the rest condition.

Once the system is programmed, the traverse speed, s_t, is determined by a continuous square wave output from PB7 whose frequency is derived from a counter number, N, input to the interval timer. As N increases the output frequency decreases, thus the speed of the traverse decreases. That means N is inversely proportional to s_t, or:

$$N = \frac{k}{s_t} \qquad (2.1)$$

where k is an arbitrary constant.

By measuring the distance that the traverse moved in every 10 seconds, which correspond to a particular counter number input to the interval timer within the speed range, a calibration curve can be obtained as shown in fig.2.11. This curve may be represented as:

$$\log(N) = \log(k) - \log(s_t) \qquad (2.2)$$

When $s_t = 1$ (or $\log(s_t) = 0$), $k = 15$, and $N = 15 / s_t$. Thus any number of s_t input from the console must be converted to a value of $15/s_t$ in order to produce the actual speed control.

With reference to the current table (Table 2), an input of 00000000 (binary) gives zero output current while an input of 11111111 gives fifty amps, thus any number input from the console representing a current value, I, will be converted to a value of 255 I / 50 to produce the actual current command to the DAC.

2.7.4 EXPERIMENTAL WELDS AND RESULTS

Fig.2.12 shows the setting up of the linear welding system. This experimental system is an open-loop welding system. Each test weld can be carried out using preset values of speed, direction and current level. The user is allowed to enter the required welding parameters to program a test weld. The pulsed TIG welding technique was used for the test welds.

Pulsing the welding current is a powerful technique for increasing the tolerance of TIG welding to fit-up or geometrical variations in the workpiece. The welding current is varied in a regular manner between a background level and a pulse level. Between pulses the weld pool is allowed to solidify and the weld seam is, therefore, a series of separate spots which normally overlap by about 50% of the spot diameter. Relative movement between the torch and the work can be halted during the pulse periods, which results in over lapping circular spots.

An example of a set of test weld parameters for a 1mm thick stainless steel is shown as follows:

(a) Background current = 10A

(b) Pulse on time = 0.6sec

(c) Pulse off time = 0.7sec

(d) Pulse on current = 50A

(e) Welding speed = 1mm/sec

(f) Direction of job = Right to Left

The background current level and duration are not critical as they are chosen to maintain a stable arc without forming a weld pool. The pulse current and pulse duration are significant process variables. Background currents are usually less than 15% of the pulse current and are commonly 5-10A. The amplitude of the current pulse needed is related to the material being welded and is influenced by its thermal diffusibility. Pulse duration varies as the thickness squared ranging from 100ms for metal of 0.7mm up to several seconds for metal over 3mm in thickness. The product of current and time is a constant.

A gradual reduction of current at the end of each weld is helpful in controlling workpiece warping. When the current is cut off and the arc extinguished the electrode and weld pool begin to cool, and an adequate flow of argon must be maintained until the danger of oxidation is past.

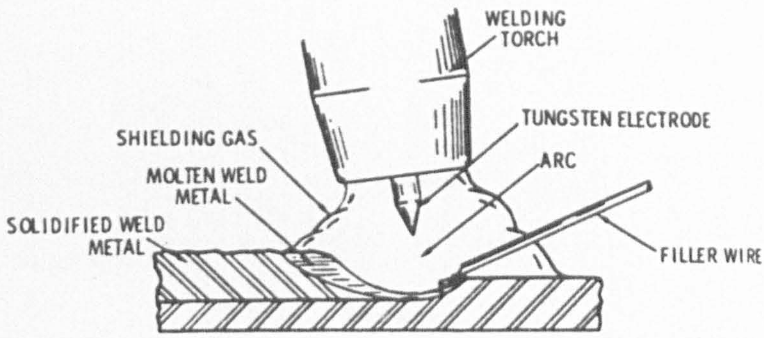
The main use of pulse TIG is for joints in which there is a difference of thickness as when dissimilar metals or circumferential welding where continuous current results in a build up of heat as the weld progresses. With pulsing, the heat diffuses away during the background periods resulting in a consistent penetration.

Fig.2.13 showing the result of a test weld on a 1mm thick stainless steel plate, which was welded with 40% overlap and good penetration. This experimental evidence demonstrates the successful use of microcomputer for TIG welding control. The microcomputer based system is easy to use, allows accurate control, and also ensures the quality of the weld.

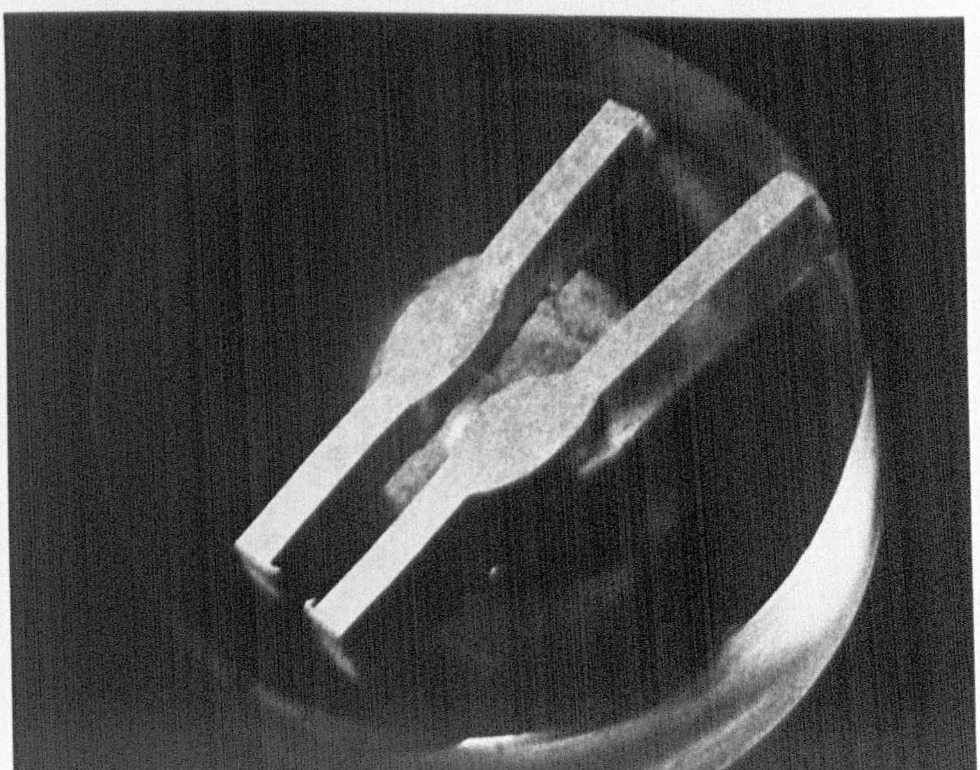
2.8 DISCUSSION

This experiment provides an overview of the basic requirements of automating TIG welding process, using a BBC computer and a linear traverse to achieve full automation on open loop mode. Clearly the process can be fully automated if a robot, with three degree of movements or more, is used instead of a linear traverse, and also the BBC microcomputer is replaced by a faster speed and bigger memory computer controller, e.g. IBM PC-AT, plus on-line sensors to provide close-loop control. Above all, computer control can be used in automating TIG welding processes.

It has been shown that the use of microcomputer is feasible in controlling d.c. TIG welding, and it is desirable to test the ability of these techniques for a.c. TIG welding. Investigations in a.c. TIG welding are concentrated on welding aluminium components, and this will be described in the next chapter as it requires different approaches in system design.



(a) The inert gas shield of TIG welding.



(b) The cross section of a finished TIG welding.

Fig.2.1 Illustration of TIG welding

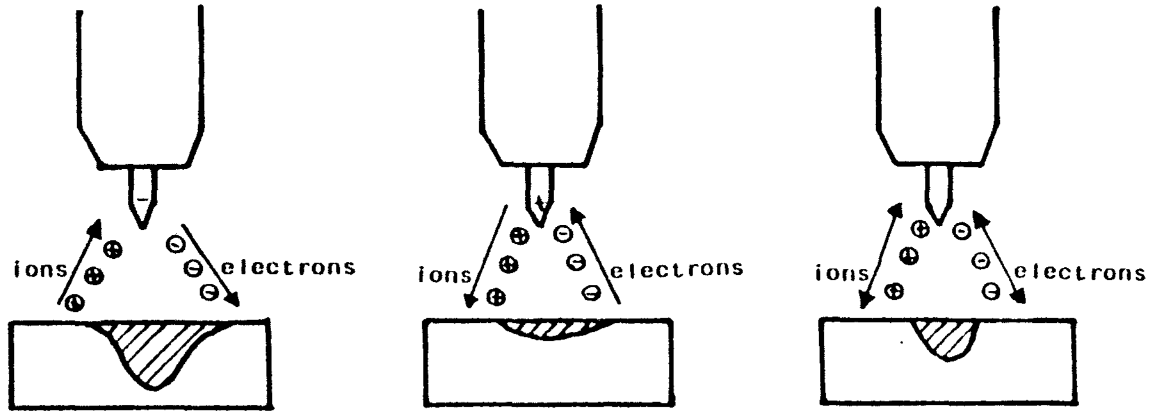
Current type	DC	DC	AC
Electrode polarity	-ve	+ve	
Penetration characteristics	 work +ve	work -ve	
Oxide cleaning action	No	Yes	Once every half cycle
Penetration	Deep & narrow	Shallow & wide	Medium

Fig.2.2 Characteristics of current types of TIG welding.

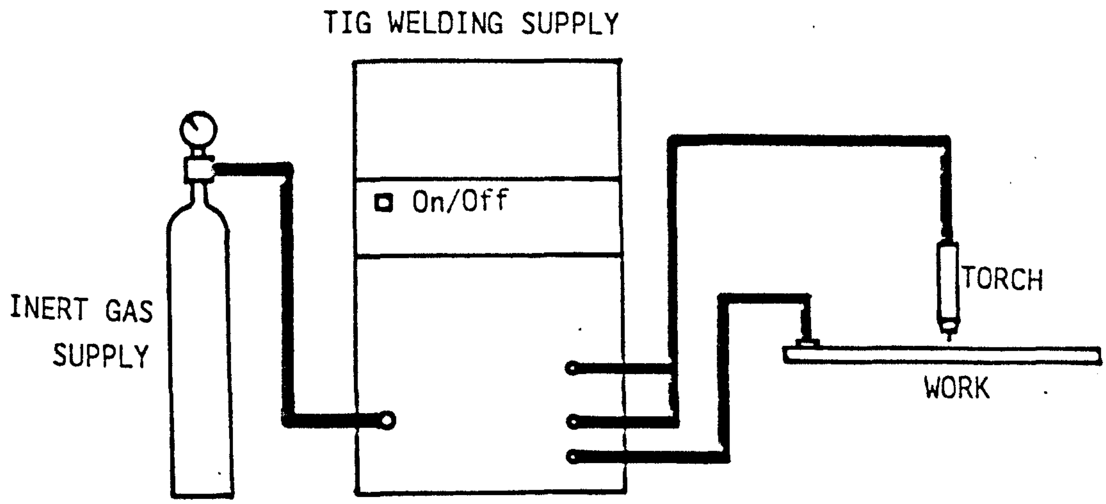


Fig.2.3 Basic features of TIG welding system.

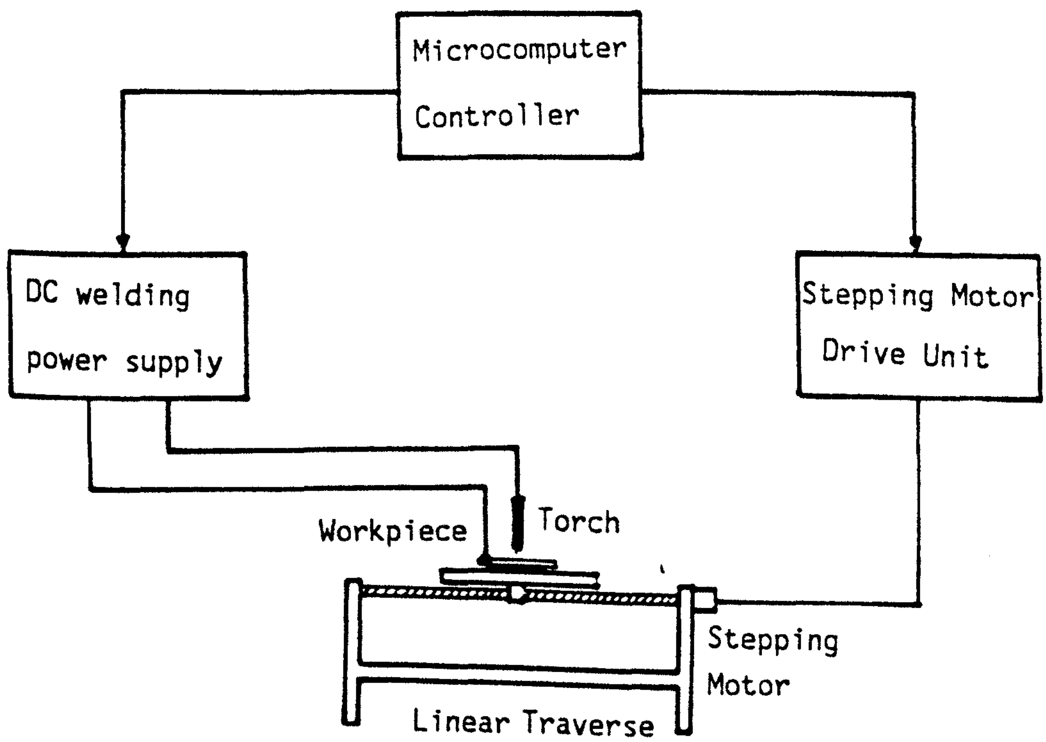


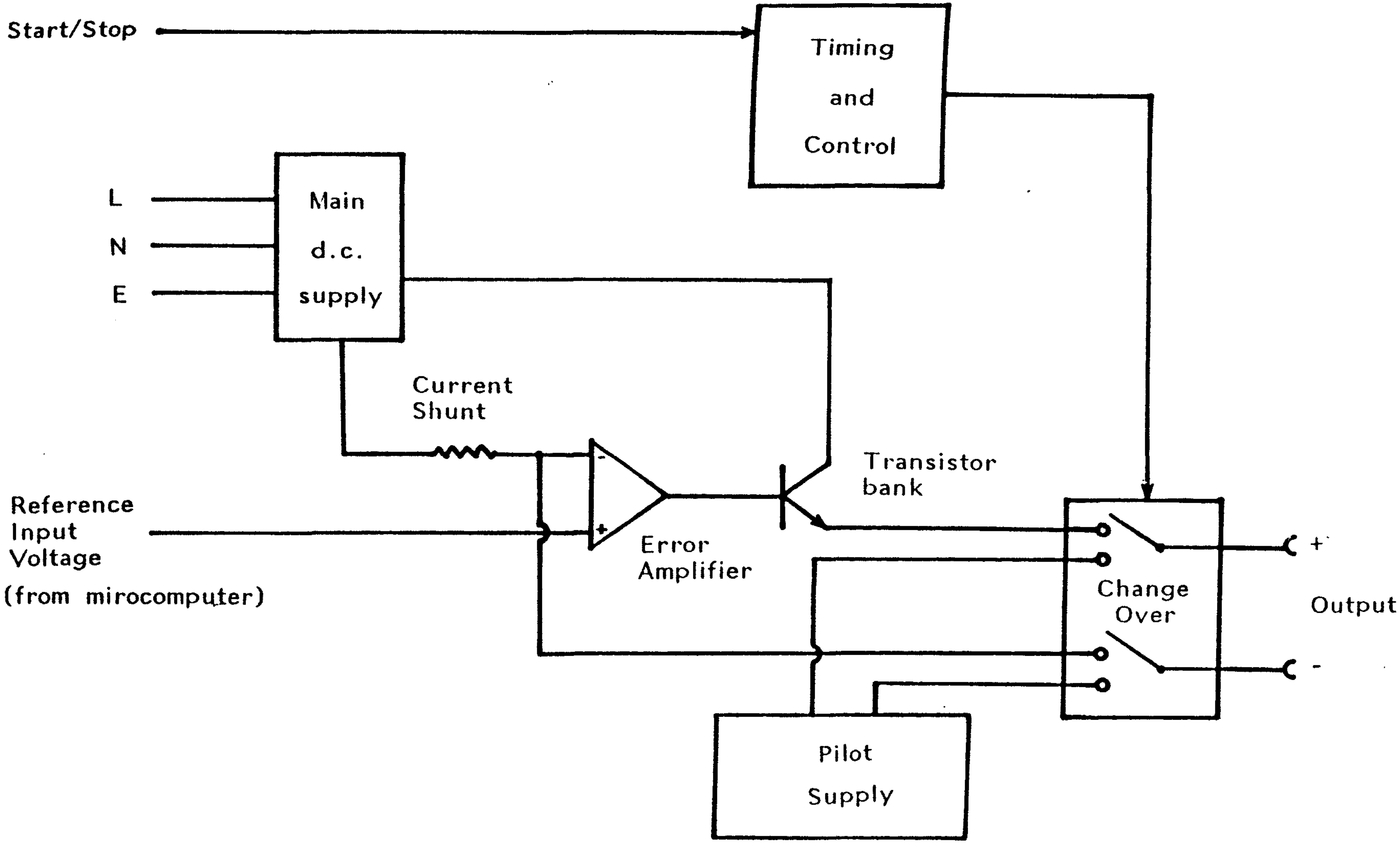
Fig.2.4 Microcomputer controlled d.c. TIG welding.

Electrode Diameter (mm)	d.c. (Thoriated)	a.c. (Zirconiated)
1.2	70	30
1.6	150	60
2.4	240	90
3.2	380	150
4.0	400	210
4.8	–	275
6.0	–	350

Table 2.1 Electrode Current Ratings

Reference Voltage Input (V)	Welding Current Output (A)
0	0
0.5	10
1.0	20
1.5	30
2.0	45
2.5	50

Table 2.2 Welding Current Conversions



2.5 The experimental d.c. welding supply.

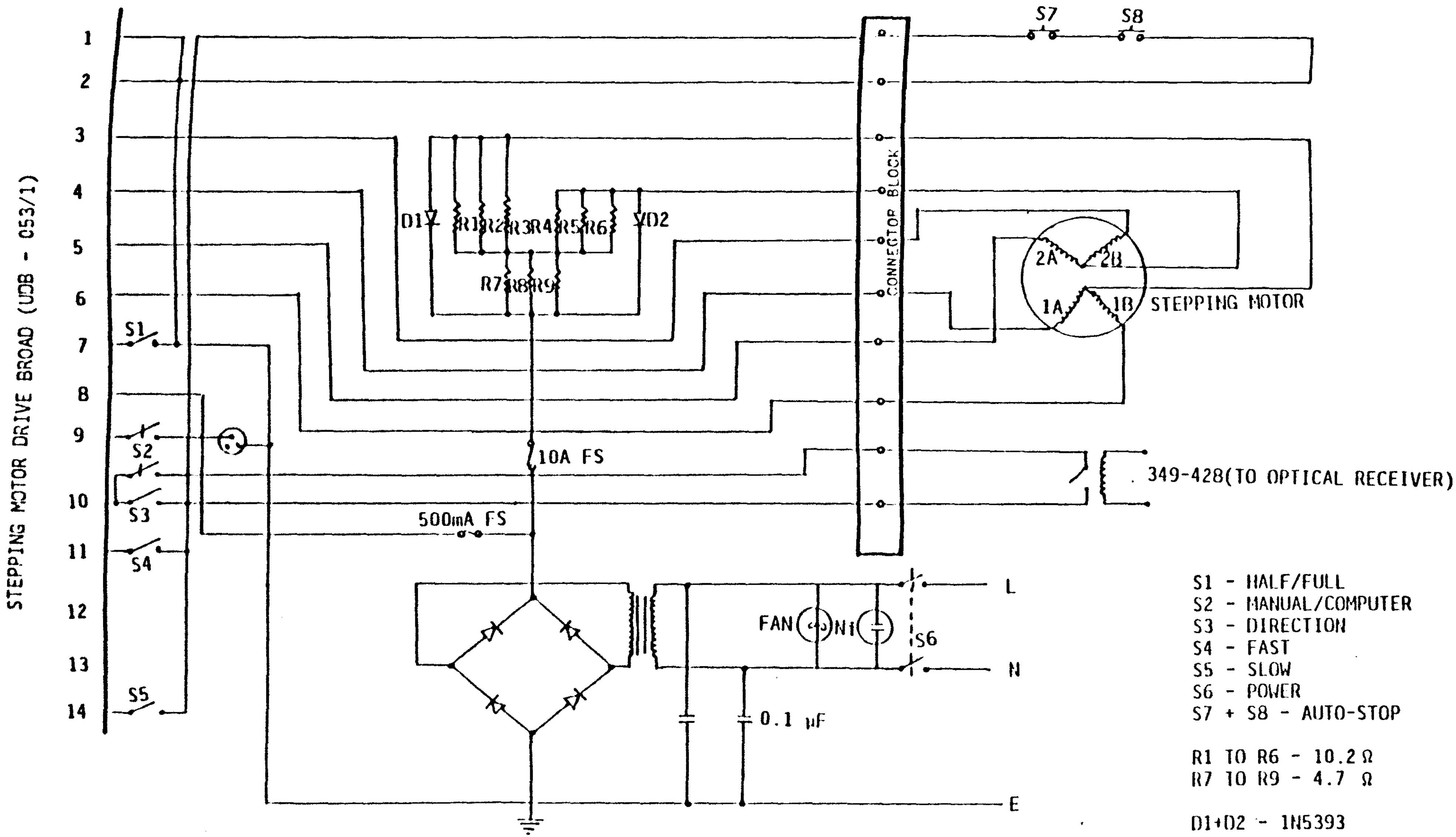


Fig.2.6 Stepping motor drive unit connections

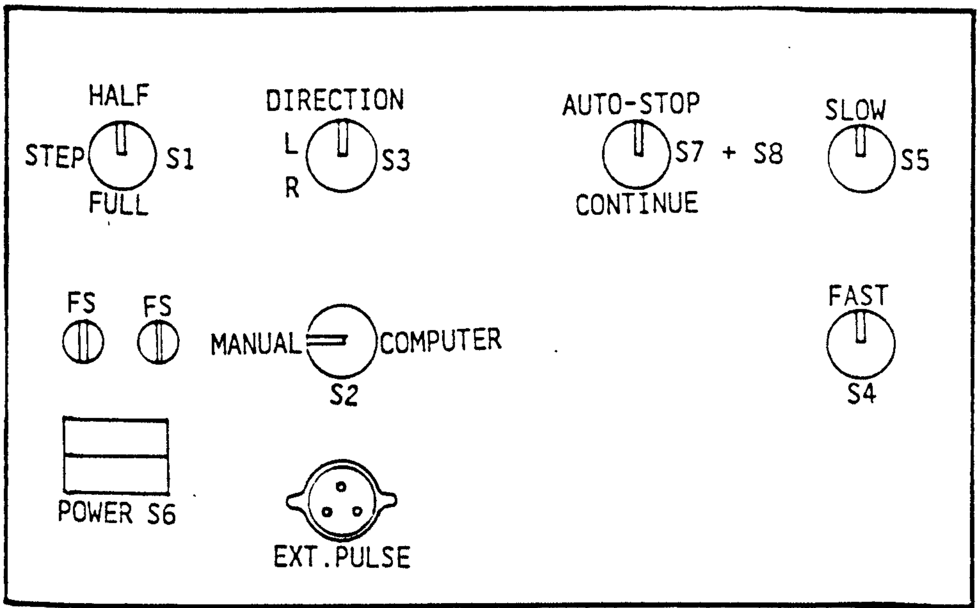


Fig.2.7 Front panel of stepping motor drive unit

S1 - HALF/FULL
S2 - MANUAL/COMPUTER
S3 - DIRECTION
S4 - FAST
S5 - SLOW
S6 - POWER
S7 + S8 - AUTO-STOP

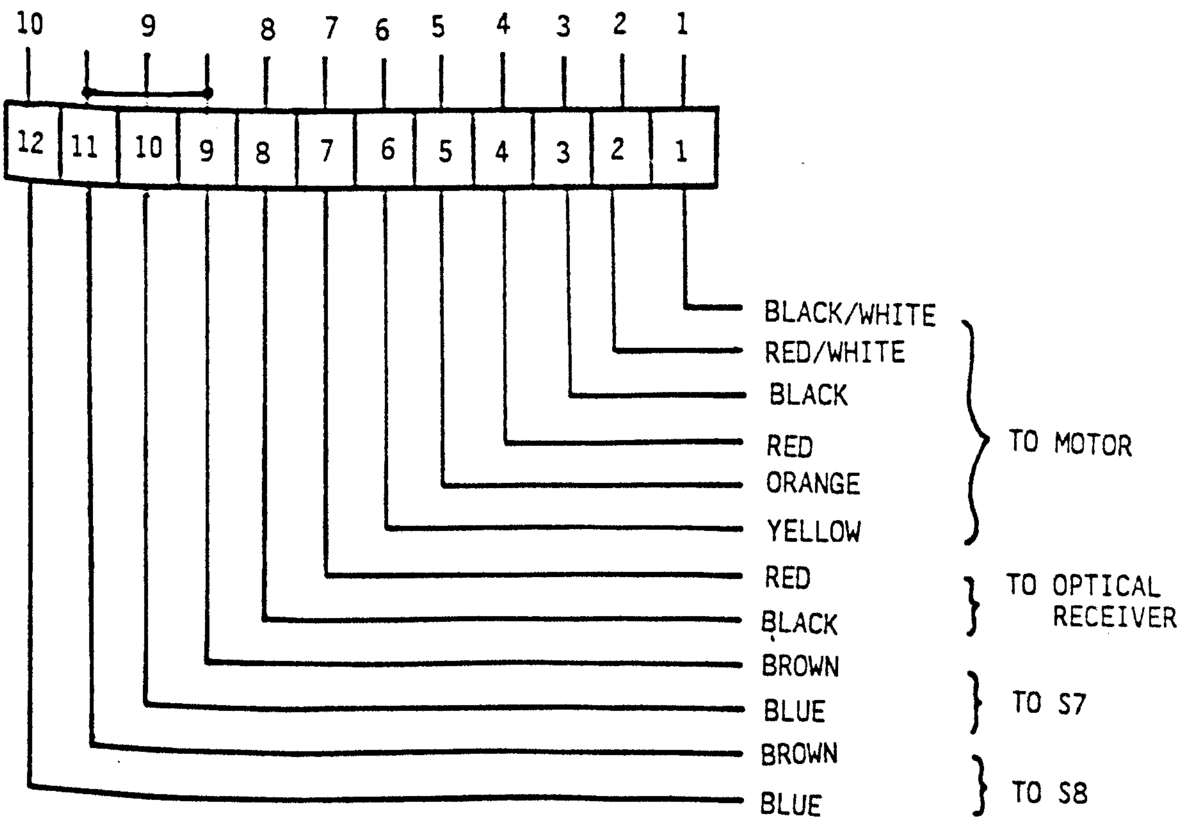


Fig.2.8 Terminal Block Connections

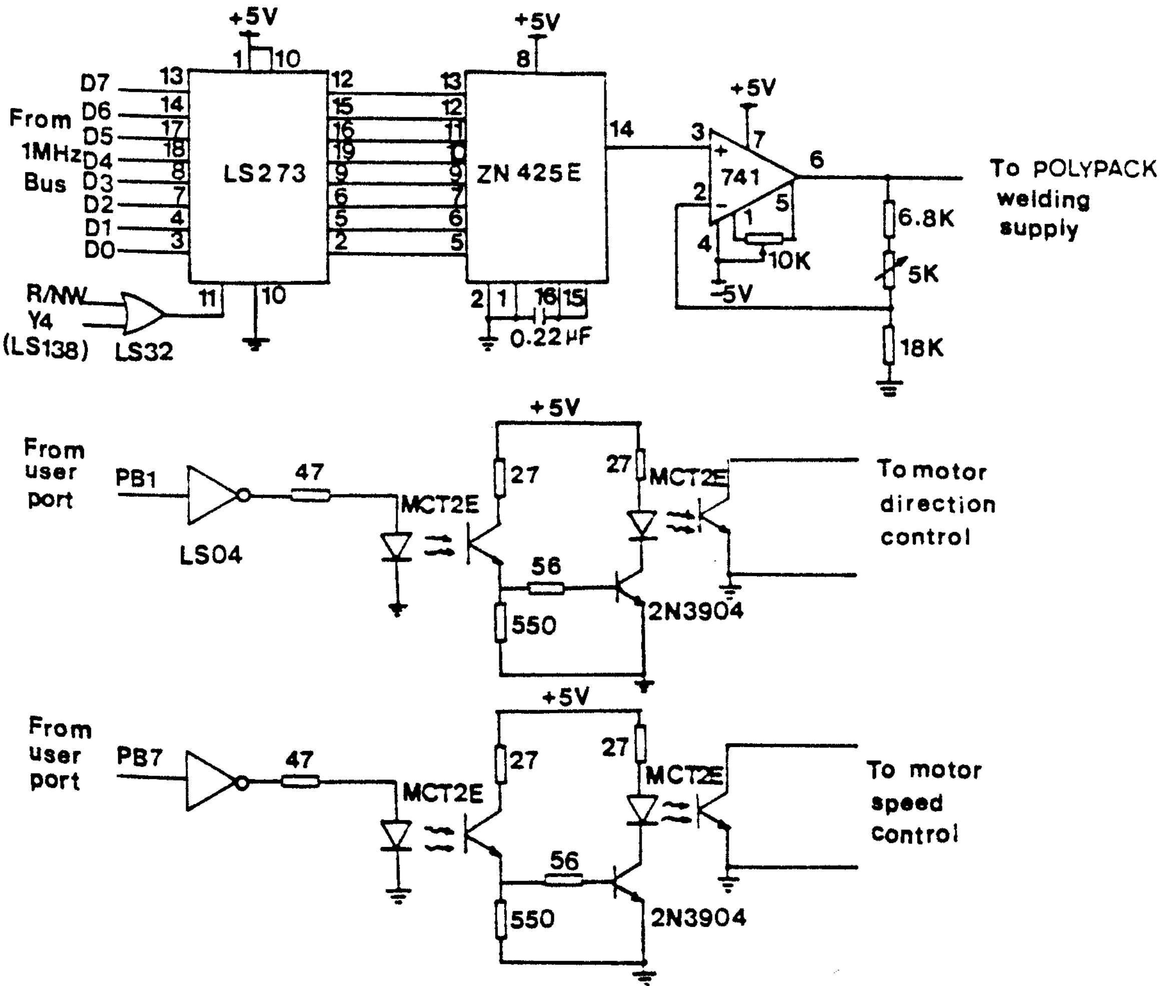


Fig. 2.9 Interface Circuit

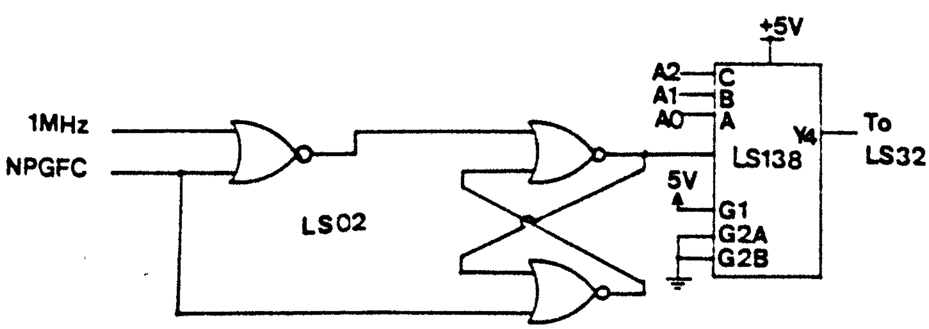


Fig. 2.10 NPGFC Clean up Circuit

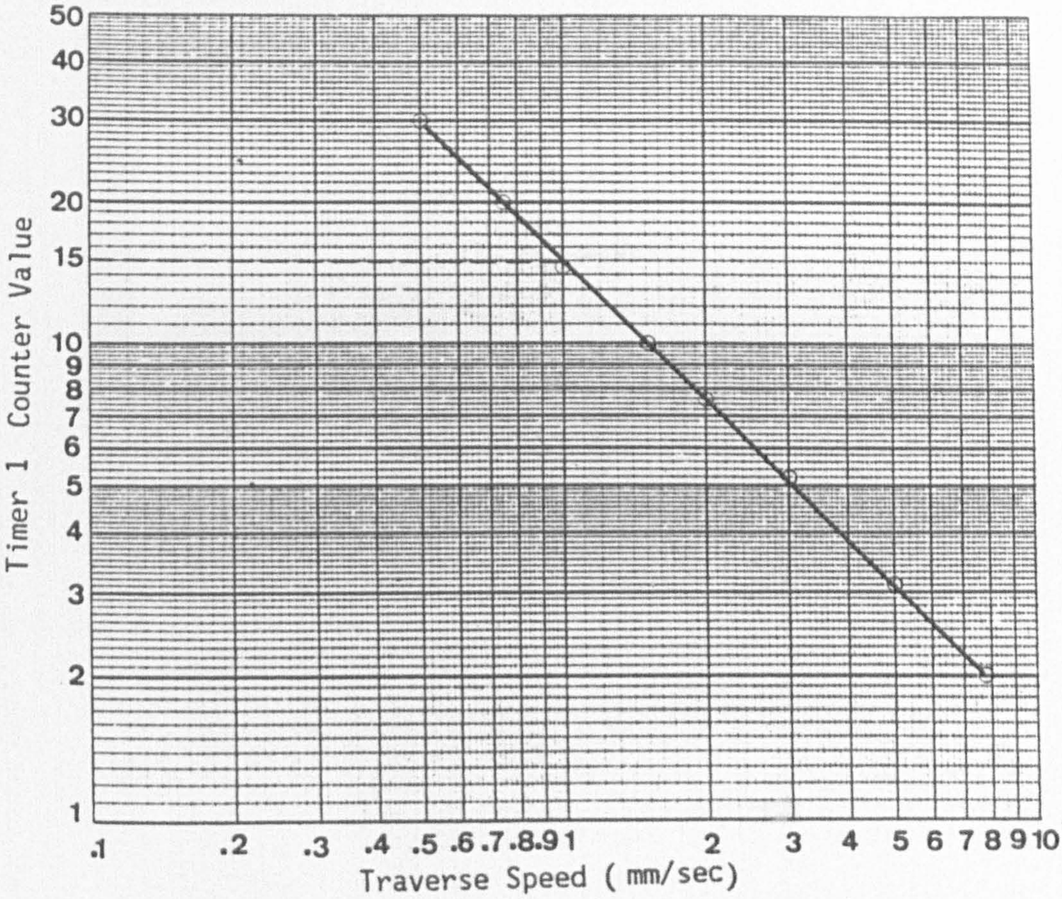


Fig.2.11 Graph of Counter Value Agains Traverse Speed

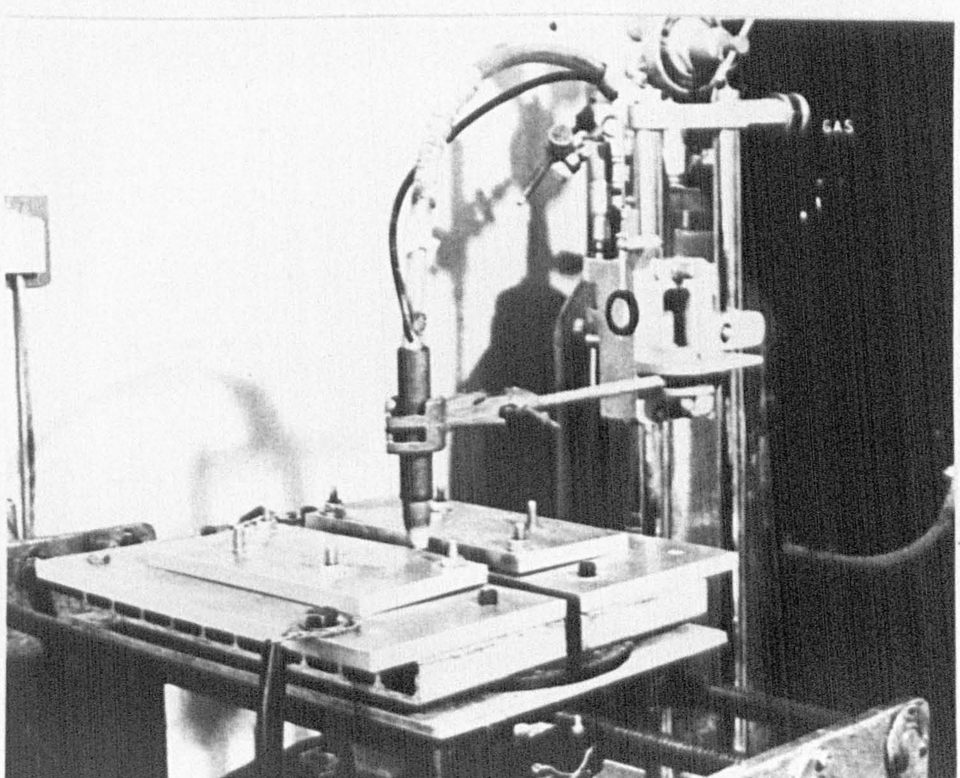
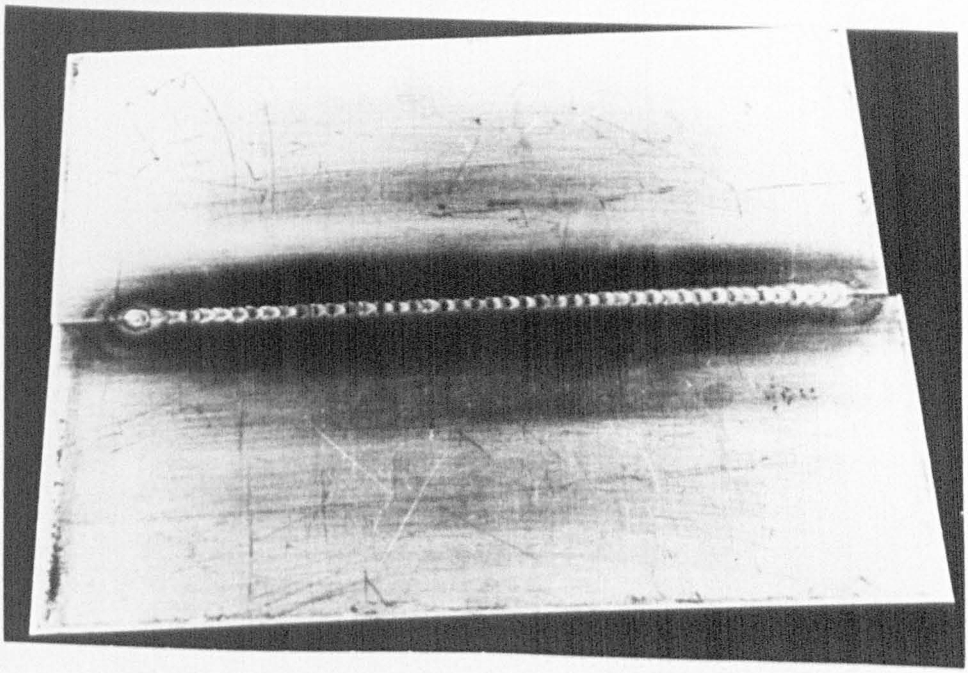
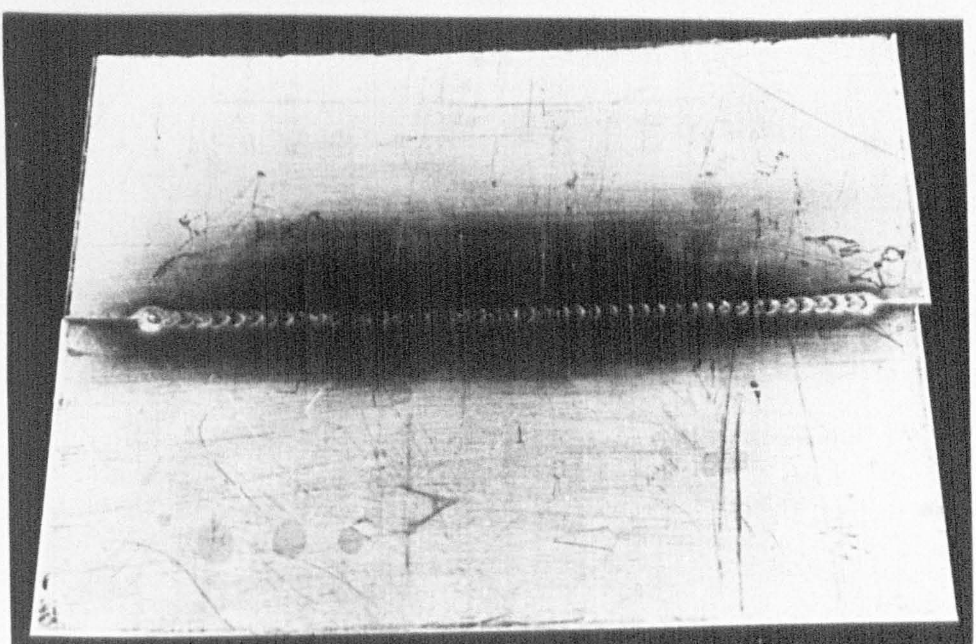


Fig.2.12 The Linear Welding System



(a) Test Weld - Front Face (40% overlapped)



(b) Test Weld - Back Face (proper penetrations)

Fig.2.13 Result of A Pulsed TIG Weld

CHAPTER 3 SUPPRESSIONS OF TRANSIENT INTERFERENCE

3.1 INTRODUCTION

It was shown in chapter 2 that a microcomputer can be interfaced to a welding system to control the welding process. Those initial tests were carried out on stainless steel plates which required only pulsed d.c. TIG welding. When these plates are replaced by aluminium plates, a.c. TIG welding is required. Due to the nature of a.c. TIG welding as described in section 2.2.2, the arc is maintained by means of a train of sparks generated by high frequency voltages, which produce destructive transient interference. It is this interference that can cause destruction, or malfunction, of small signal electronic circuits, such as the microcomputer and the peripheral devices.

Because small signal electronic circuits are designed for low switching levels to conserve power and reduce heat dissipation problems, they often cannot distinguish between a spurious transient and a legitimate signal. In an a.c. welding environment electronic devices can pick up interference by conduction, coupling, direct radiation, or any combination of the above. For these devices to operate reliably in such a noisy environment, the severe transients induced on power lines and cables or impinging directly on the facility must be reduced to an acceptable level. For this reason, a systematic approach to interference control is required in constructing an automatic welding system for a.c. TIG welding.

This chapter will describe the background theory of interference and propose a systematic approach to interference control.

3.2 TYPE OF INTERFERENCE

Interference is any extraneous electrical or electromagnetic disturbance that tends to interfere with the reception of desired signals or produces undesirable response in electronic systems. Interference can be produced by both natural and man-made sources either external or internal to the electronic system.

Interference is categorised as radio frequency interference (RFI) having high frequency, possibly high amplitude but low energy, and electromagnetic interference (EMI) characterised by low frequency and high energy [8].

Signals up to about 30MHz with a measurable high frequency voltage with respect to earth are conducted; above this frequency they can also be radiated as electromagnetic waves in free space.

Interference can be generated and distributed in a number of ways. Apart from the high frequency generator of an a.c. welding machine interference is also caused by switching surges generated when relays and switches are tripped, power dips from momentary power interruptions or a drop in voltage at the power source, and also transient voltage spikes from motor drivers, etc. This noise can enter equipment through routes other than the power cable. For example,it may come through signal cables or ground wires, or, indirectly, through the equipment case.

Elimination or reduction of interference to acceptable levels may be achieved by optical isolation, filtering, screening, grounding and careful routing of cables and layout of components.

3.3 INTERFERENCE COUPLING

The correct operation of electronic equipment depends on the frequencies and amplitudes of both the signals utilised in the system and the interference signals present in the facility. If the frequency of an undesired signal is within the operating range of the system, noise may be induced into the system. The extent of the system response is a function of the amplitude of the undesired signal relative to that of the desired signal. For example, in systems operating with high level signals, undesired signals with amplitudes of the order of volts may be tolerable, while in low level systems noise of the order of volts may produce intolerable errors in the response of the system.

Interference coupling is the stray coupling between circuits which produces an error in the response of one of the circuits. The possible sources of spurious signals and the mechanisms by which this interference is coupled into a susceptible circuit must be understood in order to guard against interference pickup by sensitive signal circuits.

The techniques for reducing pickup depend on the type of interference present. Interference is broadly classified by its coupling means, i.e., as either being conductive or free-space. Conductive coupling occurs when the interfering and interfered circuits are physically connected by a conductor and share a common ground. Free-space coupling occurs when a circuit or source generates an electromagnetic field that is either radiated and then received by a susceptible circuit or inductively or capacitively coupled to a susceptible circuit.

3.3.1 CONDUCTIVE COUPLING

Electrical cables entering an equipment provide good conductive coupling paths from interference sources external to the equipment. This interference can easily be conducted into a particular unit via the mains supply. There are two types of interference on the a.c. power lines, one is known as the common-mode (interference between either line and ground), and another is known as the transverse-mode (interference between live and neutral) [9].

Also, interference can be conductively coupled between the various circuits inside the equipment and the common d.c. power lines. If one d.c. power supply is utilised with several circuits operating over various signal voltage and frequency ranges, the operation of one circuit may adversely affect the operation of other circuits.

Another set of paths for conductive coupling of interference is offered by the signal lines. Signal lines can conductively couple interference into equipment and circuits as readily as power lines, particularly, when small signal circuits are interfaced to heavy current machines. Small variations in the relatively large current drawn by the machine can produce severe interference to electronic circuits.

The signal reference ground is another potential coupling path for unwanted signals between circuits. Since practical signal reference grounds do not exhibit a zero impedance, any current flowing in a signal reference ground will produce potential differences between various points on the reference ground. Interfacing circuits related to these various points can experience conductively coupled interference as shown in fig.3.1.

The signal current i_1 flowing in circuit 1 of fig. 3.1 returns to its source through signal reference impedance Z_R producing a voltage drop, E_{n1} in the reference plane. The impedance Z_R is common to circuit 2, hence E_{n1} appears in circuit 2 as a voltage in series with the desired signal voltage source, E_{s2}. This undesired source produces an interference voltage, V_{n2}, across the load of circuit 2. Similarly, the desired current, i_2 in circuit 2 will produce interference in circuit 1.

3.3.2 FREE SPACE COUPLING

Free space coupling is the transfer of electromagnetic energy between circuits not directly interconnected by a conductor [10]. The characteristic of an electromagnetic field are determined by the source, the media surrounding the source, and the distance between the source and the point of observation. At a point close to the source, the field properties are determined primarily by the source characteristics. Far from the source, the properties of the field depend mainly upon the medium through which the field is propagating. Therefore, the coupling is usually defined as either near field or far field. Near field coupling can be subdivided into inductive and capacitive coupling according to the nature of the electromagnetic field. In inductive coupling, a magnetic field linking the susceptible circuit is set up by the interference source. Capacitive coupling is produced by an electric field between the interference source and the susceptible circuit. Far field, or radiation coupling, is the transfer of energy from a interference source to a susceptible circuit by means of electromagnetic waves propagating through space at a distance greater than half the wavelength, $\lambda/2\pi$

(1) Near Field Coupling

When wires are located near to each other, currents and voltages on one wire will be inductively and capacitively coupled to the other wire. The wire acting as the interference source for this near field coupling may be any conductor such as a power line, a control line, or a signal line. The current or voltages induced into the other wires can further be conductively coupled into susceptible circuits.

(a) Inductive Coupling

With reference to Fig.3.2 the magnetic field H surrounding a long, straight current carrying wire is the means for inductive coupling. The magnetic field strength surrounding the wire carrying the current, i, is inversely proportional to the distance, r, from the wire, i.e. H decreases as the distance from the wire increases. The magnetic field will induce a voltage into a nearby circuit.

(b) Capacitive Coupling

When signal conductors of two circuits are near each other a capacitance, C_c, exists between the conductors. The value of this capacitance is a function of the geometry of the signal lines. The interference source voltage produces a current flow through the mutual capacitance between the two signal conductors and develops an induced voltage in the susceptible circuit. This is illustrated in Fig 3.3(a) and the equivalent circuits for Fig.3.3(a) are given in Fig.3.3(b), (c) and (d).

(2) Far Field Coupling

The ratio of the electric field (E) to the magnetic field (H) is the wave impedance. In the far field, this ratio E/H equals the characteristic impedance of the medium (e.g. E/H=377Ω for air or free space) [10]. In the near field, the ratio is determined by the characteristics of the source and the distance from the source to where the field is observed. If the source produces a high current and low voltage (E/H < 377Ω) the near field is predominantly magnetic. Conversely, if the source has low current and high voltage (E/H >377Ω) the near field is predominantly electric.

For a predominantly magnetic field the wave impedance is low. As the distance from the source is increased, the magnetic field attenuates at a rate of $1/r^3$ and the electric field attenuates at a rate of $1/r^2$.

For a predominantly electric field the wave impedance is high. As distance increases, the electric field loses some of its intensity as it generates a complementary magnetic field. The electric field attenuates at a rate of $1/r^3$ whereas the magnetic field attenuates at a rate of $1/r^2$.

In the far field, both the electric and magnetic fields attenuate at a rate of 1/r. Outside the near field region, radiated energy that has escaped is propagating away from the antenna, or source, through space. Energy radiation can be visualised by considering the finite time required for the electromagnetic fields to propagate between two points in space. Current flows through an antenna at the frequency of the applied signal, and the polarity of the field produced by this current is reversed at the same frequency. When positive charge is present at one end of the antenna, an equal negative charge is present at the other end and an electric field in the vicinity of the antenna will be established between the charges.

As the current changes directions, the charges will reverse positions, the electromagnetic field will collapse and be re-established in the opposite direction. If the frequency of the applied signal is low, sufficient time will exist between reversals for practically all the energy stored in the field to be returned to the circuit and very little radiation will occur. If however, the frequency is high and the charges reverse quickly, a field in the opposite direction is formed near the wire before a substantial amount of the field energy can return to the circuit. This part of the field is thus separated from the antenna and propagates outward through space as an electromagnetic wave.

In a reciprocal manner, wires and conductors located in a radiated field have currents induced in them and act as receiving antennas for incident electromagnetic energy. These induced currents in the wires can then be conducted into associated signal circuitry as interference. The amplitude of the resulting interference depends on the strength of the electromagnetic field in the vicinity of the wire and on the efficiency of the wire as an antenna.

3.3.3 COMMON IMPEDANCE COUPLING

Common impedance coupling occurs when currents from two different circuits flow through a common impedance. The voltage drop across the impedance seen by each circuit is influenced by the other. An example of this type of coupling is shown in Fig.3.4. The ground currents 1 and 2 both flow through the common ground impedance. As far as circuit 1 is concerned, its ground potential is modulated by ground current 2 flowing in the common ground impedance. Some noise signal, therefore, is coupled from circuit 2 to circuit 1 through the common ground impedance.

3.4 METHODS FOR INTERFERENCE SUPPRESSION

When there is an interference problem, there is always a source of the noise. In order for a noise source to cause interference there must be a coupling path between the noise source and the susceptible device. Therefore, interference can be reduced by isolating the source of noise, by filtering the interference out of the susceptible device, and by reducing the coupling between signal systems by modifying the signal systems in such a manner that interaction between the systems does not produce interference in either one.

The primary methods available for combating interference are listed below:

(1) Filtering

(2) Isolation

(3) Shielding

(4) Grounding

(5) System Orientation

3.4.1 FILTERING

Although interference may be manifested in several ways, in most cases the resulting interference currents are the major sources affecting the system. Unfortunately, it is virtually impossible to prevent interference current from flowing between two points which are connected by a conductor, so a possible approach to the problem is to divert the interference current away from the signal paths using filters.

An interference filter is intended to act as an impedance mismatch network which filters out high frequency signals and absorbs transient energy. It generally consists of a set of passive components which provide unwanted interference signals with a high series impedance into the equipment and low shunt impedance to the ground.

Resistor-capacitor (RC) and inductor-capacitor (LC) decoupling networks can be used to perform filtering actions between circuits, or to keep power supply noise from entering the circuit. The bandwidth of a filter is depended upon the values of R and C, or L and C.

The RC filter is a dissipative filter, in which the undesirable noise voltage is converted to heat and eliminated as a noise source. The LC filter is a reactive filter, in which the noise voltage is just removed from across the load impedance. The LC filter, however, has a resonance frequency,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{3.1}$$

at which the signal transmitted through the filter may be greater than if no filter was used. Thus, it can attenuate the noise voltage by keeping this resonant frequency well below the passband of the circuit connected to the filter. The amount of attenuation in an LC filter at resonance is inversely proportional to the damping factor

$$\xi = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{3.2}$$

where R is the resistance of the inductor.

There are various type of filters available and they need to be carefully selected for particular applications.

(a) Mains Filter

Mains filters are interposed between the power input to the equipment and subsequent circuits so that they prevent interference energy being fed from the supply and also to prevent interference generated within the equipment from being fed back to the supply line.

There are two ways in which an interference signal can be propagated. In the symmetrical or differential mode, the interference signal travels down one line of the supply mains and returns via the other line. In the asymmetrical or common mode the interference signal flows down both the live and neutral lines as if they were one, and returns via the earth.

A basic mains filter generally consists of a inductor in series and a capacitor in parallel across the supply line forming a low-pass filter network. The network attenuates interference energy above 10KHz, while passing the 50Hz power to the equipment.

In a basic mains filter of fig.3.5 the inductor behaves as a low impedance to low frequencies and a high impedance to high frequencies, effectively blocking them and absorbing their energy. The capacitor acts in a reverse way and blocks low frequencies whilst passing high frequency currents. Both inductance and capacitance are related to frequency and hence the performance of the filter increases as the frequency increases.

Better performance mains filters normally employ toroidal wound inductors having balanced winding connected, so their currents produce opposing flux in the core preventing saturation and reducing their effects of any out of balance signal. Filters with this feature (fig.3.6) provide better filtering action by returning differential mode signal to the supply path and dissipating common mode signal to earth through capacitors.

Mains filters as described will protect against most spikes and interference noise. Occasionally, however, a very high voltage spike can saturate the inductors in a filter and so get through. This can be prevented by selecting filters with built-in transient suppressors at the filters input terminals.

Transient suppressors are solid state voltage dependent resistors. They let no current pass under normal conditions, but will conduct at high voltages. If such a suppressor is fitted to a filter, it will conduct the high voltage part of a spike to earth, effectively clipping its peak. The filter then deals with the remainder of the spike.

Care must be taken in locating the mains filter in an equipment. Filters need to be as close as possible to the power cable entry. Ideally, the filter should be the first component the power cable encounters when it passes through the equipment frame. The filtered output wiring should be kept from the input wiring, and a perfect grounding of the filter case is necessary. Filters fitted with transient suppressors need to be installed so that the suppressors face the source of noise. Normally this means that the suppressors face the mains, but if the filter is being used to isolate noisy equipment, such as an a.c. welding supply, the suppressors should face the equipment.

(b)Signal Filter

Apart from power line pollution, interference picked up by other control cables or signal lines can also cause problems for computer and other digital circuits because certain kinds of extraneous electrical pulses can be interpreted as data or instructions, causing errors in operation. The degree of sensitivity depends somewhat on the type of equipment and the type of disturbances. In the a.c. welding environment high frequency noise can be either radiated through air from the welding arc or conducted directly through the power cables and control lines. Digital electronic equipment becomes a prime receiver of high frequency noise. In order to ensure clean signals flow in a noisy environment, as well as using mains filters, small signal filter are also required for the input and output of a signal link between equipments. This type of filters, either active or passive, is often in the form of a RC circuit.

3.4.3 GROUNDING

In the welding environment, grounding serves as not only to establish a ground reference level, but also to minimise unwanted noise and pickup of interference. Proper use of grounding and shielding, in combination, can solve a lot of interference problems. A good grounding system must be designed just like the rest of the circuit. The grounding principles are just as applicable to large complex electronic systems as they are to individual circuits on a single wiring board. Grounding, if used improperly however, can become a primary source of interference coupling [11].

There are two basic objectives involved in designing a system grounding. The first is to minimise the noise voltage generated by currents from two or more circuits flowing through a common ground impedance. The second is to avoid creating ground loops which are susceptible to magnetic fields and differences in ground potential.

Generally, signal circuits are grounded for safety and to provide an equipotential reference for signal voltages. There are two main types of grounding options: (i) single point grounds, and (ii) multipoint grounds. These schemes are shown in figs. 3.7.

(A) SINGLE POINT GROUNDING

A single point grounding is one in which separate ground conductors extended from one point on the earth electrode to the numerous circuits (fig.3.7(a)). An important advantage of this configuration is that it helps control conductively coupled interference. As long as wiring distance are less than $\lambda/10$ at RFI frequency the single point ground is desirable [12].

The limitation of this configuration occurs if long conductors are required in a large installation. Long conductors introduce large self-impedances at high frequencies and produce inductive coupling between the ground conductors. Stray capacitance between the ground leads also allows coupling between grounds.

When single point grounding connections are employed, ground leads should always be kept as short as possible to prevent inductive or capacitive interference coupling.

(B) MULTIPOINT GROUNDING

Multipoint grounding uses many conductive paths from the earth counterpoise to the various system. With each system, circuits are multiply connected to the nearest available low impedance ground. Multipoint grounding frequently simplifies the circuit construction inside complex equipment. This method can be used to minimise the ground impedance at high frequencies, particularly above 10MHz [13]. However, it suffers from an important disadvantage. Because of the large number of closed loops in a multipoint ground, the 50Hz power currents flowing through the ground system can conductively couple into signal circuits to create intolerable interference.

Normally at frequencies above 10MHz a multipoint grounding system is preferable; below 10MHz, a single point grounding system can be used provided the length of the longest ground conductor is less than $\lambda/10$.

In the a.c. welding system the noise source is at about 5MHz which gives λ=300,000/f KHz = 51m. If the ground leads are kept less than 10m, single point grounding can be used.

3.4.4 ISOLATION

It has been mentioned previously, interference signals not only come from the mains supply but also are coupled from control cables and ground loops. It is, therefore, necessary to apply isolation methods to prevent interference signals flow between each system units.

(a) Isolation Transformer

Because of the interference threat that stray power currents pose to control circuits, steps must be taken to isolate these currents from signal return paths. Obviously, one way of reducing the effect is to configure the power return using an isolation transformer, so that the neutral does not share a path in common with the signal system.

Isolation transformers are best suited for controlling power line common mode noise. These interference signals are generated between the power line conductors and the ground plane. They can be both high frequency and low frequency. The control process consists of directing noise current flow by using an interposing electrostatic shield tied to the ground.

(b) Optical Isolations

Another way to break the ground loop between circuits and prevent interference coupling is to use fibre optics and optical couplers. In an optical system, signals are transmitted in the form of photons which have no electrical charge and, therefore, cannot be affected by the electromagnetic fields as experienced in EMI environments.

Fibre optics can offer solutions to EMI coupling and crosstalk problems associated with electrical hard wired systems (fig.3.8). It is ideal to use fibre optics as a communications medium between the noisy equipment such as the welding power supply and the microcomputer. The command signals from the microcomputer can be converted into light waves by a light emitting diode (LED) which sends the light down the fibre optic cable. At the other end of the cable, a detector converts the light waves back into electrical signals for controlling the welding power supply. Thus, the welding power supply and the microcomputer are electrically isolated and conductive interference coupling from the communications link is precluded.

Optical couplers are especially useful in digital circuits. The basic optical coupler consists of a LED optically coupled to a photo transistor. Both devices are contained in the same package (fig.3.9). This type of circuit gives almost perfect isolation against any difference in ground potential.

3.4.5 SHIELDING

In solving conductive interference coupling problems, radiation should also be considered. According to the a.c. welding specifications, the space all around the weld zone at a distance of 50 feet in all directions is referred to as the high field intensity zone. To minimise unwanted noise pickup from radiation all equipment and signal links in this zone should be shielded. Shielding provides a barrier between the external environment and the internal environment; when properly designed and implemented, it offers significant wideband protection against radiation.

(a) Shielding of Devices

An ideal shielded enclosure should be a conductive seamless construction with no openings, in order to prevent outside fields from penetrating equipment and to prevent internally generated noise from escaping the enclosure. Unfortunately, an ideal shield enclosure is never achieved, because of ventilation openings, doors and covers, cable-through holes, and connectors. The effectiveness of a device depends upon a number of parameters, the most notable of which are the frequency and impedance of the impinging wave, the shield materials, and the number and shape of shield discontinuities. For practical considerations in designing an enclosure, the following need to be noted:

(1) The number and size of openings should be kept to the minimum compatible with their functions.

(2) Ventilation openings or slots need to be covered with perforated grids.

(3) Continuous electrical contact should be maintained between grids and chassis.

Metal covers are normally considered to be the best shielding material. Steel is preferable to aluminium or copper due to good absorption loss provided its thickness is greater than 1mm. Below that thickness, aluminium or copper make equivalent or better shields, because of their superior conductivity.

(b) Shielding of Lines

Shielding is required not only for device enclosures, but also for many of the cables which connect the various devices. Interference may be radiated from a cable or transferred by radiation or common impedance circuit elements into a cable circuit. It can be conducted through interconnecting cables to the other devices. Because of close proximity in cable runs, inter-cable crosstalk may occur as a result of electromagnetic transference between cables.

Several types of shielded cables are available. These include: shielded signal wire, shielded multiconductor, shielded twisted pair, and coaxial. Cables are also available in both single and multiple shields in many different forms and with a variety of physical characteristics. In practice, where a high degree of shielding is needed, cables with multiple shields separated by insulation should be used. Overall shields for multipair cable should not be used for signal return paths. All individually shielded signal circuits should have insulating sleeves or coverings over the shields. Coaxial cables carrying high energy level signals should not be bundled with unshielded cables or shielded cables carrying low level signals. Grounding a number of conductor shields to a connector by means of a single wire should be avoided. Such a single wire acts as a common impedance element across which an interference voltage can be developed and transferred from one circuit to another.

3.4.6 SYSTEM ORIENTATION

There are three major considerations for interference control in the system orientation.

1. Suppressing Source of Interference

(a) Ensure the welding power supply is properly shielded.

(b) Filter the power supply cables connecting to the mains.

(c) Shield the welding cables.

2. Eliminating Interference Coupling.

(a) Twist low level signal leads.

(b) Place low level leads near chassis.

(c) Shield signal leads using coaxial cables.

(d) Shielded cables used to protect low level signal leads should be grounded at one end only.

(e) Keep the length of signal leads as short as possible.

(f) Avoid common ground leads between the welding supply and electronic devices.

(g) Keep ground leads as short as possible.

(h) Separate signal leads from the welding cables.

(i) Place electronic circuit boards in shielded enclosures.

(j) Filter or decouple any leads entering enclosures containing sensitive devices.

(k) Use fibre optics to break ground loops.

3. Reducing Interference at Equipment

(a) Use mains filters or isolation transformers for power supplies.

(b) Separate signal and hardware grounds.

(c) Use filters and optical couplers when applicable.

(d) Use shielded enclosures.

It should be realised that noise voltage usually needs to be minimised to the point where it is no longer comparable with the signal. In all but the simplest cases, a single unique solution to the noise reduction problem may not exist. Compromises are generally required, and there is usually more than one technique by which the noise objective can be met.

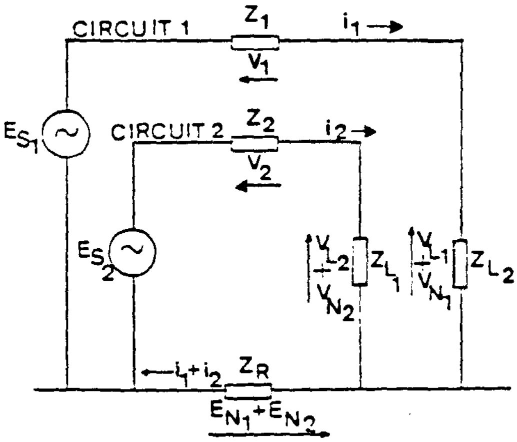


Fig.3.1 Coupling Between Circuits
by Common Return Path Impedance

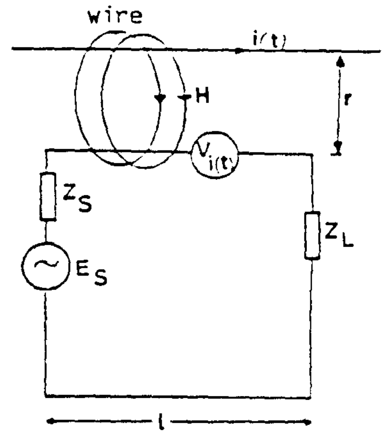
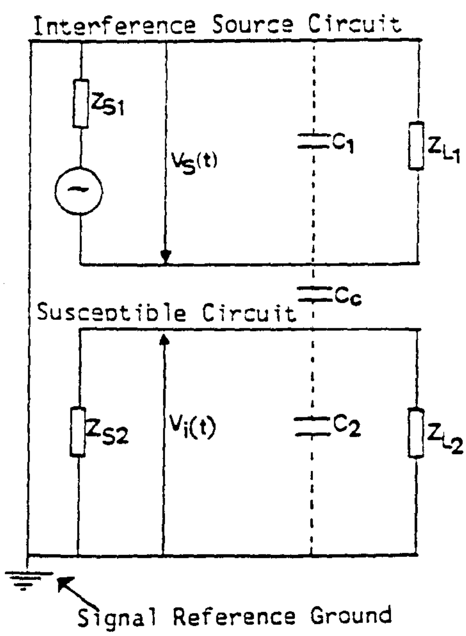
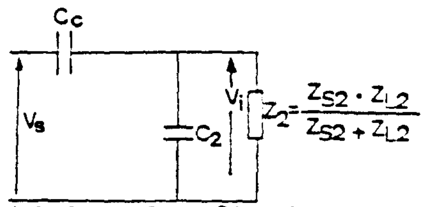


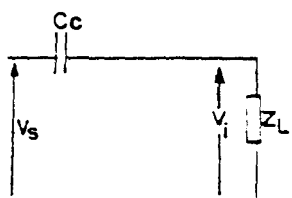
Fig.3.2 Inductive Coupling



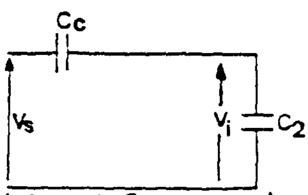
(a) Coupling Between Circuits
by Mutual Capacitance



(b) Equivalent Circuit



(c) Low Frequency Approximation



(d) High Frequency Approximation

Fig.3.3 Capacity Coupling

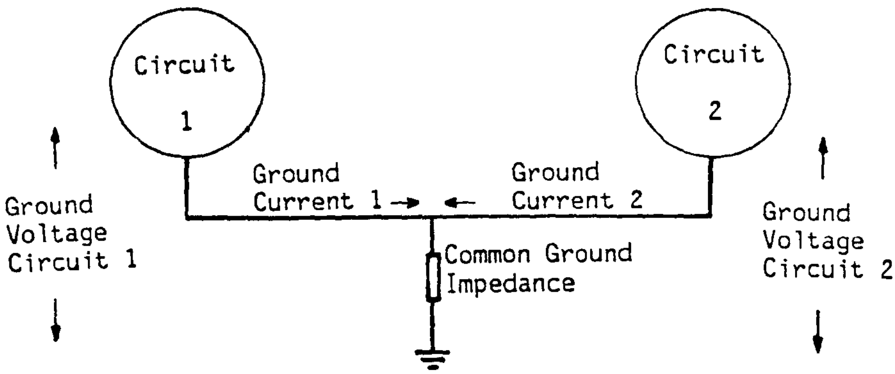


Fig.3.4 Common Impedance Coupling

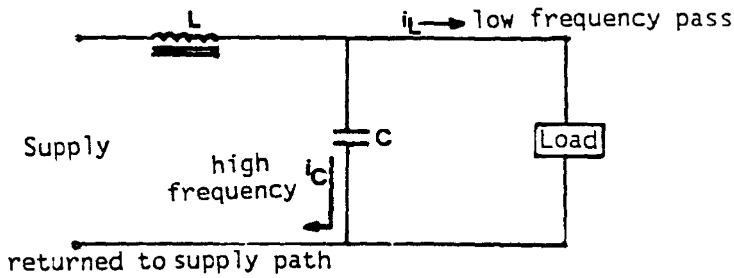


Fig.3.5 Basic Features of a Mains Filter

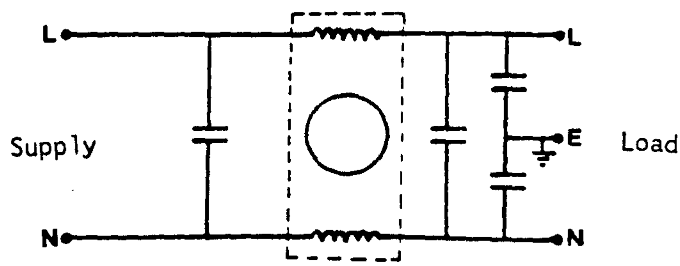
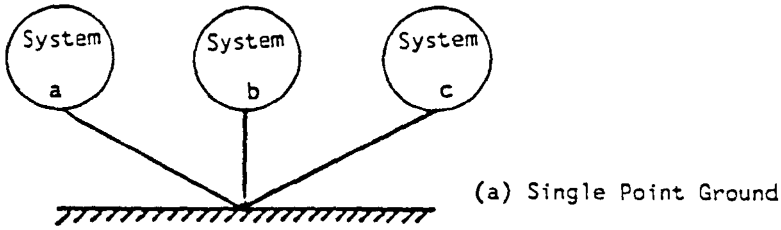


Fig.3.6 Mains Filter with Inductors using Balanced
Windings on a Toroid Core



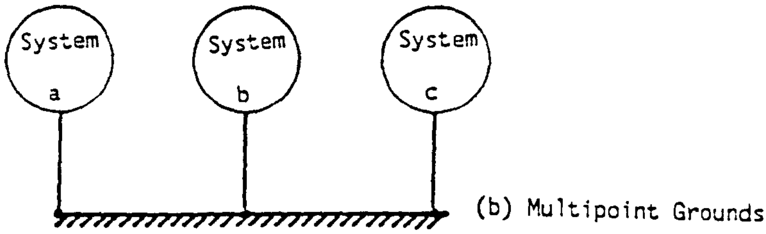


Fig.3.7 Grounding Connections

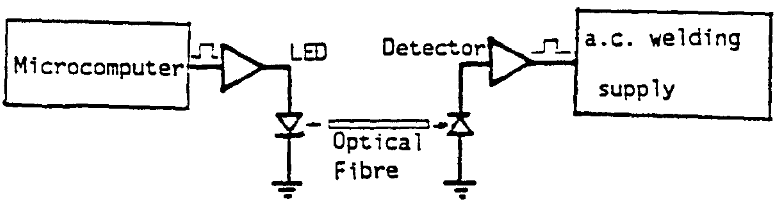


Fig.3.8 Optical Fibre Link

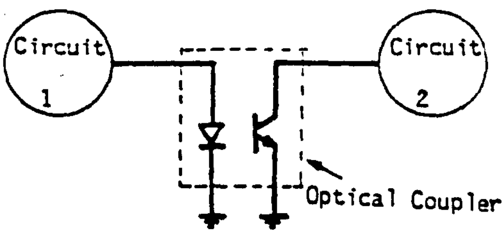


Fig.3.9 Optical Isolator

CHAPTER 4 AN EXPERIMENTAL ALUMINIUM WELDING SYSTEM

4.1 INTRODUCTION

The causes of EMF interference and some methods for the suppression of that interference have been presented in Chapter 3. This chapter shows how these methods can be implemented and also describes experiments on aluminium welding.

4.2 CONCEPT

The first steps in solving interference problems include determining the source of the interference and then how the source of the interference and the susceptible devices are coupled.

It has been pointed out that the main source of interference in an aluminium welding system is the high frequency generation unit in the welding power supply [14]. This device enables the arc to be ignited without touching the electrode onto the workpiece, thus preventing electrode contamination. It also maintains the a.c. arc by continuous re-ignition when zero crossing occurs at every half cycle of a.c. current.

The high frequency generator of an a.c. welding power supply consists of an iron-cored transformer with a high voltage secondary winding, a capacitor, a spark gap between oscillatory circuits, and an air core transformer, one coil of which is in the high voltage circuit and the other is in the welding circuit (Fig.4.1(a)). The capacitor is charged every half cycle to 3000-5000V and discharged across the spark gap. The discharge sets up oscillatory currents in the welding circuit and these are superimposed on the welding current (fig.4.1(b)) thus maintaining the arc. It is this oscillatory current which is a source of electrical noise.

Once the high frequency unit is turned on, noise is coupled back to the mains as well as to other circuits; thus, any sensitive electronic equipment which shares the same mains supply, is interfaced to the welding machine, or placed nearby, may be subjected to damaging spurious voltages. Interference can also be coupled by direct radiation from the a.c. arc. To overcome these problems, several methods in reducing interference were considered.

A block diagram of the a.c. welding system is shown in fig.4.2. It is similar to the system described in Chapter 2, but, the differences are the welding machine is replaced by an a.c. welding source and the microcomputer is electrically isolated from the high current equipment using fibre optics. This experimental system was designed with the objective of finding methods to suppress interference, in order to ensure computer control of the welding process in the a.c. welding environment. Once these methods are considered to be acceptable a more complex automatic welding system, using a three or more axis robot with larger memory controller and adaptive sensors, may be developed using the same principles.

4.3 EVALUATION OF INTERFERENCE PROBLEMS

Prior to starting system development, preliminary tests were undertaken to locate the sources of interference, in order to use a systematic approach for the evaluation of interference problems.

4.3.1 PRELIMINARY TESTS

To confirm the assumptions of interference problems which may encountered in an a.c. TIG welding system, the system was first set up without any methods of interference suppressions. Preliminary tests were performed by switching on both the microcomputer control unit and the stepping motor drive unit, whilst keeping the a.c. welding power supply off, to confirm correct operation of the system. The two units were then switched off and only the a.c. welding power supply was switched on, in order to ensure that the system could be used at least for manual welding. The next step for the test was to use the microcomputer to control the a.c. welding power supply in such a way that, if a 'START' command is typed in, the a.c. welding power and the high frequency generator were switched on, and this will continue to be the case until a 'STOP' command is entered.

Prior to starting tests, the torch was clamped away from the workpiece to prevent arc ignitions. Hence, if the a.c. welding power supply is switched on, no welding current will flow without the arc being ignited, and only the high frequency generator can produce oscillatory signals to the torch. It is these oscillatory signals which are of interest for finding out the source of interference problems.

When the test was started, the welding rig began vibrating and produced mechanical noise as soon as the a.c. welding power supply was switched on. The monitor screen showed 'snow' effects and unexpected characters. The 'STOP' command was not able to terminate the a.c. welding power supply as the control program had been destroyed. The system was eventually switched off manually. It was evident that the high frequency generator acted as the source of interference to those electronic circuits. It was obvious that the interference could couple through power cables and signal lines and cause problems, but the effect of the radiated interference also needed to be investigated.

To evaluate the severity of the radiated interference a battery operated digital counter with LED display was placed close to the torch but with no physical connections to the system. The counter was set for continuous display in the sequence from 0 to 9. When the high frequency generator was switched on, the counter display jammed and ceased to operate in sequence. However, after the counter was reset and placed into a screened diecast box, it operated correctly.

Preliminary tests proved that the approaches to transient interference problems must be considered before carrying out any welding of aluminium. Considerations for the suppression of transient interference included the selection of mains filter, the design of system grounding and device isolation, and the use of shielding technique.

4.3.2 REDUCING POWER DISTURBANCE

One of the major interference problems with the system was the a.c. power supply disturbance. If power disturbance was not considered in the basic design, the effect of mains-borne noise could cause system malfunctions. One way to reduce power supply disturbances is to use mains filters, which prevent transients being fed onto the mains and also supplying filtered power to the equipment.

In this experiment, three different types of mains filters were used, one connected to the welding supply unit which suppressed transient signals feeding back to the mains power supply, and the other two connected to the microcomputer control unit and the stepping motor drive unit to prevent transients from reaching the equipment.

The filter used for blocking transients feeding back to the mains is a high performance power filter (type no. L1826TS) produced by Belling Lee Intec Ltd. It is a 2-line filter fitted with transient suppressors providing 100dB attenuation at frequencies from 200KHz to 10GHz and protection against transient interference. The maximum operating current is 100A which is compatible with the AAC350 welding supply having a maximum input current of 98A. The effect of introducing this filter on the mains signal is shown in fig.4.3. These results were taken at a phase line input to the welding machine. Fig.4.3(a) shows the high frequency signal at the frequency of about 5MHz with the amplitude of ±200V of the mains voltage, where (b) and (c) are the results of before and after filtering. It is clear that adding a filter to the power input effectively suppresses high frequency transient signals being outputted from the welding machine, thus protecting the other equipment sharing the same mains supply.

In practice, power line disturbances also come from many other sources which cause interference. The fluctuations of the mains voltage often cause problems with electronic equipment. It is, therefore, necessary to protect such equipment using the same technique of filtering and transient suppressing. In the welding control system, a 15A 2-line mains filter (Y20947) was fitted for the microcomputer control unit protecting the BBC microcomputer and its peripherals. This filter is suitable for general purpose suppression over a wide frequency range from 80KHz to 100MHz and also incorporates a transient suppression device in the form of a voltage dependant resistor. Another mains filter fitted to the stepping motor drive unit is a 10A mains filter (RS 238-441) designed to filter mains borne interference in a frequency range 150KHz to 30MHz.

The above filters were selected to meet individual application requirements. The selection of filters was based on the frequency bandwidth of the interference, input current, attenuation, permissible leakage current, construction preference, and the cost for the application.

4.3.3 SYSTEM GROUNDING

Another way to reduce transient interference is the consideration of proper grounding. While grounding techniques can solve some transient interference problems, many transient interference troubles occur because of uncontrolled grounding configurations which create ground loops. Fig.4.4 shows the grounding configuration of the a.c. welding system.

The design of the system grounding was based on the concept of single grounding as the main components of the system were connected close together. With this concept, the three system units are all referenced to a single point, and this single point is then connected to the facility ground. Thus, closed path for interference currents in the signal ground network are avoided, and the interference voltage in the a.c. welding unit ground is not conductively coupled into other signal circuits via the signal grounds.

A ground loop can be formed when both ends of a circuit are grounded, as in the example of fig.4.5. The loop can be broken by using isolation methods.

4.3.4 ISOLATION AND SHIELDING

For isolating the computer and other electronic circuits from the noise source, isolating transformers, fibre optics and opto-isolators were used.

To achieve a greater degree of interference reduction, shielding techniques were applied. Fig.4.6 shows that the optical transmitter and receiver were housed in two separated diecast boxes which were earthed. The stepping motor drive board and switching control circuit were placed inside an earthed aluminium cabinet with ventilation holes screened by a copper wire mesh. The stepping motor drive unit was placed very close to the welding rig to provide easier operation for the welder. Therefore, it must be shielded correctly against radiation from the welding arc.

The welding current supply and current return cables are typical examples of interference radiators, and other signal and logic cables are the receivers of interference. In order to ensure system operation within the high field intensity zone, shielding of cables and devices is essential.

4.4 HARDWARE

Fig.4.7 shows the system hardware, in which the welding unit is the AAC350 Argonarc a.c. welding power supply. The unit has a self-contained high frequency generator, argon and water valves, fitted with a delay control, and a welding contactor. The welding contactor controls the various circuits for welding inert gas, water flow, welding current, high frequency and auxiliary equipment. It is normally operated using a foot-switch in manual welding. In order to switch the welding power supply on or off by the BBC microcomputer a relay was connected to the welding contactor. This relay was controlled by the information received from the optical receiver via the fibre optic link from the BBC microcomputer.

There are three fibre optic links between the optical transmitter and receiver. One is for switching the welding power supply, and the other two are for controlling the speed and direction of the welding rig.

The direction of the welding rig is determined by the input signal to pin 10 of the stepping motor drive board (Unimatic UDB-053/1). The welding table traverse to the left when pin 10 is set high and traverse to the right when pin 10 is low. Thus, connecting a relay to this input will allow the microcomputer to control the direction of the workpiece movement.

The speed of the welding rig is determined by the pulse rate applied to the stepping motor drive board. Since the external pulse input of the drive board has an active pull up resistor, it must be driven by an open collector logic gate. An opto-isolator was selected to provide the required open collector logic.

Both the welding power supply and welding rig are controlled from program running in the BBC microcomputer. If the program was written so that the welding rig starts moving at a given velocity just after switching on the welding power supply and keeps moving until the end of a weld, it would normally give an acceptable weld provided that the torch was set in position and the arc was immediately ignited in response to the power on. In practice, however, for the same setting of welding parameters, the delay time for an arc to be initiated and settled differs from job to job due to the variations in the aluminium surface. In this case, if the delay time takes longer than is preprogrammed, the welding rig will start moving before an arc is formed, and the weld will be out of position. It is for this reason, that an arc ignition detector was designed to obtaining a feedback signal to the microcomputer in order to provide synchronisation between arc ignition and the movement of the welding rig.

4.4.1 PERIPHERAL INTERFACING

Peripheral electronic circuits were interfaced to the user port of the microcomputer. The user port consists of eight lines which can be individually programmed to act as inputs or outputs under the control of a Data Direction Register. For controlling the a.c. welding system, four signal lines were used (pins PB0, PB1, PB2, and PB7). PB0 was used to switch the welding power supply on or off, PB2 was the signal received from the arc detector described in section 4.4.3, and PB1 and PB7 were used to set the direction and speed of the welding rig.

The eight lines of the user port are configured as inputs after reset with pull up resisters pulling the signal high. To ensure that no signal was transmitted to the control circuitry when welding was not taking place, TTL logic inverters were connected directly to the user port. Once a particular line is programmed to be low, the inverter output becomes high which enables the optical transmitter to send information down the fibre optical cable, and therefore, commands the rest of the controlling circuits.

4.4.2 OPTICAL TRANSMITTER AND RECEIVER

The purpose of using optical transmission is to isolate the microcomputer from the electrically noisy welding power supply and the stepping motor drive unit which is placed very close to the welding rig. The principle of optical transmission is to convert electrical signals into light waves by the use of an optical transmitter. These light waves can then be sent down an optical fibre to the destination. The optical power output is controlled by the applied current. In the case of a LED operating under a binary pulse code modulation, this involves switching between 0V and 5V. A general interface circuit of the optical transmitter and receiver is shown in fig.4.8.

There are two reasons for using an opto-isolator in the design. One is to provide current amplification for the LED, the other is to provide isolation between the microcomputer and the peripheral circuits. Since the microcomputer acts as a central controller, and it contains many electronic devices which are sensitive to interference, it should be given maximum protection against interference coupling.

The basic operation of the optical receiver is the conversion from light intensity to electron current. The detector converts the optical power into an electrical current. This current is small and must be amplified by a low noise amplifier designed to work with the detector. In the circuit (fig.4.8) the two transistors (BC109) and an op-amp (741) are acting as a current amplifier and a voltage controller respectively. To ensure that the correct information was sent to the welding unit and the motor drive unit, filters and transient suppressors were built into the optical receiver for the elimination of noise interference, which could be coupled from the links between the optical receiver and the two units.

4.4.3 ARC IGNITION DETECTOR

The arc ignition detector works on the principle of converting arc light into electric current and give a threshold voltage to the microcomputer indicating whether the arc is on or off. It consists of a photo detector, a differential amplifier, a low-pass filter, a comparator and an opto-isolator (fig.4.9). The photo detector converts the light into electric signal which is then amplified by a differential amplifier. This differential amplifier is also used for backing off the background signal to provide a true signal representing the arc light. The low-pass filter is designed to eliminate the noise produced by the arc. The comparator converts the signal to TTL compatible in order to be interfaced to the microcomputer. The opto-isolator in the design is to isolate the peripheral circuits from the microcomputer, in order to reduce interference which may be picked up in the system.

4.5 SOFTWARE

Software written for the experimental system is in the form of a command control program. It responds to user input commands and generates control signals to the peripheral circuits. Since the computer processing speed in this experiment was not critical in respect to the welding speed, the program was written in BASIC language for convenience.

4.5.1 CONTROL SEQUENCE

Details of the software structure are shown in Appendix II. It can be summarised in the following six steps:

(a) Wait for weld parameter inputs.

(b) Convert welding length and speed into time, so that the weld process can be controlled by the internal timer of the microcomputer.

(c) Request for start operation command. Once it is instructed by the user, energise the contactor relay to switch on the welding power supply.

(d) Wait until the arc ignition signal is received, and produce a delay in order to ensure a molten pool is produced, then enable the internal timer to control the speed and direction of the welding rig.

(e) Increase speed gradually to compensate for temperature effect on the weld.

(f) At time up, reset system, acknowledge the user, and return to the initial state for the next weld.

4.5.2 EFFECT OF TIMING

The control parameters such as the welding speed and the welding length are dependent upon timing. The welding speed can be varied by changing the counter number which is input to the internal timer as described in Chapter 2. Total time taken for the preset welding length is calculated from:

$$\text{welding time} = \frac{\text{welding length}}{\text{welding speed}} \qquad (4.1)$$

Where the welding length is set by the operator and the welding speed is derived from the average speed for the operation. The value of welding time is calculated for a moving weld. For stationary welds the timing relies on the welding time set by the operator.

4.5.3 OPERATION

Once programmed the user is prompted to define the weld parameters. These include, the direction of movement (left or right), the initial speed of the welding rig (0 - 7mm/s), and the required length of weld.

Only when valid values for these have been entered will the screen display:

Welding system standby

Press SPC bar to start

To start welding, an active low signal is output to the user port, PB0, commanding the welding power supply to be switched on. Port PB2 is then polled to detect if the arc has been ignited. Before a valid input signal is obtained, the program will produce a message:

Waiting...

When a stable arc is formed, the program will output values to move the rig in the required direction at the preset speed, and the screen will show:

Welding in progress

After a weld is performed, the user will be instructed by:

Job completed

Press SPC bar to start again

and the system is reset to the initial state for new welds.

4.6 EXPERIMENTAL SETTING

A few operational procedures were essential when carrying out an experiment.

(a) Before switching on the mains supply of the AAC350 Argonarc Welder, all electronic equipments must be switched off and the traverse correctly earthed.

(b) The Argonarc/Metal arc switch was turned to the 'Argonarc' position. If welding at currents below 70A, the high frequency switch was set to the 'continuous' mode.

(c) The argon gas and cooling water supplies were turned on. The 'purge' button was pressed and the flow of cooling water and argon gas adjusted to the required level. Release the 'purge' button. The 'Gas Delay' control was set to the time required for the post weld gas flow.

(d) The 'Current Selector' switches were set to obtain the required welding current. The values for Argonarc Welding currents were printed in red on the indicator plates.

(e) The 'Argonarc/Metal Arc' switch was turned to 'off' position, and the torch and weld job positions setup.

(f) Other equipment was turned on, and the stepping motor drive unit was set for computing control. The 'Manual direction' switch was set to off. 'Auto-stop' mode was used for automatic operations.

(g) The required welding parameters were entered and the welding machine was switched on again ready for weld operations.

4.7 EXPERIMENTAL WELDS AND RESULTS

This section describes the experimental welds carried out in order to assess the feasibility of automating aluminium welding.

4.7.1 WELD TESTS

The experimental welding system is open-loop. All welds were carried out using pre-set welding parameters, which meant that the torch position, gas, welding current, welding length, and the direction and speed of the welding rig had to be predetermined. The system was programmed for straight line welds.

The shielding gas used was pure argon. The surfaces of the plates to be welded were first scraped to remove the oxide layer. They were then clamped on a jig which was designed for holding the workpiece and also as backing for the workpiece to remove the excess heat built up during welding. After switching on the gas, water, welding current and the high frequency unit the arc was struck by bringing the tungsten electrode near the workpiece. The high frequency sparks jumped the gap and the welding current flowed. The arc length was manually set to about 3mm. The arc was held in one position on the plate until a molten pool was obtained and welding then commenced, proceeding at the preprogrammed speed and direction. As the weld proceeded, temperature build up on the plates increased with respect to time, and this resulted in the changing of the weld bead size and penetration. Possible ways of overcoming this effect include varying the welding current or the welding speed. Since the AAC350 a.c. welding power supply could only provide manual preset currents and was not able to be switched to different levels by the computer, the alternative method of programming the welding rig to move at an increasing speed, whilst keeping the welding current constant was used. The gas flow rate was set depending on the plates to be welded. A chalky white appearance of the weld indicated excessive current and overheating, while a black appearance on the weld metal indicated insufficient argon supply.

4.7.2 WELDED SAMPLES

Weld tests were carried out using corner joints. A jig was used to mount the plates together at right angles. The electrode was aligned to the centre of the corner at 70° to the line of weld. The jig was held by the welding rig and traversed smoothly along the joint line.

Fig.4.10 shows the experimental results, in which sample (a) was welded using a preset welding current of 77A and a constant welding speed of 0.8mm/s, sample (b) was welded using a preset welding current of 71A and a ramped welding speed from 0.8mm/s to 3.5mm/s for the welding length of 115mm, and sample (c) was welded manually using 75A preset welding current. Both (a) and (b) were 1mm thick and (c) was 0.7mm thick.

It is evident that for a given welding current, the welding speed determines the amount of energy that is delivered per unit length of weld. Changes in energy per unit length have a strong effect on the finished welds. As in the cases of (a) and (b), the different control of welding speed resulted in the different finished weld qualities. Since the welding speeds can be controlled by the microcomputer controller, the result of welds are predictable. For manual welding, however, the quality of a weld can vary from time to time depending upon the welder's ability.

All the welds were fusion welds, employing TIG welding without using filler materials. This form of welding was particularly useful for welding thin plates. The welds were of high quality and provided the necessary strength properties for structural components. The finish weld seams were spatter-free, smooth and flat and needed no further treatment. In the automated welding system the results can be made consistent by proper control of the welding speed.

4.7.3 WELDING SPEED

Welding conditions and metal temperature exerted a considerable influence on the weld. The characteristics of a weld may be determined by the following expression [15]:

$$Q = 8k.T_m \left(\frac{1}{5} + \frac{\nu.d}{4\alpha} \right) \qquad (4.2)$$

where Q is the rate of heat per unit area input to the workpiece, k is the thermal conductivity, T_m is the melting temperature, α is the thermal diffusivity, ν is the welding speed, and d is the fused diameter.

Since k, T_m, and α are constant values, by keeping the welding speed, ν, constant the fused diameter, d, increases as heat, Q, building up in the workpiece. Thus, to ensure a fine weld finish which maintains the same fused diameter, the welding speed needed to be increased in order to compensate for the temperature effect on the weld.

The welding speed of the linear system ranges from 0 to 7mm/sec. In the experiment the welding speed was set to increase by 10% of its previous value after each period of 2 seconds. Fig.4.10 (a) and (b) show the results of a constant welding speed and a ramped welding speed, respectively. In comparison the latter method was proved to be acceptable.

4.7.4 WELD PARAMETERS

To achieve acceptable weld quality the weld parameters should be chosen with regard to the geometry and position of the joint. In the welding procedure the following parameters were specified:

(a) welding current,

(b) arc length,

(c) initial welding speed,

(d) electrode diameter,

(e) rate of flow of shielding gas, and

(f) length of weld.

The optimum welding conditions derived from this experiment are shown in Table 4.1. All the parameters are suitable for fusion welds of corner joints from 1 to 3mm thick aluminium plates.

4.7.5 ELECTRODE DIMENSIONS

To ensure a quality weld in thin plate welding, the electrode needed grinding to a point. The dimensions of the electrode may affect the behaviour of an arc and thus affects the result of a weld. For thicker plates the electrode should be properly broken and ground tapered by following the supplier's suggested procedures. Improper breakage may cause a jagged end or a bent electrode which usually results in a poorly shaped arc and electrode overheating. Fig.4.11 indicates suitable preparations for both d.c. and a.c TIG weldings [5,16].

4.7.6 WELDING CONTROL

There are two basic factors affecting the weld quality. These are the heat factor and the welding factor, as shown in fig.4.12.

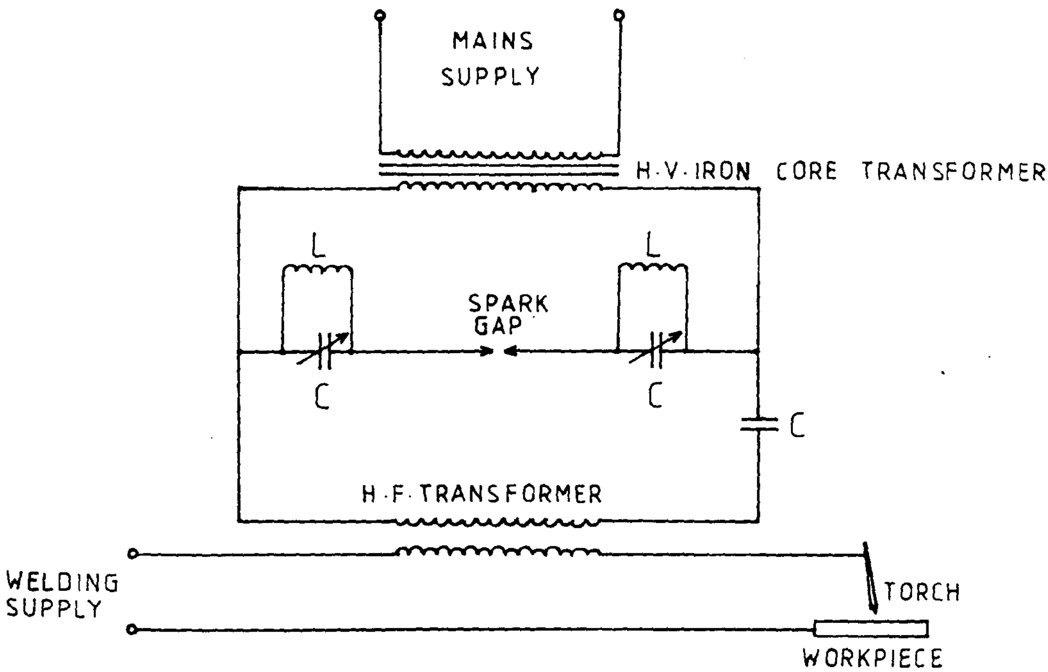
The heat factor is a balance between effective heat input and heat sink in the workpiece [17]. Effective heat input depends on welding current, arc voltage, welding velocity and efficiency factor, that is, the share of the total arc heat energy received by the workpiece. Heat sink is a portion of effective heat that is not utilised for melting the workpiece. Arc voltage depends on the electrode extension, shielding gas flow rate, and the stability of the welding power supply. All these variations may cause considerable fluctuations in weld penetration, and thus affecting the quality of a weld.

The welding factor is a balance between the arc pressure displacing the molten metal under the arc and the flow of the molten metal [18]. There is a layer of molten metal under the arc, in which the temperature gradient, according to depth in the weld pool, approximates in value to the temperature gradient in the region of transition from the forward to the rear part of the weld pool. The thicker the layer, the slower the heat transfer to the base metal. If the flow rate is high enough, a relatively cold molten metal flows under the arc, and reducing penetrating ability of the arc. If the flow rate is slow, the workpiece is exposed to the arc under pressure and the arc penetrates deeper. In this regard, welding speed is a good example of the complex interrelationship between welding variables and welding results.

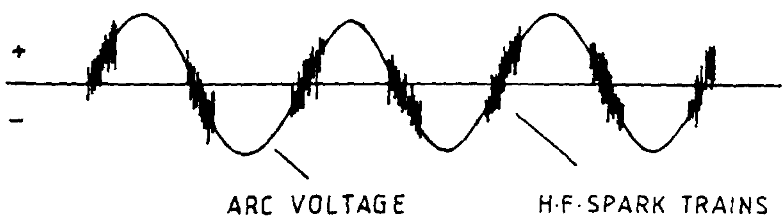
4.8 DISCUSSION

Fig.13 shows the experimental setting of the welding rig and the welding supply for a.c. welding. Both units were controlled by a micro-computer. It was evidence that the welding system was capable of welding aluminium under the high frequency interference conditions and produced better finish welds at higher welding rate than those performed by manual welding. However, a noticeable limitation of the system is its open loop operation. In many cases, the workpiece may be distorted resulting from the intense heat built up, and the torch may deviate from the joint. To ensure weld qualities, the addition of sensory feedback is required in order to form a closed loop operation system.

As the objective of this experiment was to investigate the possibility of automating aluminium welding process, the experimental results successively show that the automation of aluminium welding is feasible provided a proper EMI control is included in the system design. Applying the same principle of design, more sophisticated systems, such as the closed-loop automatic welding systems can be developed to give a higher degree of reliability and better quality of welds. In particular, using a robot with more degrees of freedom and with adaptive sensory control fully automated welding becomes possible.



(a) H.F. OSCILLATOR



(b) ARC VOLTAGE WITH SUPERIMPOSED
H.F. SPARK TRAINS

FIG.4.1 A.C. WELDING SOURCE

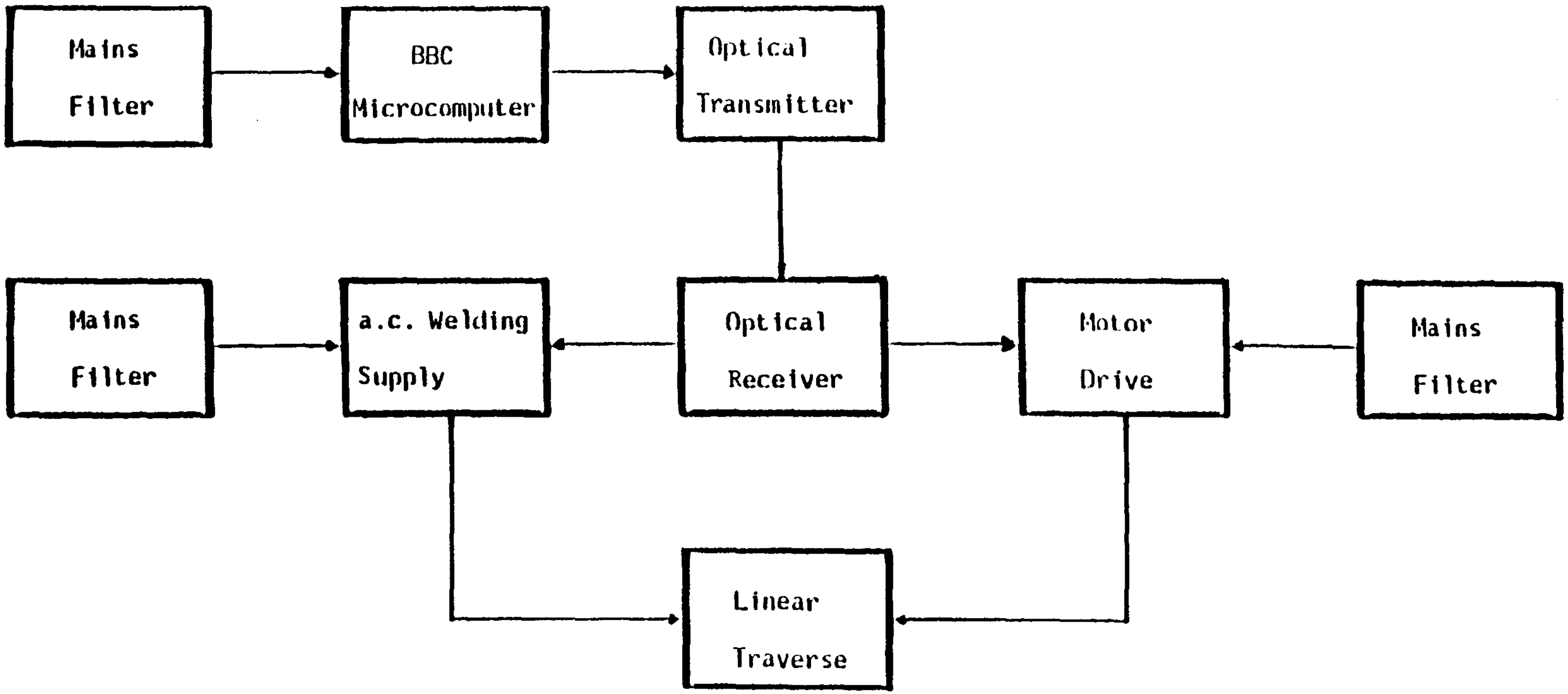
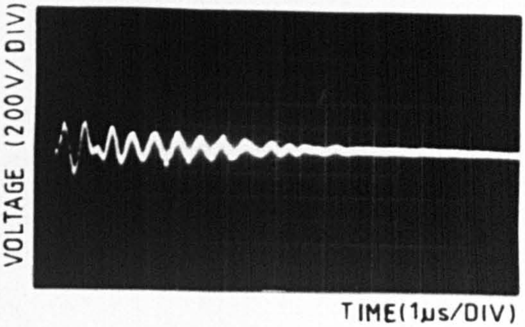
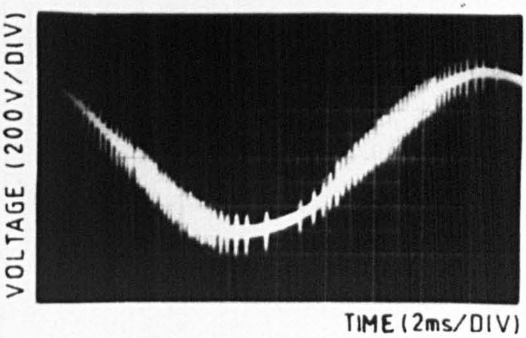


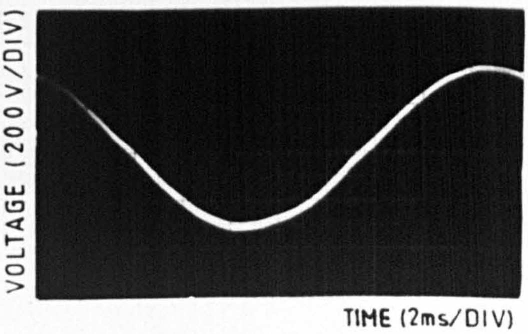
Fig.4.2 Block Diagram of The a.c.Welding System



(a) H.F. SIGNALS



(b) SIGNALS FEEDING BACK TO THE MAINS WITHOUT FILTERING



(c) SIGNALS MEASURED AFTER FILTERING

FIG. 4.3 EFFECT OF USING MAINS FILTER

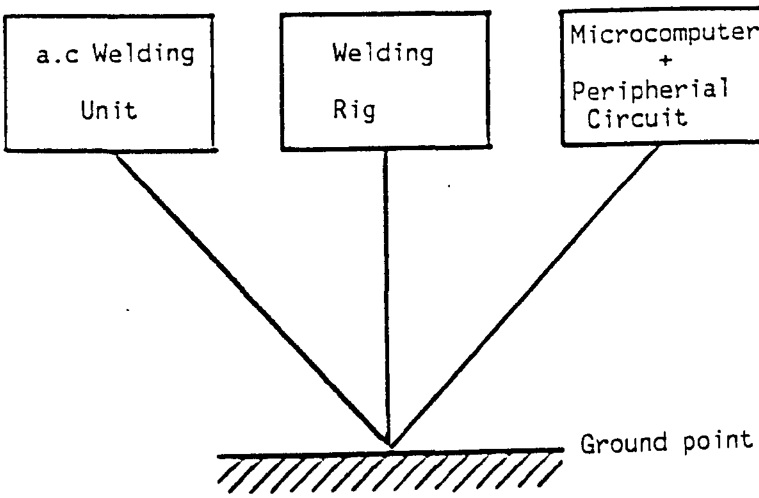


Fig.4.4 System Grounding Configuration

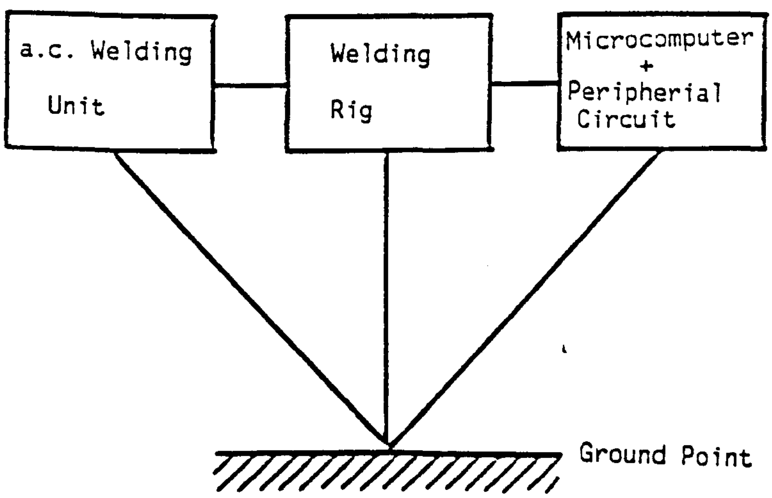


Fig.4.5 Ground Loop Configuration

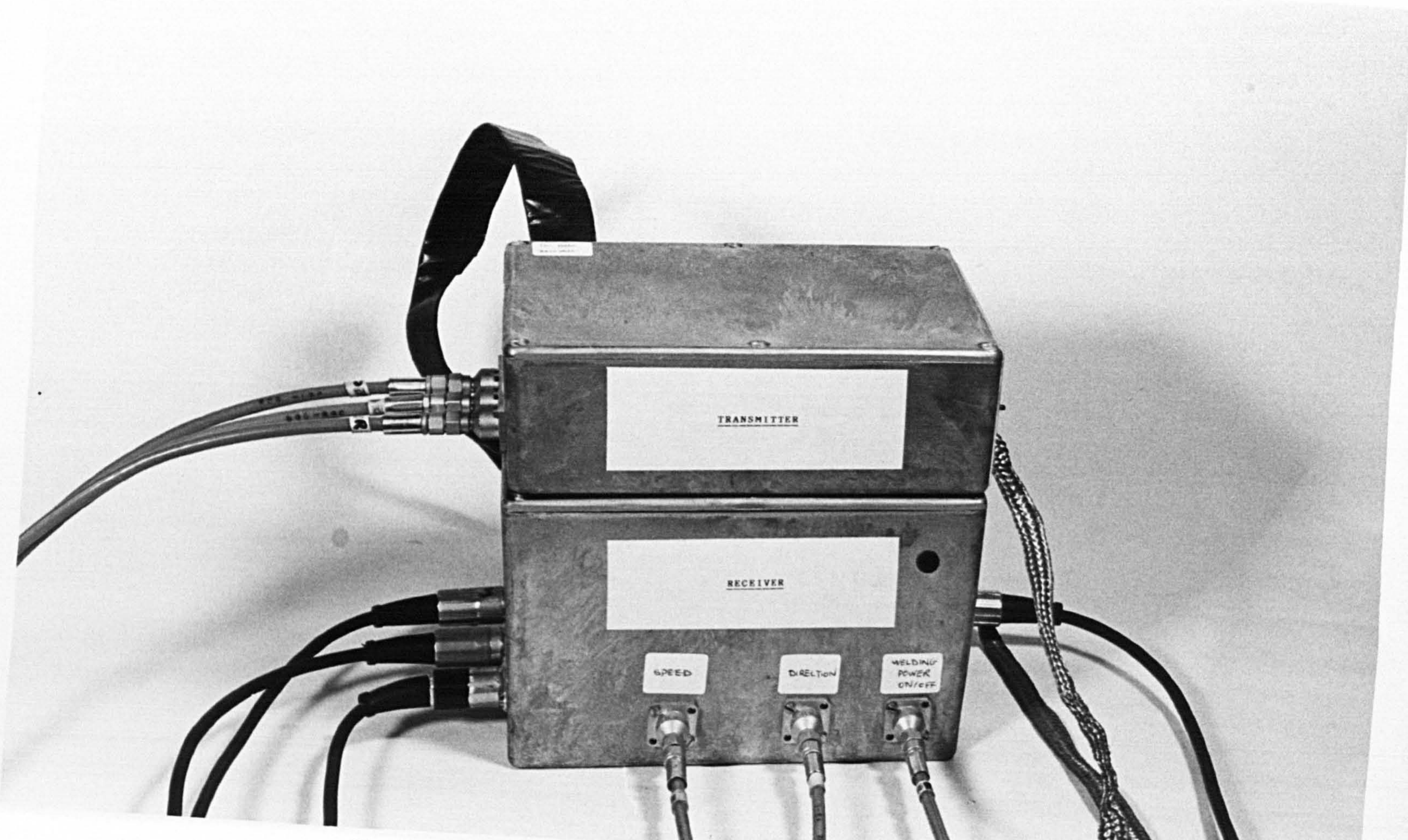


Fig.4.6 Shielded Optical Transmitter and Receiver

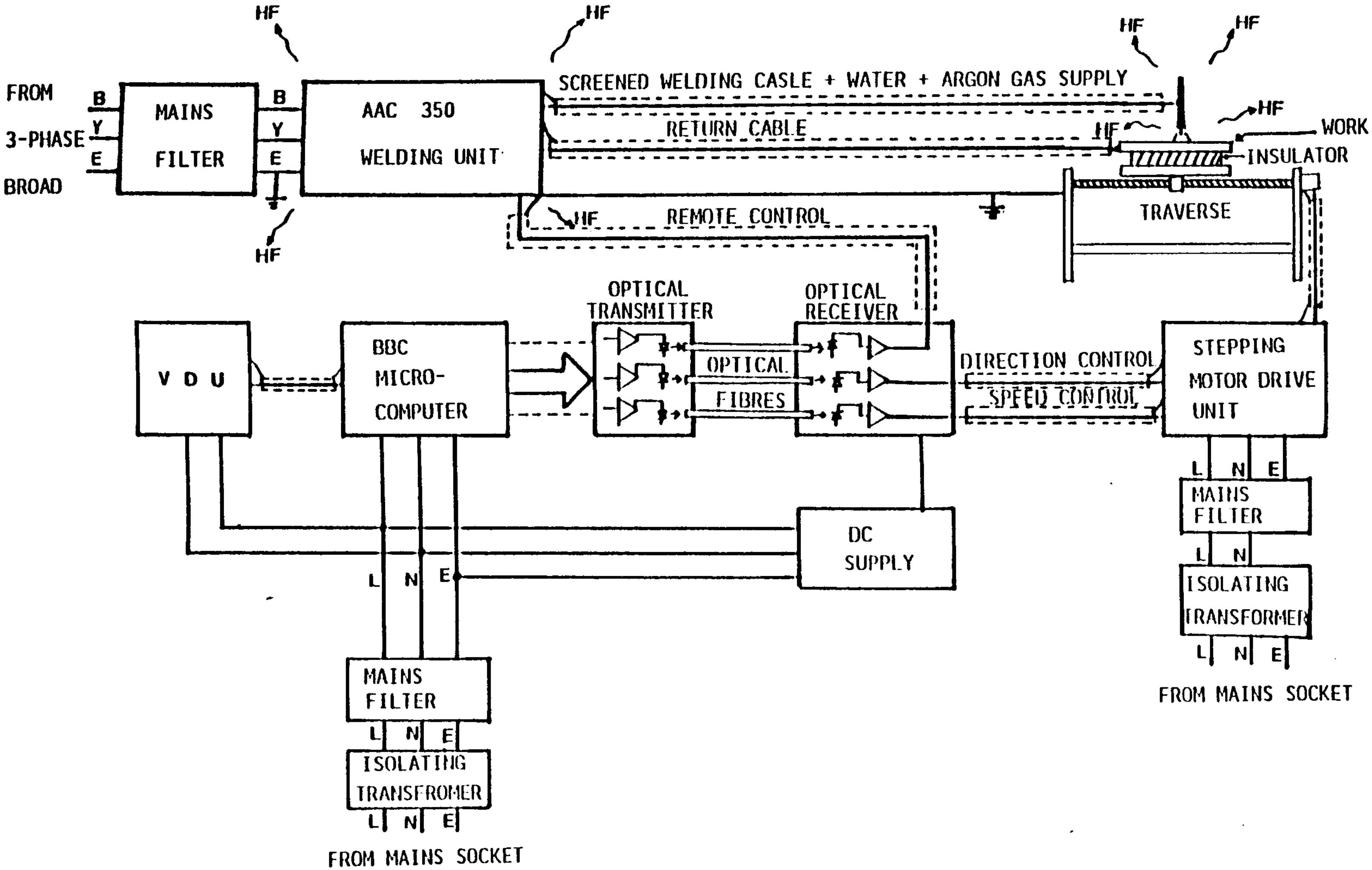


Fig.4. 7 System Wiring Configuration

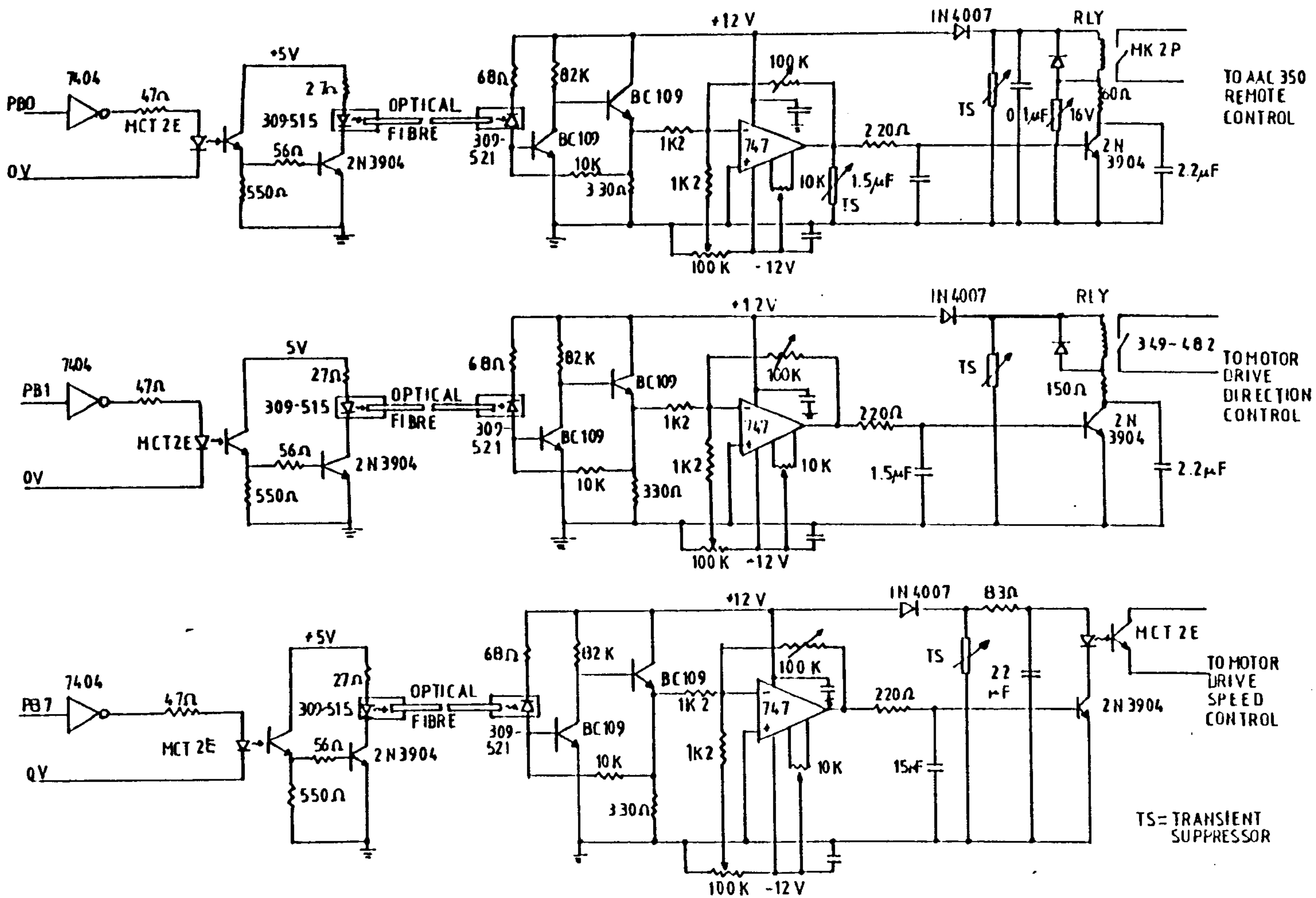


FIG 4.8 OPTICAL TRANSMITTER AND RECEIVER CIRCUITS

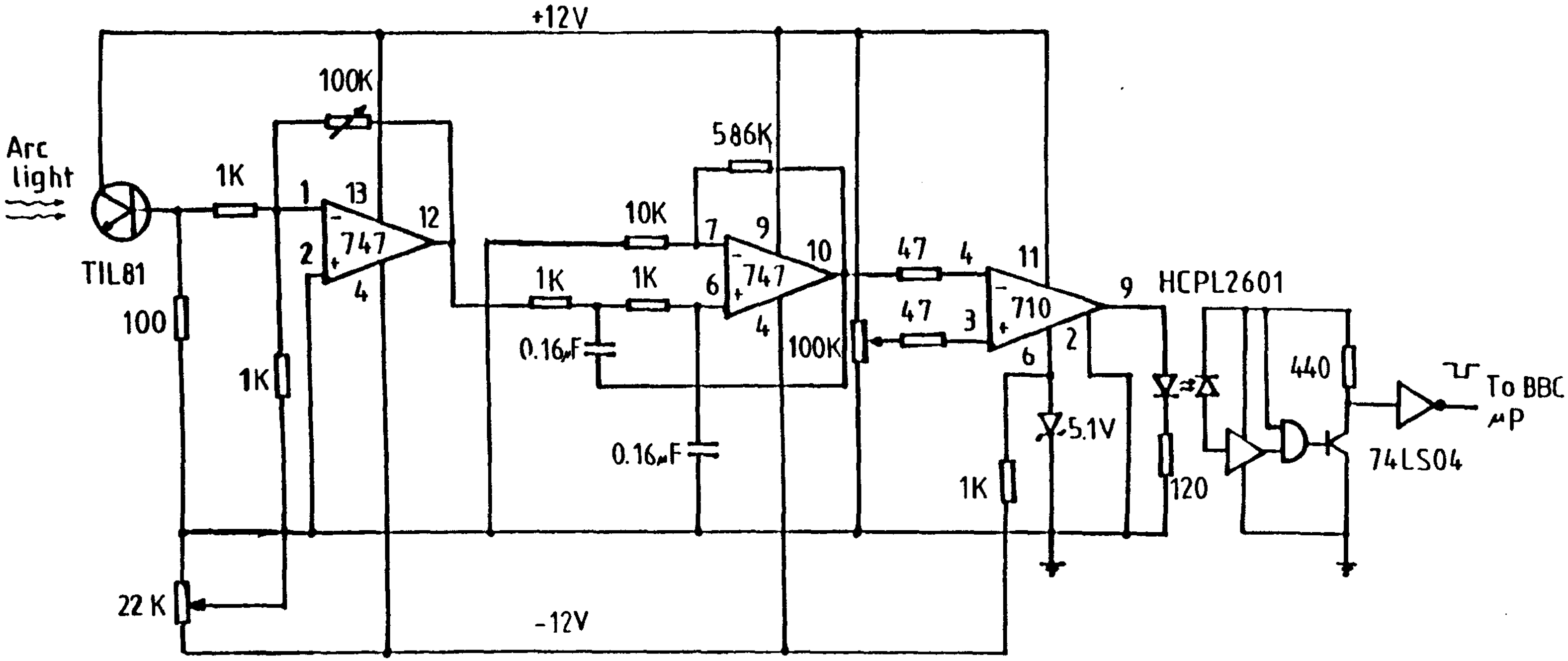
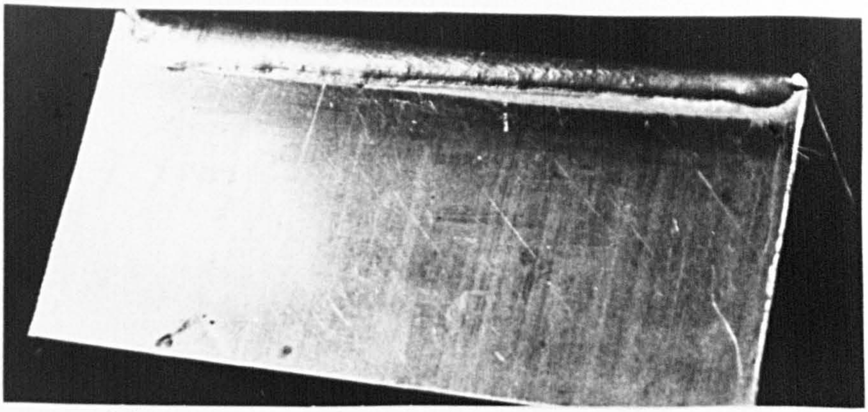
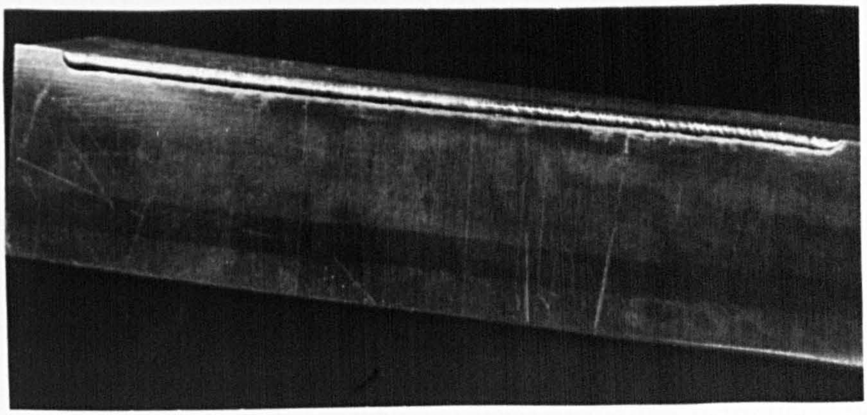


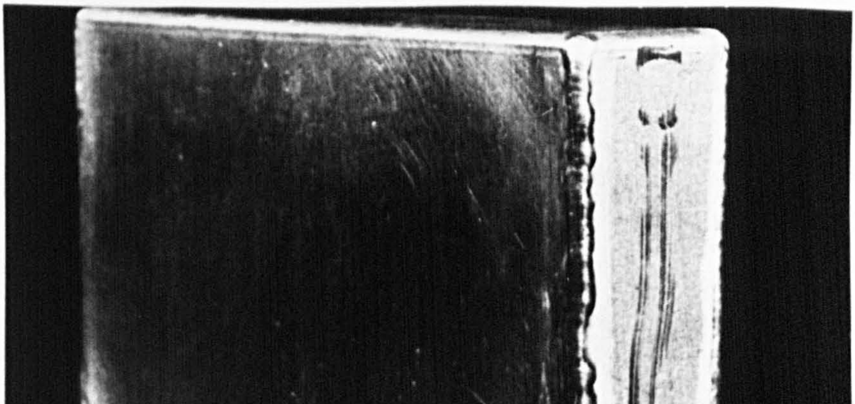
Fig.4.9 Arc Ignition Detector



(a) Welded sample of constant current and speed



(b) Welded sample of constant current and ramped speed



(c) Manual welded sample

Fig.4.10 Experimental results

Workpiece thickness (mm)	1	2	3
Welding current (A)	64	78	88
Argon pressure (bar)	20	20	20
Electrode diameter (mm)	2.4	2.4	2.4
Arc length (mm)	2.5	2.5	2.5
Initial welding speed (mm/s)	0.8	0.7	0.6

Table 4.1 Welding parameters for the experiment

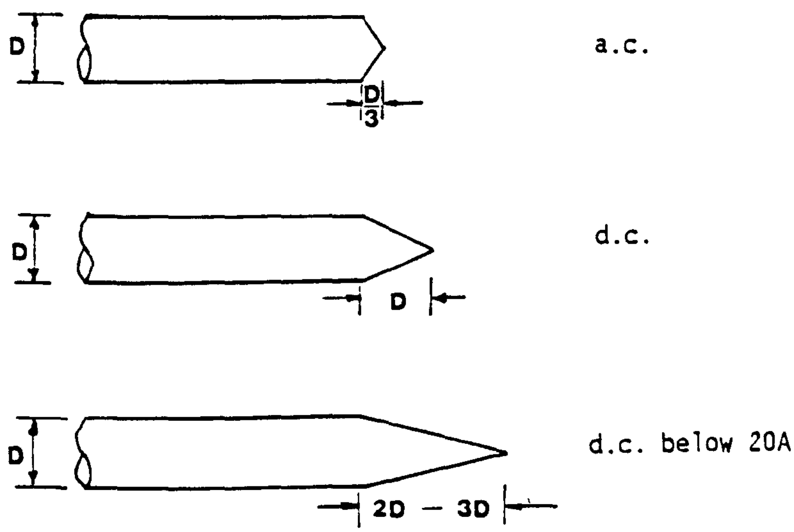


Fig.4.11 Electrode preparation

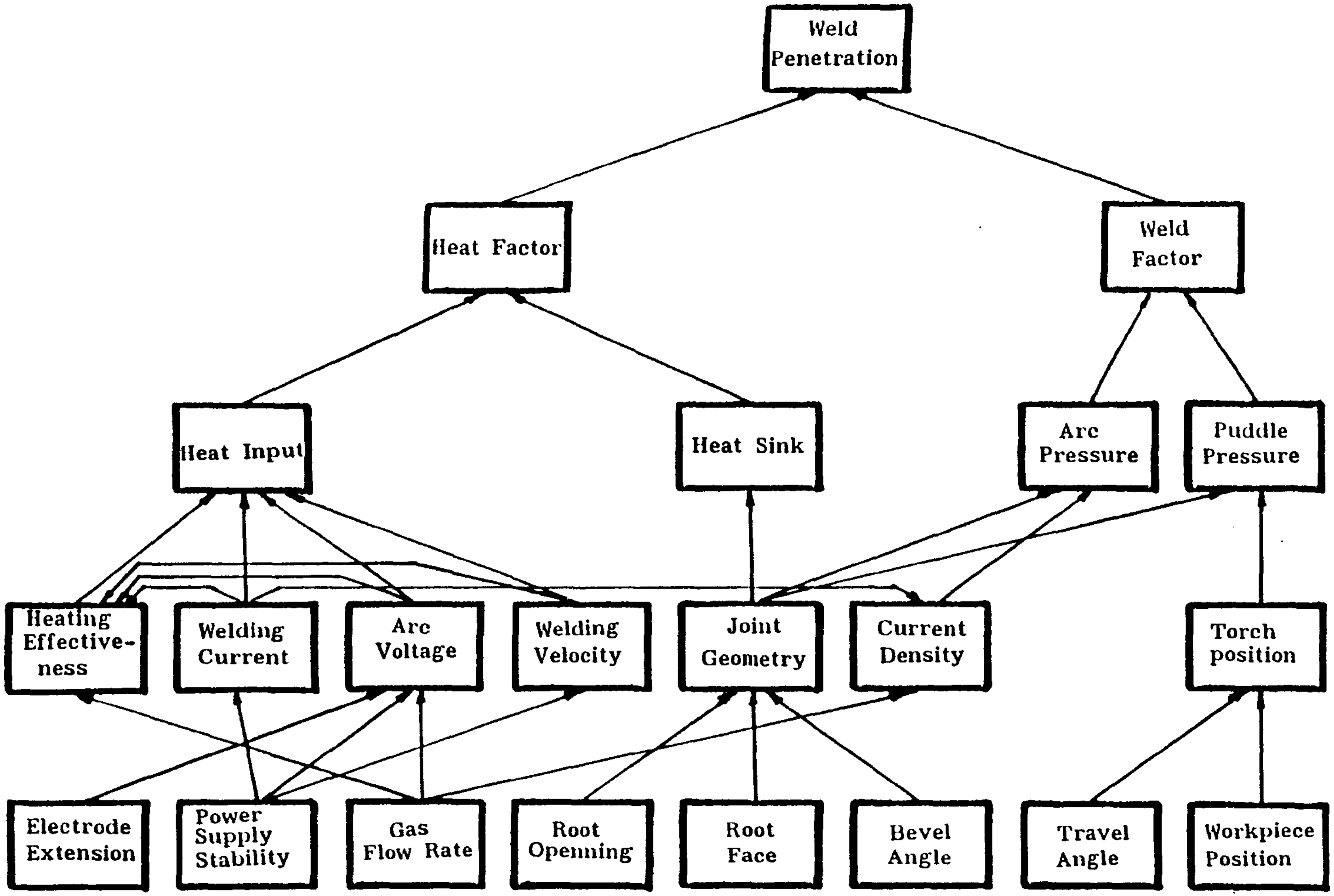
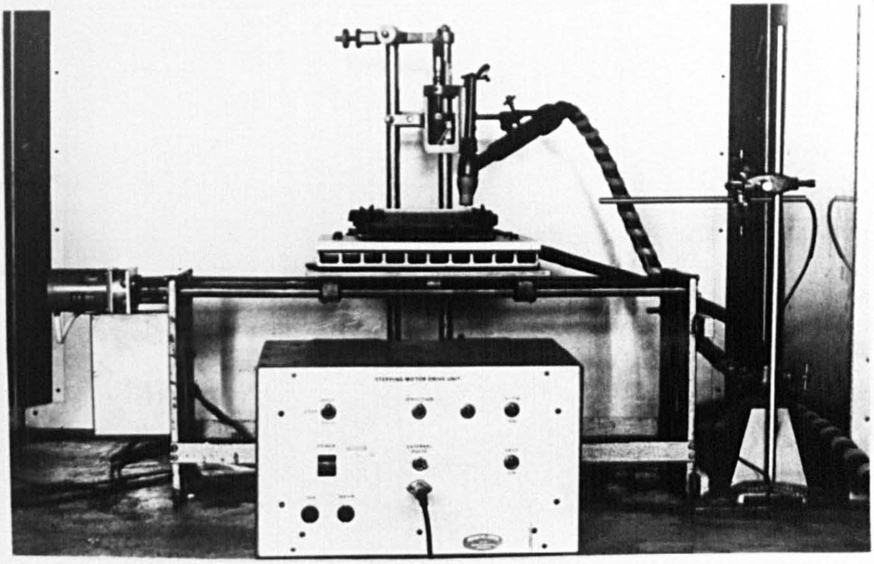
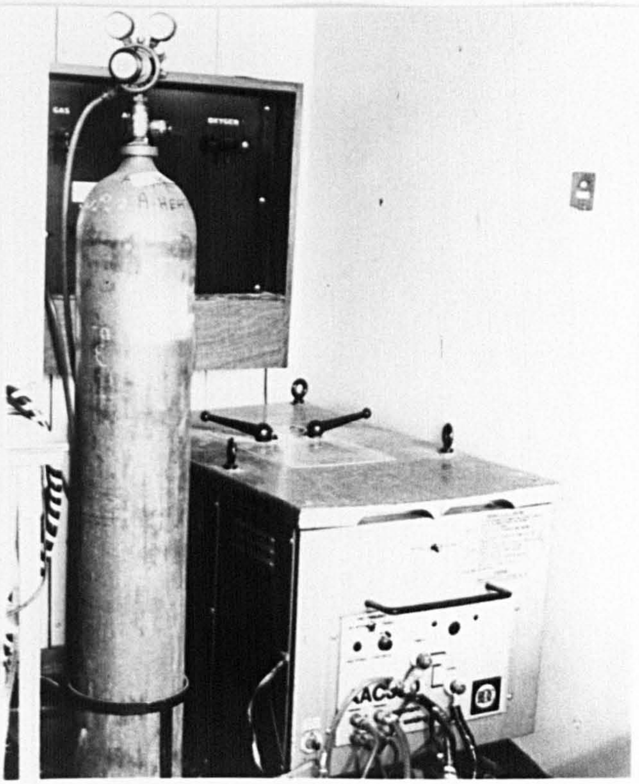


Fig.4.12 Effect of Welding Variables and Operating Conditions on The Depth of Weld Penetration



(a) The welding rig



(b) The welding power supply

Fig.4.13 Experimental settings

CHAPTER 5 WELDING SEAM TRACKING

5.1 INTRODUCTION

Robots are now widely used for automatic welding [19]. Applications include those needing no feedback information and those where fit-up variation, or metal distortion occurs, and constant monitoring and real time adjustment of the operation are required [20]. A host of variables add uncertainty to the process and sensory feedback is required to keep the welding torch on the seam for an effective weld. Uncertainty is introduced by parts or fixtures that deviate from the standard, poor fitting of parts, or warping part caused by heat gradients of the welding process itself.

It is for these positional uncertainties that the need arises for seam tracking in automated welding.

In this chapter, the nature of the positioning errors and the principles of a seam tracking system are described. The information concerning the positioning errors is important in determining how to track the seam for an effective weld. It also outlines the requirements for the seam tracking system developments. Present commercially available seam trackers are reviewed. Because of the wide variety of joint configurations and metal surface conditions no one seam tracker will provide all solutions. This led to the investigations of two different type of seam trackers, each with its own advantages. The adaptation of seam tracker to robotic welding provides a closed-loop control for automating the welding process. Experimental data indicates the importance of seam tracking in automating welding, and this is covered in Chapter 6 and Chapter 7.

5.2 POSITIONING ERRORS IN ROBOTIC WELDING SYSTEM

A robotic welding system needs to position the welding torch above the centre of the weld seam, while maintaining a programmed welding speed and torch orientation. Allowable positioning error depends on the process involved. There are many factors which can cause positioning errors.

(a) Mechanical Vibrations

A robot normally is driven along several axes by motors. Depending on the natural frequencies, traverse vibrations, etc., the welding torch may oscillate while welding is being carried out, particularly during sudden starts and stops.

(b) Backlash

Backlash affects accuracy when drive torque changes direction. Backlash is usually unspecified and is highly dependent on wear and adjustment of the mechanisms.

(c) Temperature Effects

Robot system accuracy specifications usually assume constant temperature. If the temperature varies significantly, the effects can be severe enough to require the path to be reprogrammed. For example, the welding arc may heat up the robot's wrist joints producing positioning errors. Thermal expansion caused by heat input to the workpiece holding fixture can also cause the seam to deviate from the preprogrammed path [21].

(d) Shifting Torch Location

The torch position can shift because of accidental contact of the electrode tip with the molten weld pool, or after the electrode is changed.

(e) Workpiece Holding Fixture Tolerance

Fixtures necessary to hold the workpiece during welding may need to be slightly oversized to accommodate size variation from part to part. Therefore, there is a corresponding uncertainty in workpiece location.

Weld spatter and other problems on the fixture can cause errors in workpiece location. Fixture wear is another potential factor. However, thermal expansion due to progressive heat input is perhaps the most significant source of fixture error.

(g) Workpiece Tolerance

Locating the weld joint accurately depends on the workpiece having surfaces a fixture can hold, which are accurately located with respect to the weld joint. To ensure positioning accuracy, an acceptable dimensional tolerance between suitably located and oriented surfaces and the weld joint location must be provided.

5.3 ANALYSIS

The capability of the robot to position a torch properly on the welding seam is affected by the tolerances on the movements of the torch in x,y and z directions and the drifts of the seam during welding. The torch position tolerance depend upon the features of the robot as outlined above. If taking the robot tolerance into account and measuring the seam drifts at the beginning of each cycle, then the state of the torch can be easily determined.

5.3.1 WELDING SEAM POSITIONS

If we assume that the shifts of the robot's position in x, y and z directions occur independently of one another, a mathematical model can be formulated to describe the position of the welding seam. The model should also take into account the inaccuracies in the sensor (e.g. seam tracker) measuring the position of the seam. A linear dynamic system [5.3] described by equations (5.1) and (5.2) has the desired characteristics.

$$Ui(n) = Ui(0) + Wi(n) \tag{5.1}$$

$$Gi(n) = H*Ui(n) + Vi(n) \tag{5.2}$$

Where i = x, y, z, the standard cartesian axes. In these equation, Ui(n) is the actual position of the torch in direction i with respect to some reference position, at the beginning of the nth cycle. Ui(0) is the initial taught position. Wi(n) represents the drifts in the position of the seam. Gi(n) is the reading obtained from the sensor measuring device, which represents the position of the seam at the nth cycle, with respect to some reference point. H is the factor converting the distance to measuring units. Vi(n) represents the error signal due to seam tracker tolerance.

Equation (5.1) gives the position of the seam, in terms of the initial position and the drift at nth cycle. Equation (5.2) deals with the measurement error of the sensor.

The behaviour of the process Vi can be studied by taking the difference between Gi(n) and H*Ui(n) from a set of repeated measurements.Then a mean value of Vi(n) can be obtained. Let this mean value be Vmi. Now, replacing Vi(n) by Vmi in equation (5.2) we obtain

$$Ui(n) = [Gi(n) - Vmi]/H \tag{5.3}$$

and the drift of the seam can be defined by

$$Wi(n) = Ui(n) - Ui(0) \tag{5.4}$$

Using this equation the actual seam deviation can be calculated and this value can be fed back to the robot controller for error corrections. The ability of tracking the seam is based on the information feedback from the sensor and the response of the robot controller.

5.3.2 FEEDBACK SYSTEM

The idea of a feedback system is that the output of a process is observed and compared with what is desired. If there is a difference, or error, the process inputs are changed in such a way as to cause the error to be reduced. For seam tracking, the location of the centre of the seam from previous passes, is compared with the current position. A correction is then made to maintain the torch on the joint between the plates to be welded.

Fig.5.1 shows a feedback system which operates in a closed loop sequence. The desired and the actual seam positions are compared, and a measure of the difference is generated to inform the controller to drive the robot in order to reduce the error. The sequence is such that if the seam is shifted to the right, for example, the controller will be instructed to direct the robot torch to the left.

In summary, feedback systems improve positioning accuracy and provide self-tracking of the welding seam.

5.4 SEAM TRACKING

The basic requirement for a seam tracking system is the ability to determine the position of the part to be welded relative to the welding torch. The position of the torch must be controlled to within the centre of the seam. In general, seam tracking enables the robot to adapt to the work environment, i.e. to modify the path of the torch tip to produce offset from the sensed path.

5.4.1 SEAM TRACKING SYSTEM

Fig.5.2 shows the basic structure of a seam tracking control system which is based on three functional modules. These modules are the tracking sensor, tracking processor and robot controller. The tracking sensor should provide spatial information describing the seam relative to the torch. It should include its own data acquisition and filtering capability. It should be able to present the unprocessed data to the tracking processor. The tracking processor takes data from the sensor and converts it to the position commands required to redirect the torch path. The robot controller receives position information in the coordinates of the workpiece and converts them to commands to drive the individual joints of the robot.

5.4.2 SEAM TRACKING METHODS

There are two approaches for seam tracking known as two-pass and one-pass systems.

Two-pass systems involve an initial trial run when the robot passes along the expected seam route monitoring any deviations of the workpieces from their expected positions. During the second run the robot performs an accurate weld with its sensors disabled. Such a system is not able to compensate for errors in the workpiece if it moves after the first run, for instance due to thermal distortion during the welding process.

In one-pass systems the robot senses the seam during the welding process and dynamically adjusts the robot's position to follow it.

5.4.3 SEAM TRACKING APPLICATION

The addition of a seam tracker to a welding system directs the robot to keep the weld seam within the field of sensing area. Torch position information may be extracted from several different types of sensors which require varying degrees of signal processing.

Because low tolerances in the dimensions of the components to be welded lead to a loss of quality in the welded product, at present automated welding can only be used for manufacturing finished products when high cost seam trackers are used, For instance, while a vision based sensor system can provide an effective solution to the seam tracking problem, its cost may limit its use in many robotic welding applications. It is for this reason research has been carried out on the development of low cost sensors, such as the infra-red and ultrasonic seam trackers.

5.5 REVIEW OF SEAM TRACKERS

Seam tracking devices range from simple to extremely complex [22 - 25]. It is technically appealing to try to develop a general purpose seam tracker to meet a wide variety of needs. Practical limitations, however, show the need for a range of seam trackers, each satisfying particular requirements.

The development of seam trackers has so far resulted in the emergence of three major types of commercially available seam trackers [26]. Each type is classified by the type of sensor used.

5.5.1 TACTILE SENSING

The original seam tracking devices actually used on robot systems were tactile sensors. Typical designs used a mechanical probe equipped with strain-gauge devices to follow the weld seam. Signals are produced proportional to positional deviations of the probe. These signals are used to modify the torch position.

The major advantage of this type of tracker is its relatively simple design and, therefore, low cost. However, since physical contact is required, they cannot generally differentiate between a change in seam area and a change in seam height. Also, they are not adaptable to suit a variety of seam geometries and further more there is a tendency for the probe to lose contact with the seam. Because of these limitations, they are not a practical solution for many robot welding applications.

5.5.2 THROUGH-THE-ARC SENSING

A another method used to correct torch position is through-the-arc sensing. In operation, this tracking technique makes use of an oscillating torch which acts as a sensor to obtain arc voltage and welding current information in the joint. To track across the weld seam, the torch is oscillated from side to side within the joint. The oscillations of the torch causes changes in current sensed at the joint sidewalls. These changes are proportional to fluctuations in distance between the work-piece surface and the electrode tip. By monitoring these changes, signals can be generated to guide the torch path so that the oscillating pattern is centred on the groove.

To maintain a constant arc length, a preset voltage that represents the desired electrode extension is programmed into the robot controller. Feedback signals originating at the electrode tip constantly sense this voltage value and adjust the torch's position accordingly from the robot controller. By combining cross-seam tracking and arc length control, through-the-arc sensing can keep the arc in the root of the joint and the torch at the proper standoff distance. Fig.5.3 illustrates the principle method.

Although through-the-arc sensing has the potential to produce complete topographical information describing the seam by making current and voltage measurements across the entire profile, it is not applicable to thin metals and many weld joint geometries, and linear welding speeds are limited by the oscillation requirements. This method also requires a very stable welding power supply.

5.5.3 VISION-BASED SENSING

More sophisticated and specialised seam trackers include vision-based sensors, using either white light TV monitoring or laser illuminated techniques. This method normally uses a camera to view the welding seam and generate a digital image. Information extracted from this image concerning the size, shape and relative position of the seam can be used with suitable algorithms to provide guidance of the torch on the required path.

A television camera generates a two-dimensional image of a scene. Additional information must be encoded in the scene if three-dimensional measurements are to be made from a TV image. Structured light, in the form of a cone of laser light, is used in many systems to resolve this ambiguity. As shown in fig.5.4, when the light is projected on the metal surface, a light stripe appears on the illuminated seam. The weld joint profile can then be captured, since each point on a stripe will lie both on the known light structure and the line-of-sight determined by the image of the point.

Vision systems can be considered as extremely good seam trackers, as they have demonstrated both speed and flexibility. However, the hardware required for vision-based seam tracker is often expensive, it is for this reason that its use is limited in robot welding applications.

5.6 PRACTICAL CONSIDERATIONS

An effective seam tracker should provide a tracking signal to adapt weld process variables to produce the desired weld for conditions of varying seam geometry. In accommodating a wide range of practical welding conditions the following requirements should be considered in seam tracking design:

(1) Tracking is performed during the welding process to correct for real time distortions due to temperature gradients.

(2) No contact between sensor and workpiece.

(3) The tracker should be unaffected by the high electromagnetic interference environment associated with arc welding.

(4) A tracker operating in real time must be immune to smoke, spatter, heat, UV radiation and intense light.

(5) The sensor head should be compact and with minimal extensions beyond the dimensions of conventional torches.

(6) The tracker design should meet the objectives at minimum cost.

Tactile sensors provide a seam tracking technique at relatively low cost. Unfortunately, they cannot easily be adapted to suit a variety of seam geometries because of their physical contact requirements. This technique is not viable for most robotic welding applications that require adaptive control sensing. Despite the advantages of through-the-arc sensing, it is not suitable for this research as the method relies on relatively thick metals with well defined joint sidewalls. This technique can track only during welding, and cannot search for the seam before welding. Vision-based sensors were considered to be ideal for adaptive control sensing for the aluminium welding system, but the only drawback is that hardware costs are relatively high. For this reason research was concentrated on investigations of alternative seam trackers, which fulfil the basic requirements but also keeping the system cost to a minimum.

5.7 THE EXPERIMENTAL SEAM TRACKERS

Considering the practical requirements of the experimental system, two low cost seam trackers were developed [27]. Each device includes a sensor which gathers the seam information just ahead of the weld pool. Each is attached to the torch and measures the distance of the sensor from the workpiece, and by including a sweep motion it is able to map out the contour of the gap to be welded.

The first sensor uses an infra-red transmitter and receiver, whilst the second uses an ultrasonic transmitter and receiver. Both sensors are able to work in close proximity to the torch and accurately record gaps greater than 1mm and overlapping plates with thickness greater than 0.5mm. The ultrasonic sensor has higher resolution than the infra-red sensor and is less dependent on the surface condition. The infra-red sensor however can be operated at higher sweep rate.

Both systems provided non-contact sensing and low cost construction. They were used with the TIM robot to produce TIG welds. They directly communicate via a RS-232 interface with the TIM controller and supply an 8-bit message word, which gives both the direction and the amount of offset of the torch from the seam.

Descriptions of these seam trackers will be presented in the next two chapters.

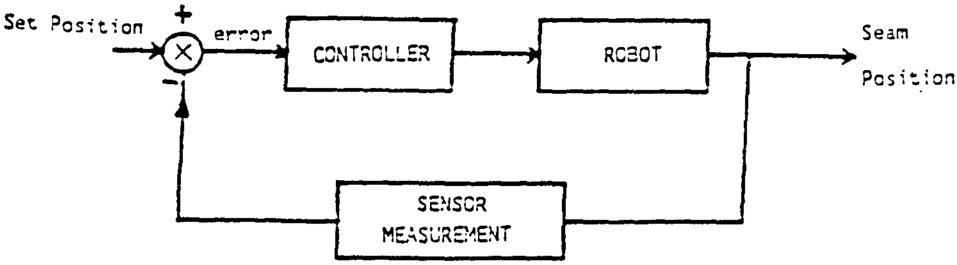


Fig.5.1 Basic Feedback System

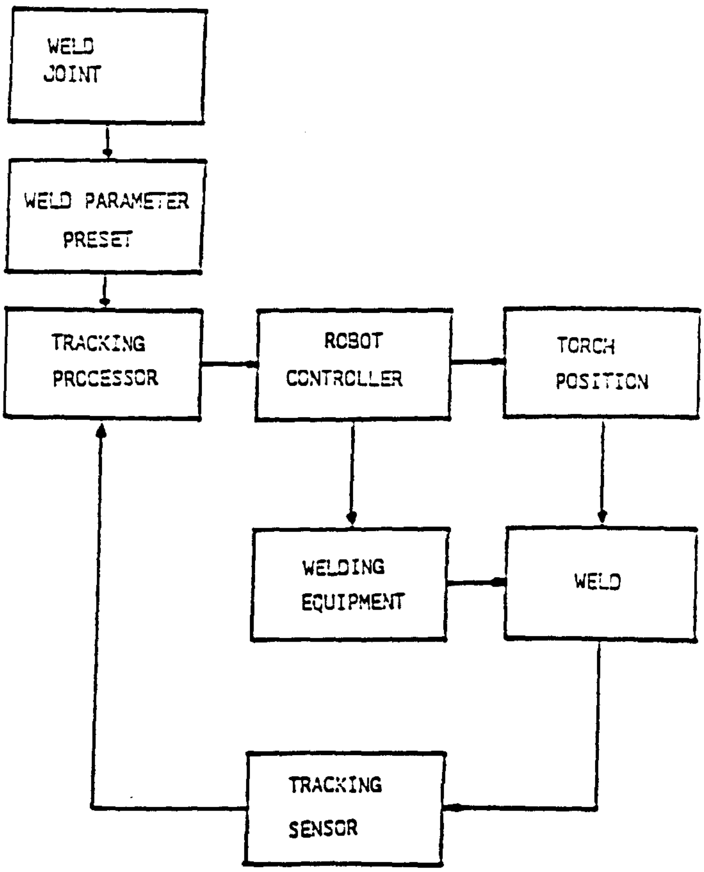


Fig.5.2 A Seam Tracking System

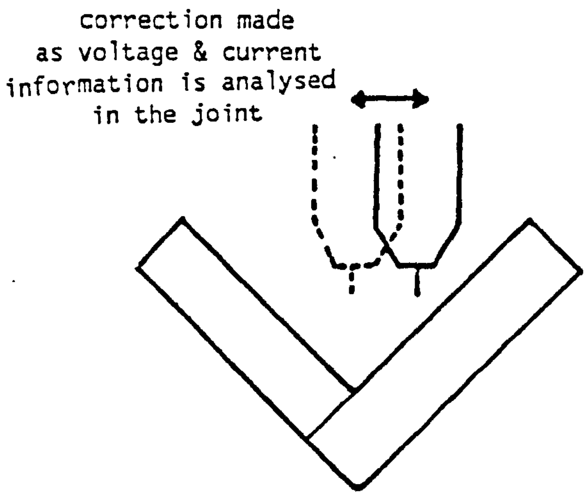


Fig.5.3 Through-the-arc-sensing

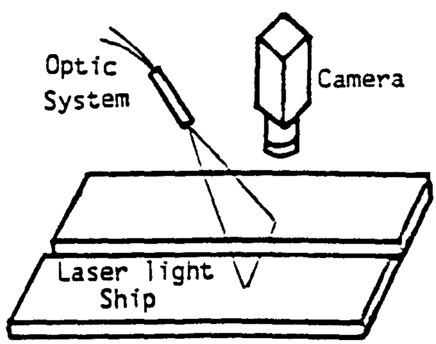


Fig.5.4 Vision - Sensing

CHAPTER 6 INFRA-RED SEAM TRACKER

6.1 INTRODUCTION

In general, one of the principal problems in maintaining weld quality is the control of the torch position relative to the seam. The operation and control of all parameters necessary for joining by TIG welding are well understood, and the welding robots have been demonstrated as suitable for automatic operation. Nevertheless, good welding depends on the torch following the welding seam, and the seam tracking problem must be resolved in each case, to suit particular conditions of geometry, precision of parts, desired quality level, and production requirements.

An ideal robot would cater for all these problems but such a robot would be complex and the cost would easily exceed practical economic levels. Therefore a lower price robot fitted with low cost application specific sensors is a more realistic solution for robotic welding. Therefore the use of a low cost infra-red sensor for seam tracking was investigated.

In this chapter the hardware and software development of an infra-red seam tracker is described. Experimental results are given. This is a realisation of preliminary work [28] at Liverpool University, relating to the development of low cost sensors for robotic welding.

6.2 CONCEPT

The concept is based on the idea of range finding using pulsed infra-red light. The sensor consists of a simple infra-red transmitter and receiver and measures signal variations as a function of sensor to workpiece spacing. By sweeping the sensor across the seam, 256 depth measurements are taken and a contour of the seam can be reconstructed since a reduction in signal occurs when the light passes over the seam.

Fig. 6.1 shows the configuration of the developed sensor. This design used an infra-red light emitting diode as the transmitter and an infra-red detector as the receiver. The infra-red light is pulsed at 1KHz to provide a synchronisation signal to the sensor processor and also to reduce noise pick up from the welding arc. The strength of this light is inversely proportional to the distance travelled as it hits the workpiece and is reflected to the receiver. The received signal amplitude which contains the information of the seam is then converted into a digital form for data processing.

The centre of the seam is determined by the interpretations of the sensed pattern obtained from the 256 data samples. If the sensor is attached onto the torch in such a way that, the torch is originally pointed at the centre of the seam, then the calculated centre value should occur in the middle of a sweep.

However, if the seam is distorted or the torch strays away from the seam during welding, the sensed pattern will be shifted in position and the centre value will occur off the centre of a sweep. In this case, the seam tracker will signal the robot controller and provide error calculations for correcting seam position offsets.

The rate of the sweeping motion of the sensor is controlled by a stepping motor and the initial position of the sensor relative to the seam position is detected using a slotted opto-switch.

6.3 HARDWARE

Hardware development of the infra-red seam tracker consists of six sections as shown in fig.6.1. It was designed as a target system, which contains its own processor for operation control and data analysis, and can be directly interfaced to the robot controller. The overall design was based upon the requirement of keeping the system cost as low as possible.

6.3.1 SENSING MECHANISM

The sensory head was designed to be compact and easy to attach to the robot torch. The main components of the sensor consisted of an infra-red LED (RS 306-077) and an infra-red detector (RS 306-083). Fig.6.2 shows the configuration of the sensor mechanism. The infra-red LED and detector were mounted closed to each other, so that the receiver was 20mm above the electrode tip and 10mm away from the torch, and the transmitter was fixed at an angle of 6° from the receiver and pointing to the surface directly below the receiver. A fibre optic glass of 5mm in diameter and 50mm long was mounted on the receiver, in order to ensure the capture of data when exposed to the intense heat during welding.

It is obvious that the signal amplitude of the receiver which receives the reflected infra-red light spot from the surface indicates the distance from the workpiece to the sensor. To extend this scheme to determine the profile of a seam, the sensor was swept across the seam by a stepping motor which was mounted on the top of the torch. The stepping motor does not make complete revolutions, but performs a to and fro sweeping motion over an angle of ±14°. The sensor was placed at a radius of 20mm away from the axis of the motor shaft. If the motor turned at

±14° about the centre of the seam then the sensor scribes an arc of length 10mm across the seam. For each sweep, some 256 depth measurements were taken and a surface profile was obtained. The reference position of the seam was calculated based on the initial position of the sensor relative to the seam. The initial position of the sensor was determined using a slotted opto-switch (RS 306-061). This switch comprises an infra-red emitting LED and integrated photodetector housed in a slotted moulding. The photodetector responds to the infra-red beam being broken as an object passes through the slot. The switch was mounted in such a way, that the beam would be broken when the sensor made the first sweep across the seam. This initialised the sweep controller. Thereafter the number of stepper motor pulses are counted until a preset value is reached. Then the counter is re-initialised and the motor direction reversed. Thus the sensor makes continuous sweeps, back and forth across the seam.

6.3.2 SWEEP MOTION CONTROLLER

The sweep motion controller was designed using a SIGMA 20-2220D200-E003 stepping motor [6], a DIGIPLAN 1054 stepping motor drive [29], and an INTEL 8253 programmable counter [30].

The stepping motor used is a two-phase motor with permanent magnet rotors. It moves through discrete angular steps with resolution of 1.8° in response to voltage pulses applied to the motor drive.

The stepping motor drive from DIGIPLAN is based on the design using a bipolar, bilevel bridge with current regulation. The bipolar system gives the high torque per watt from the motor since all the windings are fully utilised, i.e., current is always flowing in one direction or the other in each winding. The use of bilevel switching is largely responsible for the high overall efficiency and there is an absence of the audible noise associated with chopper regulated drives at stand still. The drive uses both high and low voltage power supplies, the high voltage supply being used to overcome winding inductance and ensure a rapid build-up of motor current. When the current reaches the required level the high voltage supply is switched off and the low voltage supply takes over, minimising the drive current losses. The motor drive is controlled by an INTEL 8253 programmable counter together with two opto-isolators (RS307-963) which supply the required interface signals to the Motor Clock In and the Motor Direction inputs of the stepping motor (fig.6.3). The Motor Clock In responds to a low-going transition which causes the motor to advance one step. This input should remain at logic 0 for not less than 5μs and not more than 30μs and another low-going pulse should not occur within 50μs. The direction of the motor rotation is dependent upon the logic level at the Motor Direction input. The inputs have built-in pull-up resistors greater than 4kΩ and 12V for logic 1.

The 8253 consists of three counters and a control word register. Each counter is a 16-bit with a count rate up to 2.6MHz. The counters are fully independent and each can have separate mode configuration and counting operation. The complete functional definition of the 8253 is programmed by the system software. The counter input and output are configured by the selection of modes stored in the control word register. There are six modes which can be selected for operation as follows:

MODE	DEFINITION
0	Interrupt on Terminal count.
1	Programmable One-Shot.
2	Rate Generator.

3 Square Wave Rate Generator.

4 Software Triggered Strobe.

5 Hardware Triggered Strobe.

For controlling the speed and direction of the sweep motion, only mode 2 and 3 were used. Both modes are based on the principle of generating accurate time delays.

The Rate Generator is a divide by N counter which generates a series of pulses. The output period equals the number of input counts in the count word register. The counter starts counting when the gate input is set high, and disables counting when the gate goes low (fig.6.4). This mode is used for controlling the sweep speed by programming the input counts together with the synchronisation of the gate input to produce the required frequency signal.

Operation of the Square Wave Rate Generator is similar to the Rate Generator except that the output remains high until one half the count has been completed and goes low for the other half of the count. This is accomplished by inputting even numbers for the count. If the count is odd, the output will be high for (N+1)/2 counts and low for (N-1)/2 counts. This mode is used for setting the sweep length in both to and fro directions of sweep motion.

Since the 8253 operates with a 5V power supply whilst the stepping motor drive required 12V for the logic 1, an interface circuit is needed. This is achieved by using an open-collector transistor type of opto-isolator, which not only supplies the required interface signals but also isolates the stepping motor drive from the processor board.

6.3.3 TRANSMITTER CIRCUIT

The transmitter was constructed using few components as shown in fig.6.5. The 555 timer forms the basis of a pulse generator which supplies transmitting signals to the infra-red LED. It operates in a form of a monostable with adjustable frequency circuits.

A pulse is generated by first charging the timing capacitor C2 to two-thirds of the supply potential via both R2 and VR2, and during this time the output goes high. C2 is then discharged rapidly and drives the output to its low state. When the voltage on C2 falls to one-third of the supply voltage, the circuit remains in this state until the set time elapsed. The time that the output is in the high state is known as pulse width and given by [31]:

$$t = 1.1\ (R2 + VR2)\ C2 \qquad (6.1)$$

where both R2 and VR2 are in the unit of Ω and C2 in F, thus t is in sec.

The frequency of the output pulses is defined from the adjustable frequency circuit. When the circuit is switched on, C1 charges until TR1 begins to turn off, cutting off TR2 and discharging C1 through R1 and VR1 until TR1 is turn on and cycle repeats. The output of TR2 charges from high to low and triggers the 555 to initiate a monostable timing. The pulse repetition frequency is determined by:

$$T = (R1 + VR1)\ C1 \qquad (6.2)$$

Both pulse width and frequency can be controlled by choice of values for C2, R2, C1 and R1, and by adjusting VR2 and VR1. Taking (R1 + VR1) about hundred times higher in value than (R2 + VR2) the required output waveform with a mark and space ratio of about 1 to 100 is obtained. The transmitter operates at a frequency of about 1kHz. The pulses pass via a current amplifier, which consists of TR3 and TR4, and transmit through the infra-red LED. As well as generating pulses for the LED the transmitter also extracts trigger signals for the receiver.

6.3.4 RECEIVER CIRCUIT

Fig.6.6 shows the receiver circuitry. The infra-red detector responds to the reflected radiation from the infra-red LED. The pulses of infra-red energy from the transmitter therefore cause small pulses of current to flow through the infra-red detector and the 1KΩ resistor, generating small voltage variations.

The signal generated from the detector is inputted to an adjustable amplifier (Differential a.c. Amplifier 9454) which provides signal filtering and voltage amplification. The amplifier is used to calibrate the received signal levels for sensor position settings. Output from the amplifier is then fed to an RS3300 fast ADC (analogue to digital converter) for data processing.

The 3300 is a high speed 'flash' 6-bit device with an operating frequency up to 15MHz. The conversion is performed in a parallel manner by 64 auto-balanced comparators with resistor ladder networks. An internal voltage reference is featured and the outputs are via tri-state latched buffers. The operating sequence consists of the 'Auto Balance' phase $\phi 1$ and the 'sample unknown' phase $\phi 2$ (fig.6.7). Each conversion takes one clock cycle. With the phase control low, the 'Auto Balance' phase $\phi 1$ occurs during the high period of the clock cycle.

The 3300 can be operated in the continuous clock mode or the pulse mode. The former is used for continuous sampling and the later for sampling taking place only during the pulse period which applied to the converter. As the received signal is a series of pulses the 3300 is set to operate in a pulse mode. The method is to keep the converter in the $\phi 1$ phase during the standby state. A conversion is initiated by strobing the clock input with two $\phi 2$ pulses. The analogue value captured in the comparator latches on the trailing edge of the first $\phi 2$ pulse. Data is then transferred into the output registers on the leading edge of the second $\phi 2$ pulse. Both the conversion rate and the repetition rate depend on the input clock to the 3300.

The conversion rate is derived from a 74S124 clock generator which gives 1μs clock period for $\phi 2$ pulses. To ensure conversion occurs during the trigger pulse, a divided-by-8 counter is constructed using a 74LS393. The counter is enabled by the trigger pulse. The counter output is the result of dividing the clock signal by eight and it is then ANDed with the clock signal forming an input clock for the 3300. In such a way the conversion takes place around the centre of each trigger pulse.

6.3.5 SENSOR PROCESSOR

The task of analysing and interpreting the received signals was performed by the processing unit. This unit consists of two parts, one for the capture and analysis of data and also communication with the controller for deviation corrections, and the other for the control of the speed and direction of the sensor sweep motion. Both parts are based on the Intel 8085 microprocessor which contains the essential memory and communication facilities. One of the reasons for choosing the Intel processor was due to the support facilities, such as the development systems, debugging systems and etc., which were already available in the research group.

Fig.6.8 shows the circuitry of a microprocessor system. The 8085 is an 8-bit parallel CPU (Central Processing Unit). It has a multiplexed address and data bus. The memory section consists of two 1420s and two 2764s giving 4K byte of RAM (Random-access Memory) and up to 8K byte of EPROM (Erasable Programmable Read-Only Memory). An Intel 8155 provides 22 lines of I/O comprising two 8-bit ports (A and B) and one 6-bit port (C). Each port can be programmed as input or output. An 8251A USART generates an RST 5.5 interrupt to the CPU upon receiving a full character. The remaining circuitry has an address decoder (74LS138), an address latch (74LS373), a frequency divider (consisting of a 74LS90 and two 74LS393s), and a wait state generator (74LS74). Bus expansion is also available via five buffers (two 8216s and three 74LS244s).

The system uses the lower 32K byte address space of the 8085 and leaves the upper 32K byte for expansion. The lower half of the address bus is demultiplexed by latching the address on the trailing edge of ALE with the 74LS373. The latch outputs together with the CPU lines A8-A15 provide the required memory address signals. IO/M/ is only used by the 8155 and all other devices are memory mapped. RD/ and WR/ are pulled high by 4.7KΩ pull-up resistors to prevent spurious memory accesses during the CPU reset cycle when these lines go into tri-state. When addresses in the upper 32K are accessed, the output from the wait state generator is enabled by A15. This output pulls the CPU READY line low for one state. Direction of transfer for the bi-directional buffers is set by A15 and RD/.

Two microprocessor boards were built for the experiment. The receiver circuit and an RS-232C communication port (as describe in the following section) were interfaced to one of these boards to perform data capture, data analysis and communications to the robot controller, whilst the other board was modified by the addition of a sweep motion control circuit to provide control signals to the stepping motor drive. The second board provided a large space for further expansion if required. Both boards communicate to each other in order to perform the task.

6.3.6 COMMUNICATION LINK

Communications between the seam tracker and the robot controller is carried out via an RS-232C serial link, which is the EIA (Electronics Industry Association) standard which covers the electrical specifications for bit-serial transmission. The standard uses nominal ±12V pulses to effect information transfer. The main signal lines are TxD (transmit data) and RxD (receive data), RTS/ (request to send), and CTS/ (clear to send). These lines are used to provide handshaking and information transfer between the two systems. The baud rate is set to 4800 with full duplex transmission.

After data capture and analysis, if correction is required, the seam tracker sends a deviation value in a single byte to the robot controller. Communications to the robot controller is driven by software which is written for the 8251A USART (fig.6.9). It serves as the interface between the parallel data processing CPU and the RS-232C serial link.

The USART has five internal registers: receive data, transmit data, mode, status, and control. Upon reset, the first byte sent to the USART as control sets the MODE. The next byte sent as control is latched in as

CONTROL. The MODE determines whether the USART is to be used in synchronous, or asynchronous, mode. The CONTROL indicates the word length and other transmit parameters.

Although the 8251A supports basic data transfer, it does not provide the voltage levels required by RS-232C since it is TTL compatible. To accomplish the interface between TTL and RS-232C special line drivers and receivers are needed. This is achieved by using the CMOS 1488 for TTL to RS-232C line driver and the CMOS 1489 for the RS-232C to TTL line receiver.

An asynchronous transmission format is used, in which numbers (or characters) are send one at a time without necessarily having any fixed time relationship between one number and the next. When the USART wishes to send a number, it precedes the number with a start bit by switching the state of the line from the high (idle) condition to the low (active) condition for one bit time. The data bits are sent out following the start bit. After the data has been transmitted a parity bit may be added before one or more stop bits. The purpose of using a start bit is to allow the robot controller to identify the first bit of each number. The parity bit is used for error detection by making the number of '1' bits even or odd. After the byte is read, a new parity is generated by the controller. If the regenerated parity bit does not match the recorded parity bit, there is an error of at least one bit. The stop bits provide a well defined time for the controller to get ready for the next number. When no information is being transmitted, it is conventional to leave the line in the idle state.

6.4 SOFTWARE

The performance of the system control depends on software support. This is accomplished by:

(1) controlling the sensor sweep length in order to obtain sufficient data.

(2) capturing data.

(3) analysing the data and deducing the seam position.

(4) guiding the robot for seam tracking.

The language used is the Intel 8085 assembler and details of software listing is shown in Appendix III.

6.4.1 SENSOR SWEEP CONTROL

Upon power on, the sensor sweep control board waits for a ready signal from the data processing board which detects the starting signal from the robot controller. It is then initialised by setting up the I/O section of the 8155 as follows:

PORT	I/O	DESCRIPTION
A	OUTPUT	Provide motor control signals.
B	INPUT	Reserved for data transfer from data processing board.
C	INPUT	Detect synchronisation signal from data processing board.

The sensor sweep motion is controlled by counter 0 and 1 of the 8253, initially these counters are disabled to ensure the stepping motor is stationary. Before starting the motor, the position of the sensor relative to the seam needs to be found. This is done by programming counter 0 in mode 2 operation, so that the speed of the stepping motor is set up, and the sensor moves in one direction only until the slotted opto-switch is enabled, then a synchronisation signal is obtained to start the main program.

During operation the speed of sweep motion is determined by counter 0 in mode 2 operation, and the sweep length is controlled by counter 1 in mode 3 operation. All control words are sent to the control word register of the 8253 via Port A. Counter 0 is driven by a 4.8KHz clock and a number of 1024 counts is set for mode 2. A slower clock of 150Hz is used for counter 1 and a number of 2756 counts is set for mode 3.

For experimental purposes this sweep length is set to scan weld joints from a closed gap to 6mm gap. However, the sweep length can be varied with respect to the variation of the weld gap. If the weld gap is small, then the sweep length together with the number of sampling data can be reduced, and this could effectively increase the sensor sweeping rate.

6.4.2 DATA CAPTURE

Before capturing data there is an initialisation procedure. The I/O section of the data capture board is defined as follows:

PORT	I/O	DESCRIPTION
A	INPUT	Receive data from ADC.
B	OUTPUT	Send ready signal to the sensor sweep control board and deviation commands to the robot controller.
C	INPUT	Detect synchronisation signal from the slotted opto-switch and the change of direction from the sensor sweep control board.

After initialisation, a ready signal is sent to the sensor sweep control board for starting operations. When the synchronisation signal is detected from the slotted opto-switch, a synchronisation signal is sent to enable the direction of the sensor sweep. The processor waits until the sensor moves to one extreme position by detecting the transition from low to high of the motor's direction control line, and then starts capturing data based upon the ADC's trigger signal which denotes the start of data conversion. The captured data are stored in a 256 byte data table which is set for later data analysis.

Prior to starting seam tracking, a reference value which corresponds to the centre of a seam is needed, and this is taken from two initialisation sweeps across the seam.

6.4.3 DATA ANALYSIS

Data captured from the sensor contains various noise as well as information which represents the weld seam. In order to interpret the data correctly, data analysis is required which discriminates the weld seam signal from the unwanted noise, and hence find the centre of the seam for effective seam tracking. If the seam is a V-prep, the analysing procedures are as follows (fig.6.10):

(1) All the data stored in the data table is summed up and divided by the number of samples. This gives the average value of the infra-red light intensity over a complete sweep.

(2) A threshold level for reducing noise distortion is taken as three quarters of the average value.

(3) Transition points of the sensed pattern to the threshold level are then obtained by comparing each stored data and the threshold value. These transition points are used for determining the position of a seam. No transition points means no seam has been detected.

(4) If there are more than two transition points, which means possibly more than one groove pattern is obtained, a method to deal with this problem is to compare each minimum value and groove width to extract the most probable groove and delete the others, thus forming a single seam pattern.

(5) Using the single seam pattern, a desired central point of the seam is regarded as the mid-point between the two transition points.

After data capture noise reduction is carried out by using the following expression:

$$t_h = \frac{3}{4n} \sum_{i=0}^{i=256} d_c \qquad (6.3)$$

where t_h is the threshold level, n is the number of samples and d_c is the captured data. This process provides the essential conditions for extracting the true weld seam from the sensed pattern.

By use of data analysis, the required weld seam can be detected correctly even if the received signals are disturbed by various sources of noise. This method is known as threshold and is also applicable to other weld joints such as butt-joints.

6.4.4 GUIDANCE OF WELDING ROBOT

The system described above is capable of measuring the position of a weld seam from a sensed pattern reflected from the seam. This capability has been integrated into a robot control algorithm so that the infra-red sensor can provide feedback to the robot controller to follow a weld seam. Real-time guidance of a welding robot consists of data processing to analyse the sensed pattern of the seam and locate its position, and the robot control algorithms that redirect the robot to follow the seam.

The robot control algorithms are available in the controller system. Parameters required from the seam tracker are the deviation value and the direction of deviation. This deviation value is obtained by comparing the reference centre value with the newly calculated centre value, and is stored in a single byte number in eight bits two's complement notation ranging from -128 to 127. Each number represents the amount of deviation from the centre of the seam and the sign represents the direction of deviation. In the two's complement representation, the negative of a number is the logical complement plus one. Normally, the most significant bit is used for the sign; that bit is zero if the number is positive and is one if the number is negative.

The robot used is capable of correcting position errors in the units of 0.1mm. If zero deviation is received, there would be no correction taking place by the robot. However, if it exceeds the limit of 0.1mm, the robot starts correction until the welding torch is on seam again.

The control operation of seam tracking is based on the communications between the seam tracker and the robot controller. When tracking is commenced, the seam tracker sends the deviation command to the robot controller. In the reverse direction the robot controller can send one of the following five values to the seam tracker. Each value represents the current state of the robot controller:

VALUE	DESCRIPTION
01	Acknowledgement after processing the last deviation value.
02	Indicate the start of welding and seam tracking.
03	Indicate the end of welding.
04	Debug request to the robot controller and the seam tracker.
05	Reset system.

Normally the robot controller and the seam tracker control programs are "boot up" upon power on or reset. Once the systems are running, both the robot controller and the seam tracker cannot be accessed by the terminal. However, a DEBUG command on the host computer may cause a debug request to be issued to the robot controller which then sends the value 04 to the seam tracker. By checking if the value 04 has been received, the seam tracker can drop into it's operating system command line interpreter so that software can be debugged.

During operation the seam tracker waits for value 02 to commence tracking. If a deviation command has been sent out, the seam tracker should not send the next command until a value 01 is received, so as to ensure the last deviation value has been processed. This continues to be the case until value 03 is received indicating the end of tracking.

6.5 EXPERIMENTS AND RESULTS

A series of experiments was conducted on both the scanning and tracking of a weld seam. Scanning included weld seam extraction and deviation measurements, whilst tracking was carried out on various types of weld seam samples. Results obtained from these experiments provide valuable references to explore the usefulness and limitations of the seam tracking system.

6.5.1 SEAM EXTRACTION

The first step in seam tracking process is to extract the weld seam location from each recorded scan. The weld seam geometry is described according to the seam shape by features such as cross-section area, gap width, and edge displacement, etc. To obtain this information, a series of static scanning tests were carried out corresponding to three types of weld joints, namely overlap, butt, and V-prep (fig.6.11). In each case, the test plates were arranged so that the sensor could scan across the seam with the same sweeping rate and the same number of capturing data. These results are shown in figs. 6.12, 6.13, and 6.14, where the whole range of the sweep displacement represents a single sweep for the sensor to move from one extreme to another, and the received signals correspond to the intensity variations in the reflected infra-red light.

Static scans on three sets of different thickness's of overlapping plates were carried out with the same sensor height, i.e. distance between the sensor to the lower plate was set to be 12mm. Fig.6.12 (a), (b) and (c) are the results taken from these tests, and the shapes of the overlap joints are clearly extracted. Using any of these detected patterns, the position of a seam can be located as the transition point of the pattern to the average level of the received signals. With reference to these results, it is evident that the strength of infra-red light is inversely proportional to the distance it travelled as the upper plate reflected stronger light than the lower plate. However, some information was lost at the seam edges, due to the fact that, some of the light was reflected to the receiver and some scattered away when the sensor moved across the seam. The thicker the workpiece, the bigger the scattering effect at the seam edge. Although the sensed pattern can be affected by many terms, such as the weld joint dimensions and surface conditions, the principle method for seam tracking still applies.

More scattering effects can be seen in fig.6.13. These results were obtained by scanning across the gap between two similar plates with thickness of 6mm. These plates were arranged to give three different gap widths for individual tests. The closed gap butt joint shows the scattering effects on those rounded corners of the joint which forms a shallow seam. The perceived seam became wider as the gap was increased. To locate the centre of this type of joint, algorithms designed for the V-prep can be applied, since their sensed patterns are similar in shape.

Three pre-machined V-prep samples were used for static scanning. They differ only in sample thickness, and thus, provide different groove dimensions. Fig.6.14 shows the corresponding results. One aspect common to each set of results, is that the information corresponding to the centre position of each V shape groove is lost due to the scattering effects. However, the system had managed to capture sufficient data for the supporting software to extract the seam position.

6.5.2 SEAM DEVIATION DETECTION

Seam deviation detections were made on a V-prep sample using dynamic scans. The sample had a straight line seam of 1mm wide. It was cut into a few sections, across the seam, so that they could be arranged to form the desired seam deviations as shown in fig.6.15 (a). The sensor mounted on the torch was programmed to follow a straight line path along the seam of one of the two sections. When the sensor reached the end of the first section, it continued to move in a straight line, but the seam of the remaining section was at a preset angle to the first. The sensor output then indicated deviations from the preprogrammed path.

Fig. 6.16 shows the results of two sets of deviation measurements. Each data sample from the graph represents a calculated centre value of the seam from a recorded scan. Both plots were based on 40 seam location values along 40mm distance within the seam deviation area. Plot (a) was obtained from a test run on a seam with 20° deviation. Plot (b) shows the results of a similar test but on a seam with 45° deviation.

It is obvious that the seam tracker is capable of extracting the seam from each scan and measuring the seam position, thus giving the correct deviation value to the robot controller for seam tracking.

6.5.3 SEAM TRACKING TRIALS

In any real welding processes, a weld seam path may be distorted causing deviation or off-line, due to the reasons of thermal expansion, mechanical vibrations, fixture tolerance, and system errors, etc. Seam deviation may happen suddenly or gradually building up. To simulate these situations and perform seam tracking, two sets of experiments were carried out using the same sample as described in section 6.5.2. One experiment was on the tests of a weld seam off-line tracking, whilst the other on the tracking of a seam with various corners. The first was to simulate a sudden deviation, and the latter was catered for the gradual change of weld seam path.

Fig.6.15 (b) shows the arrangement of a test sample. The sample consisted of two sections of straight line seam. A seam tracking test was first carried out by attaching the two sections with zero offset between the two seams. The torch together with the sensor was programmed to follow the seam path, and the results obtained are as shown in fig.6.17 (a). By varying the offset for the same test, (b), (c) and (d) were obtained. Each graph represents a plot of seam deviation against tracking distance. A total of 160mm tracking distance was recorded close to the area where deviation occurred. During seam tracking, each deviation value was calculated by comparing the newly detected centre value with the previous seam location. If any deviation occurred, the robot would direct the torch to the actual seam position and then take the latest seam location as a new reference for the next scan. This can clearly be seen from the graphs, which show that as the torch following the seam, deviations are small. When the torch reaches the offset point, a rapid change occurs and the magnitude of deviation is proportional to the distance of offset. After the torch is directed back on seam, deviation values become smaller.

Another experiment was carried out with the same tracking procedure. The sample used in this experiment consists of three sections of straight line seams. The three sections were arranged to form two different seam features as shown in fig.6.15 (c) and (d). Fig.6.18 (a) and

(b) are the corresponding results. In case (a), the robot corrected the seam positions twice as the torch followed through the two corners. In case (b), significant deviations can be observed at the points where the seam turned away from its previous path, and the direction of deviation with respect to the centre of previous seam path is indicated by the plus and minus signs in the graph.

All these results confirm that the system is capable of performing seam tracking.

6.5.4 EFFECT OF INTERFERENCE DURING WELDING

As mentioned in Chapter 3 and 4, interference plays an important part in welding automation process. In addition to the suppression of transient interference from high frequency source, power supply, and other unwanted electrical noises, the radiation spectrum of a welding arc needs to be considered, particularly when an optical sensor is used. The radiation spectrum of the welding arc ranges from ultra-violet, through the visible range as far as the infra-red range (fig.6.19) [32]. Ultra-violet radiation shown in the spectrum is particularly strong. From the visible to the infra-red range less intense radiation is emitted from the arc. In order to obtain the best signals possible a waveband with as little radiation emission as possible in the spectrum should be selected . For this reason, the infra-red diodes of 940nm wavelength were used to minimise the effect of the welding arc and thus to ensure the efficiency of the sensor system. Furthermore, a suitable optical filter with narrow bandwidth might be used to reduce the interference of the arc, but the disadvantage in using optical filters is their relatively low transmissibility which would result in part of the reflected light energy being absorbed by the filter and reducing the capabilities of the sensor. The possible way to overcome this problem is either by using infra-red laser diodes to raise the light strength, or by the use of electrical filters together with data processing techniques to replace the optical filter. The latter method was chosen because at that time laser diodes were comparatively expensive.

However, the developed sensor system was tested with and without welding, and both results indicated that the system is suitable for seam tracking. Limitations exist, such as the speed dependance and workpiece surface conditions.

6.5.5 EFFECT OF TORCH SPEED

Various tests were carried out to analyse the effect of torch speeds on the system. Some of the results are shown in fig.6.20 (a) and (b). In each case, three different torch speeds were tested, and they were: 1mm/sec, 5mm/sec, and 10mm/sec. Results shown in each figure were obtained from tests similar to that described in section 6.5.2, in which the samples have seam paths with a 20° and a 45° bends at the second sections, respectively. Seam deviations were measured with respect to the first section of the path. As the torch speed increases, the loss of information at the corner of the bend becomes more significant, which indicates a possible tracking failure at the portion where deviation occurs. In addition, as the torch speed increases, the amplitude of deviation increases as the sensor scans at the position further away from the corner. Beyond about 10mm/sec, it is likely that the second section of the seam could be out of the preset sweep range, and thus result in tracking failure. This may be overcome by increasing the sweep length, but this would slow down the system further. Therefore, a compromise is required in setting up the range of the sensor sweep.

6.5.6 EFFECT OF SURFACE CONDITIONS

Another limitation of the system is its dependence on the workpiece surface conditions. Fig.6.21 shows the experimental results of surface scanning; (a) was obtained from a polished plate with a thick black line drawn at the centre, (b) from a plate with half section polished and the remaining half painted in black, and (c) from a rusty plate with half section being polished. It is clear that the sensed patterns are affected by the surface conditions of the workpiece being scanned. Workpieces are usually prepared by cleaning the weld join sections before welding, but in worst cases, dust may cover some part of a workpiece causing unfavourable reflective characteristics, or if two plates are to be joined together with one plate cleaner than the other, then the sensed pattern may be altered resulting in difficulty in finding the centre of the seam.

6.6 DISCUSSION

The infra-red seam tracker works on the principles of range finding and sweeping the sensor across the seam. Hardware development was based on low cost and compactness. Software design was mainly concentrated on data processing to provide a measure of seam deviations to the robot controller. Programs were written in Intel 8085 assembly language, providing high speed for real time control. The system is capable of locating the seam position from each scan and producing a deviation value relative to the previous seam position. It also has as an available output, an

RS-232C interface, thereby providing simple means for transmitting seam deviation and direction of deviation to any robot controller which can accept real time information via this interface.

Seam tracking can be performed by either two-pass or single-pass methods. Experimental results provided evidence of the sensing abilities. Although the seam tracking system is affected by high speed operations, it is generally acceptable as normal welding speeds are relatively slow in comparison with the speed limit of the system. The main disadvantage, probably, is the dependence of workpiece surface cleanness which requires more control of workpiece preparation and constantly monitoring of the working environment. Nevertheless, the infra-red seam tracker provides a solution for general seam tracking to ensure weld quality with low cost. Fig.6.22 shows the seam tracker in action for TIG welding.

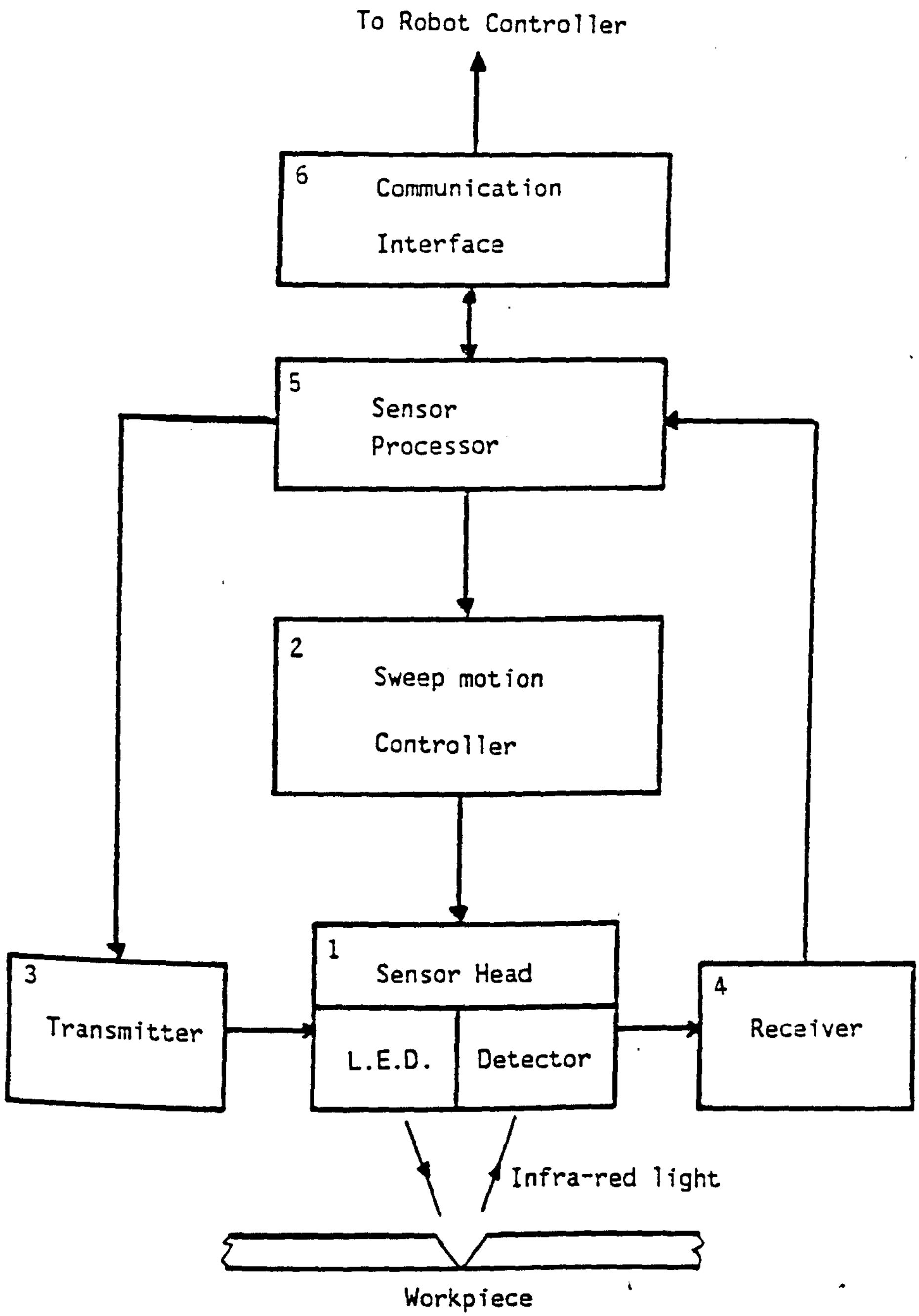


Fig.6.1 Infra-red Seam Tracking System Configuration

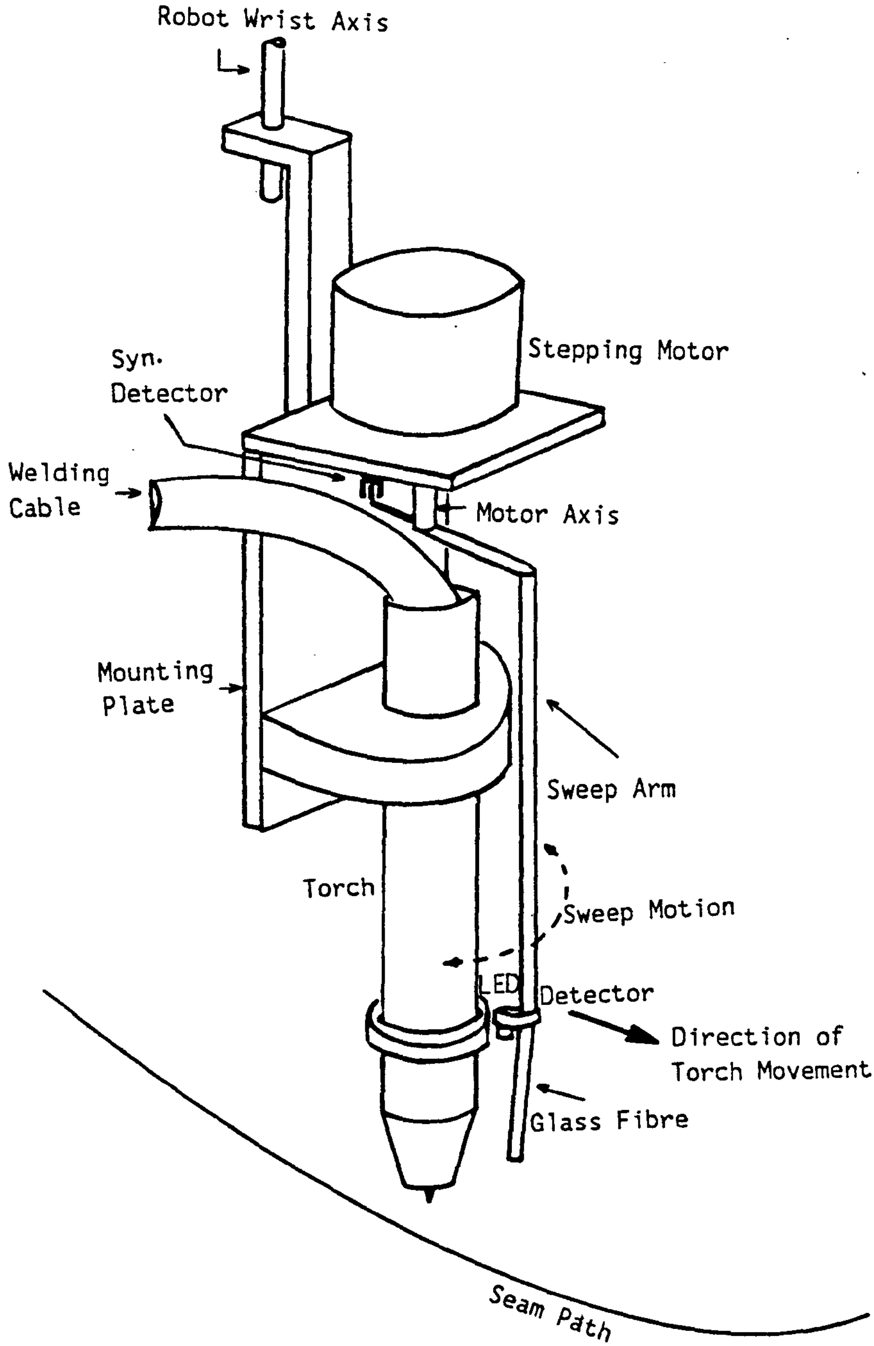


Fig.6.2. Sensor Mechanism

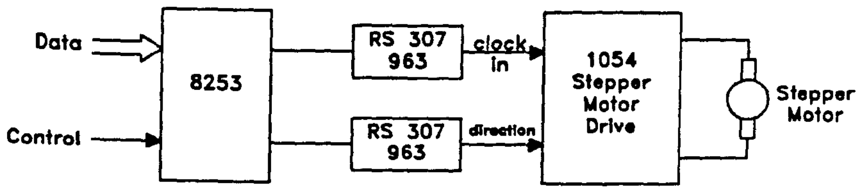


Fig.6.3 Sweep Motor Control

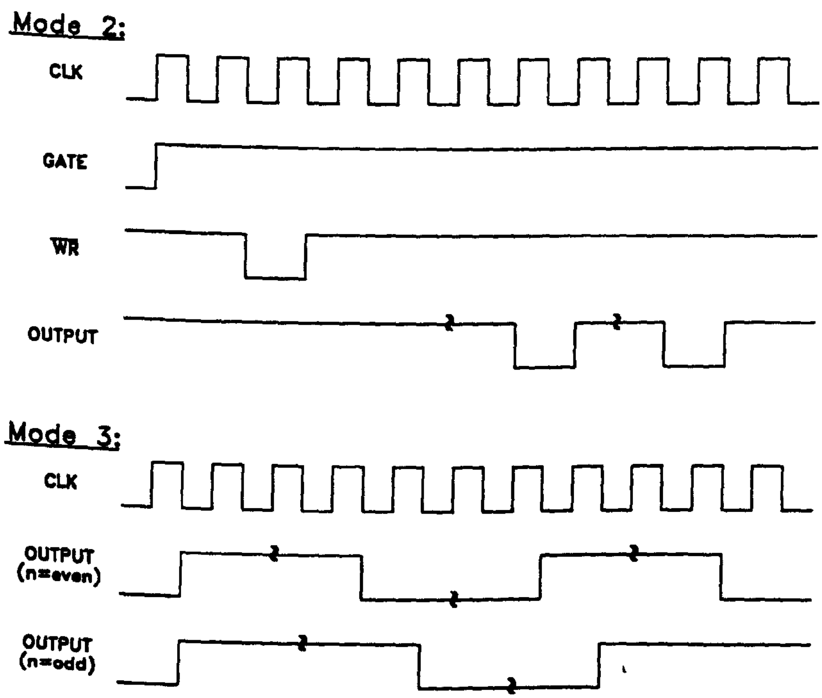


Fig 6.4 Operation Modes of 8253

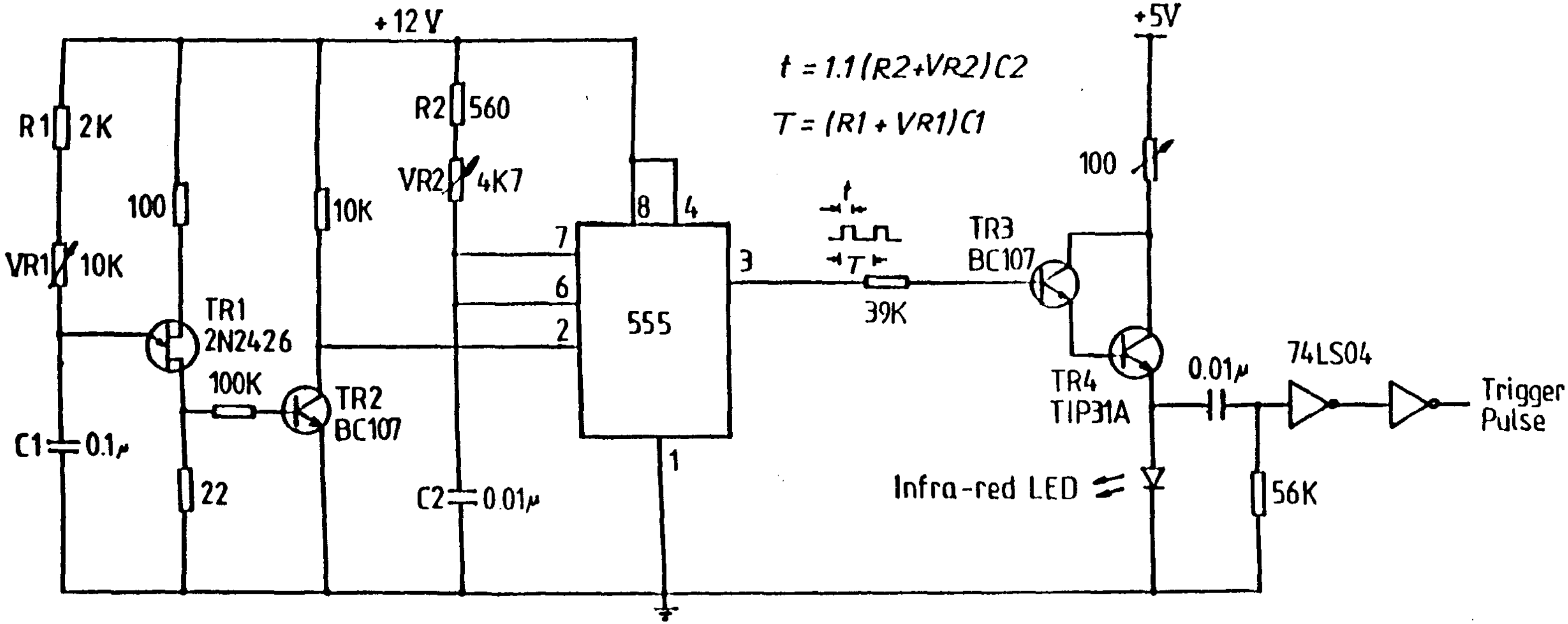


Fig.6.5 Infra-red Transmitter Circuit

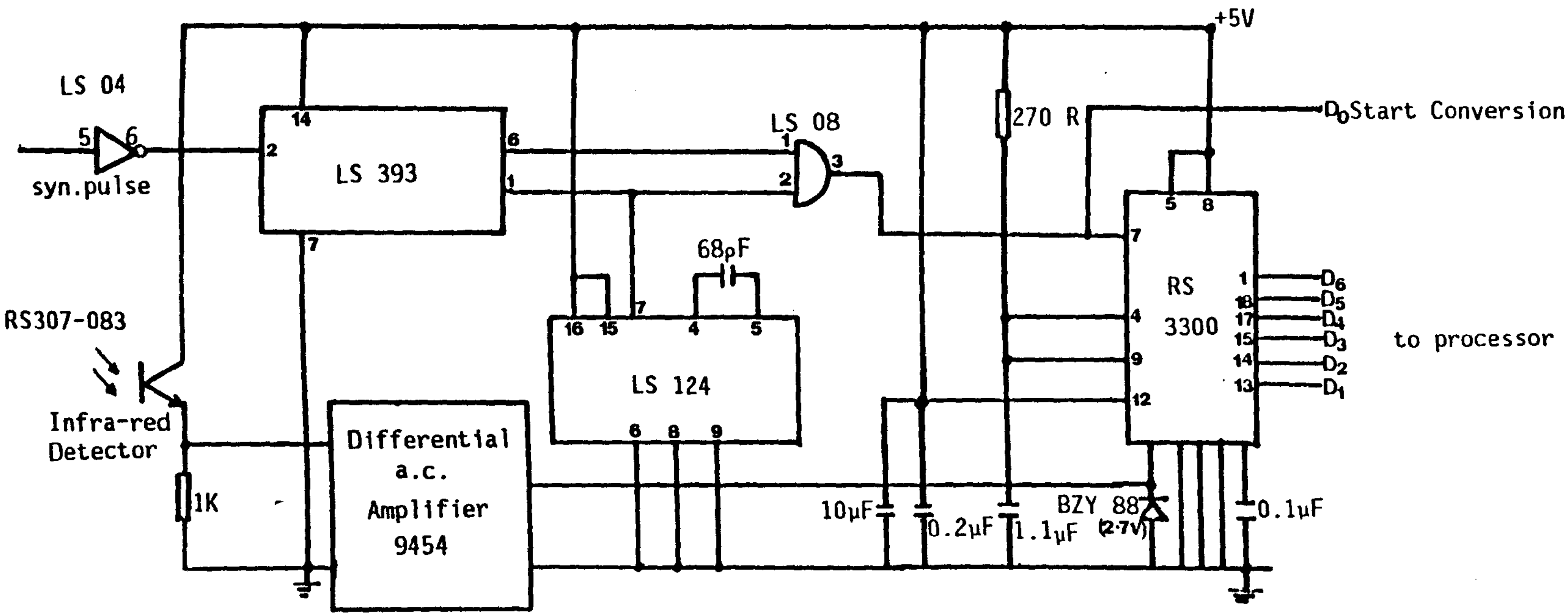
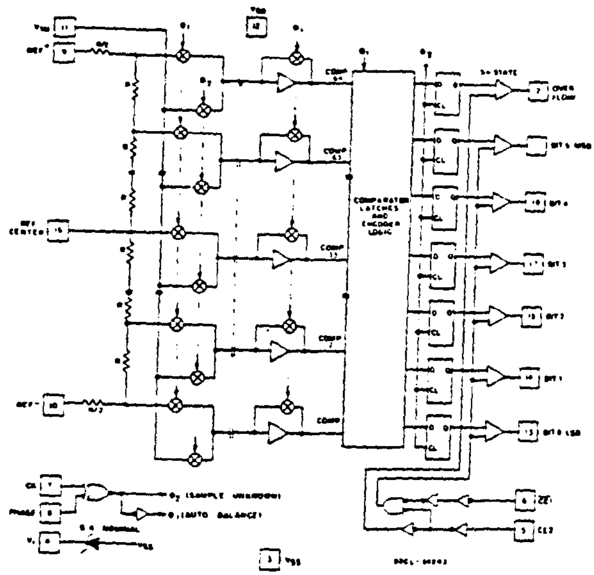
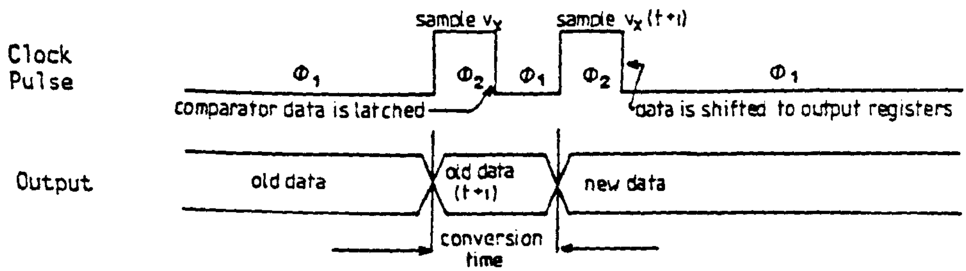


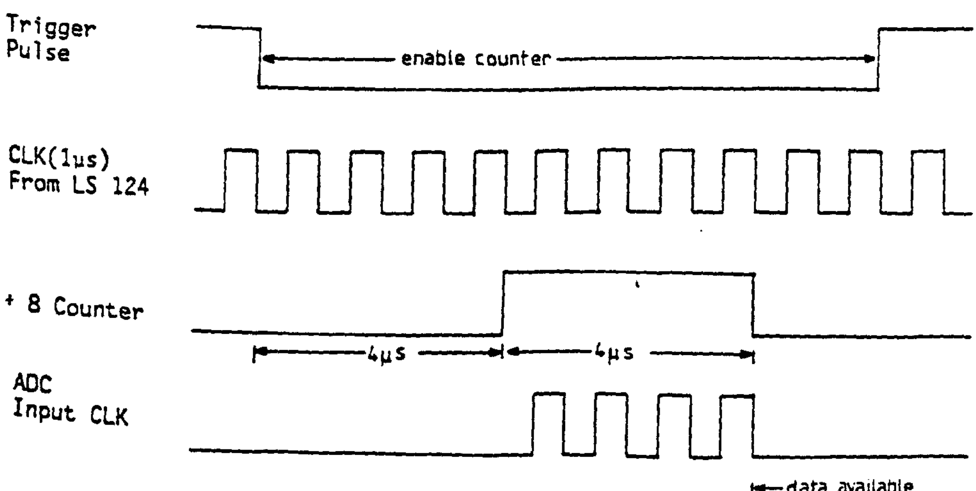
Fig.6.6 Infra-red Receiver Circuit



(a) Block Diagram of the 3300 ADC



(b) Pulse Mode Operation



(c) ADC Input Clock

Fig.6.7 Data Conversion Timing

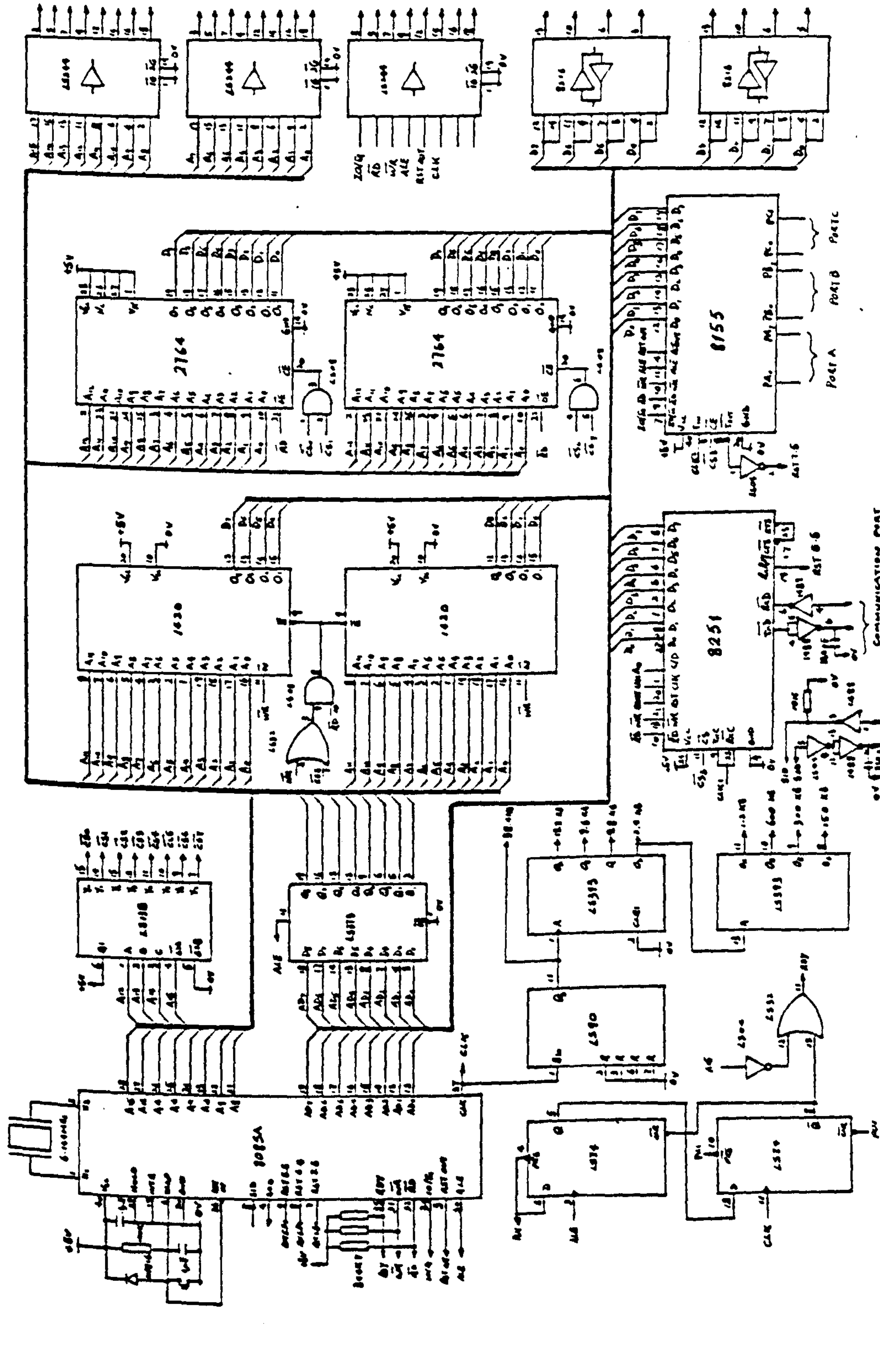
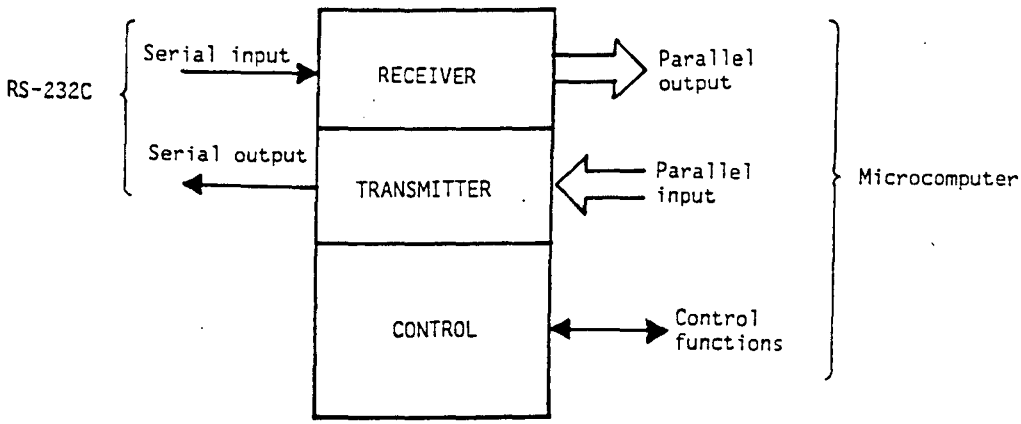
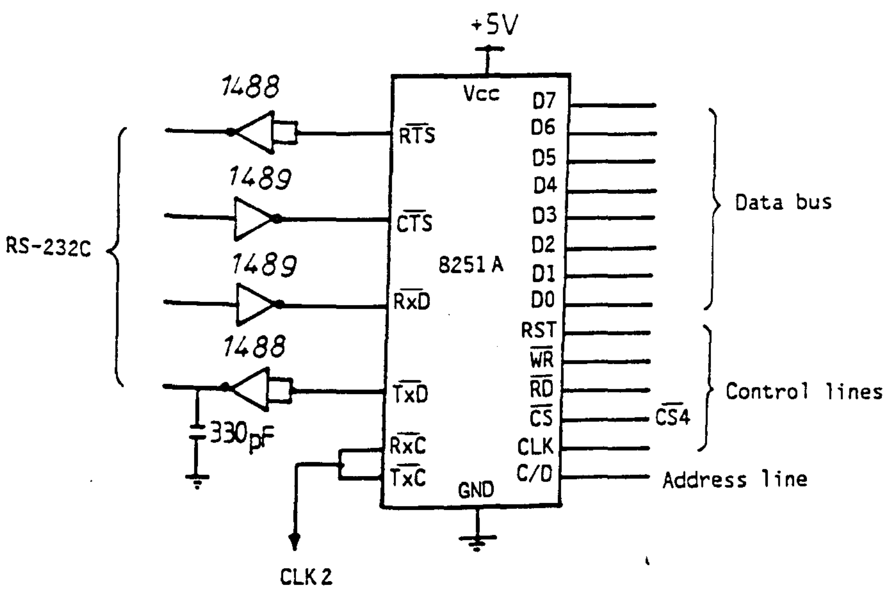


Fig.6.8 Microprocessor Circuit



(a) Block Diagram of the USART



(b) Interface Circuit

Fig.6.9 Communication Interface

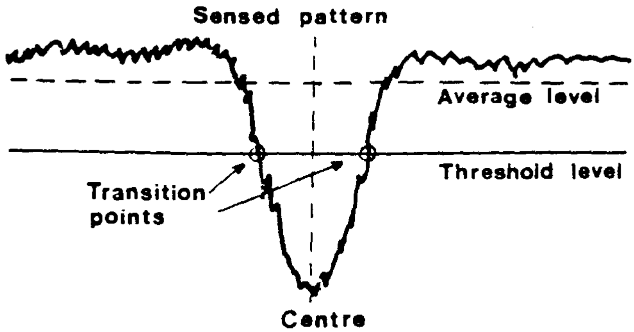


Fig.6.10 Algorithm Representation

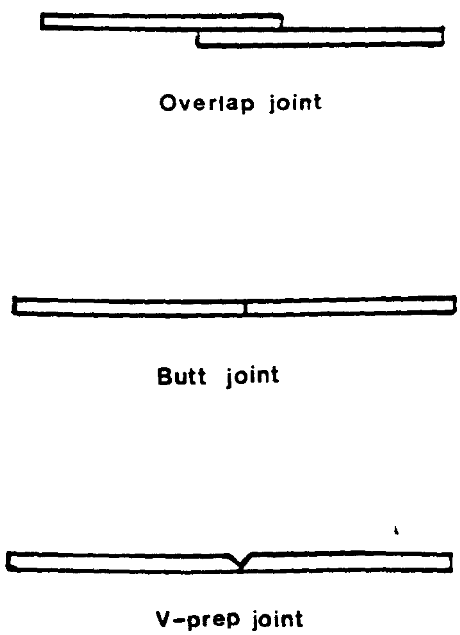


Fig.6.11 Type of Weld Joints

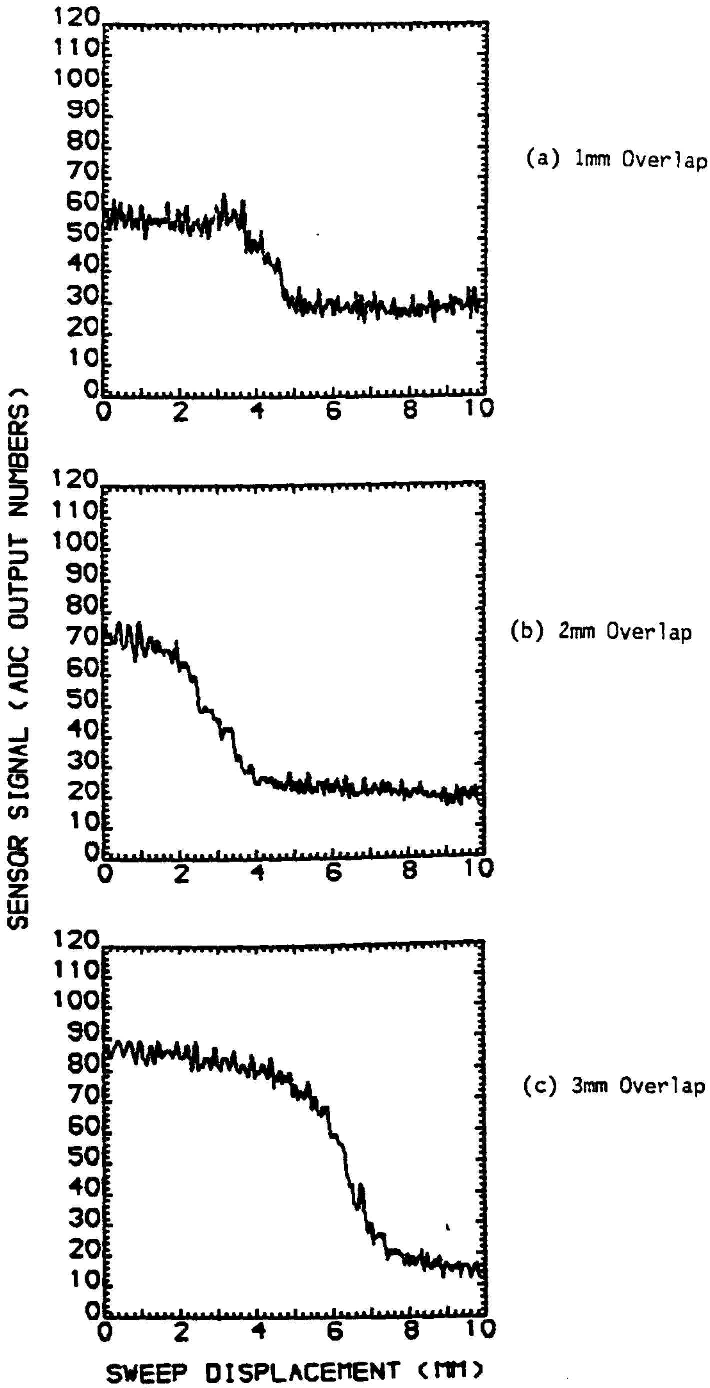
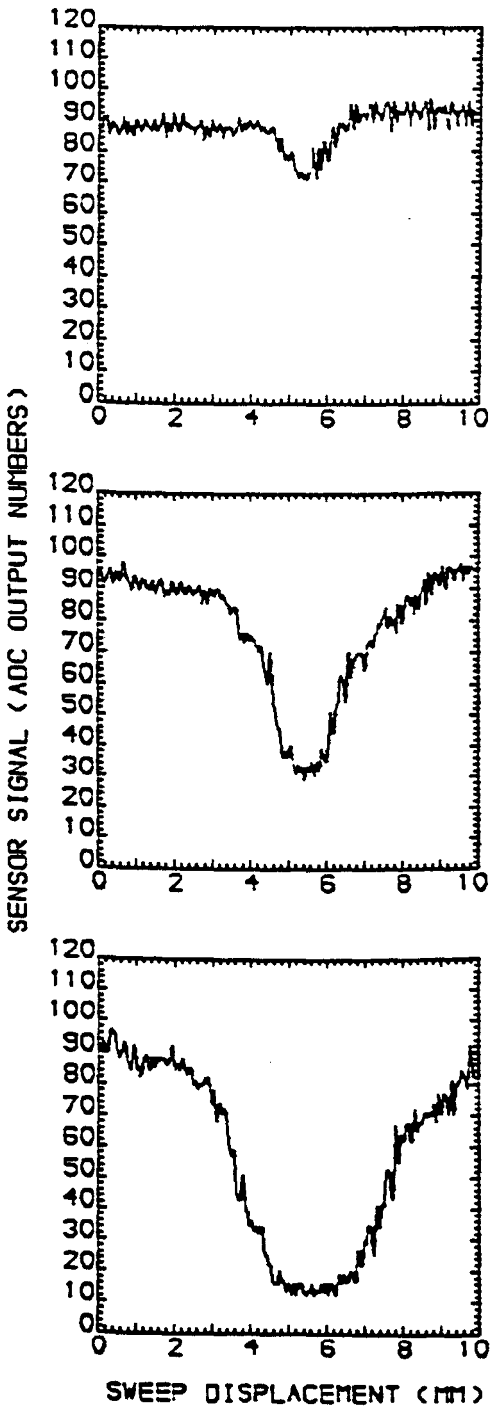


Fig.6.12 Static Scans Over Overlapping Plates



(a) Closed Gap Butt Joint with Guillotine Edges

(b) 3mm Gap and 6mm Deep Butt Joint

(c) 6mm Gap and 6mm Deep Butt Joint

Fig.6.13 Static Scans Over Butt Joints

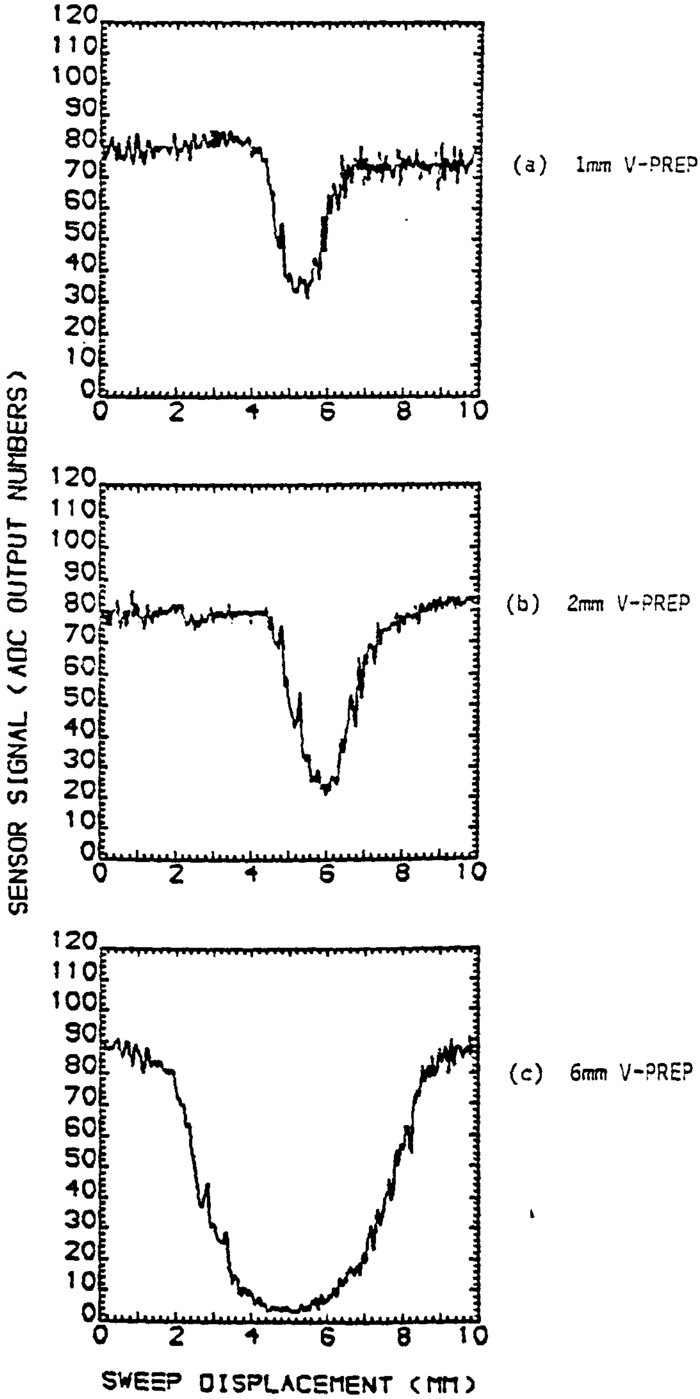
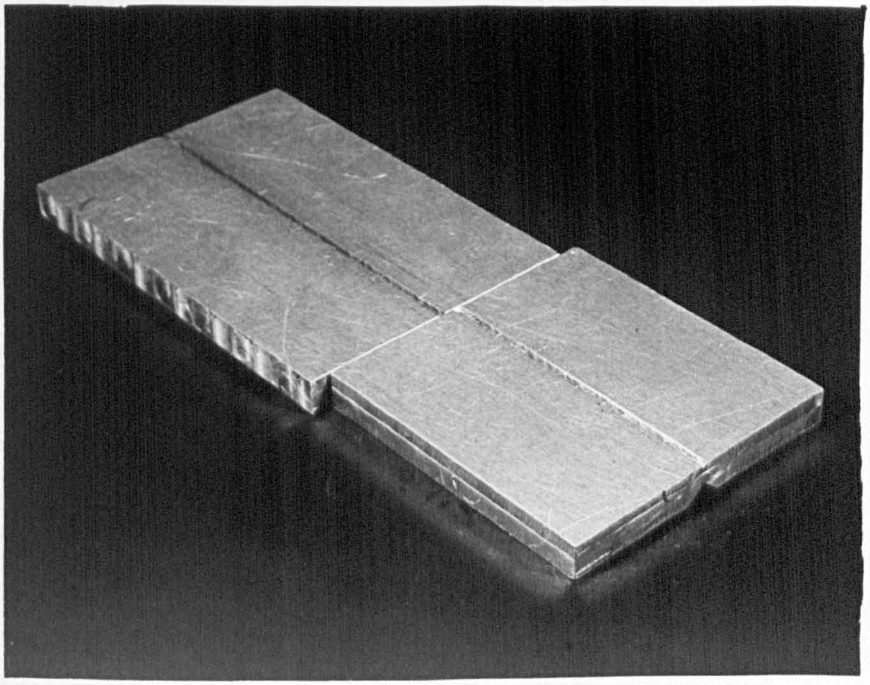
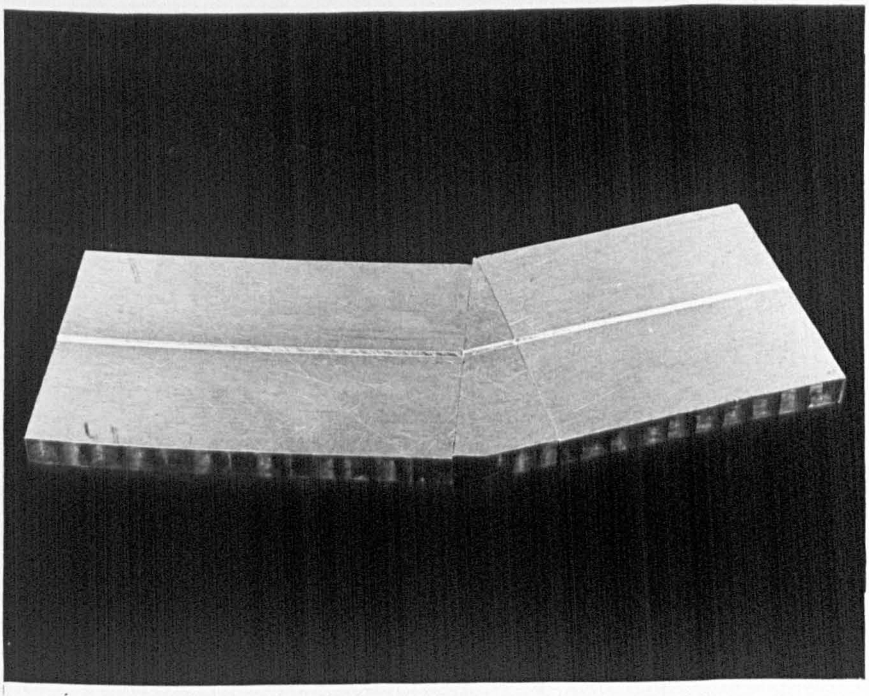


Fig.6.14 Static Scans Over V-PREPs

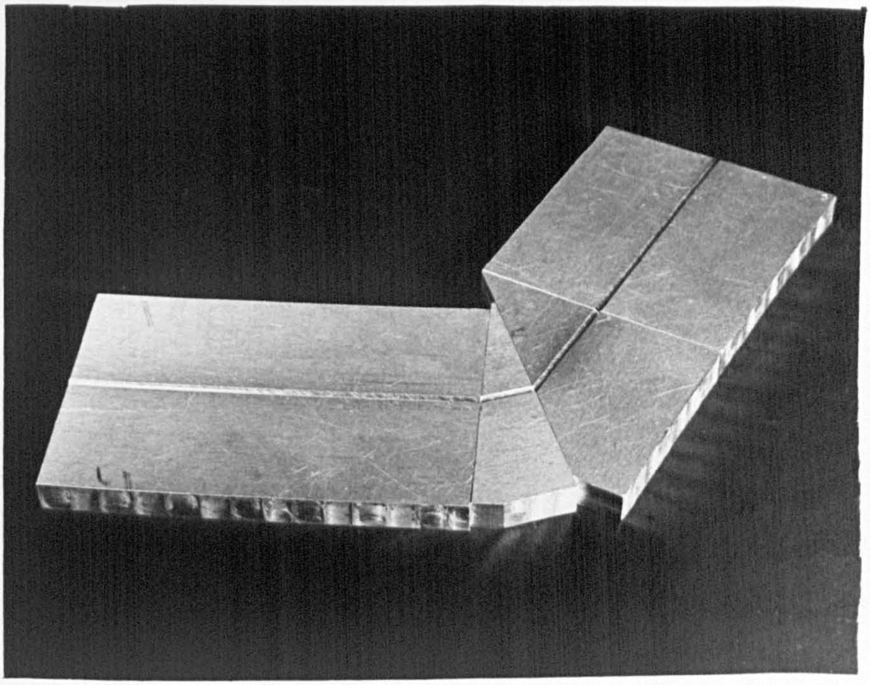


(b)

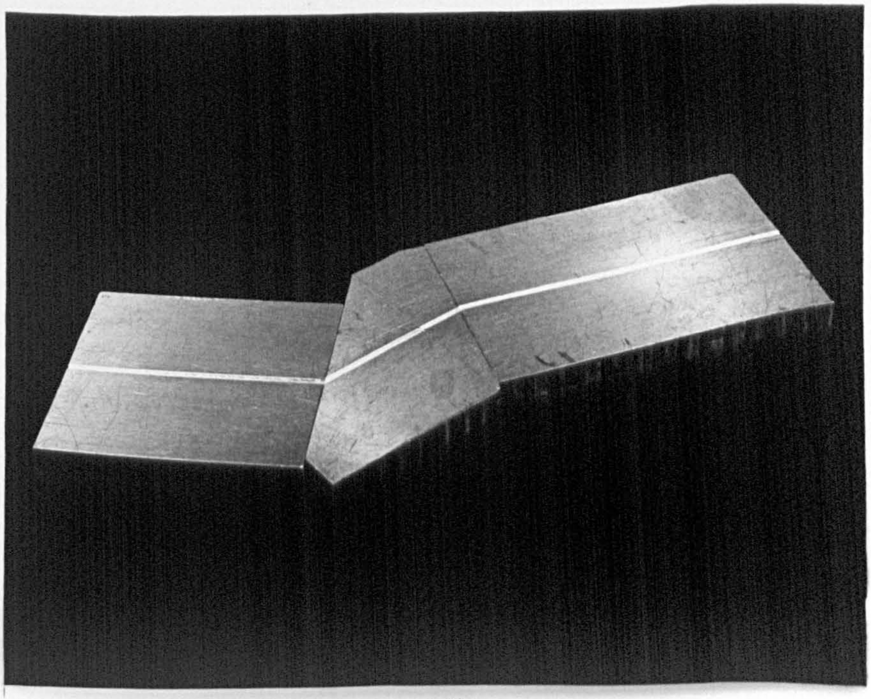


(a)

Fig. 6.15 Seam Deviation Arrangements



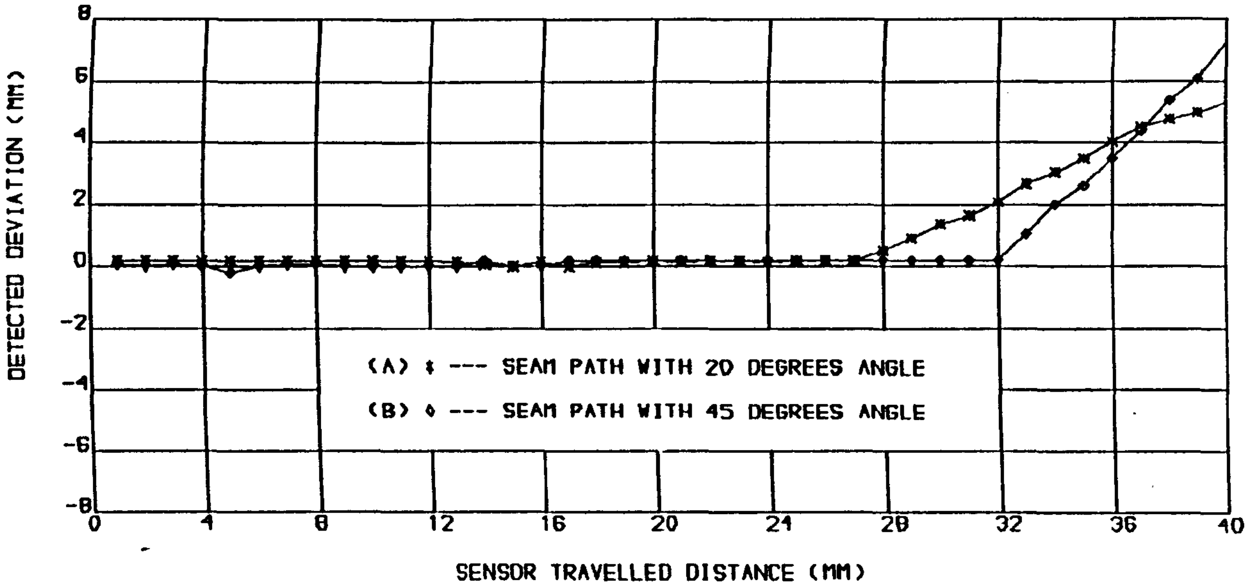
(c)



(d)

Fig.6.15 Seam Deviation Arrangements

GRAPH OF DETECTED DEVIATION AGAINST SENSOR TRAVELLED DISTANCE



TYPE OF WORK: 1MM THICK V-PREP

SENSOR HEIGHT: 12MM

TORCH SPEED: 1.00MM/S

NUMBER OF DEVIATION VALUES: 40

FIG. 6.16 DEVIATION DETECTIONS ALONG A STRAIGHT LINE PATH OF TORCH MOVEMENTS

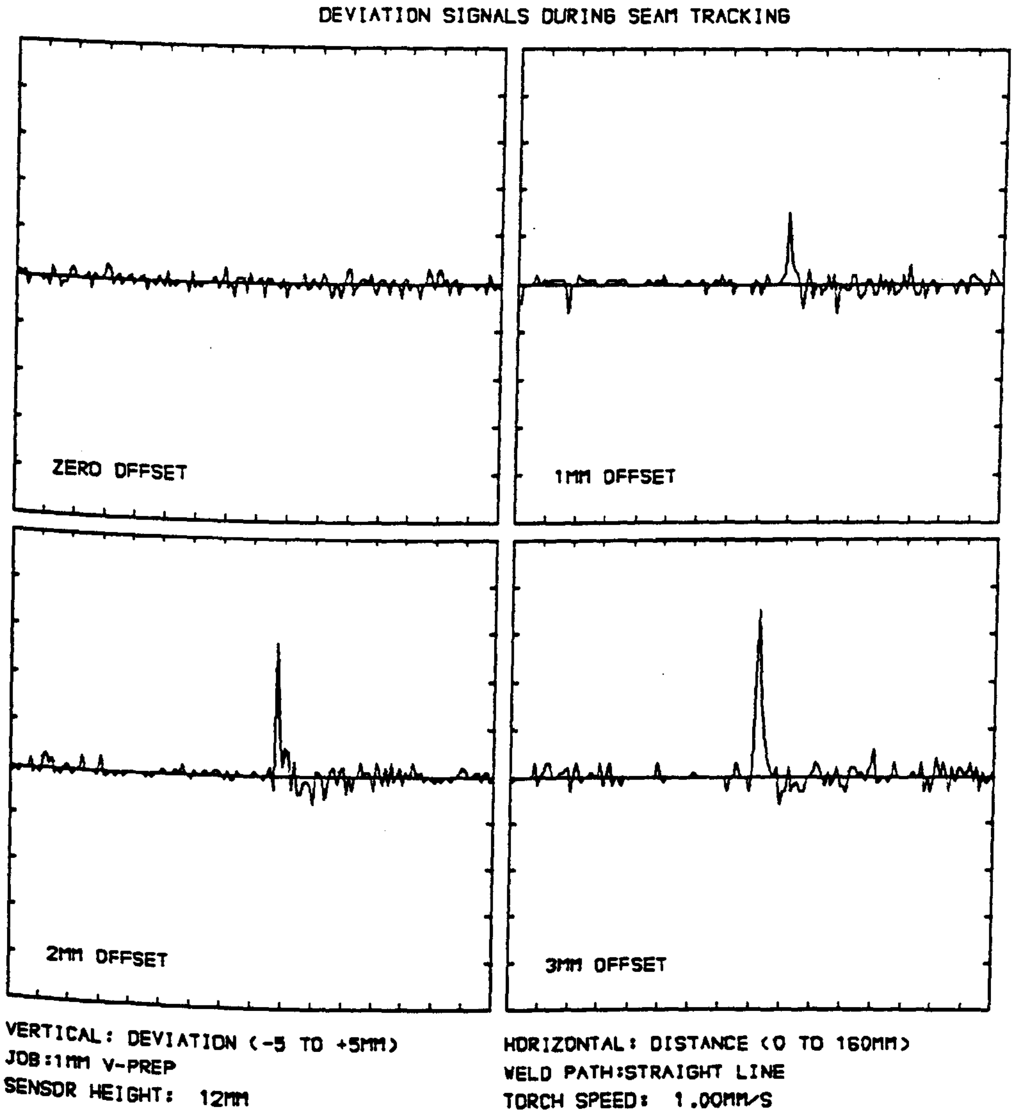
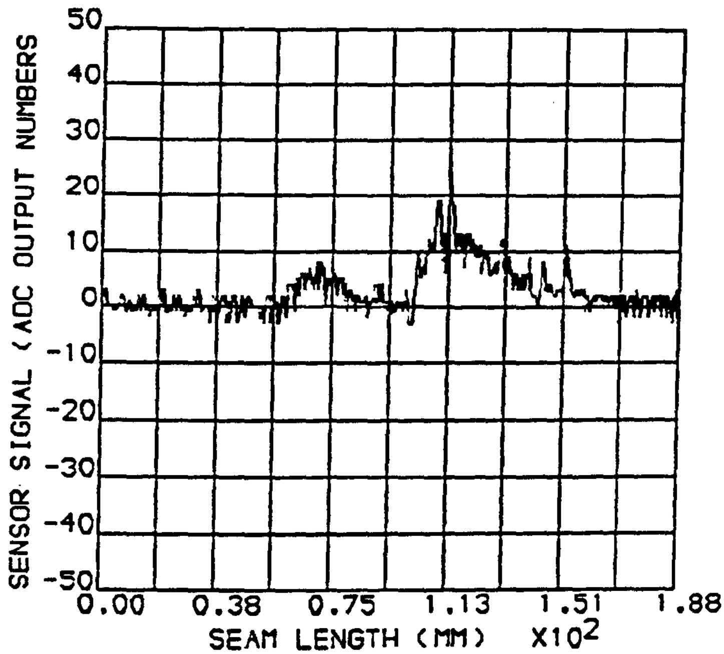
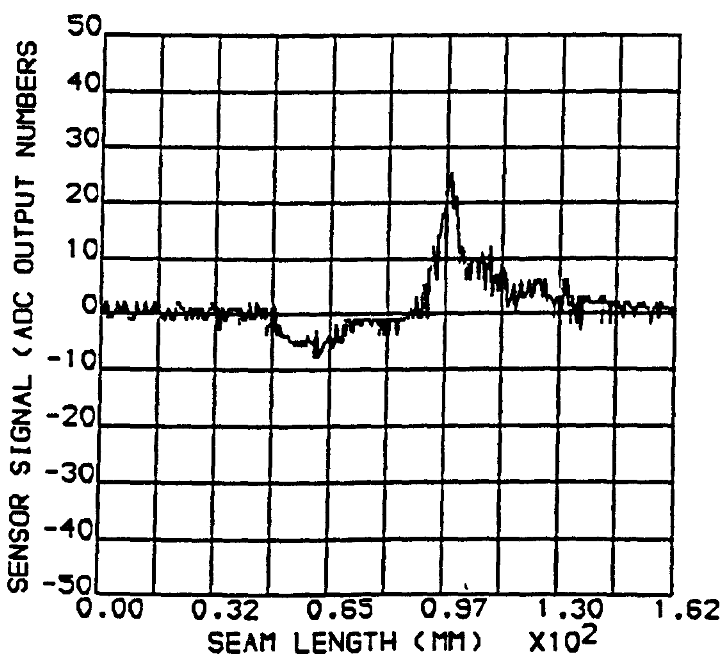


Fig.6.17 Sensor Signals During Tracking of Offset Seam Paths



(A) SEAM PATH BENDED WITH 20 AND 45 DEG CORNERS



(B) SEAM PATH BENDED WITH 20 DEG DOWN AND 45 DEG UP

Fig.6.18 Sensor Signals During Tracking of Seam Path Corners

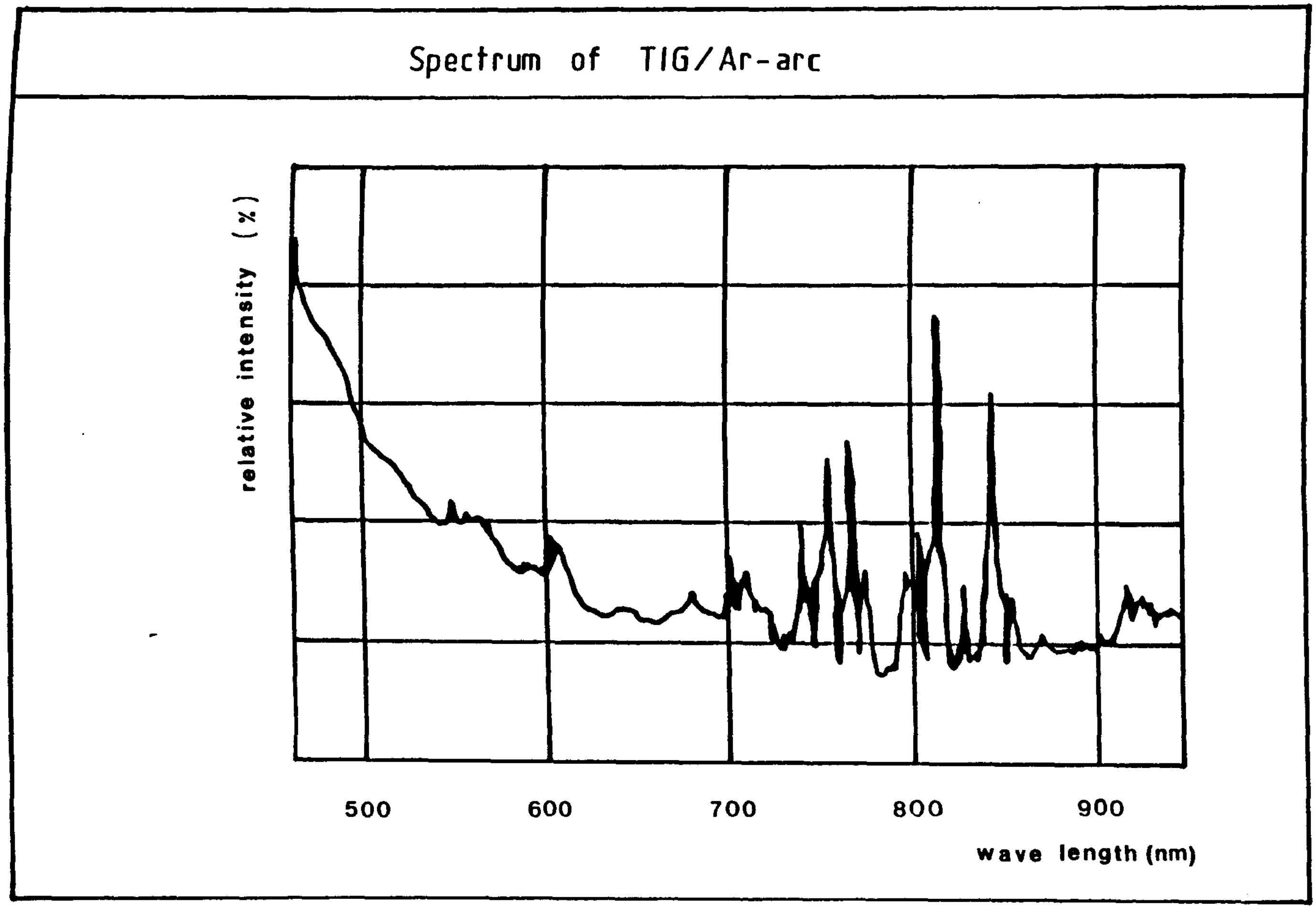
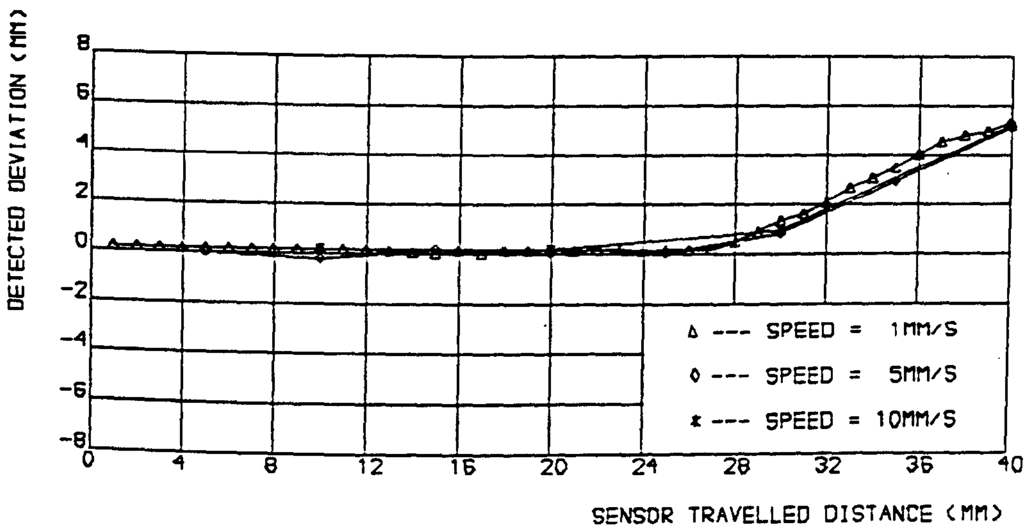
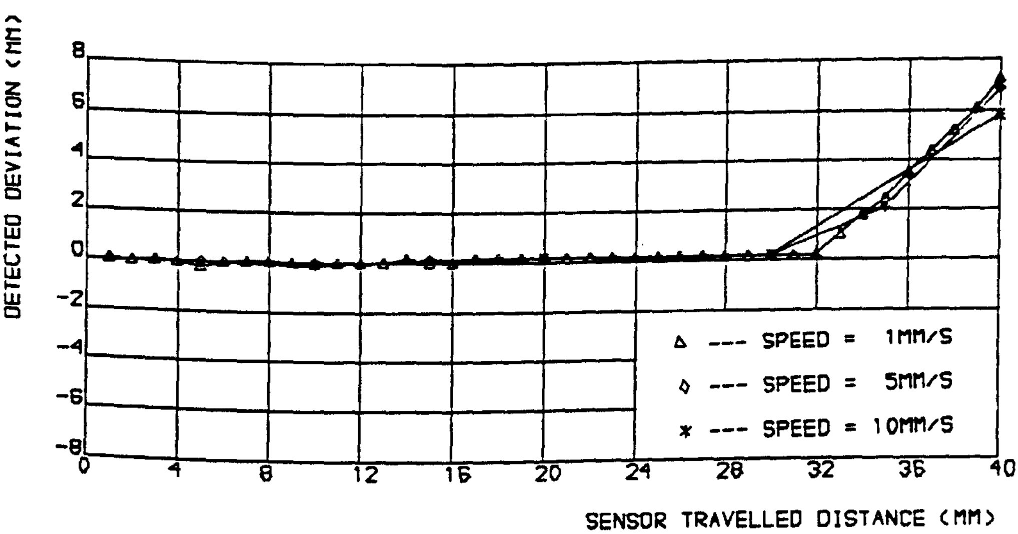


Fig.6.19 Radiation Spectrum of TIG Welding Arc



(A) 1MM THICK V-PREP WITH 20 DEGREES CORNER PATH



(B) 1MM THICK V-PREP WITH 45 DEGREES CORNER PATH

FIG. 6.20 DEVIATION DETECTIONS AT VARIOUS SPEEDS

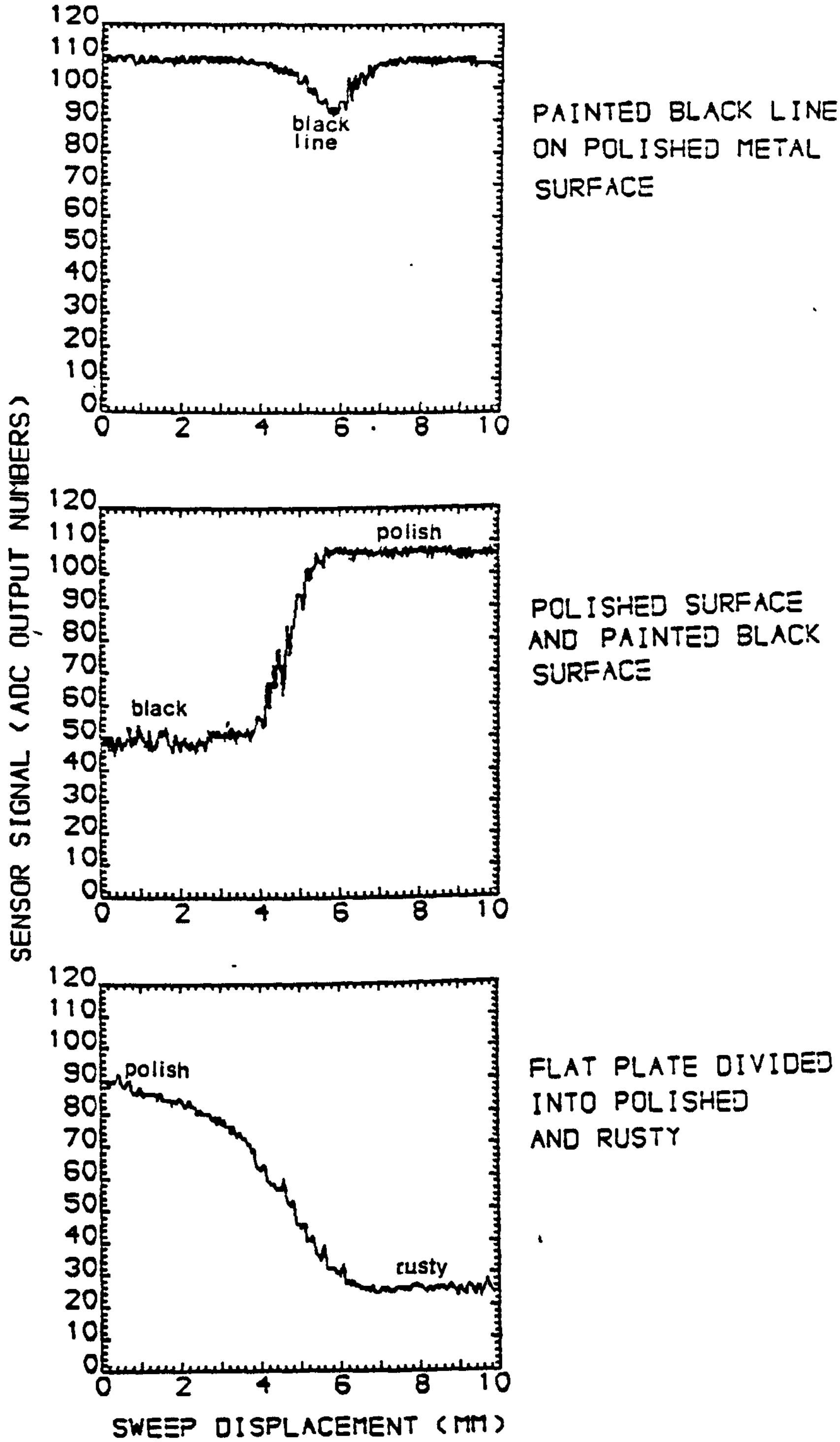


Fig.6.21 Surface Scan Tests

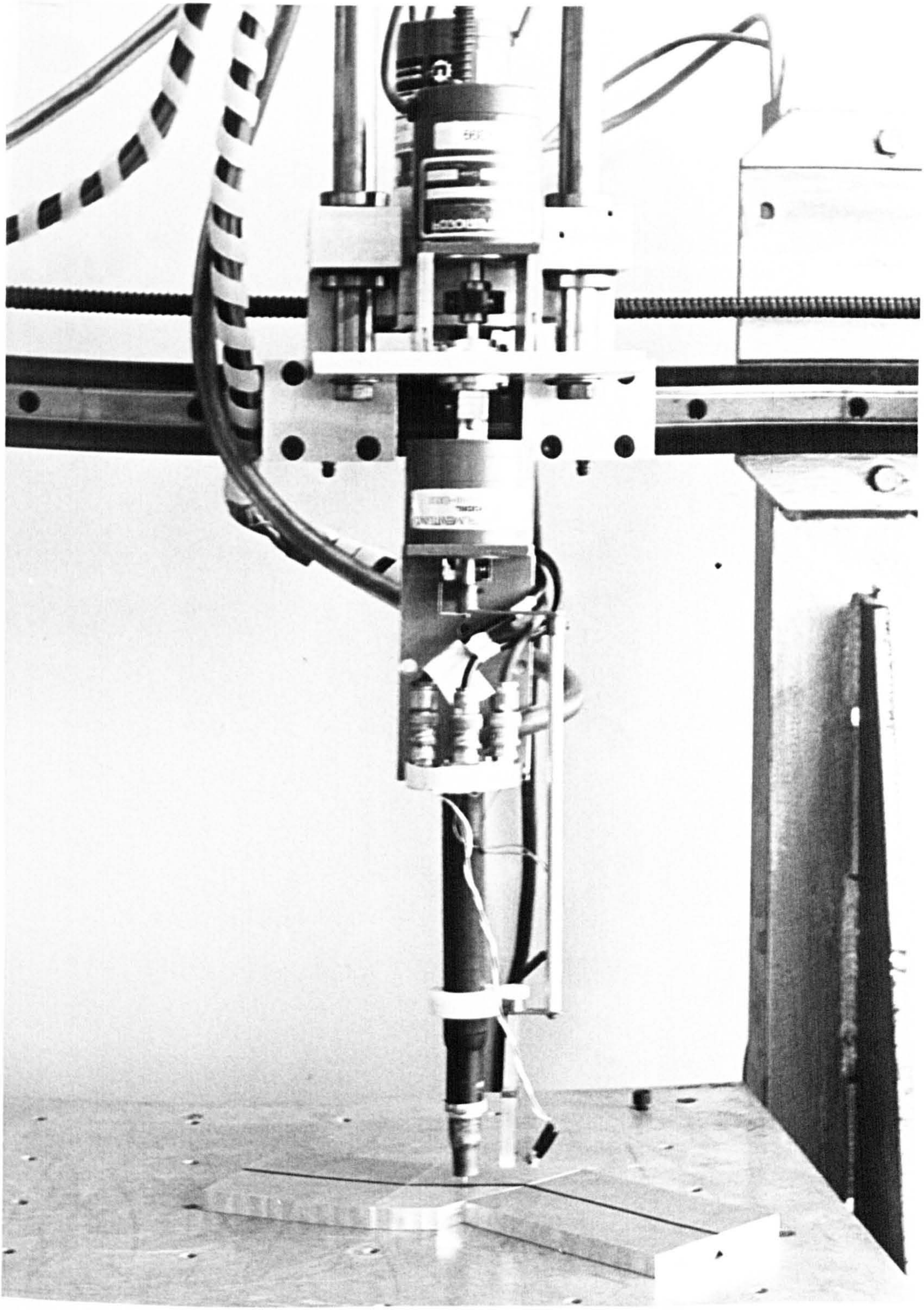


Fig.6.22 The Infra-red Seam Tracker

CHAPTER 7 ULTRASONIC SEAM TRACKER

7.1 INTRODUCTION

One important aspect of any automated high quality welding system is the provision of on-line sensor for seam tracking to ensure weld quality. As this is one of the major objectives of the research project, investigations were carried out on the design of seam tracking systems. The seam trackers considered are in the group of preview sensors. Based on different physical principles, one common factor is that the information is gathered just ahead of the weld pool. They do not rely on the welding process to generate feedback signals to the robot controller as in the case of through-the-arc sensing. They are relatively low cost and compete with the popular, but expensive vision seam tracking systems.

The previous chapter described the development of an infra-red seam tracker and analysed its sensing abilities. This chapter will present another approach in designing a seam tracker using ultrasonic transducers.

The intention was to develop a system which could overcome the problems encountered in the infra-red seam tracker. The infra-red seam tracker is based on analysing the intensity variations of the received light when reflected from the workpiece being scanned. The method is very much dependant on the workpiece surface conditions for maintaining consistent reflective characteristics. The ultrasonic seam tracker, however, works on the principle of measuring the phase difference between the transmitted signal and the received signal. Because ultrasonic waves are pressure waves which are less sensitive to the workpiece cleanliness, they can be used for displacement measurements. The operations of the ultrasonic seam tracker are similar to that used for the infra-red seam tracker. By sweeping the transmitter and receiver pair across the seam, the phase difference and hence the path difference between the transmitted and the received signals can be measured. Both seam tracking systems were designed to meet the requirement of sensing thin plates, particularly in the range of thickness from 0.8 to 3.3mm.

7.2 DESIGN CONSIDERATIONS

This work was initiated to explore the feasibility of ultrasonic sensing for seam tracking of thin workpieces. The requirements were similar to the infra-red seam tracker which provided remote sensing abilities with relatively low cost. Ultrasonic sensing, ranging in frequency from about 18KHz to the megahertz region, has been widely used in industry and most of the developments, which has been concerned with non-destructive testing, use high frequency transducers with contact sensing methods. For remote sensing, it is often advantageous to use the lower range of ultrasonic frequencies to reduce absorption effects [33 - 34] and provide directional sensing through air. Ultrasonic sensing has characteristics that make it advantageous in some situations when compared with infra-red sensing. For the detection of the mechanical shape of a weld seam it is necessary to use a means that interacts with the mechanical outline. Both the infra-red and ultrasonic sensing methods use this principle, however, the infra-red sensing may sometimes be confused by irrelevant changes in surface properties such as grease or dirt on the workpiece. For high resolution it is preferable to use ultrasonics.

Ultrasonic sensing techniques are often employed for the measurement of object displacement [35]. The concept of measurement is based on the determination of echo signals from the object. Most of the progress in this field has been in the area of transit time and signal attenuation measurements rather than phase measurement. Preliminary tests were carried out on the possible suitability of transit time, signal attenuation, and continuous phase comparison methods using 40KHz ultrasonic transducers. The results of such tests were used to decide the most likely solution to the problem of seam tracking.

7.2.1 TRANSIT TIME METHOD

The principle of the transit time method is simply to place the transmitter and receiver transducers together to form a sensor, and measure the time elapsing from the moment the ultrasonic pulse is transmitted to the moment the echo is received. The total time taken to travel from the transmitter to the workpiece and back to the receiver is obviously twice the time taken between the sensor and the workpiece. As the velocity of sound is known and the time taken is a linear function of the distance, the distance between the sensor and the workpiece can be calculated by

$$x = c\ t/2 \tag{7.1}$$

where x is the distance, c is the velocity of sound and t is the total time taken. With this method, the accuracy of distance measurements rely mainly on the accuracy of time measurement, which depends on what sensor frequency is used for the required sensing resolution.

When a voltage pulse is applied to the electrodes of the transmitting transducer, the transducer vibrates with an amplitude which gradually increases until a steady value is reached. At the instant when the pulse is removed, the oscillations of the transducer do not cease immediately but decreases in amplitude to zero in an exponential manner. Fig.7.1(a) shows the form of oscillations of the transmitting and receiving transducers and fig.7.1(b) gives the block diagram of the experimental set up.

The received signal shows that, once activated by a voltage pulse, the oscillations in a transducer build up gradually to a steady state, reaching their maximum amplitude after a finite period of time, and then trail off at the end of pulse. It was found that, if the applied pulsing time was too short, the vibrations of the transducer did not have enough time to reach their maximum possible amplitude, the wave amplitude in air could not reach its steady values and this introduced jittering effects due to the pulse shape building up and trailing off. Thus, for maximum detectability the applied pulse should be wide enough to obtain steady maximum amplitudes of the oscillations. As the transducers chosen have an operating frequency of 40KHz, the pulse applied should be a multiple factor of 1/40K seconds (= 25μsec) in order to obtain accurate results. This means that the method is useful only for sensing resolutions above centimetres and because a wave travels 1cm in 30μsec not suitable for detecting weld seams formed by plates of 1 or 2mm thick.

7.2.2 SIGNAL ATTENUATION METHOD

Another test was carried out with the signal attenuation measurement. Similar to the transit time method, a pulse of ultrasonic waves was emitted by a transducer, travelled in air and was reflected from the surface of the workpiece. The echo came back to the receiver and its level was measured. Measurements were made using a boxcar detector [36]. The boxcar detector is basically a sample-and-hold system whose time of sampling is determined by a reference pulse which is related to the signal of interest. It arranges the timing and duration of the sampling 'window' such that it looks at the signal. Thus, only the signal and the noise occurring within the window contribute to the output. The noise, however, is reduced by the low-pass filter at the output (fig.7.2a). The output is a d.c. voltage proportional to the mean signal pulse amplitude and can be applied directly to the X-Y recorder. The boxcar detector comprises two instruments, the 9415 linear gate and the 9425 scan delay generator. The linear gate provides the sample and hold, and averaging functions and the scan delay generator provides the gating pulse of suitable width, position etc. to open the gate at the correct time. In this test the amplitudes of the signal received at various distance from the reflecting surface were measured and the amplitude variation depicted in fig.7.2b was obtained. It can be seen that neighbouring maxima and neighbouring minima are one half-wavelength apart and that the distance between a maximum and its neighbouring minimum is a quarter-wavelength. It is obvious that the received signal amplitude depends both on distance travelled and the phase angle of the ultrasonic wave. Using 40KHz as the operating frequency, this method is limited in the measuring range up to only 2mm in displacement, which is considered to be too small for the application.

7.2.3 PHASE COMPARISON METHOD

The last test was carried out by the phase comparison method. A signal of 40KHz was fed from a continuous sinusoidal wave oscillator to the transmitting transducer and, at the same time, to a phase meter in order to provide a reference for phase comparison. The ultrasonic vibrations generated by the transmitter travelled towards a flat metal plate and were reflected back to the receiving transducer. The vibrations were then changed into electrical signals. These latter signals were fed to the other channel of the phase meter. By comparing the two signals, a phase difference was obtained. As the transducers were moved away from or towards the metal surface, the phase between the transmitter and the receiver signals changed accordingly. If the transmitted signal is defined as $f_t(t)$ and the received signal as $f_r(t)$, the phase of $f_r(t)$ lags behind the phase of $f_t(t)$ because of the finite time of travel of the ultrasonic waves through the air. This can be shown as follows:

$$f_t(t) = a_1 \sin\omega t \tag{7.2}$$

$$f_r(t) = a_2 \sin\omega(t - 2x/c)$$

$$= a_2 \sin(\omega t - \phi) \tag{7.3}$$

where a_1 and a_2 are the respective amplitudes, ω is the angular velocity, t is the time, x is the distance between the sensor and the metal surface, c is the velocity of sound, and ϕ is the phase difference. Taking λ as the wavelength, then

$$\phi = \omega \frac{2x}{c} = \frac{4\pi x}{\lambda} \tag{7.4}$$

Clearly, the phase between the transmitted and the received signals is a measure of path covered by ultrasonic waves and, consequently, of the reflecting surface distance. The wavelength of about 8mm used corresponds to 360° phase difference which provides a measuring range for about 4mm from the reflecting surface displacement. This phase difference method doubles the measurement range when compared with the resolution of the boxcar detector and is within the range for seam tracking of 0.7 - 3.3mm thick plates. Therefore, it was decided to concentrate effort on the method of phase measurement for the development of the ultrasonic seam tracker.

7.2.4 PRINCIPLES OF ULTRASONIC SENSING

The ultrasonic sensor operates using the principle of obtaining dimensional information of a seam by sweeping the sensor across the seam. Fig.7.3 shows the arrangement for the actual operation of the sensor. Both the transmitting and receiving transducers were housed in a mechanised sensor head. The sensor head was mounted on an axle which was connected to the d.c. motor by means of an extension arm. The sweep motion is driven by the d.c. motor and the sweep distance is controlled by a slotted opto-switch which was placed on the top of the d.c. motor. As the sensor scans across the seam, 100 phase difference measurements between the transmitter and the receiver are recorded, and each phase value is converted into a count number. By interpreting these numbers a seam profile can be reconstructed, from which the centre of a seam can be determined. During operation, each scan produces a value representing the centre of the seam and each centre value is taken as a reference of the seam position for the next scan. The difference between a reference and a currently detected centre value gives a deviation error which is then sent to the robot controller for positioning correction. This continues to be the case as the sensor moves along the seam.

7.3 HARDWARE

A block diagram (fig.7.4) shows the hardware configuration of the ultrasonic sensing system. Developments include the construction of the sensor head and sweep controller, the generation and detection of ultrasonic waves, and the logic circuit which enables the system to operate as a seam tracker. Since the objective of this experiment was to investigate the method of ultrasonic sensing for seam tracking rather than building a ranging system, the development of the microprocessor as for the infra-red seam maker was not necessary. A commercially available BBC microcomputer was used to serve for data processing and system control.

7.3.1 SENSING HEAD DESIGN

The transducers used are the piezoelectric type (RS 307-351 and RS 307-367) having dimensions of 16mm diameter and 12mm height, with an angle divergence of about 20°, and a resonant frequency of 40KHz. By placing the transmitting and receiving transducers together above a metal surface, finite surface displacement of a fraction of a millimetre can be detected using the phase comparison method. The detection is normally reliable for a flat metal plate which has an area greater than the detectable zone of the receiving transducer. However, if the object is small such as a small portion of narrow seam, the ultrasonic waves received contains components partially reflected from the object and partially from the area surrounding the object. Then, phase cancellation occurs which results in confusing measurements, causing difficulties for the interpretation of the object position. One of the ways to overcome this problem is to reduce the detecting area. For this reason, it was necessary to design a mechanical housing for the transducers capable of detecting small object. Various types of sensor housing design were tested and the best results were obtained from the configuration as shown in fig.7.3. In this design the receiving transducer was housed in an aluminium shell, which was extended by a metal tube,reducing the receiver's diameter from 16mm to 3mm. The transmitter mounting was designed in such a way that it provided the maximum signal transmission by keeping the transmitter diameter to 16mm, and also allowed the receiver to plug through just besides the transmitter keeping the dimensions of the sensor head to a minimum. The sensor head was connected to a sweeping arm which was extended 40mm from the axis of a d.c. motor (RS 336-309). The d.c. motor was mounted above the welding electrode. Because the sweep motion is relatively slow for the required welding application, the d.c. motor was geared down from 6000 r.p.m. to 37.5 r.p.m.

7.3.2 MOTOR CONTROLLER

A motor control circuit was designed to provide bi-directional movement control of the 6V precision servo d.c. motor. The circuit shown in fig.7.5 comprises a slotted opto-switch (RS306-061), two monostable timers (555), and a single-pole changeover reed relay (RS349-399). The slotted opto-switch provides a negative transition pulse, to trigger the monostables for the timing of sweep displacement, and at the same time,to signal the microcomputer for start scanning. The first monostable provides a 12V signal down a wire of five metre length to the microcomputer which was placed away from the robot, and the second controls the relay to be switched between plus and minus 6V in order to drive the servo d.c. motor in the required sweep direction. As the time delay generated by the monostable is dependant on the RC value, the length of each sweep can be varied by adjusting the 1MΩ variable resistor. When a trigger pulse is detected by the monostable, the delay operation is started and the output of the monostable goes high which allows the motor to be driven by the +6V supply. Once the time delay is up, the output of the monostable falls to 0V, thus applying -6V to the motor, forcing it to rotate in the opposite direction. When the sensor return to its initial position, the light beam of the slotted opto-switch is again broken, and the sweep motion is repeated.

7.3.3 GENERATION AND DETECTION OF ULTRASONIC WAVES

A signal generator (Variable Phase Oscillator TYPE VPO230) supplies a continuous sinewave to the transmitter and also provides a reference signal to the phase comparator. The supply frequency is adjusted to 40KHz as this is the point at which the transducer reaches its maximum efficiency. The receiver is a combination of op-amps designed to amplify and filter the received signals.

Ultrasonic signals transmitted to the surface are reflected and only a fraction of signals are captured by the receiver. The transmitter and receiver are matched pairs which means that the receiver has a greater affinity for detecting signals transmitted by the transmitter than for those produced by other sources. Because the sensor is required to work in the welding environment, filtering is essential to avoid mechanical vibrations and electrical noise interference.

Referring to the circuit diagram of Fig.7.6, IC1a is used to remove unwanted r.f. signals present at the input. This stage has a gain of 100, and high rejection of signal above the ultrasonic band. IC1b is a second-order active RC bandpass filter whose centre frequency is tuned at

40KHz. The circuit gives a Q at about 8, which means the filter bandwidth is about 5KHz, and hence only allows signals at 40±2.5KHz to passing through to the phase comparator. Any unwanted signals outside the filter band can be removed.

7.3.4 PHASE COMPARATOR AND COUNTER CIRCUIT

Signals from the receiver circuit together with the reference signals are input to the phase comparator for extracting phase differences between the two signals. A circuit timing diagram of Fig.7.7(a) shows the method of phase extraction where the output pulses correspond to the resultant phase differences.

The output pulse from the phase detector may be read and counted directly by a computer. Resolution of the phase measurement mainly relies on the clock rate applied to the counter. The maximum possible phase value produced by the phase comparator is 12.5μs which corresponds to 180° phase difference between the transmitter and the receiver signals. If the phase is counted by the 1MHz clock of the BBC microcomputer, then each count from the counter represents 14.4° of phase difference and only about 12 counts for the whole range of measurements. In order to increase the resolution, a 10MHz crystal oscillator was used to generate high frequency pulses which were modulated with the outputs from the phase detector forming a series of bursts so that a maximum of 125 counts can be obtained for 360° phase measurement. A separate 8-bits counter was built to count the 10MHz bursts. The timing diagram of fig.7.7(b) denotes the differing pulses present at various points in the circuit.

Fig.7.8 shows the interfacing circuit of the sensor system. The phase comparator is based on the detection of zero-crossings of the in-coming signals. Zero-crossing comparators (IC1a,b) are used to provide a simple and effective means of performing such an operation. These comparators produce output signals that changes state each time the analog input signals pass through a reference voltage of 0V. The input sine waves are therefore converted into square waves, and the resultant zero-crossing intervals are provided for phase comparison.

Phase comparison is perform by IC4 together with IC2a and IC3a. IC4 is a D-type positive edge triggered flip-flop and its output, Q, depends on the inputs of CK and CLR by connecting PR and D to high. The required input signals to CK and CLR are provided an OR gate and a NAND gate of IC2a and IC3a respectively.

A flip-flop of IC6 and a few logic gates were used in the circuit to synchronise the various stages. The 8-bit counter formed by IC9 and IC10 starts counting with the arrival of a negative going edge at the reset input and the latch (IC11) is held at the previous state while the counter is counting. Once counting is complete, the corresponding phase count is obtained, the latch becomes transparent and performs latching operation again as soon as the reset signal goes high. Each output from this latch is taken as the number of phase counts.

7.3.5 AVERAGING CIRCUIT

Because the sensor system is designed for seam tracking, it must be capable of operating in the welding environment. In the inevitably electrically noisy environment produced in TIG welding, certain amounts of instability occurs in the received signal because of interference disturbances of the transmission path. The resulting instability in the received signal is referred to as 'phase jitter'. The system was tested by placing the sensor closed to the torch. Once an arc is struck, phase obtained from the phase comparator showing jitter, which results in the microcomputer failing to identify the true phase count. As the sensor was brought away from the arc, the phase reading became stable. It was observed that the jitter was mainly due to the interference from the welding arc, particularly the a.c. arc.

An approach to obtain jitter tolerance led to the addition of a signal averaging circuit which is shown as part of the interfacing circuit in fig.7.8. The averaging circuit consists of a digital-to-analog converter (IC12), a low-pass filter (IC13a), and an analog-to-digital converter (IC15). IC12 is used to convert the phase count into a d.c. level which corresponds to the distance travelled by the ultrasonic waves. When jitter occurs, the IC12 produces alternating signal outputs which oscillate above and below the previous d.c. level. By taking the average value of these alternating signals using a low-pass filter, the required d.c. level can be obtained. Since the rate of sweep of the sensor is relatively slow compared with the jitter frequency, the IC13a was designed with a cut-off frequency at 500Hz in order to filter out random oscillations. The purpose of using an analog-to-digital converter was to interface the sensor circuit to the BBC microcomputer. Experimental trials showed that satisfactory results could be obtained by adding the averaging circuit.

7.3.6 INTERFACE TO THE 1MHZ BUS

A BBC model B microcomputer was used for analysing data captured by the sensor circuitry and to provide deviation values to the robot controller. The sensor circuitry was interfaced to the 1MHz bus of the microcomputer.

This is also shown in fig.7.8 where IC21 is a line receiver which is enabled by the decoded address and converts the 12V sweep synchronisation signal into 5V for TTL compatibility. IC4a and IC14b are the tri-state latches which latch the phase lead or lag transitions and hence provide information for phase comparison.

The 8-bit data outputs from the ADC of IC15 are interfaced directly to the data bus as they are already tri-state buffered. IC17 latches the asynchronous start of conversion request from the CPU, and generates the required start of conversion signal (SOC), synchronised with the low level period of the ADC clock as required. At the end of conversion, EOC goes high. This state is detected by the CPU which then enables the output of the ADC on to the data bus thus reading the data in the normal way. As the output enable time of the ADC is 500ns, it is necessary to include one wait state in reading the ADC.

IC19 transfers the data from the microcomputer after computation and IC20 converts the digital number into an analog signal which is outputted to a X-Y recorder by IC13b. IC8 is used for decoding the read/write actions and other logic circuits are used for the synchronisations of various stages.

After data processing, the calculated deviation values are sent to the robot controller via an RS423 serial interface which is provided by the BBC microcomputer. The serial interface offers both input and output serial data transfers, and both have 'handshaking' capabilities. A single byte word, which contains both the direction and the amount of seam position offset, is sent at each time.

7.4 SOFTWARE

Software was written for analysing the data obtained by the phase measuring system, and then to give the correct information to the robot controller for seam offset corrections (Appendix IV). The language used is the 6502 assembler which is provided with the BBC microcomputer.

7.4.1 DATA CAPTURE

Although the sensor sweep motion is set by hardware in order to reduce the software processing time, data capture and analysis still require software support. Each scan across the seam is recorded, based on the synchronisation signal supplied from the slotted opto-switch which acts as a start scanning indicator. Once a synchronisation signal is detected through bit 2, data storage is set up allowing 100 pieces of data to be read during each scan. Before capturing data, initial phase lead or lag between the transmitter and receiver signals is read and stored for later reference. The conditions of phase lead or lag are determined by the values obtained from bit 0 and bit 1 as shown in the timing diagram of fig.7.9(a). If bit0=1 and bit1=0, the transmitter signal is leading the receiver signal, or if bit0=0 and bit1=1, the transmitter signal is lagging the receiver signal.

To start data capture, a zero is written to location &FCC2. This generates the asynchronous start of conversion signal. When a logic '1' in the most significant bit is polled from location &FCC0., the conversion is complete and the data can be read from location &FCC1.

7.4.2 DATA INTERPRETATION

The captured data require suitable interpretations to make them meaningful. As illustrated in fig.7.9(b), the number of phase counts, N, is directly proportional to the phase difference ϕ, between the transmitter and receiver signals, as long as the phase ϕ is less than π. If ϕ is greater than π and less than 2π,phase lead changes into phase lag, then N is inversely proportional to ϕ. One way to obtain linear measurements of ϕ from zero to 2π is to carry out data conversion once a phase lag is detected. The expressions for data conversion are shown as follow:

$$\text{Phase lag count} = \text{captured data} \qquad (7.5)$$

$$\text{Phase lead count} = 250 - \text{captured data} \qquad (7.6)$$

where 250 is the maximum phase count for $\phi = 2\pi$.

Using these expressions, a linear curve was obtained as shown in fig.7.10(a) by holding the transmitting and receiving transducers together and measuring the surface. When the transducers were housed in the mechanised sensor head, experimental results as shown in fig.7.10(b) indicates that only a linear approximation of phase counts may be obtained. The sensor housing geometry introduces extra scattering and multiple reflections, which affect the transmission and reception path and thus causing non-linearities. However, the characteristics of (b) showed stay consistent as long as the same sensor head is used.

As shown in (a), the linear curve is in fact the average plot of (b). Using this relationship some software support can make the sensor system produce linear measuring characteristics. This is achieved by setting up a look up table which stored the 250 data from curve (b), each data representing the number of phase counts corresponds to a data on the linear curve (a) at the corresponding displacement. The 250 data values of (a) are equivalent to the counting numbers of the 250 data locations.

7.4.3 SEAM POSITION DETERMINATION

The evaluation algorithm for the determination of the seam position is based on the analysis of the sensed pattern. In general, the detection of different weld seam geometries results in different seam profiles being obtained and this requires different algorithms for each of the individual needs. Software developed in this experiment was concentrated on the evaluation of a groove pattern, which may represent either a V-prep or a butt joint as both have similar characteristics. Fig.7.11 shows a particular sensed pattern and the method for seam position evaluation. The evaluation mainly comprises of four steps:

(1) First the maximum, ϕ_{max}, and minimum, ϕ_{min}, values of ϕ over the whole range are extracted. Then the mean value, ϕ_{mean}, of ϕ is captured by $(\phi_{max} + \phi_{min}) / 2$. This gives a reference level to deduce the transition points in the sensed pattern.

(2) The upper portion of the sensed pattern is 'smoothed' by threshold, so that, any distortion occurring at the edges of a seam due to scattering or multiple reflections can be eliminated. Hence only the groove portion is used for determining the seam position.

(3) By searching through the data storage, transition points x_1 and x_2 are obtained as the interceptions of the sensed pattern to the mean reference level. The seam centre is therefore the mid-point between the two transition points, i.e. $x_c = (x_1 + x_2)/2$.

(4) Upon starting operation, the first sweep across the seam produces a centre value which is stored for seam location reference. After initialisation, each centre value is compared with the previous one to deduce a deviation value and also the direction of deviation, and the reference centre is refreshed by the current centre value.

Although the method is designed for V-prep and butt joints, it can be easily converted for overlap joints. In the case of welding an overlapped joint, the weld point is regarded as the crossing point joint of the sensed pattern to the medium line.

7.4.4 COMMUNICATION TO ROBOT CONTROLLER

Communications between the seam tracking system and the robot controller is carried out by a serial link from the RS-423 port. Interfacing to the serial port can be achieved either via the operating system or writing directly to hardware. Making access through the operating system may require relatively simple software programming, but longer processing time. Since timing is important for real time control, it was decided to write directly to hardware.

The RS-423 port (fig.7.12) is implemented through a 6850 ACIA and a customised ULA chip. Sending and receiving data through the RS-423 port is performed by taking account of the status register and accessing the input and output data buffers [37].

When receiving serial data, it is necessary to check on bit0 of the status register. This bit goes 'high' when a byte is received. If the input data buffer is not read before the input logic has successfully collected a second byte, then the original one will be lost, because it will be overwritten in the buffer.

When sending data, two conditions need to be considered. Firstly bit 3 in the status register must be 'low', as this indicates clear to send or the external device is willing to accept data. A data byte should not be sent to the data output buffer if bit 3 is 'high'. Secondly, bit 1 also needs to be checked once a 'low' is detected from bit 3. When the internal logic transfers a byte from the output buffer to the serial output register, this bit 1 goes 'high' signifying that a subsequent byte is loaded into the output buffer. Ignoring either bit 3 or bit 1, may cause bytes of data to be lost from the output stream.

The control operation between the robot controller and the seam tracker is similar to that as described for the infra-red seam tracking system in section 6.4.4.

7.5 EXPERIMENTS AND RESULTS

The course of the actual seam tracking is determined from the positions of those features which are normally located in a definite geometrical relationship to the seam. As these position detections become the basic requirement for the development of a seam tracker, the major concern in this experiment is the task of obtaining seam profiles and hence determining deviation errors. Various tests were conducted initially using seam scanning methods to assess the abilities of the system in detecting different seam geometries. Position sensing of the seam was then carried out for deviation measurements.

7.5.1 SEAM PROFILE DETECTION

A direct way to obtain dimensional information of the seam geometry is to sweep the sensor across the seam. To assess the ability of seam profile detection, a series of tests were conducted using both static and dynamic scanning across the seam. Three types of prepared weld joints known as the overlap, butt and V-prep samples were used for the static scanning tests. These samples were made from 1 to 3 mm thick aluminium plates which were arranged to allow the sensor scanning across the seam. Dynamic tests were carried out using a welded sample. The sample was set moving along the welded line whilst the sensor was scanning across. For all these tests, the signals obtained from the sensing system corresponded to the phase count distribution in the scanned area of the seam. Hence, sensor signals were available whose amplitude had a characteristic shape related to the seam image picked up. The results are shown in fig. 7.13 to 7.17. It is convenient to present the phase counts of each result in the form of ADC readings obtained for comparison purposes. These readings correspond to the phase variations in the reflected wave when the sensor is swept across the seam. Each result was taken from the same sweeping rate of 1 sample/s. The sweep length was adjusted to 10mm and the sensor height was set to 17mm.

Three sets of static scanning test results are shown in figs. 7.13, 7.14, and 7.15. In each case, the whole range of sweep displacement represents a single sweep for the sensor to capture 100 data of phase counts within the area across the seam. Fig. 7.13 shows the sensed patterns obtained from scanning three different thickness's of overlapping weld joint samples. Each pattern represents its corresponding seam profile. The greater the phase differences that occur on the graph, the thicker the overlapped plates sensed. Fig.7.14 shows other sensed patterns obtained from scanning across different gap width of a 1mm thick butt joint sample. These results illustrate the effects of gap variations. In the case of the closed gap test, the received signals contain insufficient information to define where the seam occurs. As the gap width increases, a better defined seam profile is obtained. Fig.7.15 shows the results from scanning different sizes of V-prep samples.

Dynamic scanning tests were carried out by moving the welded samples at the speed of 9mm/s along the line of finished welds, whilst the sensor was sweeping across the welds. Fig.7.16(a) shows a welded sample which was fused with various welding currents along the centre line of a 2mm thick stainless steel plate. The welded line contained various groove depths as the weld was conducted using ramped currents. Using the dynamic scanning method, a sensed pattern was obtained as shown in fig.7.16(b), in which the detected phase counts are plotted with respect to time. Each groove pattern in the plot represents the results of a sweep across the welded line. Fig.7.17 shows the back face of another welded sample and its corresponding sensed pattern. The sample was a well penetrated finished weld and no cleaning was applied for the scanning test. Experimental procedure was repeated as for the previous dynamic scanning test.

Experimental results show that the sensor was capable of capturing a seam profile by both static and dynamic scanning. It could also obtain surface information from uncleaned metal workpieces, such as those were used in the dynamic scanning tests. This proved to be the advantage over the infra-red seam tracker.

7.5.2 ANALYSIS OF THE DETECTED SIGNALS

It is evident that the seam profile can be extracted by the phase comparison method from each scan across the seam. However, as well as the cross section geometries of the seam, the disturbed signals are also shown in each sensed pattern. These are particularly noticeable at the edges of the butt or V-prep seam. This may be explained that the ultrasonic signals transmitted from the transmitter are not only subject to the propagation path losses, but are also subject to the scattering and multiple reflection effects which can cause signal disturbances. Fig.7.18 is an example of scattering and multiple reflections at the seam edge. The effects occur primarily in the following three situations.

(1) Where the sensor and the workpiece are all still.

(2) Where the sensor is still and the workpiece is moving, and

(3) Where the sensor and the workpiece are both moving.

In the first static situation the received signal coming from a number of signal paths is in the form of a standing wave. In this case, the received signal phase remains unchanged, as long as the sensor and the workpiece are all standing still.

In the second situation, where the sensor is held stationary and the object is moving, the time delay is different at any instant of time along the multipath. It is difficult to isolate and identify each path of a reflected wave while the object is in motion.

In the third situation, where the sensor and the object are moving, the resultant received signal is the sum of all reflected waves from different angles, depending upon the momentary attitude of the seam and whether or not the direct signal transmission path is blocked.

The last situation is the experimental situation where results were obtained. Suppose the received signal is the sum of all reflected waves from different angles, then the vibrations due to the several waves are superposed and form a series of wave trains, which may be written as

$$f_1(t) = a_1\sin(\omega t - \theta_1) \tag{7.7}$$

$$f_2(t) = a_2\sin(\omega t - \theta_2) \tag{7.8}$$

where a's are the amplitudes of the reflected signals at the receiver, and θ's are the corresponding phase shifts of the reflected signals from different reflecting path.

$$\begin{aligned} f_r(t) &= f_1(t) + f_2(t) + \ldots \\ &= a_1\sin\omega t\cos\theta_1 - a_1\cos\omega t\sin\theta_1 \\ &\quad + a_2\sin\omega t\cos\theta_2 - a_2\cos\omega t\sin\theta_2 + \ldots \\ &= \sin\omega t\Sigma a\cos\theta - \cos\omega t\Sigma a\sin\theta \end{aligned} \tag{7.9}$$

put $\Sigma a\cos\theta = A\cos\phi$ and $\Sigma a\sin\theta = A\sin\phi$

$$\begin{aligned} f_r(t) &= A\sin\omega t\cos\phi - A\cos\omega t\sin\phi \\ &= A\sin(\omega t - \phi) \end{aligned} \tag{7.10}$$

Thus the resultant vibration is simple harmonic and its amplitude is

$$A = \sqrt{\{(\Sigma a\sin\theta)^2 + (\Sigma a\cos\theta)^2\}} \tag{7.11}$$

and its phase angle ϕ is

$$\phi = \tan^{-1} \frac{\Sigma a\sin\theta}{\Sigma a\cos\theta} \qquad (7.12)$$

It is clear that the resultant phase is a measurement of the phase change of each reflected signal from its corresponding reflecting path. Fig.7.14(c), where the sensed pattern shows less distortions at the beginning and the end of a scan, shows that the sensor is at the position where the flat portions of the sample are being detected. As the sensor moves near to the seam, scattering and multiple reflections occur causing a and θ to change depending on the seam geometries. The variations of a and θ result in signal disturbances. When the seam occurs, direct reflected signals are much stronger than those multi-reflected signals and it is clearly shown in the sensed patterns. Using threshold technique for software programming, signal disturbances can be eliminated and the seam position can be determined.

7.5.3 DEVIATION MEASUREMENTS

The main objective of using a seam tracking system is to detect the presence of the seam and provide deviation values to the robot controller in order to perform closed loop control for automated welding. To investigate the abilities of the sensor in position sensing, an experiment was carried out on seam deviation measurements. A straight line seam of 1mm wide V-prep was originally placed below the torch with the electrode pointing directly to the centre of the seam. The sensor was mounted 15mm from the torch and 17mm from the surface of the workpiece. By sweeping the sensor across the seam, the position of the seam was detected. When the seam was shifted away from its original position, an offset in seam position was detected from the following sweep and a deviation value was then obtained from the RS-423 port. Fig.7.19 shows the sensing linearity to the V-prep seam. The abscissa indicates the seam position offset from the original position of the seam, and the ordinate is the deviation value obtained from the RS-423 port. The sign of each value in the graph represents the direction of seam deviation. These results confirm that the deviation values sent to the robot controller are linearly proportional to the seam position offsets.

7.5.4 TEMPERATURE EFFECT

When the sensor is used for seam tracking during welding, temperature build up around the sensor area must be considered as the velocity of sound varies with temperature. The relationship between the velocity of sound and temperature is given in the following expression [38]:

$$c = \sqrt{\gamma \ r \ T_k} \qquad (7.15)$$

where c is the velocity of sound in m/s, γ is the ratio of specific heat (for gas) at constant pressure to the specific heat at constant volume, r is a constant whose value depends on the particular gas involved, and T_k is the absolute temperature in degrees of kelvin.

It can be shown that, for an ideal gas, i.e. one obeying Boyle's law, the velocity of sound varies with temperature t (in degrees celsius) as follows:

$$\frac{c}{co} = \sqrt{1 + \frac{t}{273}} \qquad (7.16)$$

c and co represent the velocities of sound at temperatures t and 0°C, respectively. Values of co for number of gases are given in Table 7.1 [39].

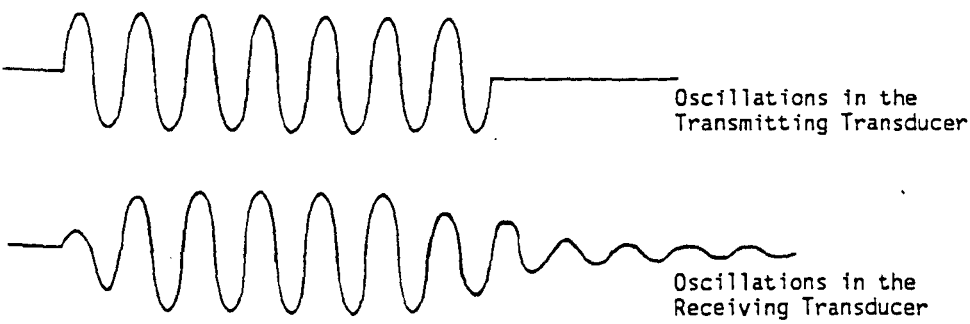
It was found from experiment that the reflected wave amplitude and the phase angle decreased as temperature increased. However, over the comparatively short range of the system the seam was detectable when the sensor was swept across the seam. The effect of temperature variations may result in the sensed pattern shifting upper or lower compared with its previous state, but the location of the seam still can be extracted using threshold methods.

7.6 DISCUSSION

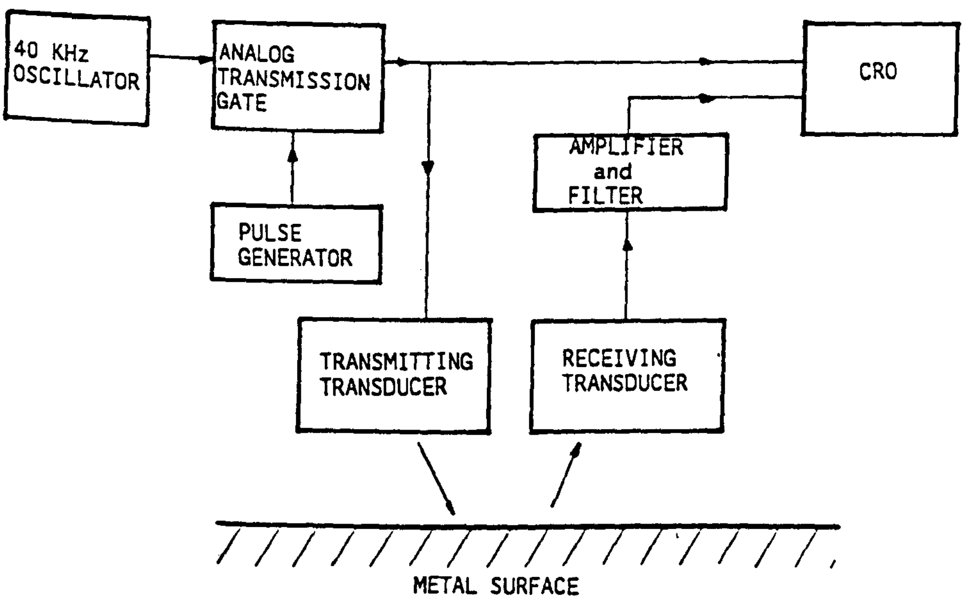
The ultrasonic seam tracker was designed based on the phase comparison between the transmitted and received signals. The system was implemented successfully in use with the TIM 3 cartesian robot. Fig.7.20 shows a VDU display of a V-prep seam profile which was obtained during real time operation. The graph was plotted after threshold of the sensed pattern. It is evident that signals reflected back from the seam reveal its presence and position. Using this information, deviation values which correspond to the seam offset from its previous position can be deduced, and thus provide feedback signals to the robot for closed loop control to ensure weld quality.

When comparing the infra-red and ultrasonic techniques, the former can be operated at higher sweep rates but suffers mainly in dirty and dusty environments and is sensitive to the colour of the workpiece or to its optical transparency. The ultrasonic seam tracker, however, has higher resolution and is less dependent on the surface cleanliness of the workpiece. The system was developed at lower cost as the sensor sweep mechanism was designed using a precision d.c. servo motor instead of a relatively expensive stepping motor and the stepping motor drive system which were used in the infra-red seam tracking system. The addition of an averaging circuit in the ultrasonic seam tracking system provided an effective technique for obtaining better defined sensed patterns.

The ultrasonic seam tracker has the advantages, common to most of the electronic sensors, of real time control and contactless operation. It is also compact, with simple circuitry, and easy to use.

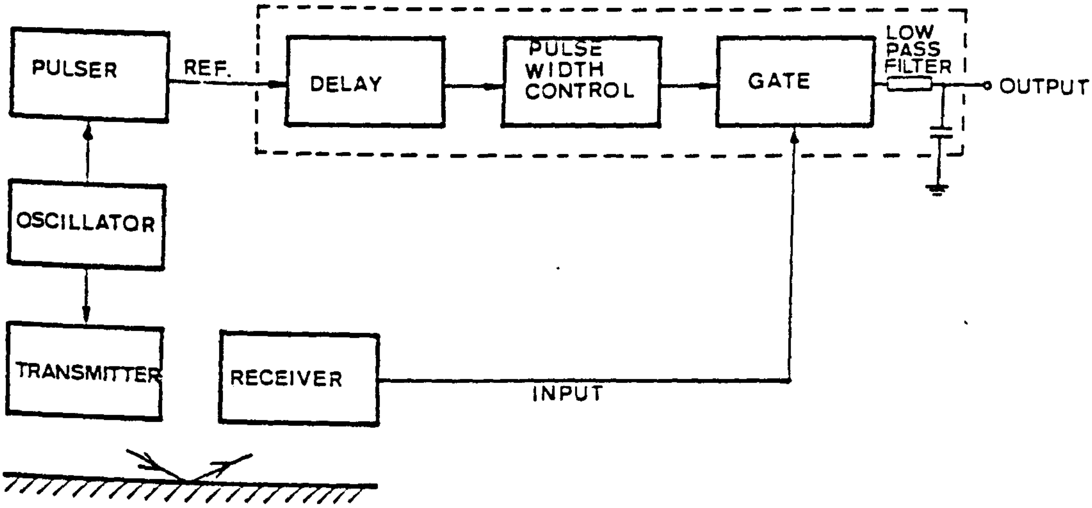


(a) Oscillations in Transducers in Pulsed Echo Method

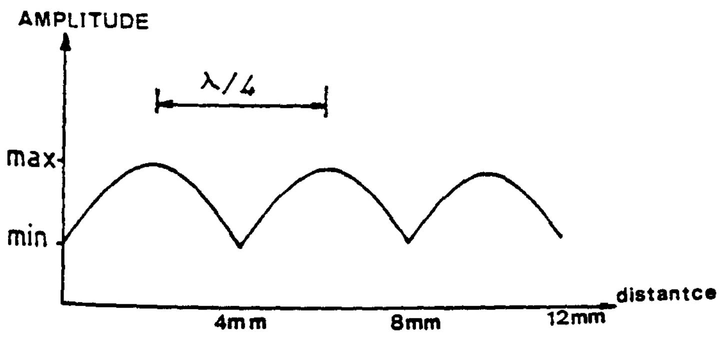


(b) Experimental Setting for Pulsed-Echo Method

Fig.7.1 Transit Time Method



(a) Experimental setting



(b) Variation of Amplitude with Distance from the Source

Fig.7.2 Signal Attenuation Method

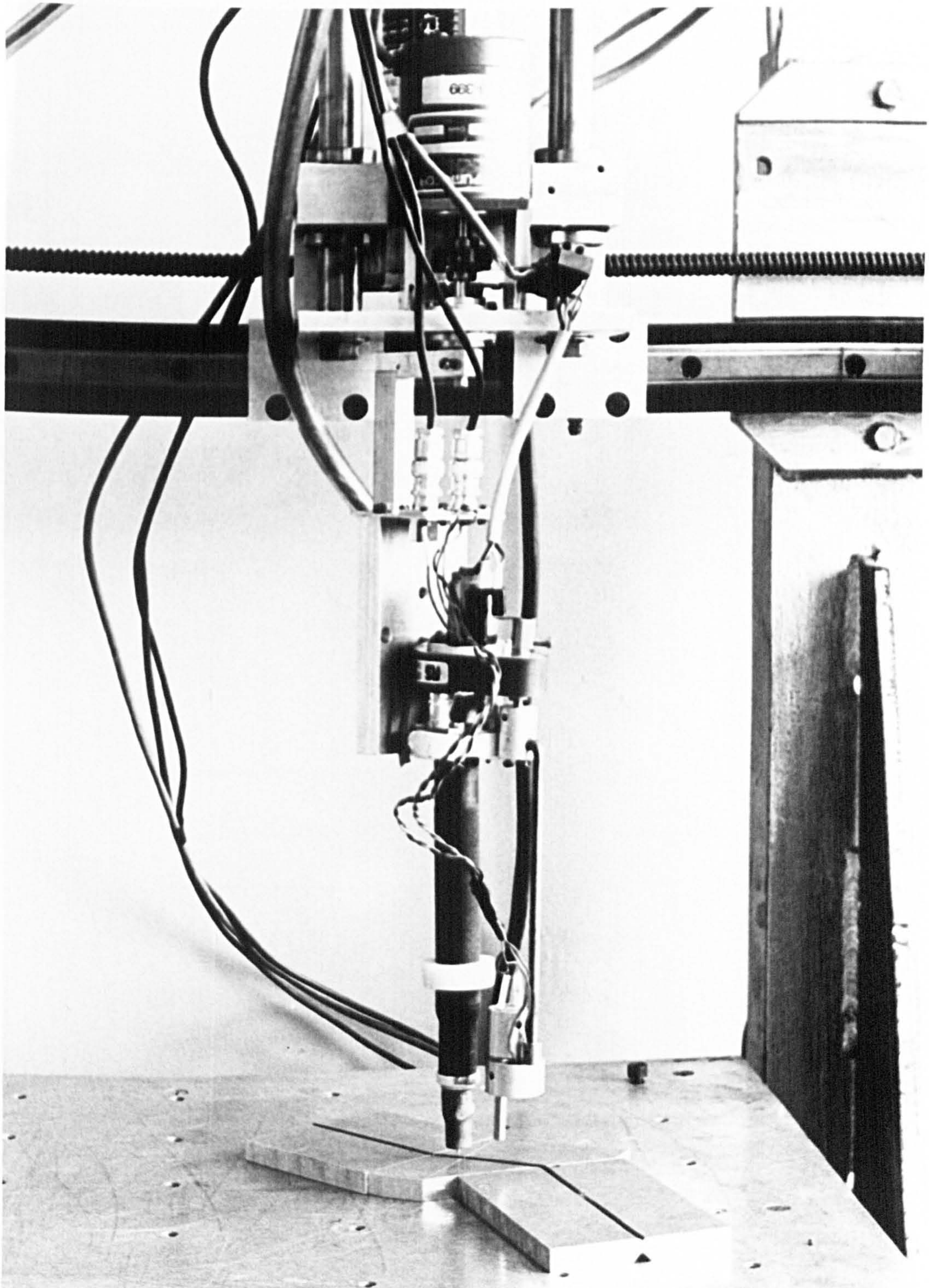


Fig.7.3 The Ultrasonic Sensor

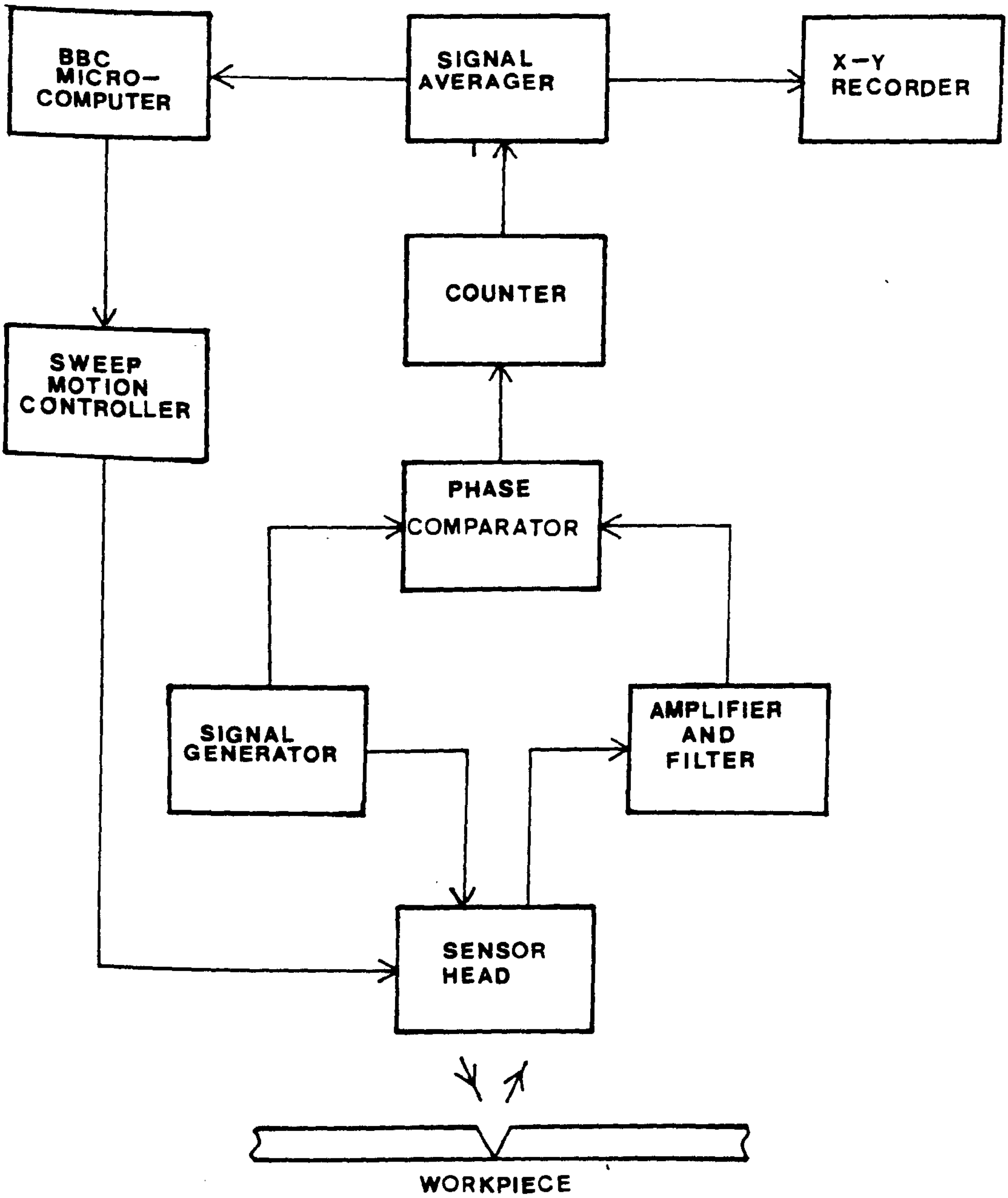


Fig.7.4 Block Diagram of Ultrasonic Seam Tracker

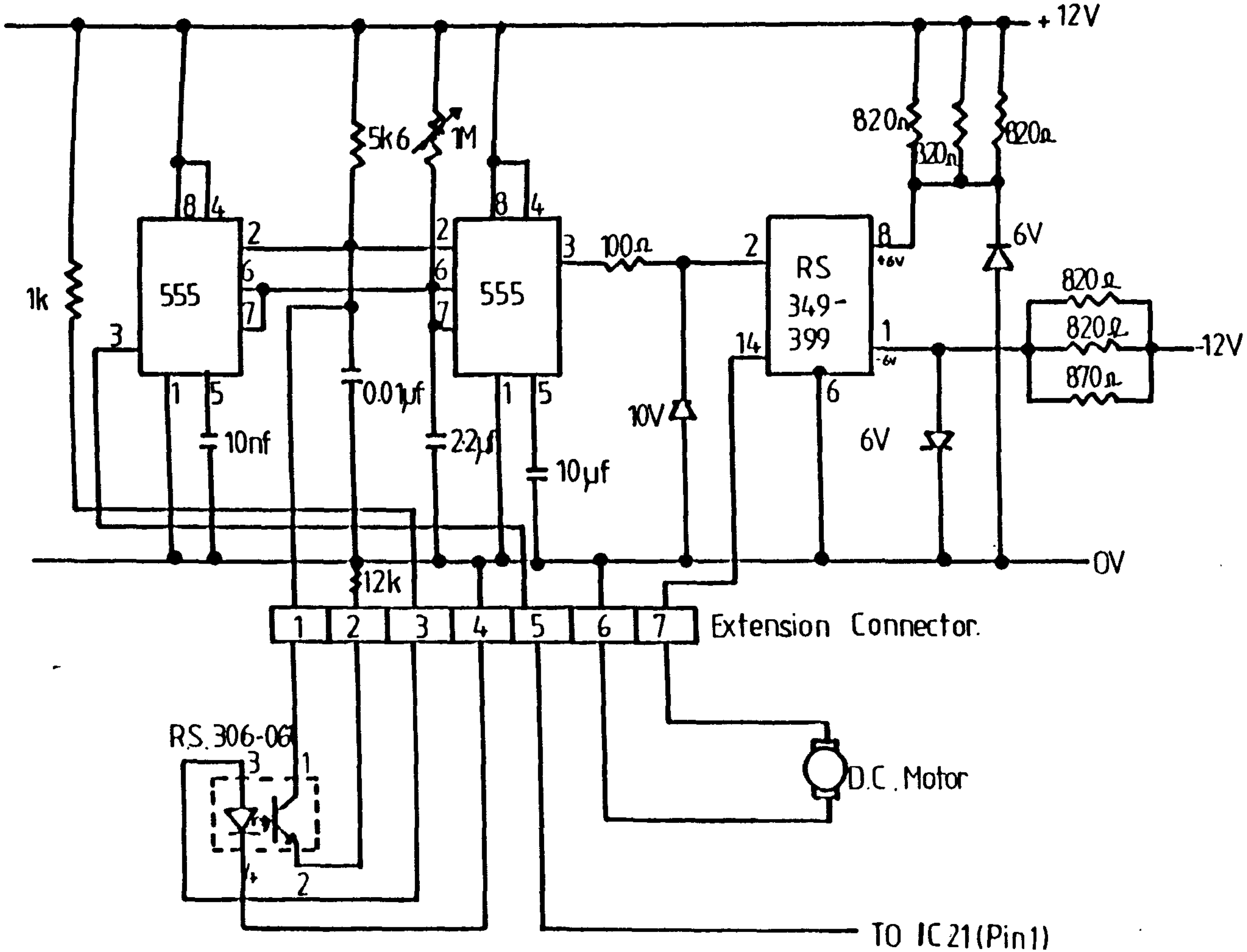


Fig.7.5 Sweep Motion Drive Circuit

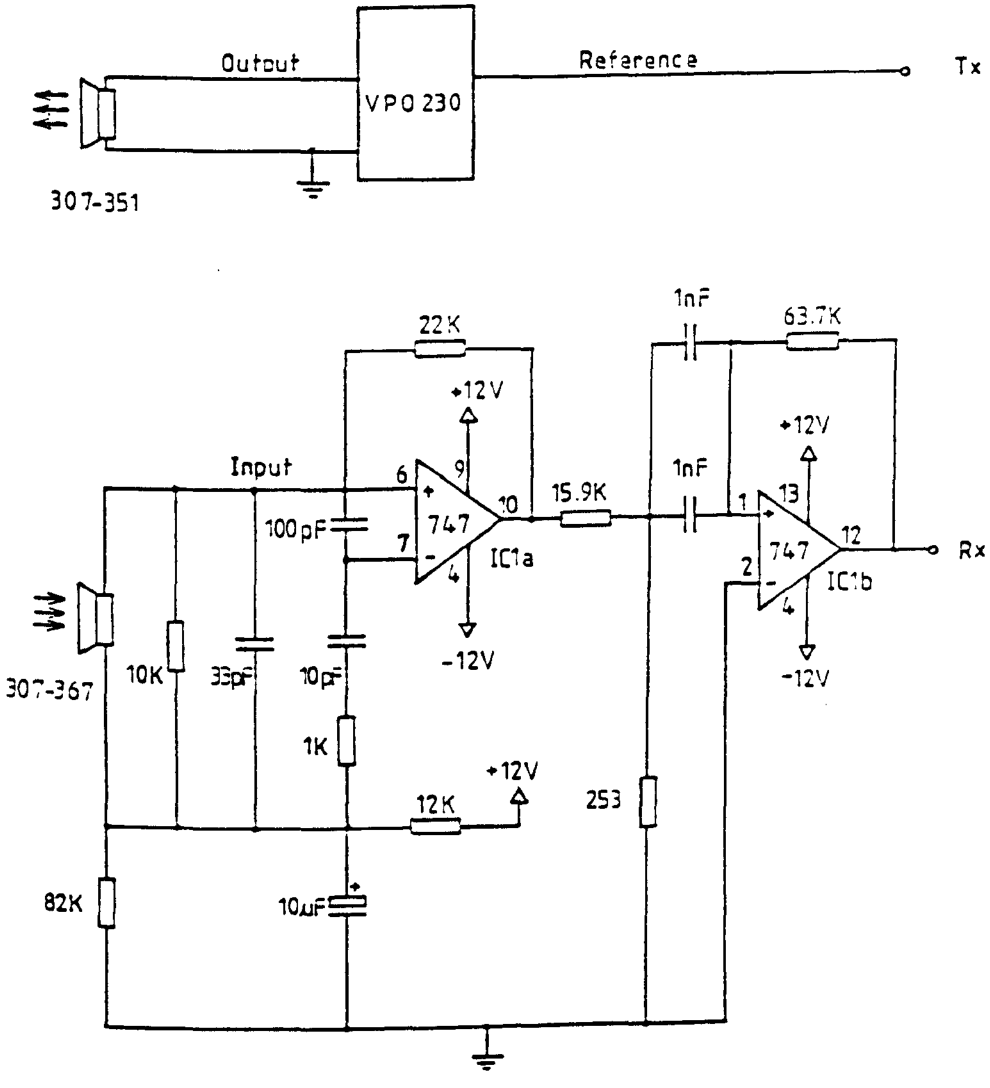


Fig.7.6 Transmitter and Receiver

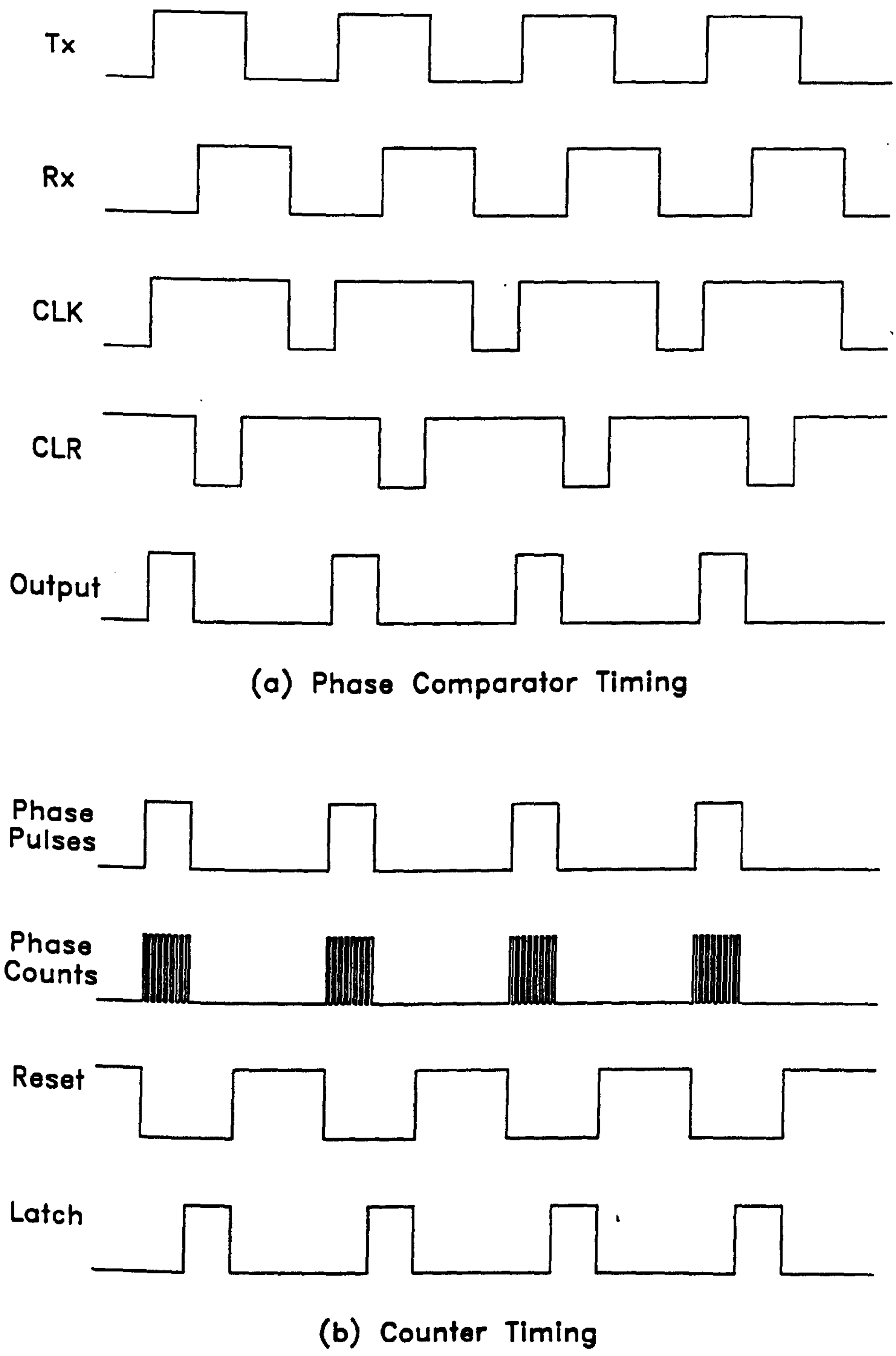


Fig.7.7 Circuit Timing Diagram

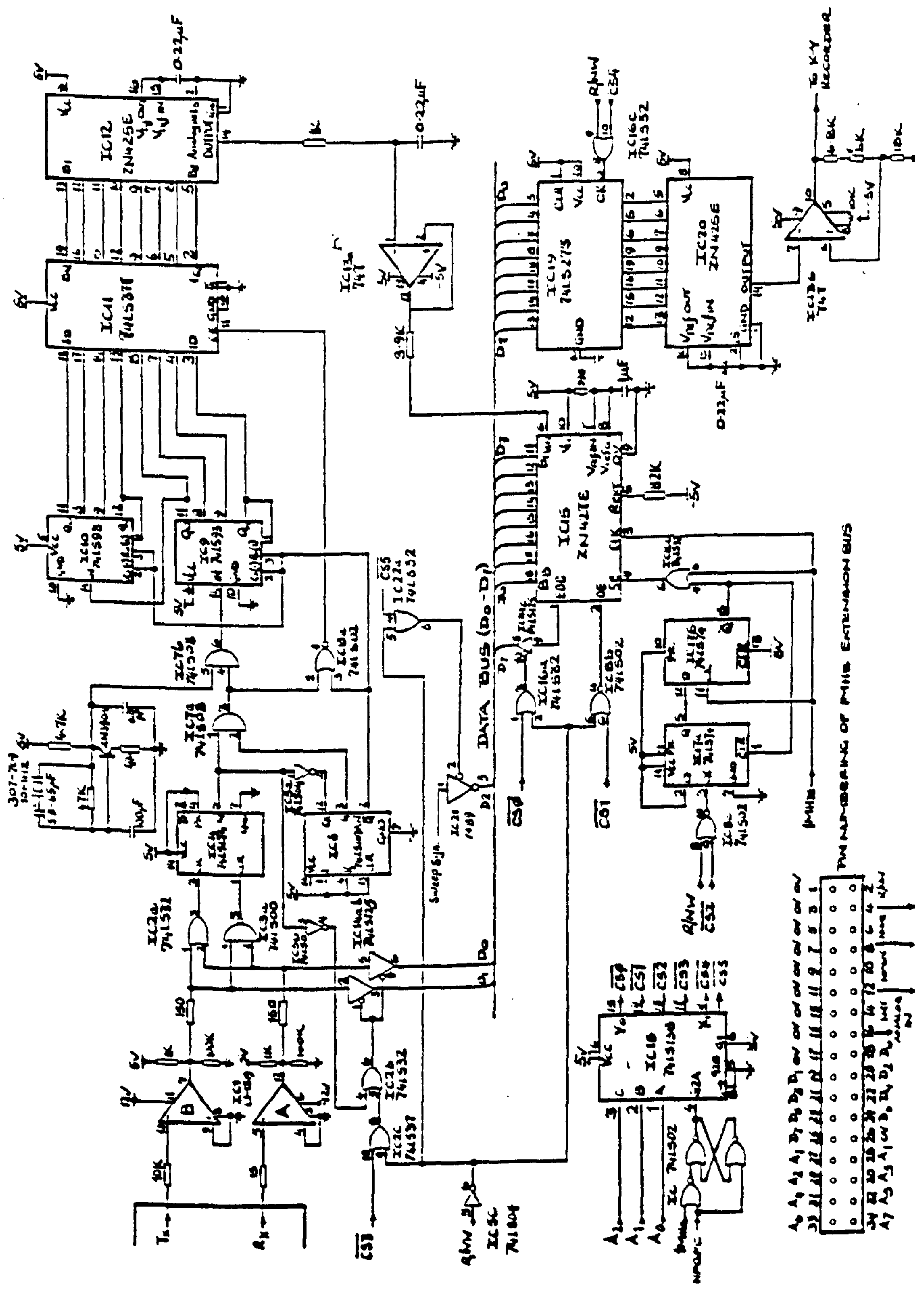
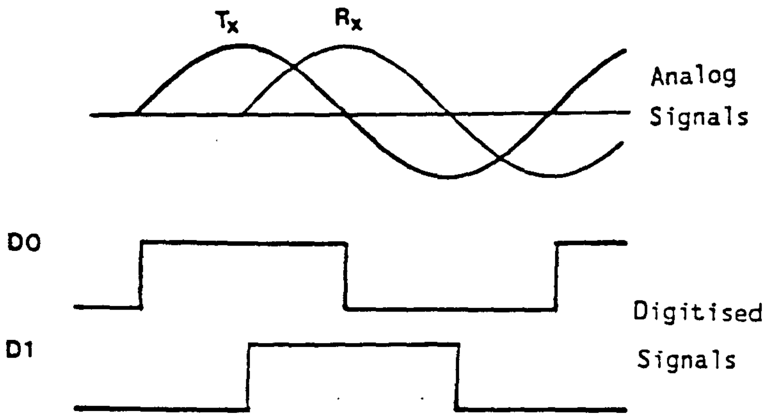
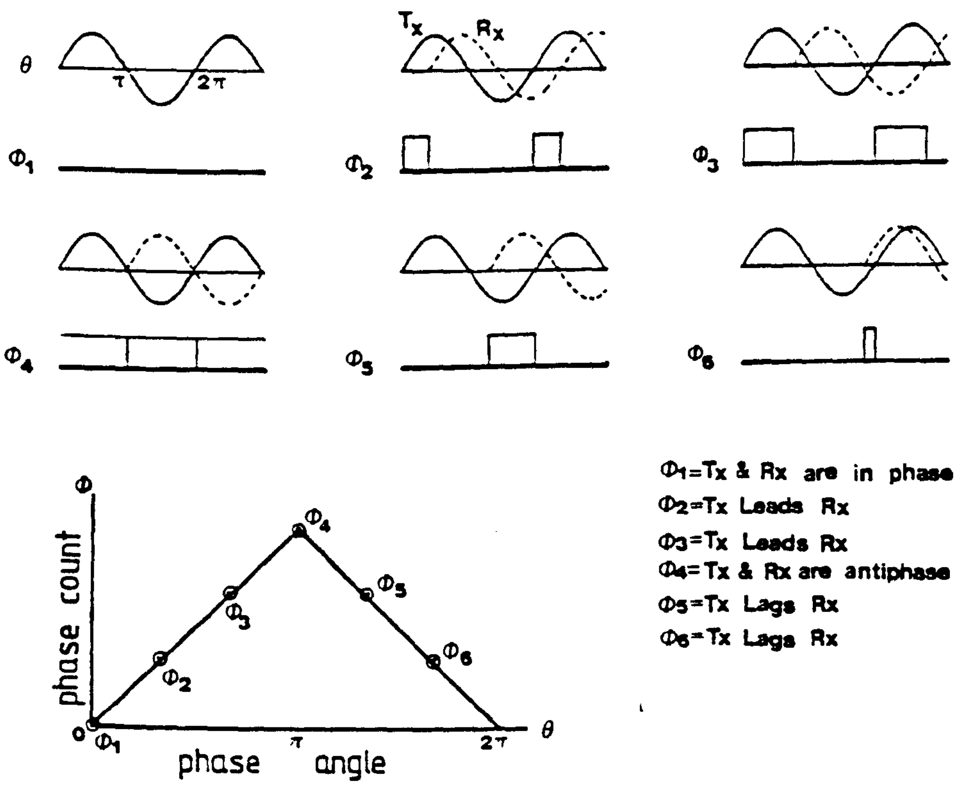


Fig.7.8 Interfacing Circuit

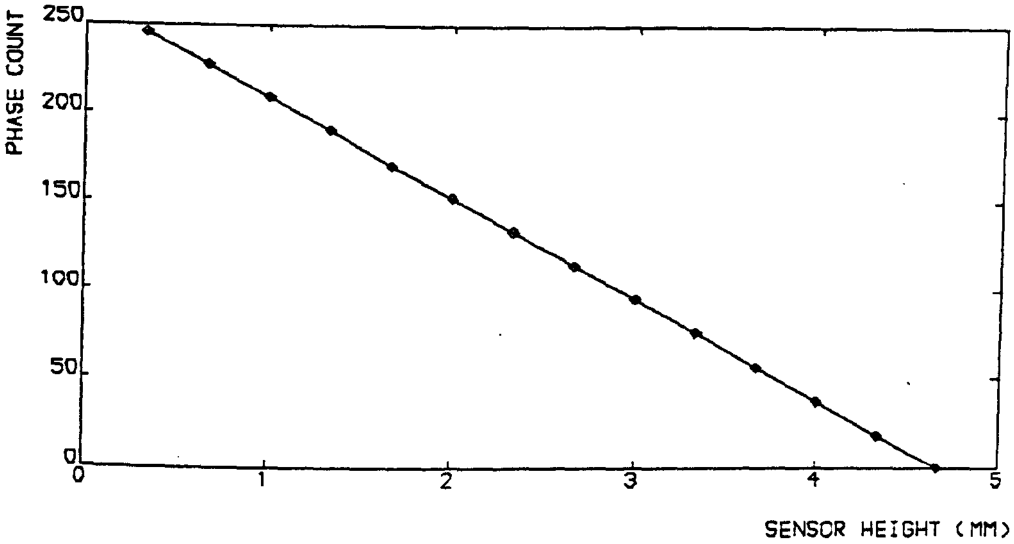


(a) Signal Representation

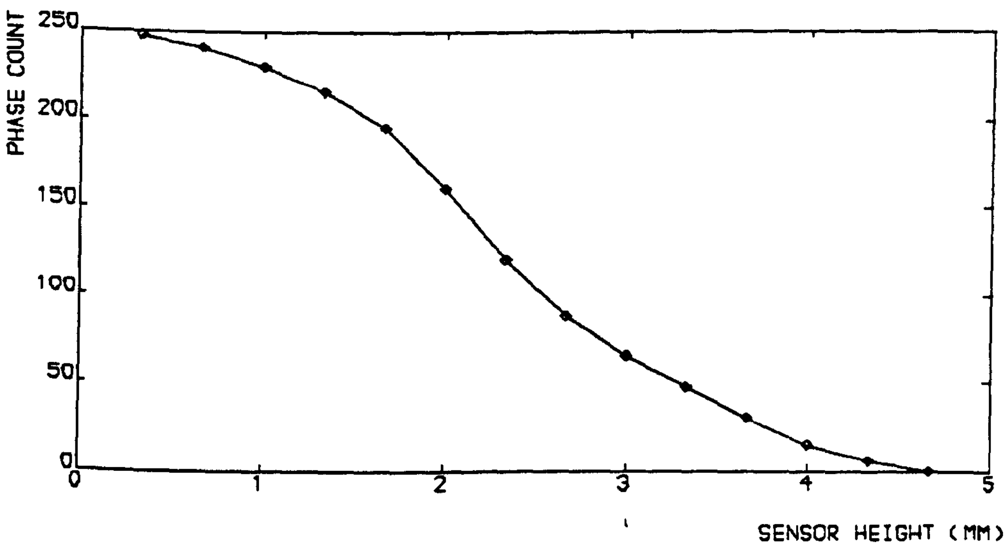


(b) Phase Lead/Lag

Fig.7.9 Relationship Between Phase Count and Phase Angle



(a) Receiver signals without using sensor housing



(b) Receiver signals from housed sensor head

Fig.7.10 Sensor Characteristics

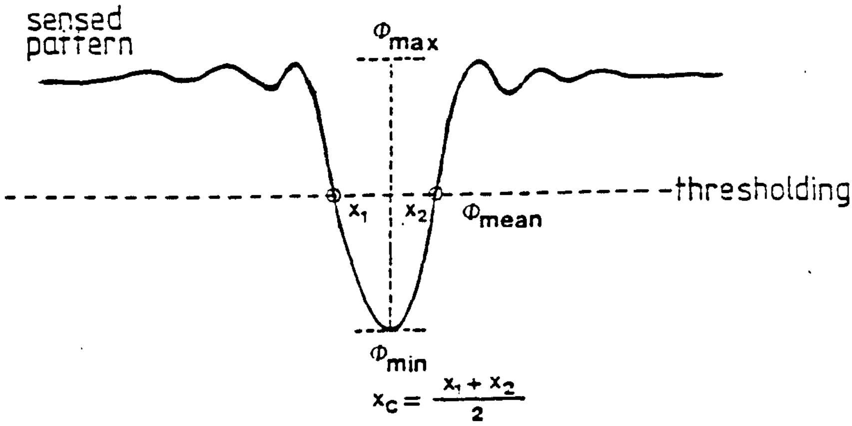


Fig.7.11 Seam Position Determination

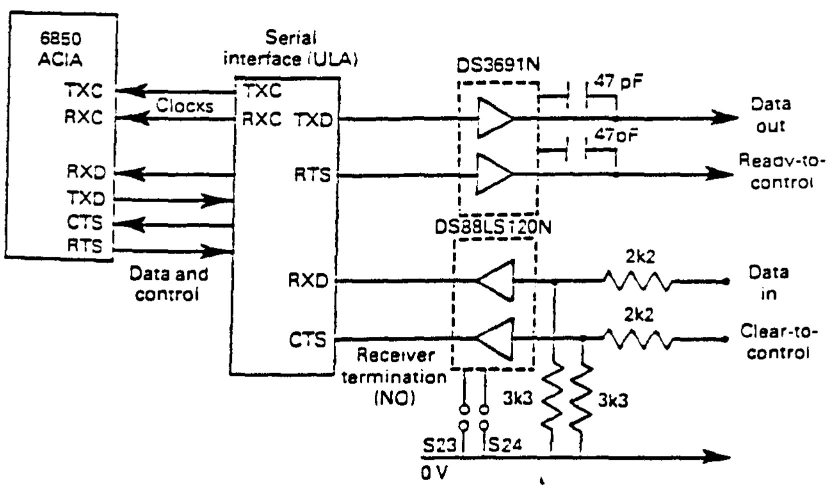


Fig.7.12 RS-423 Serial Interface

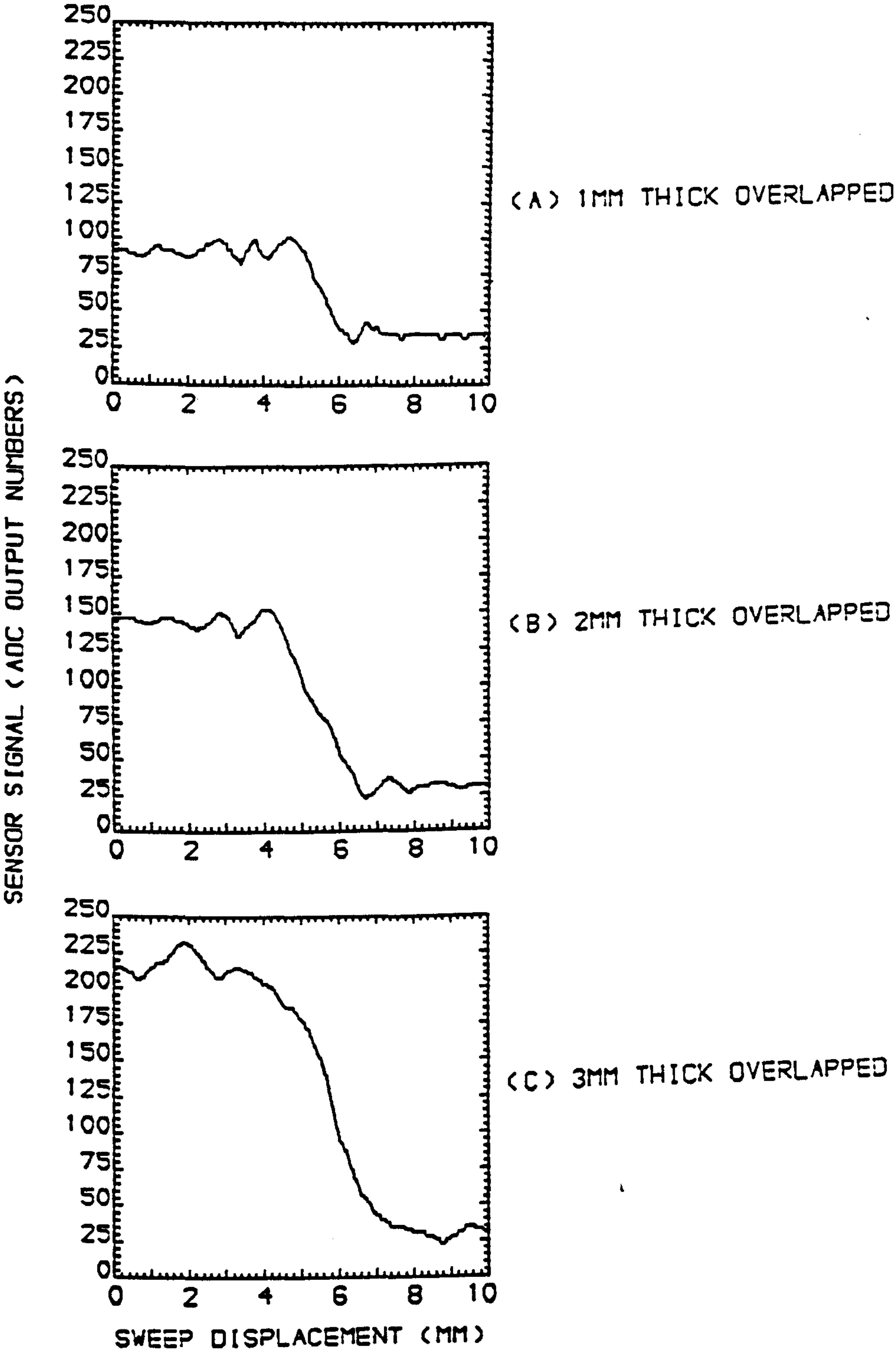


Fig.7.13 Overlapping Joints

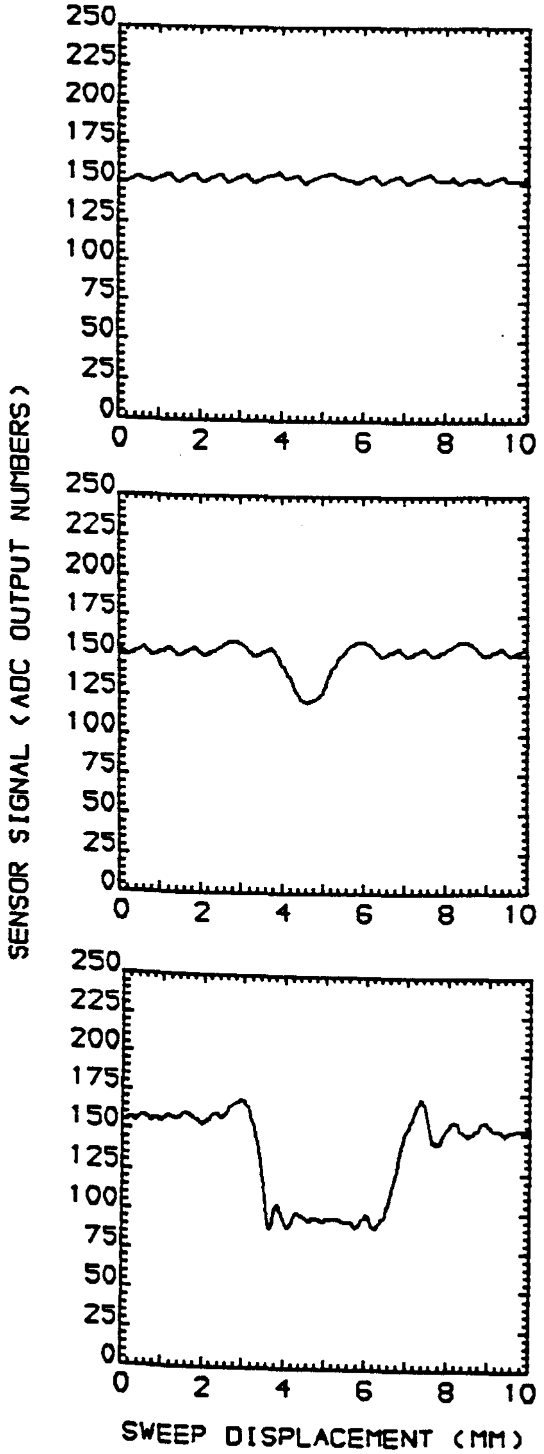


Fig.7.14 Butt Joints

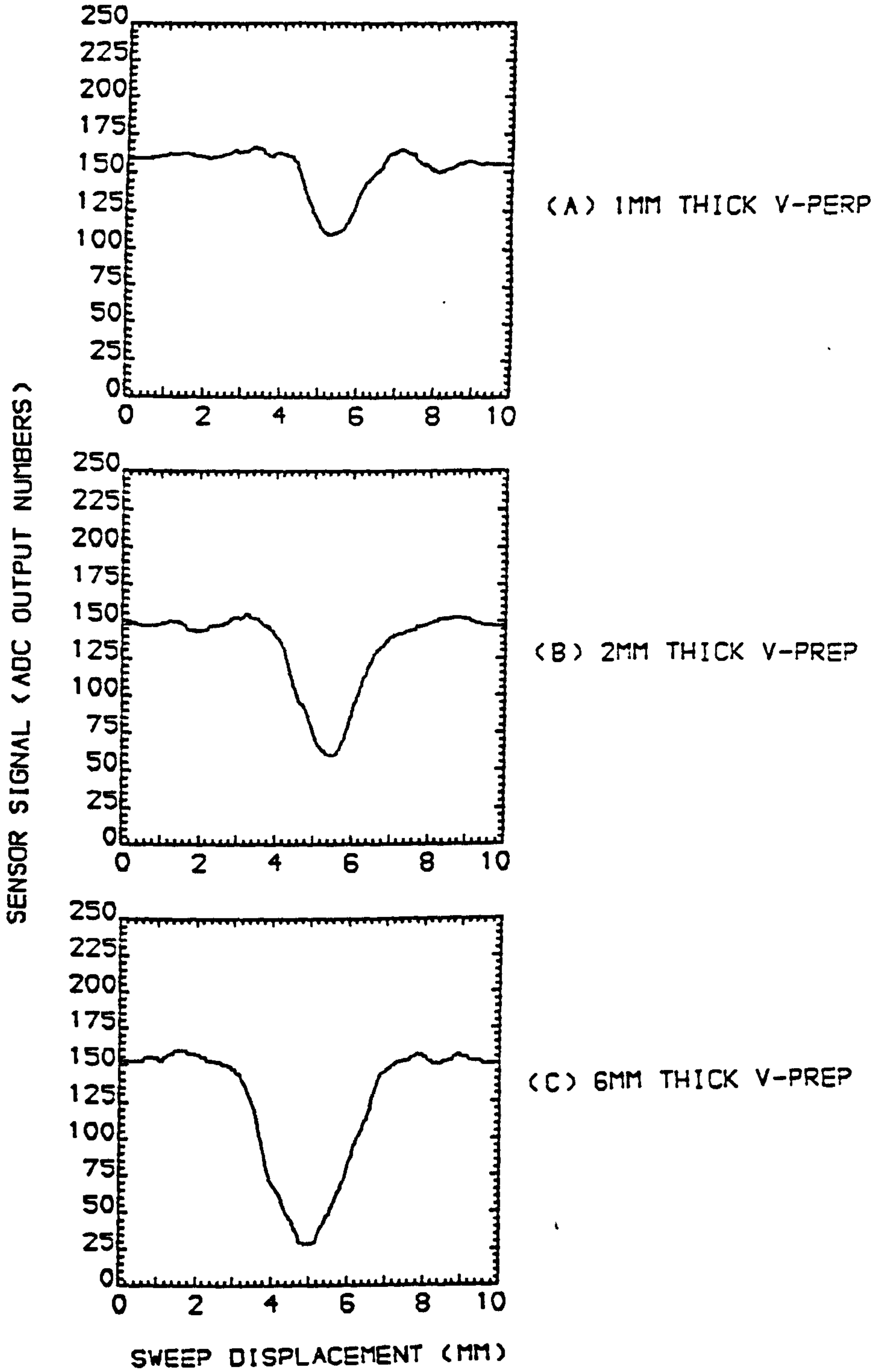
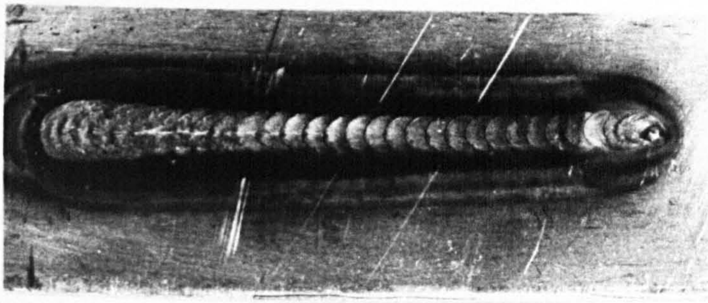
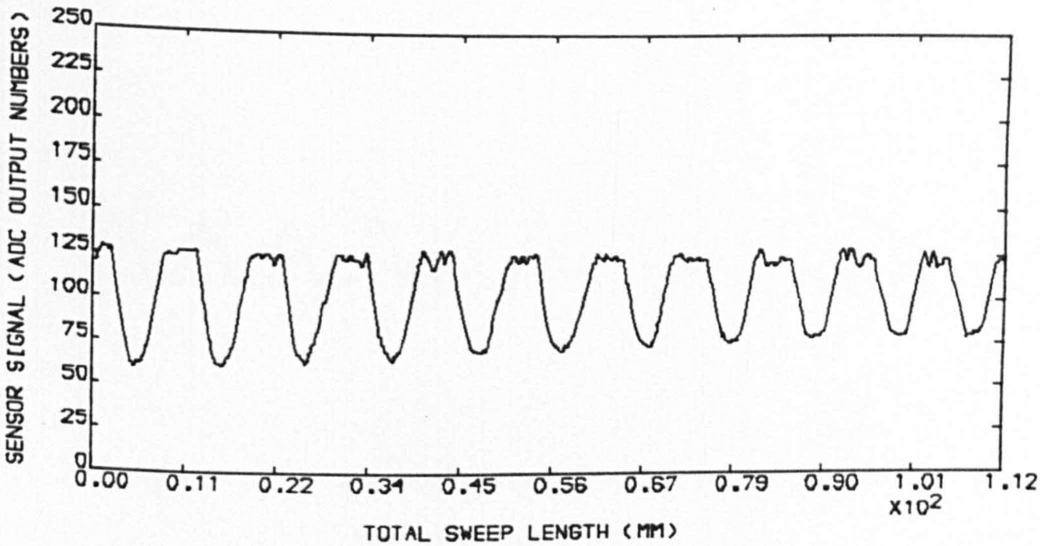


Fig.7.15 V-prep Joints



(a) Welded sample



TYPE OF WORK: FRONT FACE

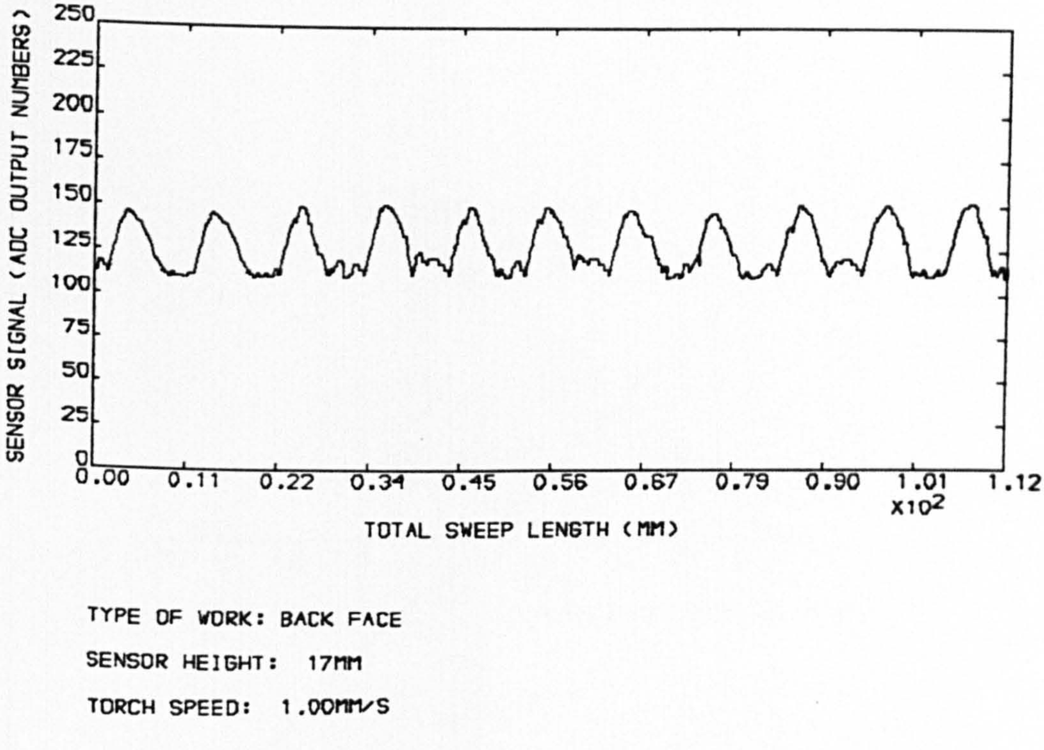
SENSOR HEIGHT: 17MM

TORCH SPEED: 1.00MM/S

(b) Scanning test

Fig.7.16 Front face of a welded sample

(a) Welded sample



(b) Scanning test

Fig.7.17 Back face of a welded sample

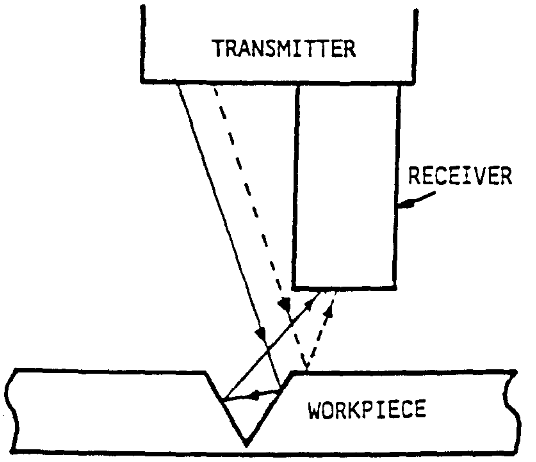


Fig.7.18 Multiple Reflection Situation

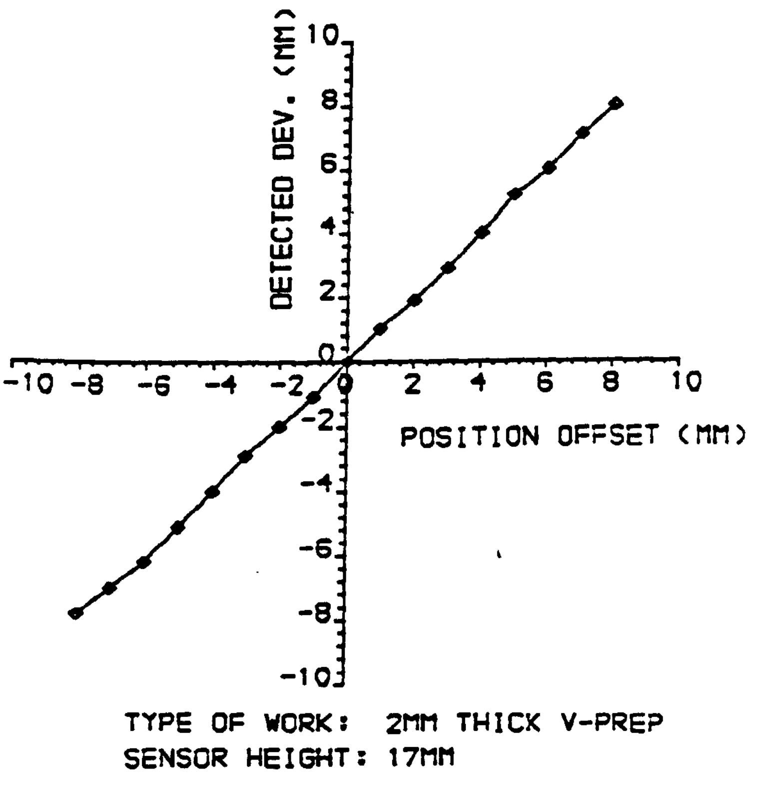


Fig.7.19 Seam Deviation Measurements

Gas	Velocity c_o (m/s)
Air	330
Argon	320
Helium	970
Hydrogen	1300
Nitrogen	310
Oxygen	330
Carbon dioxide	260
Neon	430

Table 7.1 Velocities of sound for some common gases at 0° and atmospheric pressure

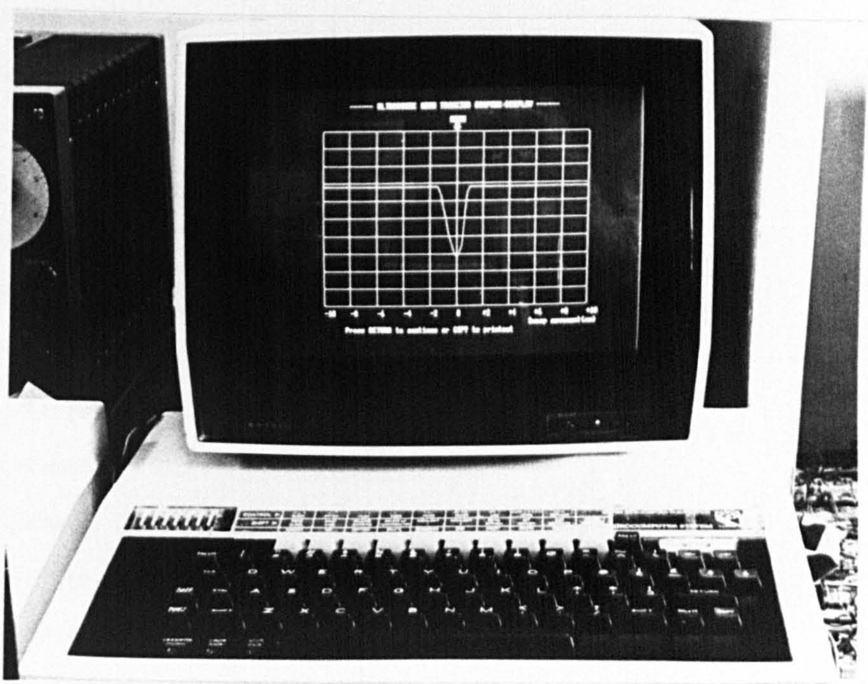


Fig.7.20 Graphic display of a seam profile

CHAPTER 8 ROBOT POSITION CONTROL

8.1 INTRODUCTION

The advances made in robotics over the past decade have resulted in the production of industrial robots and sensors which may be employed cost-effectively in a wide variety of welding applications. The ability of an industrial robot system to follow a preprogrammed, continuous trajectory results in increasing levels of productivity and weld quality. These robots, which exhibit their characteristics in motion and geometry, may be grouped into four basic motion-defining categories [40] :

(a) Cartesian coordinates (three linear axes).

(b) Cylindrical coordinates (two linear and one rotary axes).

(c) Spherical coordinates (one linear and two rotary axes).

(d) Polar or articulated coordinates (three rotary axes).

Fig.8.1 illustrates these categories. The movements of axes and wrist are shown by arrows. Each of these configurations offers a different shape of work envelope. For different applications, different configurations may be appropriate. However, in spite of the many advantages of using robots, the positional accuracy requirement of the welding torch with respect to the seam is one of the major concern in welding automation. The positional variations that exist in typical welding situations are simply too large to permit anticipatory preprogramming of the weld trajectory. A desirable solution, as described in previous chapters, is to incorporate real-time sensory feed back into the robot system and employ feedback control techniques to compensate for unexpected changes in the seam position relative to the torch. This approach is dependent on the robot position control algorithm.

In this chapter, the fundamental features of robot position control algorithm are discussed. Several computational models are developed for the searching and tracking of various seam paths. Experimental results are used to assess the positional control ability.

8.2 TIM-3 ROBOT CONFIGURATIONS

Both the infra-red and ultrasonic seam trackers were tested in conjunction with a robot controller based upon an Intel 8085 microprocessor system which controls the TIM-3 cartesian coordinate system robot.

8.2.1 AXES GEOMETRY

The TIM-3 robot is a three-axis machine. It consists of a table (Y-axis) for the support and movement of the workpiece, and a track system (X-axis and Z-axis) for moving the torch. A wrist action (RO and RI) allows the torch to be prepositioned at any request angle prior to welding the seam. Although there are five motions, the robot is referred to as having three degrees of freedom since the wrist movements are only used to position the torch and are not varied during welding. the TIM-3 robot is shown schematically in fig.8.2. The mechanical range of the system is approximately :

X axis = 500mm

Y axis = 600mm

Z axis = 200mm

RO axis = 360°

RI axis = 180°

Support table = 550mm x 550mm

The top section of the table is separated from the lower section by a tufnol middle section. This provides electrical isolation of the welding return path from the machine earth. The surface of the table has a matrix of tapped holes used for attaching workpieces or jigs.

8.2.2 CONTROLLER

The controller is the heart of the robot system. It communicates with the seam tracker and other devices in order to perform positional control for precision welding. It is based upon a Quarndon microcomputer and consists of :

(a)A QMS 8511-85B 8085 based microcomputer board.

(b)A QMS 00-1419-2 AM9511 based arithmetic processor board.

(c)A QMS 00-1201-D 32K-byte dynamic random access memory.

(d)A BBC model B microcomputer.

Fig.8.3 shows the Memory and Input/Output maps of the controller.

8.2.3 DRIVE SYSTEMS

All axes are driven by permanent magnet stepping motors, giving a resolution of ±0.01mm on the linear axes. Digiplan 1054 bi-level/bi-polar drivers are used to power the motors. The motors are driven directly by the controller. Each motor has associated with it a DIVIDER, COUNTER and ENABLE. The DIVIDER controls the speed at which the motor moves whilst the COUNTER determines the distance moved. The ENABLE enables and disables movements of its associates motor.

Thus, when the controller requires a linear movement, it loads the DIVIDER register with the speed value and the counter register with the distance value. The motion is started by activating the ENABLE signal whereupon the appropriate number of stepping pulses will be generated at the required rate. When the motion is complete an interrupt signal is generated to inform the processor.

8.2.4 ACCURACY

The robot has a positional accuracy of better than 0.1mm at any position within its working envelope, and a speed accuracy of better than 1% in the range from 10mm/s to 0.5mm/s [41]

The robot has the rigidity and accuracy required for TIG welding operations which are often difficult to achieve in a robot arm.

8.3 PATH CONTROL ALGORITHMS

The control algorithms are of great importance in an automated welding system. As the seam trackers described in chapter 6 and 7 are capable of detecting the position of a seam by sweeping the sensor across the seam, these capabilities have to be integrated into the robot control algorithm so that the seam tracker can provide feedback to the robot controller to follow a seam.

8.3.1 TORCH POSITION ALGORITHM WITHOUT SENSOR

The control algorithm employed for torch position control is an enhancement of the torch position algorithm used for blind robotic welding, i.e. welding without sensor guidance. In blind welding applications, the operator leads the robot through the trajectory required to weld a part and fixes a set of points through which the torch is required to pass. The torch trajectory between taught points is typically specified to be a straight line. Since the robot controller requires a position update at some small fixed time rate, intermediate positions between the taught points must be determined. Therefore, in order to generate a straight line path, the distance between two taught points is divided into a number of points separated by the distance that can be travelled in the time interval at the requested speed. Positions are determined by straight line interpolation between the two taught points. Robot motion, in principle, consists of commanding the robot to go to consecutive interpolation points at the fixed time interval.

8.3.2 SENSOR GUIDANCE

A sensor guided robot path is taught in same way as a blind welding path, by leading the robot through the key points on the part. The seam tracking system determines where the sensor sweep path intersects the taught path. By knowing where the seam is, relative to the torch, and what the torch's position was when the current deviation value was received from the seam tracker system, the location of the seam can be determined. Finally, the torch position is compared with the taught path to find out which interpolation point it most nearly corresponds to, and how far from the taught path the torch is at that interpolation point. This information is stored in a buffer.

As the torch moves along the taught path from interpolation point to interpolation point, it checks the buffer of path corrections generated by the seam tracking system to see if a trajectory correction offset exists. The sensor processing algorithm runs asynchronously with the robot and generates offsets for positions that the robot will arrive at in the future. The robot control algorithms, however, redirects the torch to follow the seam.

8.4 MODEL REPRESENTATION

In order to obtain the features of a seam path and the robot's response due to path deviations, seam path modelling and seam tracking simulations were carried out by means of a simulation program. This program was written in FORTRAN language (Appendix V). Path models included a straight line, a curve and a step change of seam path.

A path is represented as a set of points, defined by their x, y and z coordinates. The order of the points determines the direction of motion. For seam deviations, the seam is offset from its original path and so causes the torch to move off the seam. This results in a change in x and y coordinates. Therefore, x and y coordinates are the major concerns in the modelling.

8.4.1 SEAM PATH MODELLING

During a welding process, any variation of seam path depends upon a variety of positional uncertainties of the welding environment. A straight line seam path may remain straight during welding, or it may be distorted due to temperature effects, resulting in a curved seam path, or it may be offset from its original position by mechanical forces. To simulate these situations, three different path modelling were performed, namely straight line, curve, and step function.

The features of a seam path may be simulated by the following function:

$$y = a_1x^3 + a_2x^2 + a_3x + a_4\sin(a_5x) + a_6 \quad (8.1)$$

where a_1, a_2, a_3, a_4, $a_5$and a_6 are the arbitrary constants. By fitting suitable values into these constants, a function which represents the desired seam path may be obtained.

The three seam path models were generated by the following parameters.

(1) For a straight line path

$a_1 = a_2 = a_3 = a_4 = a_5 = 0$

$a_6 = 2 \times 10^{-3}$

(2) For a curved path

$a_1 = a_4 = a_5 = 0$

$a_2 = 0.1$

$a_3 = -0.02$

$a_6 = 2 \times 10^{-3}$

(3) For a step function path

$a_1 = a_2 = a_3 = a_4 = a_5 = 0$

$a_6 = 2 \times 10^{-3}$ for $0 < x \le x_1$

$= 2 \times 10^{-3} + d_{os}$ for $x_1 < x \le x_2$

where x_1 is the distance the step change occurs, x_2 is the total distance the torch travelled, and d_{os} is the offset distance.

8.4.2 SEARCHING AND TRACKING

Fig.8.4 to 8.6 show the three models and their corresponding sensor responses. In each figure, the solid line pattern represents the seam path which was obtained from function (8.1), and the broken line represents the torch movements along the seam path. The plot of sensor deviation against seam distance simulates the sensor response with respect to seam path variations.

Various procedures were carried out for the computation. These included:

(1) Find the torch position with respect to the seam path.

(2) Find the interception of the sensor sweep path and the seam.

(3) Calculate the angle of the torch, θ

(4) Calculate the perceived angle, β

(5) Determine the new angle of the torch by the feedback control function:

$$\theta_n = \theta_{n-1} + G_p\beta_n + G_d(\beta_n - \beta_{n-1}) \qquad (8.2)$$

where n represents the present state, n-1 represents the previous state, G_p is the product gain, and G_d is the differential gain.

Results shown in these figures were based upon the following assumptions:

(a) The centre position of a sensor sweep represents the seam.

(b) Distance of the sensor in front of the torch = 20 mm

(c) Torch/sensor velocity = 1 mm/sec.

(d) Time between each sensor sample = 1 sec.

(e) Sweep length = 10 mm

(f) Step length for iterations along the seam = 0.1 mm

Fig.8.4 simulates the situation in which the torch and sensor are originally 5mm away from a straight line seam. When searching starts the torch moves towards the seam and the sensor deviation gradually becomes smaller. The zero deviation indicates the torch is on seam.

Fig.8.5 shows a curved seam path. The torch and sensor are assumed to be originally on the seam. As the seam gradually deviates from the straight line path, the torch follows and the sensor deviation can be hardly observed in this graph.

In the case of fig.8.6, where the straight line seam has a step change in position at the centre of the seam path. The torch and sensor are again assumed to be originally on seam. When the step change occurs, the sensor deviation rises and the torch begins to move towards the new seam path. When the sensor deviation reduces to zero, the torch is again on seam.

8.5 RESULTS AND ASSESSMENTS

The above models show that the robot's response to seam tracking is dependant on the sensor deviations which correspond to the seam offset in positions. In practice, the performance of seam tracking is affected by whether the seam tracker can supply the correct deviation signals to the robot controller. If the deviation signals generated from the seam tracker are proportional to the seam position offsets, the correct seam tracking process can be performed.

8.5.1 RESPONSE TO STEP CHANGE

Fig.8.7 shows the simulations and experimental results of seam deviations during seam tracking. The experimental results were obtained by the infra-red seam tracker from tracking seam path offset experiments and were given in section 6.5.3. One set of results was taken from the experiment for zero seam path offset, and the other for a 3mm seam path offset. The tracking performance of the system demonstrates coordinated compensation for deviation errors in twist angle and position lateral to the seam path. All the results were subject to the constrain of constant torch velocity. In comparison with the computer model, experimental results show evidence that the seam tracker was working properly.

8.5.2 EFFECT ON SENSOR VARIABLES

Although it is clear that the robot position control depends upon the deviation signals supplied from the seam tracker, the effects of changing sensor variables such as the sensor sweep length, the sensor sweep rate and the sensor distance in front of the torch also need to be considered. For example, if the infra-red seam tracker is replaced by the ultrasonic seam tracker, all the sensor variables as mentioned above may not be exactly the same as in the case when the infra-red seam tracker was being used.

Fig.8.8 shows the effects on varying the sensor sweep length from 5 to 20mm by keeping the other variables constant. It is obvious that the variation on sensor sweep length can hardly affect the robot position control.

Fig.8.9 also shows no significant changes in robot position control as the sampling time (or the sensor sweep rate) changes from 0.6 to 1.2 seconds.

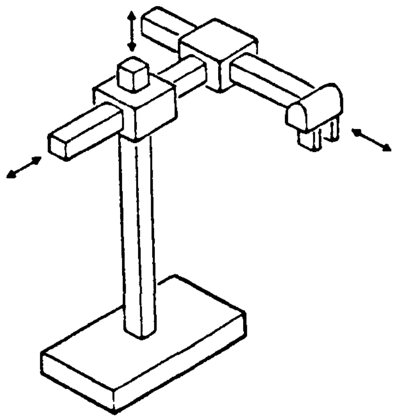
The changes in robot position control can only be observed in fig.8.10, where the sensor deviation response changes slightly as the sensor distance increases from 15 to 30mm. If this variable is kept within ±2mm as tolerance, then, even if the infra-red seam tracker is replaced by the ultrasonic seam tracker, the robot position control should remain unaffected.

8.6 DISCUSSION

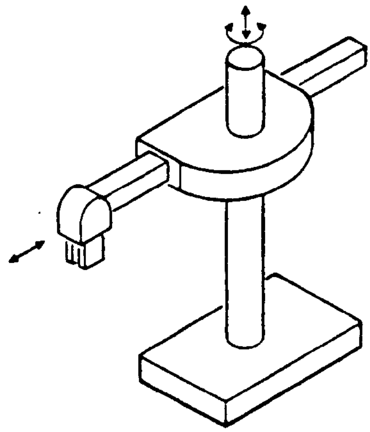
TIG welding processes are generally applied to high precision welds. The dimensions of practical weld seams can be down to less than 1mm and the arc lengths can be less than 2mm. This means that the torch is needed to be positioned within an accuracy better than 0.1mm. The cylindrical, spherical and polar arm configuration robots suffer from the fact that accuracy varies with position, and it is difficult to achieve the required value throughout the working environment. However,the TIM-3 cartesian robot has the rigidity and accuracy required for TIG welding operations.

The fundamental features of robot position control algorithm have been presented. Various models of sensor responses and torch movements with respect to the variations of seam path demonstrated that the robot position control is mainly dependant on sensor deviation values. In other words, the TIM-3 robot is capable of performing TIG welding with seam tracking if used with the seam tracker, which generates deviation signals corresponding to the actual variations of the seam path.

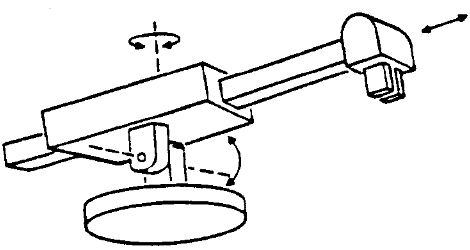
Both the infra-red and ultrasonic seam tracking systems were implemented successfully with the TIM-3 cartesian robot.



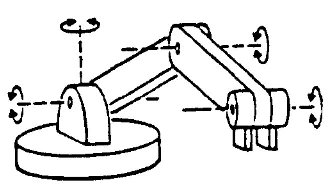
(a) Cartesian Coordinates



(b) Cylindrical Coordinates



(c) Spherical Coordinates



(d) Polar or Articulated Coordinates

Fig.8.1 Robot Configuration Categories

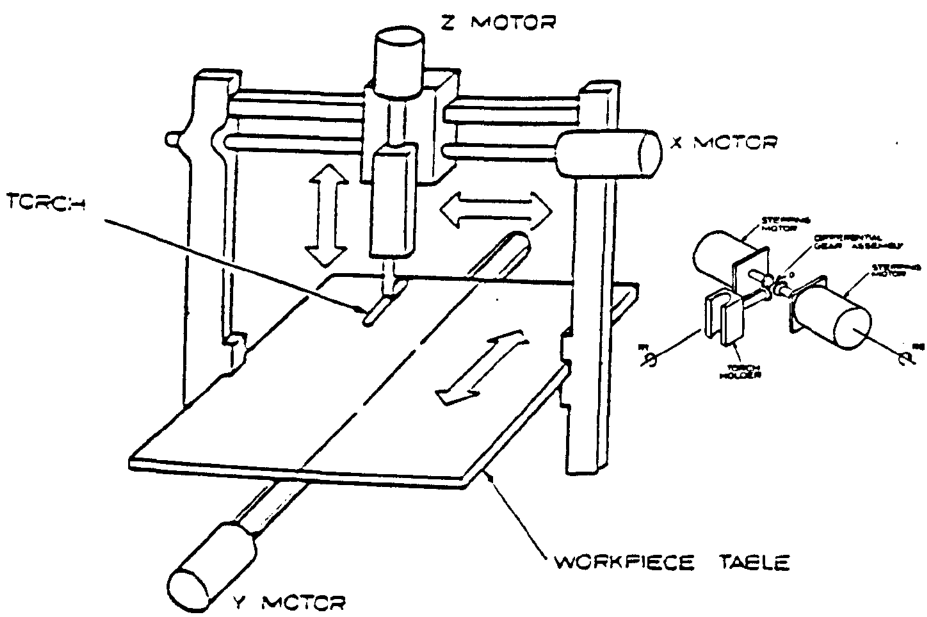


Fig.8.2 TIM-3 Robot Configurations

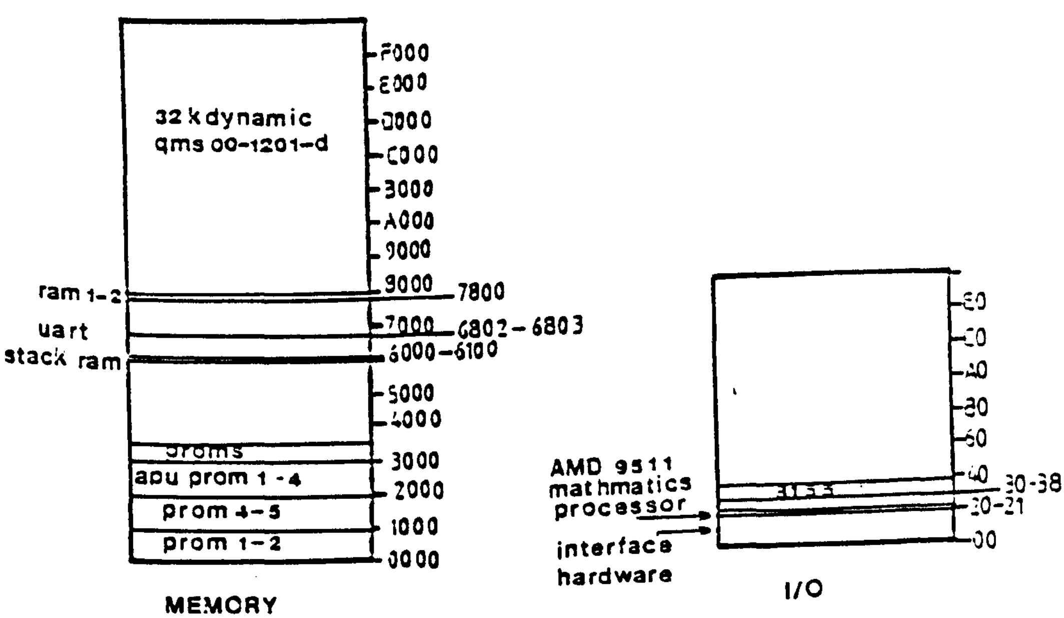
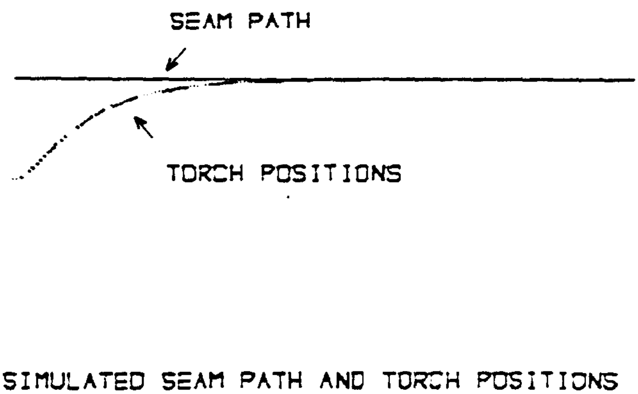


Fig.8.3 Memory and I/O maps of TIM-3 Controller



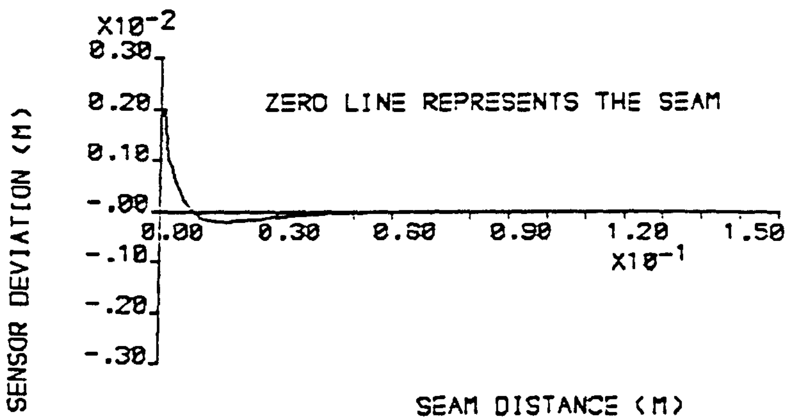


Fig.8.4 Searching for a straight line seam

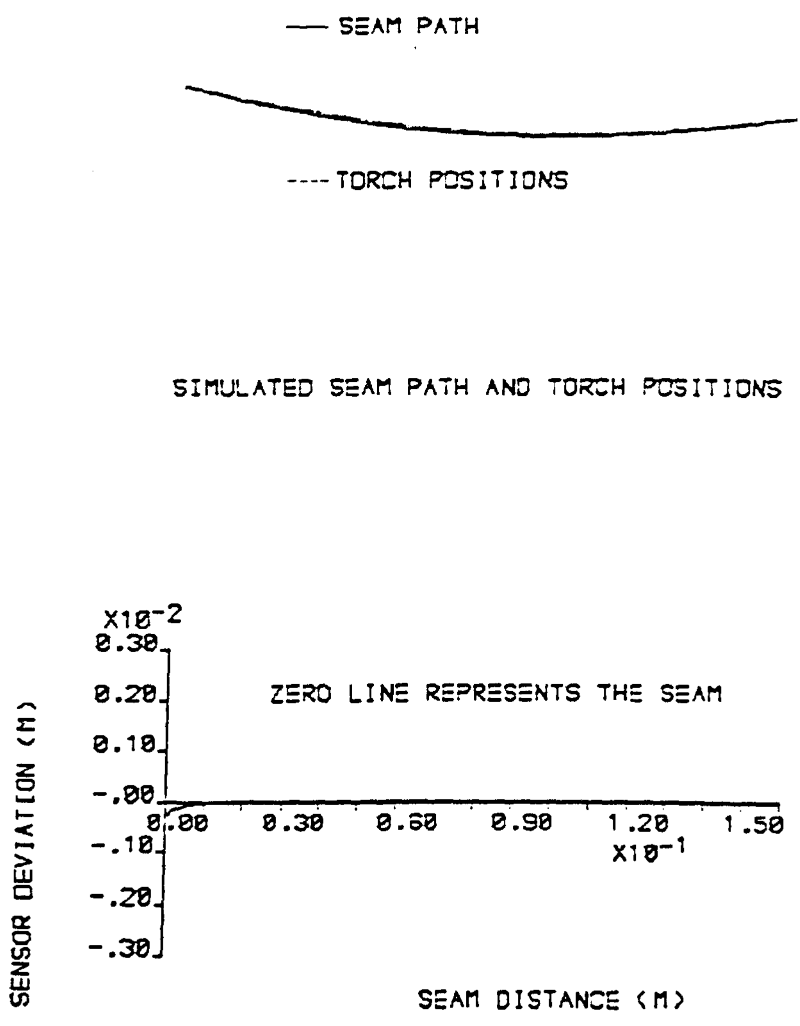
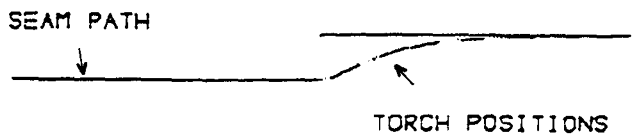


Fig.8.5 Tracking of a distorted seam



SIMULATED SEAM PATH AND TORCH POSITIONS

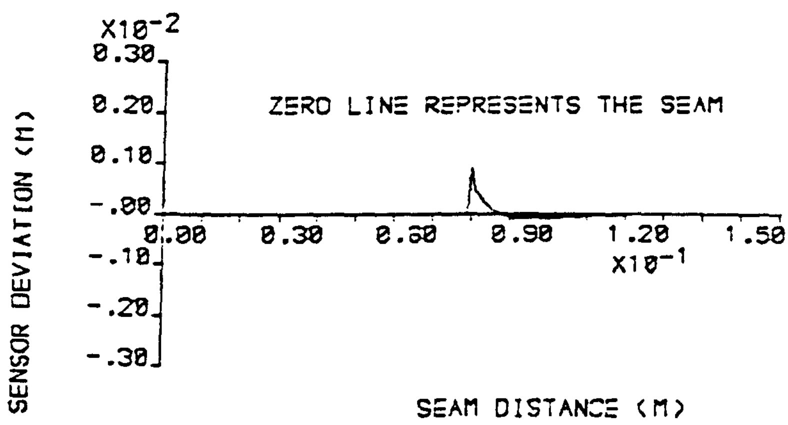
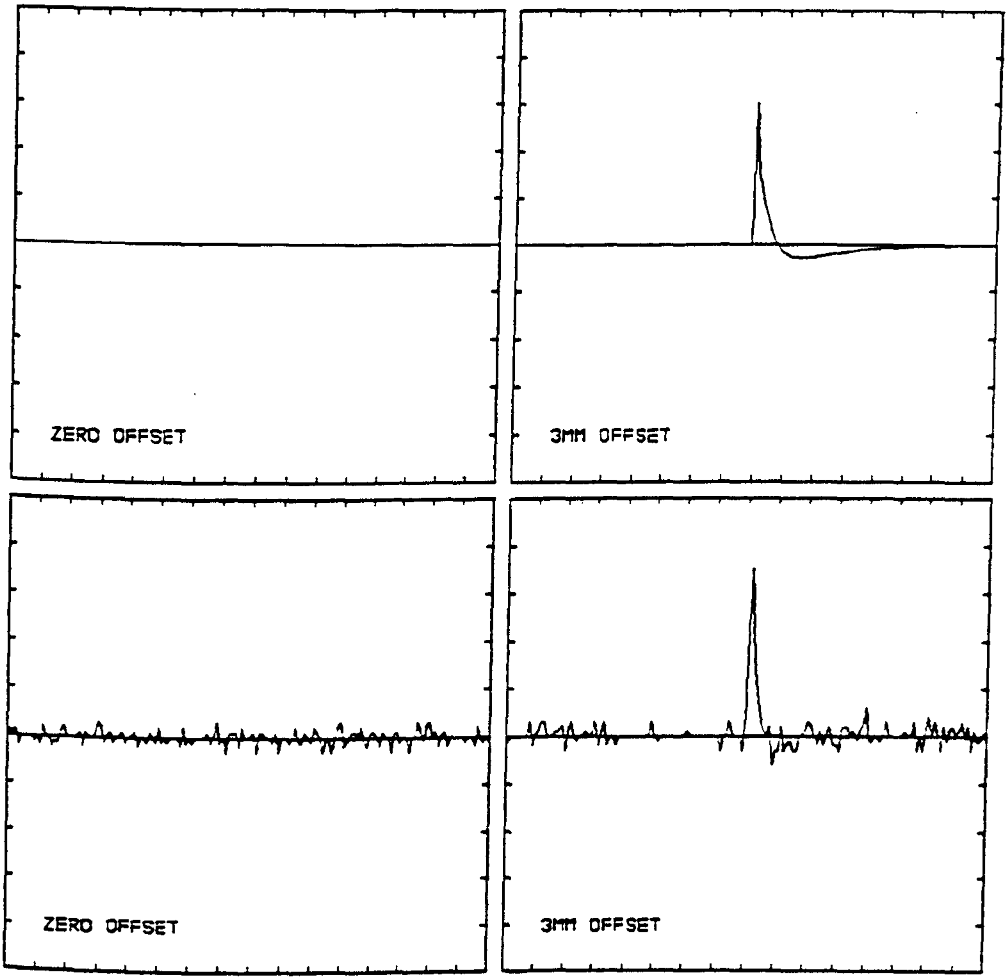


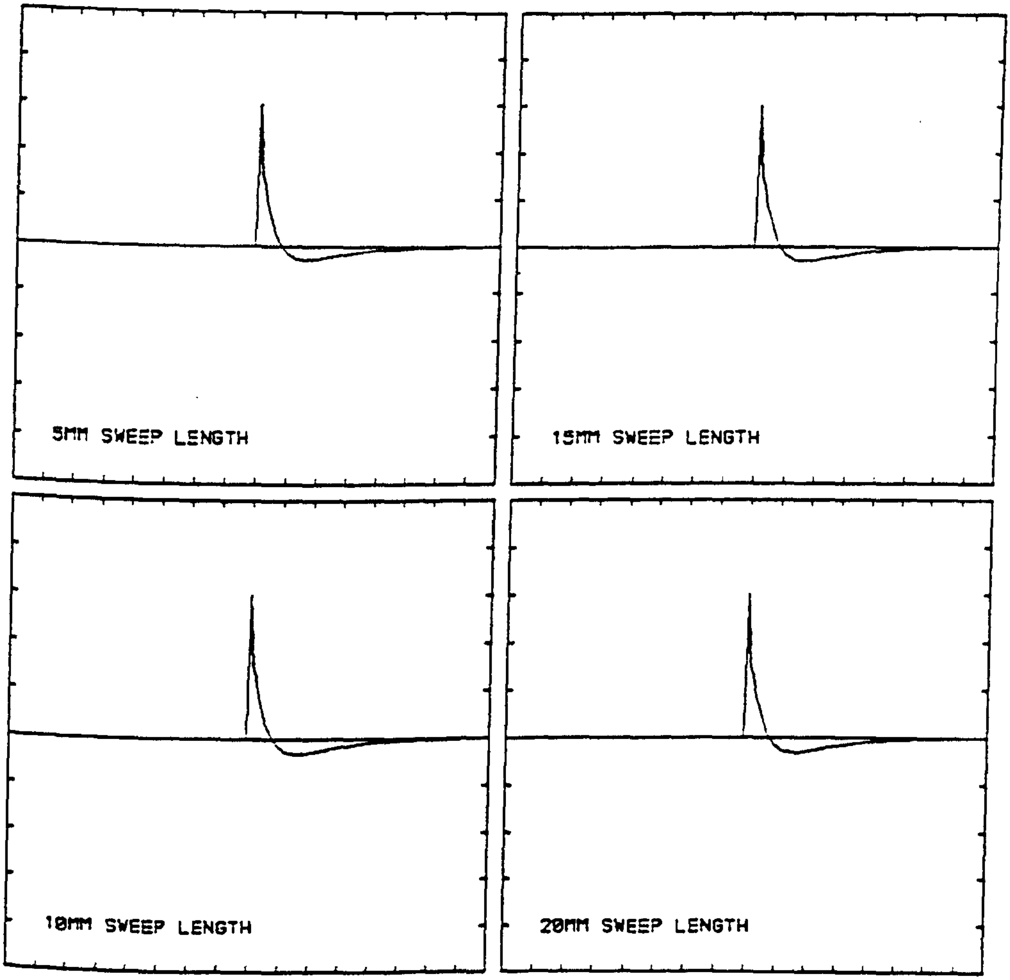
Fig.8.6 Tracking of an offset seam



Horizontal: Distance (0 to 160mm)

Vertical: Deviation value (-100 to +100)

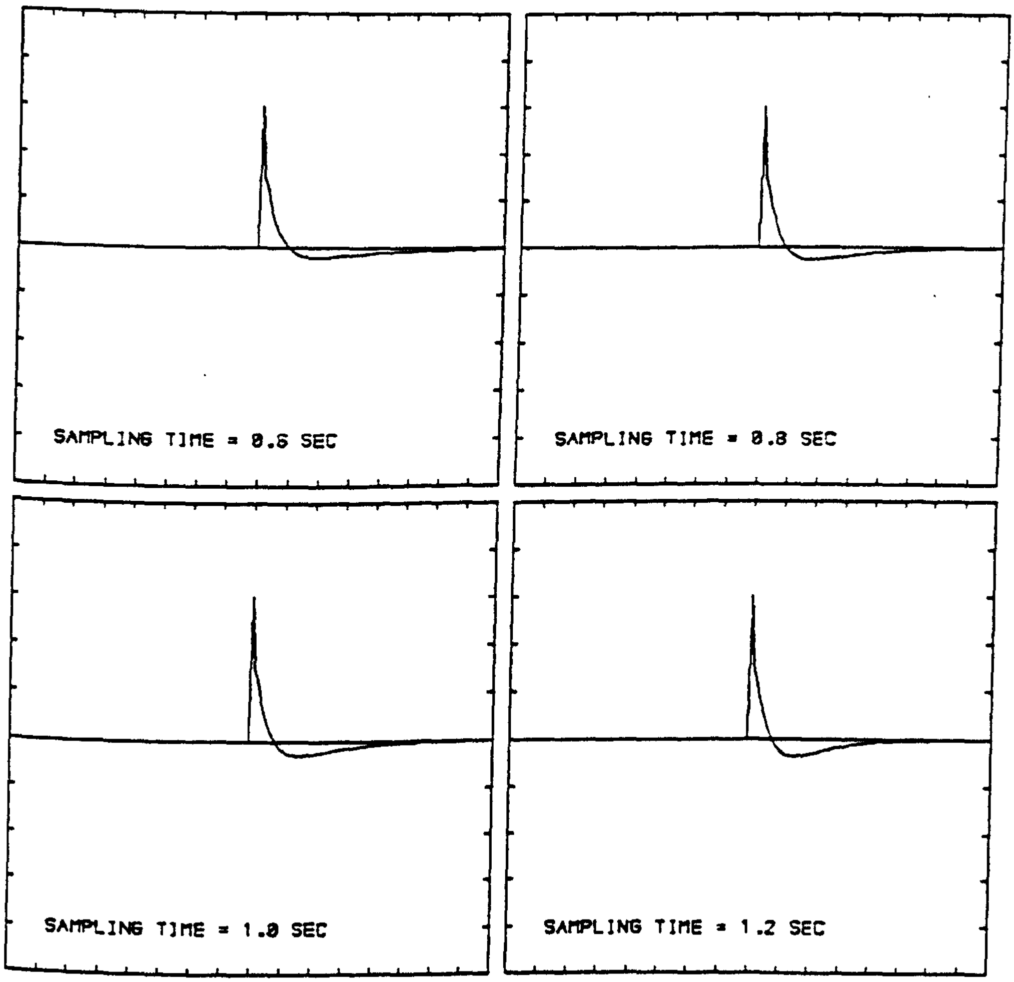
Fig.8.7 Comparisons between Computer Simulations and Experimental Results



Horizontal: Distance (0 to 160mm)

Vertical: Deviation value (-100 to +100)

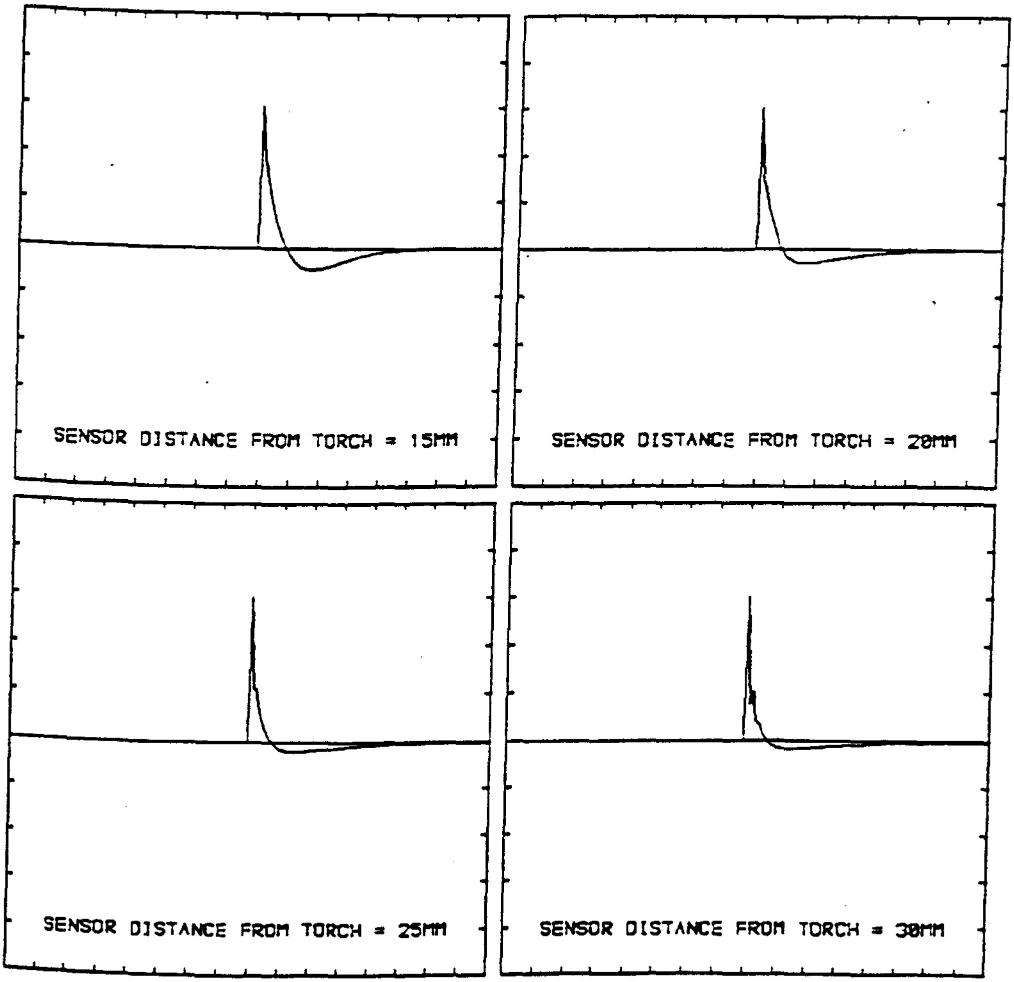
Fig.8.8 Effects of Sweep Length Variations



Horizontal: Distance (0 to 160mm)

Vertical: Deviation value (-100 to +100)

Fig.8.9 Effects of Sweep Rate Variations



Horizontal: Distance (0 to 160mm)

Vertical: Deviation value (-100 to +100)

Fig.8.10 Variations of Sensor Distance in front of the Torch

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

This research project has demonstrated the feasibility of automating TIG welding of aluminium under the high frequency (h.f.) electric transient interference conditions. In addition, for effective control in TIG welding it is necessary not only to carry out welding using robot and microcomputer techniques, but also to implement feedback control in use with sensors in order to ensure high precision and hence high quality welds.

A linear welding system was developed to investigate the feasibility of using microcomputers in controlling the TIG welding process. The welding system was first used for d.c. welding of stainless steel to test its capabilities without having h.f. transient interference. It was then converted to carry out a.c. welding of aluminium under h.f. transient interference conditions.

Interference suppressions was the major concern in automating aluminium welding. The objective was to suppress the source of interference, to eliminate interference coupling, and to reduce interference at equipment. The techniques used include filtering, isolation, shielding and grounding. The prototype which is operative showed merit of system design and construction.

In automated welding using the TIG process, high quality, high integrity welding of a joint seam requires precise seam tracking. This led to the investigation of sensors for robot guidance. Many commercially available seam trackers are vision-based systems which can achieve the required tracking performance for both speed and reliability. However, vision-based systems are normally very expensive. As one of the major considerations for system design was to minimise the cost, two low cost seam tracking systems were developed, namely the infra-red and ultrasonic.

Tests using the infra-red seam tracker demonstrated its capability performing seam tracking. Although the seam tracker may be affected by high speed operations, it is generally acceptable as normal welding speeds are relatively slow in comparison with the speed limit of the system. The infra-red seam tracker provided a solution to the problem of low cost precision welding.

A different approach to seam tracker design using ultrasonic techniques produced an alternative low cost sensor. The ultrasonic and infra-red seam trackers have the advantages common to most of the electronic sensors such as real time control and contactless operation. In comparison with the infra-red seam tracker, the ultrasonic seam tracker produces better defined sensed patterns and is less dependant on the surface cleanliness of the workpiece.

Both seam trackers were tested in conjunction with the TIM-3 cartesian robot. The TIM-3 robot has the rigidity and accuracy required for TIG welding operations. Computer simulations of robot position and sensor behaviour with respect to the variations of seam path showed evidence that the results obtained from experiments were correct.

The methods and techniques presented show considerable potential in automating the TIG welding process (d.c. or a.c) and performing seam tracking with closed loop control, at a low cost.

9.2 RECOMMENDATIONS FOR FUTURE WORK

In the automation of welding processes some further aspects need to be considered :

1) The TIM-3 robot used is a three-axis machine suitable for TIG welding. The robot has the capability to follow general weld joint paths, to store a wide range of welding parameters, and by monitoring the performance of the system, to take corrective actions. However, when more complex joint paths are involved, the robot requires more degrees of freedom to manipulate the torch or the workpiece to perform the required tasks. In recent research at Liverpool University a more advanced welding machine has been developed. It is known as the TIM-5 robot which contains the basic X-Y-Z axes as described for the TIM-3 machine, plus a wrist action. As the wrist action is an integral part of the welding operation, this system provides a further two degrees of freedom. In addition, a rotary table may also be attached to the TIM-5 robot to hold the workpiece and provide additional degrees of freedom. Alternatively, commercially available industrial robots may be used such as the PUMA 260/560/760 series robots manufactured by Unimation Inc. [42]. All these robots have the required rigidity and abilities to follow complex joint paths.

2) In the automation of aluminium welding the major problem encountered was the h.f. transient interference, which was caused by superimposing the welding current and the high frequency signals from the spark generator. Although applying interference suppression methods is one solution to the problem, it is generally considered to be expensive to achieve effective screening, especially when a large system such as a welding cell is concerned. One way to deal with this problem is to eliminate the source of interference by using other types of welding supply which provides the

same performance but without using the spark generator. This may be achieved by converting the welding current from mains frequency into a fixed higher frequency of 1 to 10KHz, for example, since the arc will stay on if the welding current having a frequency of greater than 500Hz [43]. In this way, high frequency transients can be greatly reduced and system screening will become easier and less expensive. Obviously, this requires more investigation in future research work.

3) Both the infra-red and ultrasonic sensor systems can be modified to extend their applications from seam tracking to surface detection. For example, they can be used for detecting whether there is any missed welds or missed fillers by scanning the sensor across the finished weld line. Another area where the sensor systems can be used is guidance for polishing finished welds. The only alteration required is a modification of the software.

4) In terms of low cost, a new technique may be used for circuit designs in future work. This technique involves the design philosophy of Algorithmic State machines (ASM's) and some Erasable Programmable Logic Devices (EPLD's).

The concept of ASM is to apply a software approach to perform hardware digital circuit designs [44]. The technique has the advantage of providing synchronous operation as it uses processing states, which are generated by the same clock. This makes designs easier and safer when circuit timings are important.

EPLD's were produced by a combination of CMOS and EPROM erasable cell technologies [45]. These devices provide a convenient, low cost means of integrating many TTL and CMOS SSI/MSI logic gates into a small number of packages. EPLD's are one of many families of the user-defined Application-Specific Integrated Circuit (ASIC). Using EPLD's the benefits are:

(a) low design cost.

(b) ease of design changes.

(c) multiple programming, if necessary.

(d) low power dissipation.

(e) high density products that maximise function, integration, and quality.

(f) maximum flexibility in each chip that comes from programmable architecture, and the ability to erase and reprogram.

Applying the ASM method in conjunction with EPLD's, circuit designs will become more flexible and cost effective.

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APPENDIX I

(Program listing for Chapter 2)

```
10  REM *************************************************************
20  REM *                                                           *
30  REM *  ---- PROGRAM FOR THE D.C WELDING CONTROL UNIT ----       *
40  REM *                                                           *
50  REM *     This program controls the POLYPACK welding            *
60  REM *  machine and the linear traverse. It provides four        *
70  REM *  options for the experimental and also synchronises       *
80  REM *  the X-Y recorder for data recording such as sensor       *
90  REM *  signals.                                                 *
100 REM *                                                           *
110 REM *************************************************************
120
130 REM Reset speed.
130 s=0
140 PROCspeed
150 ?&FC00=0
160 REM Display title page,
170 CLS
180 PRINTTAB(1,6);
    "TYPES OF CURRENT PULSING FOR THE DC WELDING EXPERIMENT"
190 PRINTTAB(3,11); "1. CONSTANT CURRENT PULSING"
200 PRINTTAB(3,12); "2. SELECT CURRENT PULSING"
210 PRINTTAB(3,13); "3. INCREASE CURRENT PULSING"
220 PRINTTAB(3,14); "4. INC.AND DEC.CURRENT PULSING"
230 PRINT TAB(0,20);CHR$(136);CHR$(157);CHR$(132)
240 INPUT TAB(5,20);"PLEASE ENTER SELECTION(1-4)";N
250 IF N<1 OR N>4 THEN 370
260 PROCtitle
270 REM Main program entries.
280 INPUT TAB(3,6); "Pulse on time in sec";tp
290 INPUT TAB(3,7); "Pulse off time in sec";tb
300 INPUT TAB(3,8); "Background current in amp";ib
310 IF N=1 THEN 350
320 IF N=2 THEN 360
330 IF N=3 THEN 370
340 IF N=4 THEN 380
350 PROCconstant
355 RUN
360 PROCselect
365 RUN
370 PROCincrease
375 RUN
380 PROCreturn
385 RUN
390
400 REM Subroutine for title characters.
410 DEF PROCtitle
420 CLS
430 PRINT CHR$(141);CHR$(157);CHR$(129);SPC(7);"WELDING CONTROL UNIT"
440 PRINT CHR$(141);CHR$(157);CHR$(129);SPC(7);"WELDING CONTROL UNIT"
450 PRINT TAB(3,4); "WELDING PARAMETERS:";
          TAB(3,5);"------------------";
          TAB(3,15);"WORK MOVEMENT:";
          TAB(3,16);"-------------"
460 ENDPROC
```

```
470
480 REM Subroutine for display.
490 DEF PROCdisplay
500 PROCtitle
510 PRINT TAB(3,6);"Pulse on time............";tp"sec";
          TAB(3,7);"Pulse off time...........";tb"sec";
          TAB(3,8);"Background current.......";ib"amp"
520 ENDPROC
530
540 REM Subroutine for constant pulse current.
550 DEF PROCconstant
560 INPUT TAB(3,9);"Constant pulse current in amp";ic
570 PROCdisplay
580 PRINTTAB(3, 9);"Constant pulse current...";ic"amp"
590 PROCtraverse
600 PROCstart
605 i=ic
610 REPEAT
620 PROCpulsing
630 PRINTTAB(3,22);"PRESS RETURN TO START AGAIN"
640 UNTIL INKEY(20)=13
650 ENDPROC
660
670 REM Subroutine for 2 different levels of pulse current.
680 DEF PROCselect
690 INPUT TAB(3,9);"Pulse current level 1 in amp",i1
700 INPUT TAB(3,10);"Pulse current level 2 in amp",i2
710 PROCdisplay
720 PRINT TAB(3,9); "Pulse current level 1....";i1"amp";
730       TAB(3,10);"Pulse current level 2....";i2"amp"
740 PROCtraverse
750 PROCstart
760 a=0
770 REPEAT
780 IF a=0 THEN
       i=i1
    ELSE
       i=i2
790 PROCpulsing
800 IF i=i1 THEN
       a=1
    ELSE
       a=0
810 PRINT TAB(3,22);"PRESS RETURN TO START AGAIN"
820 UNTIL INKEY(20)=13
830 ENDPROC
840
850 REM Subroutine for ramped current pulsing
860 DEF PROCincrease
870 INPUT TAB(3,9);"Step pulse current in amp",l
880 INPUT TAB(3,10);"Maximum pulse current in amp",im
890 PROCdisplay
900 PRINT TAB(3,9); "Step pulse current.......";l"amp";
          TAB(3,10);"Maximum pulse current....";im"amp"
910 PROCtraverse
```

```
 920  PRINT TAB(0,21);SPC(50);TAB(0,22);SPC(50)
 930  PROCstart
 940  i=ib
 950  IF i<=im THEN 970
      ELSE i=im
 960  PRINT TAB(3,21);"PRESS Y TO REPEAT";
             TAB(3,22);"PRESS RETURN TO START AGAIN"
 970  PROCpulsing
 980  i=i+1
 990  IF INKEY$(10)="Y" THEN 920
1000  IF INKEY(10)<>13 THEN 950
         ELSE ENDPROC
1010
1020  REM Subroutine for inc. and dec. currnet pulsing.
1030  DEF PROCreturn
1040  INPUT TAB(3,9);"Step pulse current in amp",l
1045  INPUT TAB(3,10);"Maximum pulse current in amp",im
1050  PROCdisplay
1060  PRINT TAB(3,9); "Step pulse current.......";l"amp";
             TAB(3,10);"Maximum pulse current....";im"amp"
1070  PROCtraverse
1080  PRINT TAB(0,21);SPC(50);TAB(0,22);SPC(50)
1090  PROCstart
1100  c=1
1110  i=ib
1120  IF i>im THEN
         i=im
1130  PROCpulsing
1140  IF i<im AND c<3 THEN
         i=i+1
      ELSE 1160
1150  GOTO 1120
1160  c=c+1
1170  IF c>3 THEN i=i-1
1180  IF c>3 AND i<ib THEN 1190
      ELSE 1120
1190  PRINT TAB(3,21);"PRESS Y TO REPEAT";
             TAB(3,22);"PRESS RETURN TO START AGAIN"
1200  IF INKEY$(20)="Y" THEN 1080
1210  IF INKEY(20)<>13 THEN 1200
1220  ENDPROC
1230
1240  REM Subroutine for starting welding operattion.
1250  DEF PROCstart
1260  x=ib*255/50
1270  ?&FC00=x
1280  PRINT TAB(3,12);"Operating current........";x*50/255 "amp";
             TAB(2,22);CHR$(136);"PRESS G WHEN THE RECORDER IS READY"
1290  IF GET$="G" THEN
      PRINT TAB(0,22);SPC(50)
      ELSE 1260
1300  ENDPROC
1310
1320  REM Subroutine for current pulsing.
1330  DEF PROCpulsing
```

```
1340  d=d
1350  PROCdirection
1360  t=tb*100
1370  IF s=0 THEN 1400
1380  s=0
1390  PROCspeed
1400  x=ib*255/50
1410  ?&FC00=x
1420  PRINTTAB(21,12);"....";x*50/255"amp";SPC(8)
1430  TIME=0
1440  REPEAT
1450  UNTIL TIME=t-200
1460  s=2
1470  PROCspeed
1480  TIME=0
1490  REPEAT
1500  UNTIL TIME=50
1510  s=0
1520  PROCspeed
1530  TIME=0
1540  REPEAT
1550  UNTIL TIME=100
1560  IF d=1 THEN
         d=0
      ELSE
         d=1
1570  PROCdirection
1580  s=2
1590  PROCspeed
1600  TIME=0
1610  REPEAT
1620  UNTIL TIME=80
1630  s=0
1640  PROCspeed
1650  TIME=0
1660  REPEAT
1670  UNTIL TIME=100
1680  s=2
1690  d=d
1700  PROCdirection
1710  PROCspeed
1720  TIME=0
1730  REPEAT
1740  UNTIL TIME=30
1750  s=0
1760  PROCspeed
1770  TIME=0
1780  REPEAT
1790  UNTIL TIME=100
1800  s=s
1810  PROCspeed
1820  PROCrecorder
1830  x=i*255/50
1840  ?&FC00=x
1850  PRINT TAB(21,12);"....";x*50/255"amp";SPC(8)
```

```
1860  TIME=0
1870  REPEAT
1880  UNTIL TIME=tp*100
1890  ENDPROC
1900
1910  REM Subroutine for traverse control.
1920  DEF PROCtraverse
1930  INPUT TAB(3,17);"Traverse speed in mm/sec";s
1940  INPUT TAB(3,18);"Direction (L /R)";d$
1950  IF d$="L" THEN
         d$="Left"
      ELSE
      IF d$="R" THEN
         d$="Right"
      ELSE 1930
1960  PRINT TAB(3,17);"Traverse speed...........";s"mm/sec";
            TAB(3,18);"Direction................";d$
1970  IF d$="Left" THEN
          d=0
      ELSE
          d=1
1980  IF s=0 THEN 2000
1990  s=15.4/s
2000  ENDPROC
2010
2020  REM Subroutine for traverse speed setting.
2030  DEF PROCspeed
2040  ?&FE6B=&C0
2050  ?&FE64=s
2060  ?&FE65=s
2070  ENDPROC
2080
2090  REM Subroutine for traverse direction setting.
2100  DEF PROCdirection
2110  ?&FE62=&FF
2120  ?&FE60=d
2130  ENDPROC
2140
2150  REM Subroutine for switching on the X-Y recorder.
2160  DEF PROCrecorder
2170  ?&FE62=&FF
2180  IF d=1 THEN
         r=3
      ELSE
         r=2
2190  ?&FE60=r
2200  ENDPROC
```

APPENDIX II

(Program listing for Chapter 4)

```
10  REM ************************************************************
20  REM *                                                          *
30  REM * ---- PROGRAM FOR THE AC WELDING CONTROL UNIT ---- *
40  REM *                                                          *
50  REM *    This program is written for the control of the *
60  REM * AC welding system. Once the system starts opera-  *
70  REM * tion, the program searches for the arc ignition   *
80  REM * signal and then controls the movements of the     *
90  REM * linear traverse in ramped speeds.                 *
100 REM *                                                          *
110 REM ************************************************************
120
130 REM Main program
140 REM switch to text mode.
145 MODE7
150 REM initialisation.
155 ?&FE62=&FB
160 REM reset.
165 ?&FE60=&83
170 REM control workpiece movements.
175 PROCtraverse
180 REM switch welding power supply.
185 PROCpsu
190 REM repeat.
195 RUN
200
210
220 REM Subroutine for title display.
230 DEF PROCtitle
240 CLS
250 PRINT'
260 PRINT CHR$(141);CHR$(157);CHR$(129);SPC(7);
          "AC WELDING CONTROL UNIT "
270 PRINT CHR$(141);CHR$(157);CHR$(129);SPC(7);
          "AC WELDING CONTROL UNIT "
280 PRINT TAB(3,6);"WORK MOVEMENT:";
          TAB(3,7);"_____________";
          TAB(3,12);"WELDING PARAMETER:";
          TAB(3,13);"_________________"
290 ENDPROC
300
310 REM Subroutine for traverse control.
320 DEF PROCtraverse
330 CLS
340 PROCtitle
350 INPUT TAB(3,8);"Traverse speed in mm/sec";s
360 IF s>0 THEN
       INPUT TAB(3,9);"Direction(L/R)";d$
    ELSE
       d$="L"
370 IF d$="L" THEN
       d$="Left"
    ELSE
       IF d$="R" THEN
          d$="Right"
```

```
        ELSE 330
380  PRINT TAB(3,8);"Traverse speed(0-7mm/sec)...";s"mm/sec"
390  IF s>0 THEN
        PRINT TAB(3,9);"Direction...................";d$
     ELSE
        PRINT TAB(3,9);"Direction...................Statinary"
400  IF d$="Left" THEN
        D=1
     ELSE
        D=0
410  IF s=0 THEN
        INPUT TAB(3,14);"Welding time in sec";t;SPC(5)
     ELSE 440
420  PRINT TAB(3,14);"Welding time................";t"sec"
430  S=s
440  IF s>0 THEN
        S=15.4/s
     ELSE 470
450  INPUT TAB(3,14);"Welding length in mm";l
460  PRINT TAB(3,14);"Welding length..............";l"mm"
470  ENDPROC
480
490  REM Subroutine for welding power switching.
500  DEF PROCpsu
510  IF D=1 THEN
        A=&83
     ELSE
        A=&82
520  IF s=0 THEN
        T=t*100
     ELSE
        T=l/s*100 DIV 1
530  PRINT TAB(3,18);"PRESS SPC TO SWITCH ON"
540  IF GET=&20 THEN
        ?&FE60=D
     ELSE 530
550  PRINT TAB(3,18);"WAITING......";SPC(12)
560  count=0
570  x=?&FE60 AND &04
580  IF x=0 THEN
        count=count+1
     ELSE 560
590  IF count=160 THEN
        PRINT TAB(3,18);"WELDING IN PROGRESS";SPC(30)
     ELSE 570
600  IF s=0 THEN
        ?&FE6B=&40
     ELSE
        ?&FE6B=&C0
610  set=TIME
620  REPEAT
630   REM time for
635   ?&FE64=S
640S  REM speed setting.
645   ?&FE65=S
```

```
650  S=S/1.001
660  REM set delay.
665  FOR y=1 TO 200
670  NEXT y
680 UNTIL TIME>=set+T
690 ?&FE60=A
700 ?&FE6B=&40
710 PRINT TAB(3,18);"JOB COMPLETED";SPC(23);
          TAB(3,19);"PRESS SPC TO START AGAIN"
720 IF GET=&20 THEN 730
    ELSE 710
730 ENDPROC
```

APPENDIX III

(Program listing for Chapter 6)

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```
0000             ".......*..............*...................."
0000             TAB 12
0000             WIDTH 82
0000             PROC '8085'
0000             TITLE 'The infra-red main processor'
0000
0000
0000             ;*******************************************
0000             ;*    This program deals with the capturing   *
0000             ;* of data and the conversion of analogue to *
0000             ;* digital signals. It also determines the   *
0000             ;* centre of the seam by analysing the sensed *
0000             ;* pattern and hence commands the robot to    *
0000             ;* correct seam offsets.                       *
0000             ;*******************************************
0000
0000
0000             ;Mados operating system calls
0000
0000    (0000)   reset                  equ 0
0000    (0001)   crlf                   equ 1
0000    (0002)   error                  equ 2
0000    (0003)   interf                 equ 3
0000    (0004)   rd_chr                 equ 4
0000    (0005)   wt_chr                 equ 5
0000    (0006)   message                equ 6
0000
0000
0000             ;operating system equates
0000
0000    (0001)   err_tp                 equ &01
0000    (0002)   set_ip                 equ &02
0000    (0003)   set_op                 equ &03
0000    (000A)   set_pt                 equ &0a
0000    (000B)   set_ex                 equ &0b
0000    (000C)   set_hd                 equ &0c
0000    (0011)   en_rst65               equ &11
0000    (0014)   dis_rst65              equ &14
0000    (001D)   pnt_nmer               equ &1d
0000    (001C)   pnt_hx                 equ &1c
0000    (001F)   pnt_sg                 equ &1f
0000    (0030)   in_uar                 equ &30
0000
0000
0000             ;stream equates
0000
0000    (0001)   com_stm                equ &01
0000    (0000)   dbg_stm                equ &00
0000
0000
0000             ;hardware equates
0000
0000    (0021)   port_a                 equ &21
```

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```
0000      (0022)      port_b                     equ &22
0000      (0023)      port_c                     equ &23
0000      (3001)      uar_ad                     equ &3001
0000
0000
0000                  ;step board equates
0000
0000      (0001)      find_sync                  equ 1
0000      (0002)      on_sync                    equ 2
0000      (0003)      sta_spl                    equ 3
0000      (0004)      stp_spl                    equ 4
0000      (0005)      take_data                  equ 5
0000      (0006)      debug                      equ 6
0000
0000
0000                  ;controller equates
0000
0000      (0002)      sta_sg                     equ 2
0000      (0003)      stp_sg                     equ 3
0000      (0004)      dbg_rq                     equ 4
0000      (0005)      rst_sg                     equ 5
0000      (0006)      min_width                  equ 6
0000
0000
0000                  ;memory workspace
0000
0000      (5100)      mem_base                   equ &5100
0000      (5200)      table                      equ &5200
0000      (5300)      tabmin                     equ &5300
0000      (5400)      array                      equ &5400
0000      (5500)      breadth                    equ &5500
0000      (5600)      array_pos                  equ &5600
0000
0000
5100                          org mem_base
5100
5100                  ;define workin  space
5100
5100 0000             rou_etr:                   ds 2
5102 0000             stk_pr:                    ds 2
5104 0000             stp_stk:                   ds 2
5106
5106                  ;centre calculation workspace
5106
5106 00               end_va:                    ds 1
5107 00               ref:                       ds 1
5108 0000             tot_ct:                    ds 2
510A 0000             thresh:                    ds 2
510C 00               trans:                     ds 1
510D 00               pairs:                     ds 1
510E 00               index:                     ds 1
510F 00               min_err:                   ds 1
5110 00               cen_va:                    ds 1
```

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```
5111 00           ref_ce:                  ds 1
5112 00           the_err:                 ds 1
5113
6000                      org &6000
6000
6000              ;******--- MADOS ROM HEADER ---******
6000
6000 28432957000A         db '(C)W',0,10,13
6007 41646320426F         db 'Adc Board V1.0',0   ;title.
6016 C9                   ret
6017
6020                      org &6020
6020
6020              ;********--- PROGRAM ENTRY ---********
6020
6020 214560               lxi h,beg         ;program entry
6023 CD2960               call set_er       ;set return from error
6026 C34560               jmp beg           ;as beg
6029
6029 220051       set_er: shld rtn_et       ;set routine for error
602C 213D60               lxi h,fai_rn      ;vector exit
602F 3E01                 mvi a,err_tp      ;which errors to trap
6031 DF                   rst interf        ;error exit vector
6032 0C                   db set_hd
6033 210000               lxi h,0
6036 39                   dad sp
6037 23                   inx h
6038 23                   inx h             ;sort out stack ptr
6039 220251               shld stk_pr       ;clean up
603C C9                   ret
603D
603D 2A0251       fai_rn: lhld stk_pr       ;gets here on an error
6040 F9                   sphl
6041 2A0051               lhld rtn_et       ;after error vectors
6044 E9                   pchl
6045
6045              ;*******-- INITIALISE SYSTEM --*******
6045              ; Set up input/output ports, counters,
6045              ;indirection vectors and flags etc.
6045              ;*************************************
6045
6045 3E42         beg:    mvi a,&42         ;set port B as output
6047 DF                   rst interf        ;and A as input
6048 0A                   db set_pt
6049 3EFF                 mvi a,&ff         ;reset output port
604B D322                 out port_b
604D 3E01                 mvi a,com_stm
604F DF                   rst interf
6050 02                   db set_ip
6051 C35460               jmp sta_sy
6054
6054              ;************-- START SYSTEM --************
6054              ; This routine sends a reset signal to the
```

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```
6054                   ; stepping motor drive board before the
6054                   ; commands from the robot controller can be
6054                   ; identified.
6054                   ;*********************************************
6054
6054 F7                sta_sy: rst message
6055 0A0D57616974             db 10,13,'Waiting...',0
6062 3E04                     mvi a,stp_spl    ;send signal
6064 CD7C60                   call wrt_sb      ;to second processor.
6067 E7                       rst rd_chr       ;read input
6068 FE02                     cpi sta_sg       ;port and
606A CA8E60                   jz sta_pg        ;identify
606D FE04                     cpi dbg_rq       ;command.
606F C25460                   jnz sta_sy
6072
6072
6072 3E06                     mvi a,debug
6074 CD7C60                   call wrt_sb
6077 3E00                     mvi a,dbg_stm    ;here do debug
6079 DF                       rst interf
607A 02                       db set_ip
607B C9                       ret              ;return to debug
607C
607C                   ;****-- WRITE TO THE SECOND PROCESSOR --****
607C                   ; This routine sends a command to the second
607C                   ; processor through prot B.
607C                   ;*********************************************
607C
607C E67F              wrt_sb: ani &7f          ;mask msb
607E D322                     out port_b       ;take strobe low
6080 DB23              wai_hg: in port_c        ;read strobe
6082 E608                     ani &08          ;on pc3
6084 CA8060                   jz wai_hg        ;wait
6087 DB22                     in port_b        ;read output data
6089 F680                     ori &80          ;take strobe high
608B D322                     out port_b
608D C9                       ret              ;and return
608E
608E                   ;********-- MAIN PROGRAM --********
608E
608E 3E01              sta_pg: mvi a,find_sync  ;send sign
6090 CD7C60                   call wrt_sb      ;second processor.
6093 F7                       rst message      ;message for
6094 0A0D66696E64             db 10,13,'find sync',0
60A0 3E03                     mvi a,sta_spl    ;indicate start
60A2 CD7C60                   call wrt_sb      ;sampling.
60A5 F7                       rst message
60A6 0A0D73746172             db 10,13,'start sampling',0
60B7 3E80                     mvi a,&80        ;take 128 as the
60B9 320651                   sta end_va       ;initial reference.
60BC 3E42                     mvi a,&42        ;switch off
60BE D320                     out &20          ;timer.
60C0 CD2161                   call chg_di      ;generate two sweeps
```

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```
60C3 CD2161                call chg_di     ;for initialisation.
60C6 CD4A61                call sample     ;start sampling.
60C9 CD9361                call fin_cn     ;determine centre.
60CC 3A1051                lda cen_va
60CF 321151                sta ref_ce
60D2
60D2 3A0130      rpt_lp:   lda uar_ad      ;check for
60D5 E602                  ani &02         ;from the robot
60D7 CAE560                jz no_inp       ;controller.
60DA E7                    rst rd_chr      ;if it is a
60DB FE03                  cpi stp_sg      ;stop or a reset
60DD CA5460                jz sta_sy       ;command, return
60E0 FE05                  cpi rst_sg      ;to the initial
60E2 CA5460                jz sta_sy       ;stage.
60E5
60E5 CD2161      no_inp:   call chg_di     ;if not,
60E8 CD4A61                call sample     ;start
60EB CD9361                call fin_cn     ;operation.
60EE 3A1051                lda cen_va      ;current
60F1 47                    mov b,a         ;centre value.
60F2 3A1151                lda ref_ce      ;previous
60F5 90                    sub b           ;centre value.
60F6 2F                    cma             ;compare the
60F7 3C                    inr a           ;two values and
60F8 321251                sta the_err     ;deduce an error.
60FB CD0964                call pnt_nm     ;print.
60FE CD0761                call commu      ;commu with
6101 CA5460                jz sta_sy       ;robot controller.
6104 C3D260                jmp rpt_lp      ;repeat.
6107
6107             ;******-- COMMUNICATIONS --******
6107             ; This routine communicates with
6107             ; the robot controller.
6107             ;**********************************
6107
6107 3A1251      commu:    lda the_err     ;send erro
610A CD1461                call wrt_rb     ;robot controller.
610D E7                    rst rd_chr      ;check for
610E FE03                  cpi stp_sg      ;commands
6110 C8                    rz              ;from the
6111 FE05                  cpi rst_sg      ;robot controller.
6113 C9                    ret
6114
6114             ;******-- WRITE TO ROBOT --******
6114             ; This routine writes commands to
6114             ; the robot controller.
6114             ;**********************************
6114
6114 F5          wrt_rb:   push psw
6115
6115 3A0130      rd_agn:   lda uar_ad
6118 0F                    rrc
6119 D21561                jnc rd_agn
```

```
611C F1                      pop psw
611D 320030                  sta uar_ad-1
6120 C9                      ret
6121
6121          ;*******-- DIRECTION --*******
6121          ; This routine waits for the
6121          ; direction to change from a
6121          ; high to a low before passing
6121          ; control to the next section
6121          ; of codes.
6121          ;******************************
6121
6121 DB23     chg_di:  in port_c          ;read port c.
6123 E601              ani &01            ;LSB is direction.
6125 CA2161            jz chg_di          ;repeat till high.
6128 0E10              mvi c,&10
612A DB23     not_dn:  in port_c          ;read again
612C E601              ani &01            ;to avoid
612E CA2161            jz chg_di          ;hardware
6131 0D                dcr c              ;glitches.
6132 C22A61            jnz not_dn
6135
6135
6135
6135 DB23     wat_lw:  in port_c          ;read port c
6137 E601              ani &01            ;untill low.
6139 C23561            jnz wat_lw
613C 0E10              mvi c,&10
613E DB23     ndn_ag:  in port_c          ;repeat
6140 E601              ani &01            ;to ensure
6142 C23561            jnz wat_lw         ;positive
6145 0D                dcr c              ;reading.
6146 C23E61            jnz ndn_ag
6149 C9                ret
614A
614A          ;******-- DATA SAMPLING --******
614A          ; This routine performs data
614A          ; sampling by waiting for a low
614A          ; high low pulse on the EOC.
614A          ;*********************************
614A
614A 210052   sample:  lxi h,table        ;data base.
614D 0E00              mvi c,00           ;counter numb=256.
614F CD5E61   nxt_pn:  call get_da        ;capture data
6152 47                mov b,a            ;number of sample
6153 CD5E61            call get_da        ;capture data.
6156 80                add b              ;sum up number.
6157 77                mov m,a            ;store data.
6158 23                inx h              ;inc. addr.
6159 0D                dcr c              ;dec. counter.
615A C24F61            jnz nxt_pn
615D C9                ret
615E
```

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```
615E
615E DB21      get_da: in port_a
6160 E602              ani &02
6162 CA5E61            jz get_da        ;wait for high
6165 DB21              in port_a
6167 E602              ani &02
6169 CA5E61            jz get_da        ;wait for high
616C
616C DB21      not_lw: in port_a
616E E602              ani &02
6170 C26C61            jnz not_lw       ;wait for low
6173 DB21              in port_a
6175 E602              ani &02
6177 C26C61            jnz not_lw
617A
617A
617A DB21      not_hg: in port_a
617C E602              ani &02
617E CA7A61            jz not_hg        ;wait for high
6181 DB21              in port_a
6183 E602              ani &02
6185 CA7A61            jz not_hg        ;wait for high
6188
6188 DB21              in port_a
618A CD8E61            call div_4
618D C9                ret
618E
618E 1F        div_4:  rar              ;divide accumulator by
618F 1F                rar              ;four
6190 E63F              ani &3f
6192 C9                ret
6193
6193                   extend 'adc2'
6193           ".......*...............*....................."
6193
6193           ;********-- FIND CENTRE --*********
6193           ; This routine counts the number
6193           ; of data elements and transition
6193           ; points for the determination of
6193           ; the centre of the seam.
6193           ;*************************************
6193
6193 CDA061    fin_cn: call count       ;total number of data.
6196 CDB761            call fin_th      ;decide on threshold.
6199 CDD061            call fin_tn      ;finds the error.
619C 321051            sta cen_va       ;store cen
619F C9                ret
61A0
61A0           ;********-- DATA COUNTS --********
61A0           ; This routine sums up all data
61A0           ; and store as tot_ct for the
61A0           ; calculating the average level.
61A0           ,**********************************
```

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```
61A0
61A0 010052     count:  lxi b,table      ;point to data table
61A3 210000             lxi h,0          ;clear sum.
61A6 110000             lxi d,0          ;clr de for 16-bit add.
61A9 0A         nxt_in: ldax b           ;get first parameter.
61AA 5F                 mov e,a          ;move data to de.
61AB 19                 dad d            ;add the data.
61AC 03                 inx b            ;move to next byte.
61AD 79                 mov a,c          ;check for end table.
61AE FE00               cpi &00          ;&c0 points.
61B0 C2A961             jnz nxt_in       ;repeat.
61B3 220851             shld tot_ct      ;store the total.
61B6 C9                 ret
61B7
61B7            ;*********-- THRESHOLDING --********
61B7            ; This routine deduce the threshol
61B7            ; level from (total count / total
61B7            ; number) x 3.
61B7            ;***********************************
61B7
61B7 2A0851     fin_th: lhld tot_ct      ;get the total count.
61BA 44                 mov b,h          ;move to bc prior to
61BB 4D                 mov c,l          ;division by number
61BC 110001             lxi d,&100       ;of sample (256).
61BF CD3164             call dv          ;division (bc/de).
61C2 CD2664             call mul_3       ;multiplication (x3).
61C5 110400             lxi d,4          ;proportional to thres
61C8 CD3164             call dv          ;value returned
61CB 79                 mov a,c          ;in a and store
61CC 320A51             sta thresh       ;as thres. value.
61CF C9                 ret
61D0
61D0            ;*******-- TRANSITION POINTS --****
61D0            ; This routine finds the number of
61D0            ; transition points and hence to
61D0            ; determine the centre position of
61D0            ; a seam.
61D0            ;***********************************
61D0
61D0 210052     fin_tn: lxi h,table      ;data base
61D3 110054             lxi d,array      ;array address.
61D6 3A0A51             lda thresh       ;threshold level.
61D9 B7                 ora a
61DA 47                 mov b,a
61DB 0E00               mvi c,&00
61DD
61DD 7E         fin_hg: mov a,m          ;compare data with
61DE B8                 cmp b            ;threshold value.
61DF D2FB61             jnc high         ;if data > thres.,
61E2 23         arrnd:  inx h            ;jump to f
61E3 7D                 mov a,l          ;check for
61E4 FE00               cpi &00          ;last
61E6 CA1962             jz column        ;column.
```

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```
61E9 C3DD61             jmp fin_hg
61EC
61EC 7E        fin_lw:  mov a,m        ;if data < thres.,
61ED B8                 cmp b          ;jump to
61EE DA0A62             jc low         ;found-low.
61F1 23                 inx h          ;inc. column addr.
61F2 7D                 mov a,l        ;check for
61F3 FE00               cpi &00        ;last
61F5 CA1962             jz column      ;column.
61F8 C3EC61             jmp fin_lw
61FB
61FB EB        high:    xchg           ;store +ve
61FC 73                 mov m,e        ;transition
61FD EB                 xchg           ;locatio
61FE 23                 inx h          ;increament
61FF 13                 inx d          ;column address.
6200 7D                 mov a,l        ;check for
6201 FE00               cpi &00        ;last
6203 CA1962             jz column      ;column.
6206 0C                 inr c          ;inc. counter.
6207 C3EC61             jmp fin_lw     ;go for -ve trans.
620A
620A EB        low:     xchg           ;store -ve
620B 73                 mov m,e        ;transition
620C EB                 xchg           ;location
620D 23                 inx h          ;increament
620E 13                 inx d          ;column address.
620F 7D                 mov a,l        ;check for
6210 FE00               cpi &00        ;last
6212 CA1962             jz column      ;column.
6215 0C                 inr c          ;inc. counter.
6216 C3DD61             jmp fin_hg     ;go for next +ve trans
6219
6219
6219 79        column:  mov a,c
621A 0C                 inr c
621B 3EFF               mvi a,&ff
621D EB                 xchg
621E 77                 mov m,a
621F 79        was_hg:  mov a,c        ;store the number
6220 320C51             sta trans      ;of trans. points
6223 CD0964             call pnt_nm    ;and print.
6226
6226 3A0C51    chk_ct:  lda trans      ;if trans. < 4,
6229 FE04               cpi &04        ;assume glitches only
622B DAF563             jc no_sm       ;i.e. no seam.
622E FE06               cpi &06        ;if trans. < 6,
6230 DABF62             jc one_sm      ;assume one seam.
6233 FE08               cpi &08        ;if trans. < 8,
6235 DACB62             jc two_sm      ;assume two seams.
6238 FE0A               cpi &0a        ;if trans. < 10,
623A DA2F63             jc thr_sm      ;assume three seams.
623D C34062             jmp fwd_pr     ;if greater, find pair
```

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```
6240
6240                    extend 'adc3'
6240             ".......*...............*....................."
6240
6240 3A0C51      fwd_pr: lda trans         ;find out
6243 E601                ani &01           ;trans. is even
6245 C24C62              jnz is_odd        ;or odd.
6248 3A0C51              lda trans         ;if even,
624B 3C                  inr a             ;width_pairs=trans+1-2
624C 3D          is_odd: dcr a             ;if odd,
624D 3D                  dcr a             ;width_pairs=trans-2
624E 320D51              sta pairs         ;restore width_pairs
6251 4F                  mov c,a           ;as counter.
6252
6252 210054              lxi h,array       ;refer to trans arr
6255 110055              lxi d,breadth     ;locate breadth addr.
6258 46          repeat: mov b,m           ;load trans value.
6259 23                  inx h             ;load next
625A 7E                  mov a,m           ;trans value.
625B 90                  sub b             ;cal. breadth
625C EB                  xchg              ;and
625D 77                  mov m,a           ;store.
625E EB                  xchg              ;repeat
625F 13                  inx d             ;to find
6260 0D                  dcr c             ;the next one.
6261 C25862              jnz repeat
6264 C36762              jmp fin_mi
6267
6267 210055      fin_mi: lxi h,breadth     ;locate breadth addr.
626A 1E00                mvi e,&00         ;reset reg. e.
626C 3A0D51              lda pairs         ;use width pair
626F 4F                  mov c,a           ;as counter.
6270 3EFF                mvi a,&ff         ;max no for init value.
6272
6272 BE          rep_ag: cmp m             ;if m is g
6273 DA7862              jc try_nt         ;try next one.
6276 7E                  mov a,m           ;if smaller, swop.
6277 53                  mov d,e           ;record number.
6278
6278 1C          try_nt: inr e             ;repeat for
6279 23                  inx h             ;all counts
627A 0D                  dcr c             ;and a no. of min
627B C27262              jnz rep_ag        ;values is found.
627E C38162              jmp del_pr
6281
6281 3A0C51      del_pr: lda trans         ;delete a
6284 D602                sui &02           ;pair of
6286 320C51              sta trans         ;transition points.
6289 4F                  mov c,a           ;use new trans
628A 42                  mov b,d           ;number and the
628B 78                  mov a,b           ;number of mins.
628C 320E51              sta index         ;store in index.
628F 210054              lxi h,array       ;refer to
```

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```
6292 110054           lxi d,array     ;trans array.
6295 CDA762           call mov_pt     ;ponit to
6298 3A0E51           lda index       ;min location.
629B 47               mov b,a         ;rearrange
629C 79               mov a,c         ;transition
629D 90               sub b           ;array.
629E 23               inx h
629F 23               inx h
62A0 47               mov b,a
62A1 CDB162           call mov_bl
62A4 C32662           jmp chk_ct
62A7
62A7 78       mov_pt: mov a,b         ;number
62A8 B7               ora a           ;of
62A9 C8               rz              ;min.
62AA
62AA 23       next:   inx h           ;inc. array
62AB 13               inx d           ;address.
62AC 05               dcr b
62AD C2AA62           jnz next
62B0 C9               ret
62B1
62B1 78       mov_bl: mov a,b
62B2 B7               ora a
62B3 C8               rz
62B4
62B4 7E       nxt_mv: mov a,m         ;rearrange
62B5 EB               xchg            ;array.
62B6 77               mov m,a
62B7 EB               xchg
62B8 23               inx h
62B9 13               inx d
62BA 05               dcr b
62BB C2B462           jnz nxt_mv
62BE C9               ret
62BF
62BF 210054   one_sm: lxi h,array     ;seam position
62C2 23               inx h           ;=(t1+t2)/2.
62C3 7E               mov a,m
62C4 23               inx h
62C5 86               add m
62C6 1F               rar
62C7 C9               ret
62C8
62C8 2F       mke_po: cma
62C9 3C               inr a
62CA C9               ret
62CB
62CB 0E02     two_sm: mvi c,&02       ;set counter.
62CD CDC863           call do_wd      ;consider width
62D0 0E02             mvi c,&02       ;and consi
62D2 CDB363           call do_pos     ;positions.
62D5
```

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```
62D5 0E00                 mvi c,&00        ;reset cou
62D7 3EFF                 mvi a,&ff        ;set initial
62D9 320F51               sta min_err      ;min_err.
62DC 210055               lxi h,breadth    ;consider breadth
62DF 110056               lxi d,array_pos  ;and posit
62E2 7E                   mov a,m          ;if breadth is
62E3 FE06                 cpi min_width    ;smaller than min
62E5 DA0063               jc small1        ;width, jump
62E8 EB                   xchg             ;subroutine.
62E9 46                   mov b,m          ;check for
62EA EB                   xchg             ;the last
62EB 3A0651               lda end_va       ;value.
62EE 90                   sub b
62EF FCC862               cm mke_po
62F2 47                   mov b,a          ;compare
62F3 3A0F51               lda min_err      ;with min
62F6 B8                   cmp b            ;error.
62F7 DA0063               jc small1
62FA 78                   mov a,b          ;if smaller,
62FB 320F51               sta min_err      ;store new value.
62FE 0E01                 mvi c,1
6300
6300 23          small1:  inx h            ;first
6301 13                   inx d            ;consider
6302 7E                   mov a,m          ;width.
6303 FE06                 cpi min_width
6305 DA2063               jc small2
6308 EB                   xchg
6309 46                   mov b,m          ;second
630A EB                   xchg             ;consider
630B 3A0651               lda end_va       ;position.
630E 90                   sub b
630F FCC862               cm mke_po
6312 47                   mov b,a          ;last
6313 3A0F51               lda min_err      ;consider
6316 B8                   cmp b            ;error.
6317 DA2063               jc small2
631A 78                   mov a,b
631B 320F51               sta min_err
631E 0E02                 mvi c,2
6320
6320 79          small2:  mov a,c          ;consider
6321 B7                   ora a            ;the
6322 CADE63               jz too_sa        ;second
6325 210056               lxi h,array_pos  ;seam.
6328 7E          again1:  mov a,m
6329 0D                   dcr c
632A C8                   rz
632B 23                   inx h
632C C32863               jmp again1
632F
632F 0E03        thr_sm:  mvi c,&03        ;set count
6331 CDC863               call do_wd       ;for three
```

```
6334 0E03              mvi c,&03          ;seams the
6336 CDB363            call do_pos        ;do width,
6339
6339 0E00              mvi c,&00          ;position,
633B 3EFF              mvi a,&ff          ;and error.
633D 320F51            sta min_err
6340 210055            lxi h,breadth
6343 110056            lxi d,array_pos
6346 7E                mov a,m            ;compare with
6347 FE06              cpi min_width      ;min_width.
6349 DA6463            jc too_s1
634C EB                xchg
634D 46                mov b,m
634E EB                xchg
634F 3A0651            lda end_va         ;consider
6352 90                sub b              ;position.
6353 FCC862            cm mke_po
6356 47                mov b,a
6357 3A0F51            lda min_err        ;compare with
635A B8                cmp b              ;min_err.
635B DA6463            jc too_s1
635E 78                mov a,b
635F 320F51            sta min_err
6362 0E01              mvi c,1
6364
6364 23       too_s1:  inx h
6365 13                inx d
6366 7E                mov a,m            ;consider
6367 FE06              cpi min_width      ;width.
6369 DA8463            jc too_s2
636C EB                xchg
636D 46                mov b,m            ;get
636E EB                xchg               ;position.
636F 3A0651            lda end_va
6372 90                sub b
6373 FCC862            cm mke_po
6376 47                mov b,a
6377 3A0F51            lda min_err        ;compare with
637A B8                cmp b              ;min_err.
637B DA8463            jc too_s2
637E 78                mov a,b
637F 320F51            sta min_err
6382 0E02              mvi c,2
6384
6384 23       too_s2:  inx h
6385 13                inx d
6386 7E                mov a,m            ;compare with
6387 FE06              cpi min_width      ;min_width.
6389 DAA463            jc too_s3
638C EB                xchg
638D 46                mov b,m
638E EB                xchg
638F 3A0651            lda end_va         ;get
```

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```
6392 90                    sub b            ;position.
6393 FCC862                cm mke_po
6396 47                    mov b,a
6397 3A0F51                lda min_err      ;compare with
639A B8                    cmp b            ;min_err.
639B DAA463                jc too_s3
639E 78                    mov a,b
639F 320F51                sta min_err
63A2 0E03                  mvi c,3
63A4
63A4 79           too_s3:  mov a,c
63A5 B7                    ora a
63A6 CADE63                jz too_sa
63A9 210056                lxi h,array_pos  ;consider
63AC 7E           try_rp:  mov a,m          ;position.
63AD 0D                    dcr c
63AE C8                    rz
63AF 23                    inx h
63B0 C3AC63                jmp try_rp
63B3
63B3 210054       do_pos:  lxi h,array
63B6 110056                lxi d,array_pos
63B9 23                    inx h
63BA 7E           agn_nx:  mov a,m          ;rearrange
63BB 23                    inx h            ;position
63BC 86                    add m            ;array.
63BD 1F                    rar
63BE EB                    xchg
63BF 77                    mov m,a
63C0 EB                    xchg
63C1 23                    inx h
63C2 13                    inx d
63C3 0D                    dcr c
63C4 C2BA63                jnz agn_nx
63C7 C9                    ret
63C8
63C8 210054       do_wd:   lxi h,array
63CB 110055                lxi d,breadth
63CE 23                    inx h
63CF 46           nxt_tm:  mov b,m          ;rearrange
63D0 23                    inx h            ;breadth
63D1 7E                    mov a,m          ;array.
63D2 B7                    ora a
63D3 90                    sub b
63D4 EB                    xchg
63D5 77                    mov m,a
63D6 EB                    xchg
63D7 23                    inx h
63D8 13                    inx d
63D9 0D                    dcr c
63DA C2CF63                jnz nxt_tm
63DD C9                    ret
63DE
```

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```
63DE F7                too_sa: rst message
63DF 0A0D416C6C20              db 10,13,'All too small   ',0
63F2 3E00                      mvi a,&00
63F4 C9                        ret
63F5
63F5 F7                no_sm:  rst message
63F6 0A0D4E6F2073              db 10,13,'No seam found',0
6406 3E00                      mvi a,&00
6408 C9                        ret
6409
6409 F5                pnt_nm: push psw          ;print
640A C5                        push b            ;sign
640B E5                        push h            ;and
640C 2600                      mvi h,00          ;number.
640E 6F                        mov l,a
640F B7                        ora a
6410 F21464                    jp no_ext
6413 25                        dcr h
6414 060A              no_ext: mvi b,&0a
6416 3E03                      mvi a,&03
6418 DF                        rst interf
6419 1F                        db pnt_sg
641A F7                        rst message
641B 202020202020              db '      ',0
6422 E1                        pop h
6423 C1                        pop b
6424 F1                        pop psw
6425 C9                        ret
6426
6426                   ;*****-- MULTIPLICATION --*****
6426                   ; This routine multiplies the
6426                   ; number by three.
6426                   ;**********************************
6426
6426 E5                mul_3: push h             ;multiply
6427 210000                   lxi h,0            ;value
642A 09                       dad b              ;by
642B 09                       dad b              ;three.
642C 09                       dad b              ;result
642D 44                       mov b,h            ;return
642E 4D                       mov c,l            ;to bc.
642F E1                       pop h
6430 C9                       ret
6431
6431                   ;**********-- DIVISION --**********
6431                   ; This routine divides two 16-bit
6431                   ; numbers which are contained in
6431                   ; bc and de.
6431                   ;**********************************
6431
6431 7A                dv:    mov a,d            ;negate
6432 2F                       cma                ;the
6433 57                       mov d,a            ;divisor
```

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```
6434 7B             mov a,e
6435 2F             cma
6436 5F             mov e,a
6437 13             inx d          ;for two's complement.
6438 210000         lxi h,0        ;init remainder.
643B 3E11           mvi a,&11      ;initialise counter.
643D E5      dv0:   push h         ;save remainder
643E 19             dad d          ;subtract divisor.
643F D24364         jnc dv1        ;store,restore HL.
6442 E3             xthl
6443 E1      dv1:   pop h
6444 F5             push psw       ;save counter (A).
6445 79             mov a,c        ;4 reg. left shift
6446 17             ral            ;with carry.
6447 4F             mov c,a
6448 78             mov a,b
6449 17             ral
644A 47             mov b,a
644B 7D             mov a,l
644C 17             ral
644D 6F             mov l,a
644E 7C             mov a,h
644F 17             ral
6450 67             mov h,a
6451 F1             pop psw        ;restore counter (A)
6452 3D             dcr a          ;decrement it
6453 C23D64         jnz dv0        ;keep looping
6456
6456                               ;post-divide clean up
6456                               ;shift remainder right
6456                               ;and return in DE
6456
6456 B7             ora a
6457 7C             mov a,h
6458 1F             rar
6459 57             mov d,a
645A 7D             mov a,l
645B 1F             rar
645C 5F             mov e,a
645D                               ;average value in BC.
645D C9             ret
645E
645E                end
```

No error(s) found

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Symbol table:

```
ARRAY--------5400 ARRAY_POS----5600 ARRND--------61E2 AGN_NX-------63BA
TOO_SA-------63DE BREADTH------5500 BEG----------6045 CRLF---------0001
COM_STM------0001 CEN_VA-------5110 COMMU--------6107 CHG_DI-------6121
COUNT--------61A0 COLUMN-------6219 CHK_CT-------6226 DIS_RST65----0014
DBG_STM------0000 DEBUG--------0006 DBG_RQ-------0004 DIV_4--------618E
DEL_PR-------6281 DO_POS-------63B3 DO_WD--------63C8 DV-----------6431
DV0----------643D DV1----------6443 ERROR--------0002 ERR_TP-------0001
EN_RST65-----0011 FIND_SYNC----0001 FAI_RN-------603D FIN_CN-------6193
FIN_TH-------61B7 FIN_TN-------61D0 FIN_HG-------61DD FIN_LW-------61EC
HIGH---------61FB LOW----------620A FWD_PR-------6240 FIN_MI-------6267
SMALL1-------6300 TOO_S1-------6364 GET_DA-------615E INTERF-------0003
IN_UAR-------0030 INDEX--------510E IS_ODD-------624C END_VA-------5106
```

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```
MESSAGE------0006 MIN_WIDTH----0006 MEM_BASE-----5100 MIN_ERR------510F
MOV_PT-------62A7 MOV_BL-------62B1 MKE_PO-------62C8 MUL_3--------6426
NO_INP-------60E5 NOT_DN-------612A NDN_AG-------613E NXT_PN-------614F
NOT_LW-------616C NOT_HG-------617A NXT_IN-------61A9 NEXT---------62AA
NXT_MV-------62B4 NXT_TM-------63CF NO_SM--------63F5 NO_EXT-------6414
ON_SYNC------0002 ONE_SM-------62BF PNT_NMER-----001D PNT_HX-------001C
PNT_SG-------001F PORT_A-------0021 PORT_B-------0022 PORT_C-------0023
PAIRS--------510D PNT_NM-------6409 RESET--------0000 RD_CHR-------0004
RST_SG-------0005 ROU_ETR------5100 REF----------5107 REF_CE-------5111
RPT_LP-------60D2 RD_AGN-------6115 REPEAT-------6258 REP_AG-------6272
SET_IP-------0002 SET_OP-------0003 SET_PT-------000A SET_EX-------000B
SET_HD-------000C STA_SPL------0003 STP_SPL------0004 STA_SG-------0002
STP_SG-------0003 STK_PR-------5102 STP_STK------5104 SET_ER-------6029
STA_SY-------6054 STA_PR-------608E SAMPLES------614A SMALL2-------6320
TOO_S2-------6384 TAKE_DATA----0005 TABLE--------5200 TABMIN-------5300
TOT_CT-------5108 THRESH-------510A TRANS--------510C THE_ERR------5112
TRY_NT-------6278 TWO_SM-------62CB AGAIN1-------6328 THR_SM-------632F
TOO_S3-------63A4 TRY_RP-------63AC UAR_AD-------3001 WR_CHR-------0005
WRT_SB-------607C WAI_HG-------6080 WRT_RB-------6114 WAT_LW-------6135
WAS_HG-------621F
```

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```
0000                "..........*.............*...................."
0000                TAB 12
0000                WIDTH 82
0000                PROC '8085'
0000                TITLE 'The infra-red second processor'
0000
0000                ;**********************************************
0000                ;*   This program mainly concentrate on the  *
0000                ;* control of the sweeping motor. It is syn- *
0000                ;* chronised with the adc processor board    *
0000                ;* and the robot controller.                 *
0000                ;**********************************************
0000
0000
0000                ;Mados operating system calls
0000
0000    (0000)      reset       equ 0
0000    (0001)      crlf        equ 1
0000    (0002)      error       equ 2
0000    (0003)      interf      equ 3
0000    (0004)      rd_chr      equ 4
0000    (0005)      wt_chr      equ 5
0000    (0006)      message     equ 6
0000
0000                ;operating system equates
0000
0000    (0001)      err_trp     equ &01
0000    (0002)      set_ip      equ &02
0000    (0003)      set_op      equ &03
0000    (000A)      set_pt      equ &0a
0000    (000B)      set_ex      equ &0b
0000    (000C)      set_hd      equ &0c
0000    (0011)      en_rst65    equ &11
0000    (0014)      dis_rst65   equ &14
0000    (001D)      pnt_nmb     equ &1d
0000    (001C)      pnt_hx      equ &1c
0000    (001F)      pnt_sgn     equ &1f
0000    (0030)      uart        equ &30
0000
0000                ;hardware equates
0000
0000    (0021)      port_a      equ &21
0000    (0022)      port_b      equ &22
0000    (0023)      port_c      equ &23
0000
0000
0000                ;memory workspace
0000
0000    (5100)      mem_base    equ &5100
0000
5100                            org mem_base
5100
```

```
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 5100 0000         0052 rou_ety:    ds 2
 5102 0000         0053 stk_ptr:    ds 2
 5104 0000         0054 stp_stk:    ds 2
 5106              0055
 5106 00           0056 trans:      ds 1
 5107 00           0057 pairs:      ds 1
 5108 00           0058 index:      ds 1
 5109 00           0059 min_err:    ds 1
 510A 00           0060 end_va:     ds 1
 510B              0061
 510B              0062
 6000              0063             org &6000
 6000              0064
 6000              0065 ;rom header for mados
 6000              0066
 6000 2843295700   0067             db '(C)W',0  ;rom entry
 6005 0A0D53746570 0068             db 10,13,'Stepper Motor Control',0
 601D C9           0069             ret
 601E              0070
 6020              0071             org &6020
 6020              0072
 6020              0073 ;set up ports
 6020              0074
 6020 3E01         0075 set_st:     mvi a,&01      ;Set up Port A
 6022 DF           0076             rst 3          ;as Output.
 6023 0A           0077             db set_pt      ;
 6024 3E00         0078             mvi a,00       ;stop motors
 6026 D321         0079             out port_a     ;take busy low
 6028              0080
 6028              0081 ;****-- PROGRAM INITIALISATION --****
 6028              0082 ; This section performs the requir
 6028              0083 ; initial settings prior to receiv
 6028              0084 ; a command from the adc board.
 6028              0085 ;************************************
 6028              0086
 6028 212060       0087 sta_pg:     lxi h,set_st   ;initial
 602B CD4E61       0088             call set_ers   ;settings.
 602E 220451       0089             shld stp_stk
 6031 C33460       0090             jmp beg
 6034              0091
 6034 3E00         0092 beg:        mvi a,00       ;Disable 8253
 6036 D321         0093             out port_a     ;with a low.
 6038 CD8461       0094             call intsy     ;Set up 8253 timer.
 603B              0095                            ;(Sync only.)
 603B              0096
 603B F7           0097             rst 6
 603C 0A0D57616974 0098             db 10,13,'Waiting',0
 6046 DF           0099             rst 3          ;Disable
 6047 14           0100             db dis_rst65   ;RST 6.5.
 6048              0101
 6048 CD4E60       0102 loop:       call intptr    ;command interpreter.
 604B C34860       0103             jmp loop
 604E              0104
```

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```
604E                 ;********-- COMMAND INTERPREPTER --********
604E                 ; This routine gets a command word from the
604E                 ; adc board via the 8155, decodes it and
604E                 ; then calls the relevent routine. The com-
604E                 ; mand must have a number less than 8.
604E                 ;*****************************************
604E
604E                 intptr:
604E CDB861          com_er:    call rd_bol    ;get
6051 B7                         ora a          ;command.
6052 CA4E60                     jz com_er
6055 FE08                       cpi 8
6057 D24E60                     jnc com_er
605A 3D                         dcr a          ;when a
605B 07                         rlc            ;command
605C 4F                         mov c,a        ;is received,
605D 0600                       mvi b,0        ;refer to the
605F 216860                     lxi h,com_tb   ;command table
6062 09                         dad b          ;and identify
6063 5E                         mov e,m        ;the correct
6064 23                         inx h          ;command.
6065 56                         mov d,m
6066 EB                         xchg
6067 E9                         pchl
6068
6068                 ;******-- COMMAND TABLE --******
6068                 ; There are six commands and
6068                 ; each directs the program to
6068                 ; the its corresponding routine.
6068                 ;******************************
6068
6068 F360            com_tb:    dw fin_sy      ;1
606A 8760                       dw on_syn      ;2
606C 6A61                       dw sta_sp      ;3
606E 9660                       dw stp_sp      ;4
6070 7460                       dw tak_da      ;5
6072 7560                       dw debug       ;6
6074
6074                 ;******-- tak_data --******
6074
6074 C9              tak_da:    ret
6075
6075                 ;*****-- returns to os --*****
6075
6075 3E00            debug:     mvi a,&00      ;disable the
6077 D321                       out port_a     ;motor.
6079 F7                         rst 6
607A 0A0D64656275               db 10,13,'debug',0
6082 2A0251                     lhld stk_ptr   ;find correct exit
6085 F9                         sphl           ;point
6086 C9                         ret
6087
6087                 ;******-- on_sync --******
```

```
6087
6087 F7                on_syn:    rst 6
6088 0A0D6F6E2073                 db 10,13,'on sync',0
6092 CD4961                       call stp_mt    ;disable the
6095 C9                           ret            ;motor.
6096
6096                   ;******-- stop_sampling --******
6096
6096 F7                stp_sp:    rst 6
6097 0A0D73746F70                 db 10,13,'stop_motor',0
60A5 CD4961                       call stp_mt    ;disable the
60A8 C9                           ret            ;motor.
60A9
60A9                   ;******-- park_arm --******
60A9                   ; drives the sensor to the
60A9                   ; initial position.
60A9                   ;***************************
60A9
60A9 CD8461            pk_arm:    call intsy     ;set up 8253.
60AC 3E00                         mvi a,&00      ;disable both
60AE D321                         out port_a     ;counters.
60B0 3E80                         mvi a,&80      ;set motor
60B2 320340                       sta &4003      ;speed.
60B5 3E00                         mvi a,&00      ;lsb.
60B7 320140                       sta &4001
60BA 3E20                         mvi a,&20      ;msb.
60BC 320140                       sta &4001
60BF 3E02                         mvi a,&02      ;enable
60C1 D321                         out port_a     ;direction.
60C3 0E10              rp_int:    mvi c,&10
60C5 DB23              rep_in:    in port_c
60C7 E601                         ani &01
60C9 C2C360                       jnz rp_int
60CC 0D                           dcr c          ;wait for
60CD C2C560                       jnz rep_in     ;direction low.
60D0
60D0 3E03                         mvi a,&03      ;enable both
60D2 D321                         out port_a     ;counters.
60D4
60D4
60D4 0E10              wai_lw:    mvi c,&10      ;set timer.
60D6 DB23              wlw_gl:    in port_c      ;detect
60D8 E602                         ani &02        ;for low.
60DA C2D460                       jnz wai_lw
60DD 0D                           dcr c          ;repeat to
60DE C2D660                       jnz wlw_gl     ;avoid glitches.
60E1
60E1 0E40              wai_h2:    mvi c,&40      ;reset timer.
60E3 DB23              wh2_gl:    in port_c      ;detect
60E5 E602                         ani &02        ;for high.
60E7 CAE160                       jz wai_h2
60EA 0D                           dcr c          ;repeat until
60EB CAE360                       jz wh2_gl      ;time up.
```

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```
60EE             0211
60EE 3E00        0212          mvi a,&00     ;disable both
60F0 D321        0213          out port_a    ;counters.
60F2 C9          0214          ret
60F3             0215
60F3             0216 ;******-- find sync --******
60F3             0217 ; starts the stepper motor
60F3             0218 ; running and waits for
60F3             0219 ; interrup from sync.
60F3             0220 ;*****************************
60F3             0221
60F3 F7          0222 fin_sy:  rst 6
60F4 0A0D66696E64 0223         db 10,13,'find sync',0
6100 CDA960      0224          call pk_arm
6103 CD8461      0225          call intsy
6106 3E01        0226          mvi a,01      ;enable 8253 with a
6108 D321        0227          out port_a    ;high. (speed only)
610A             0228
610A CD1F61      0229 start:   call init     ;detect on
610D CD3461      0230          call init_2   ;detect off sync.
6110 F7          0231          rst 6
6111 0A0D6F6E2073 0232         db 10,13,'on sync',0
611B             0233
611B CD4961      0234          call stp_mt
611E C9          0235          ret
611F             0236
611F             0237 ;***-- on sync detection --***
611F             0238
611F DB23        0239 init:    in port_c     ;wait for
6121 E602        0240          ani 02        ;chopper
6123 C21F61      0241          jnz init      ;sync.
6126 0E20        0242          mvi c,&20     ;short
6128             0243 glit:                  ;glitch check
6128             0244                        ;delay.
6128 DB23        0245          in port_c     ;try
612A E602        0246          ani 02        ;again.
612C C21F61      0247          jnz init      ;OK?
612F 0D          0248          dcr c
6130 C22861      0249          jnz glit
6133 C9          0250          ret
6134             0251
6134             0252 ;***-- off sync detection --***
6134             0253
6134 DB23        0254 init_2:  in port_c     ;wait for
6136 E602        0255          ani 02        ;chopper
6138 CA3461      0256          jz init_2     ;sync.
613B 0E20        0257          mvi c,&20     ;short
613D             0258 glit_2:                ;glitch check
613D             0259                        ;delay.
613D DB23        0260          in port_c     ;try
613F E602        0261          ani 02        ;again.
6141 CA3461      0262          jz init_2     ;OK?
6144 0D          0263          dcr c
```

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```
6145 C23D61                      jnz glit_2
6148 C9                          ret
6149
6149          ;******-- stop_motor --******
6149
6149 3E00     stp_mt:      mvi a,&00      ;disables
614B D321                  out port_a     ;the motor.
614D C9                    ret
614E
614E          ;******-- set_error --******
614E
614E 220051   set_ers:     shld rou_ety   ;routine
6151 216261                lxi h,fai_rn   ;entries.
6154 3E01                  mvi a,err_trp
6156 DF                    rst interf
6157 0C                    db set_hd
6158 210000                lxi h,0
615B 39                    dad sp
615C 23                    inx h
615D 23                    inx h
615E 220251                shld stk_ptr
6161 C9                    ret
6162
6162          ;******-- error_handler --******
6162
6162 2A0451   fai_rn:      lhld stp_stk
6165 F9                    sphl
6166 2A0051                lhld rou_ety
6169 E9                    pchl
616A
616A
616A          ;****-- start sampling --****
616A          ; This routine sets the motor
616A          ; speed and direction going.
616A          ;******************************
616A
616A CD9461   sta_sp:      call inter
616D F7                    rst 6
616E 0A0D73746172          db 10,13,'start sampling',0
617F 3E03                  mvi a,&03      ;enable 8253
6181 D321                  out port_a     ;both counters
6183 C9                    ret
6184
6184          ;*******-- synchronisation --*******
6184          ; This routine sets up the interval
6184          ; timer (8253) for synchronisation.
6184          ;***********************************
6184
6184 3E34     intsy:       mvi a,&34      ;mode 2.
6186 320340                sta &4003      ;(motor speed)
6189 3E00                  mvi a,00       ;LSB count.
618B 320040                sta &4000      ;
618E 3E04                  mvi a,04       ;MSB count.
```

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```
6190 320040     0317                sta &4000      ;
6193 C9         0318                ret            ;
6194            0319
6194            0320 ;******-- interval timer --******
6194            0321 ; This routine programs the 8253
6194            0322 ; to control the speed and the
6194            0323 ; sweep rate.
6194            0324 ;**********************************
6194            0325
6194 3E34       0326 inter:     mvi a,&34      ;mode 2.
6196 320340     0327            sta &4003      ;(motor speed)
6199 3E00       0328            mvi a,00       ;LSB count.
619B 320040     0329            sta &4000      ;
619E 3E04       0330            mvi a,04       ;MSB count.
61A0 320040     0331            sta &4000      ;
61A3 3E80       0332            mvi a,&80      ;mode 3.
61A5 320340     0333            sta &4003      ;(reverse)
61A8 3E5A       0334            mvi a,&5a      ;LSB count. (2D)
61AA 320140     0335            sta &4001      ;
61AD 3E16       0336            mvi a,&16      ;MSB count. (0B)
61AF 320140     0337            sta &4001      ;
61B2 C9         0338            ret            ;
61B3            0339
61B3            0340 ;********-- check_data --********
61B3            0341 ; checks for data from other
61B3            0342 ; board,i.e. is strobe low and
61B3            0343 ; returns zero if data available
61B3            0344 ;**********************************
61B3            0345
61B3 DB22       0346 chk_da:    in port_b      ;check msb of port b
61B5 E680       0347            ani &80
61B7 C9         0348            ret
61B8            0349
61B8            0350 ;******-- read_board1 --******
61B8            0351
61B8 C5         0352 rd_bo1:    push b         ;save registers used.
61B9 DB21       0353            in port_a      ;read status of.
61BB E603       0354            ani &03        ;stepper enables.
61BD D321       0355            out port_a     ;clear busy.
61BF DB22       0356 rd_stb:    in port_b      ;check port_b bit seve
61C1 E680       0357            ani &80        ;as is strobe.
61C3 C2BF61     0358            jnz rd_stb     ;wait for low strobe.
61C6 DB21       0359            in port_a      ;read status.
61C8 E603       0360            ani &03        ;clear false bits.
61CA F604       0361            ori &04        ;set busy bit.
61CC D321       0362            out port_a     ;set busy high.
61CE DB22       0363            in port_b      ;get data.
61D0 E67F       0364            ani &7f        ;clear msb (strobe).
61D2 47         0365            mov b,a        ;store in b.
61D3 DB22       0366 wait_high: in port_b      ;check strob.
61D5 E680       0367            ani &80        ;check for strobe high.
61D7 CAD361     0368            jz wait_high   ;repeat for strobe hig
61DA DB21       0369            in port_a      ;read 8254 status.
```

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```
61DC E603       ani &03         ;put busy
61DE D321       out port_a      ;low.
61E0 78         mov a,b         ;get data.
61E1 C1         pop b           ;restore b
61E2 C9         ret             ;and return.
61E3
61E3
61E3            end
```

No error(s) found

Symbol table:

```
BEG----------6034 CRLF---------0001 INTPTR-------604E COM_ER-------604E
COM_TB-------6068 CHK_DA-------61B3 DIS_RST65----0014 DEBUG--------6075
ERROR--------0002 ERR_TRP------0001 EN_RST65-----0011 FIN_SY-------60F3
FAI_RN-------6162 GLIT---------6128 GLIT_2-------613D INTERF-------0003
UART---------0030 INDEX--------5108 INIT---------611F INIT_2-------6134
INTSY--------6184 INTER--------6194 END_VA-------510A LOOP---------6048
MESSAGE------0006 MEM_BASE-----5100 MIN_ERR------5109 ON_SYN-------6087
```

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```
PNT_NMB------001D PNT_HX-------001C PNT_SGN------001F PORT_A-------0021
PORT_B-------0022 PORT_C-------0023 PAIRS--------5107 PK_ARM-------60A9
RESET--------0000 RD_CHR-------0004 ROU_ETY------5100 RP_INT-------60C3
REP_IN-------60C5 RD_BO1-------61B8 RD_STB-------61BF SET_IP-------0002
SET_OP-------0003 SET_PT-------000A SET_EX-------000B SET_HD-------000C
STK_PTR------5102 STP_STK------5104 STA_ST-------6020 STA_PRG------6028
STP_SP-------6096 START--------610A STP_MT-------6149 SET_ERS------614E
STA_SP-------616A TRANS--------5106 TAK_DA-------6074 WT_CHA-------0005
WAI_LW-------60D4 WLW_GL-------60D6 WAI_H2-------60E1 WH2_GL-------60E3
WAIT_HIGH----61D3
```

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```
      PROGRAM ORPROF
*****************************************************
*      THIS PROGRAM IS USED FOR PRODUCING SEAM      *
*    PROFILE PLOTS. IT CAN BE USED FOR CHAPTER      *
*    SIX OR SEVEN.                                  *
*****************************************************

      PARAMETER(NSAMP=300)
      DIMENSION YARRAY(NSAMP),XARRAY(NSAMP)
      INTEGER LAB(11)
      CHARACTER TITLE*60,TYPE*60
      READ(7,100) TITLE,TYPE
  100 FORMAT(A60)
      DO 200 J=0,15
         READ(7,*) (YARRAY(I),I=(16*J)+1,(16*J)+16)
  200 CONTINUE
      DO 300 J=1,NSAMP
         XARRAY(J)=J
  300 CONTINUE
C
C THE GRAPHICS BIT
      CALL GINO
      CALL SAVDRA
C     CALL DEVDAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
C
      XO=40.0
      YO=60.0
      YL=YO-4.0
      CALL AXIPOS(1,XO,YO,70.0,1)
      CALL AXIPOS(1,XO,YO,70.0,2)
      CALL AXISCA(3,10,0.0,260.0,1)
      CALL AXISCA(3,12,0.0,120.0,2)
      CALL GRID(-2,0,1)
      CALL AXILAB(LAB,11,3,1,YL,1)
      CALL GRAMOV(-50.0,0.0)
      CALL CHAANG(90.0)
      CALL CHASTR('SENSOR SIGNAL (ADC OUTPUT NUMBERS)')
      CALL GRAMOV(30.0,-20.0)
      CALL CHAANG(0.0)
      CALL CHASTR('SWEEP DISPLACEMENT (MM)')
      CALL GRAMOV(30.0,140.0)
      CALL CHASTR(TITLE)
      CALL GRAMOV(-26.0,-30.0)
      CALL CHASTR('TYPE: ')
      CALL CHASTR(TYPE)
      CALL GRAPOL(XARRAY,YARRAY,256)
      CALL DEVEND
      CALL GINEND
      DATA LAB/2H 0,2H 1,2H 2,2H 3,2H 4,2H 5,2H 6,2H 7,2H 8,2H 9,2H10/
```

```
      STOP
      END
```

```
      PROGRAM ANG2045

*********************************************************************
*         THIS PROGRAM READS THE DATA FILE C2045 AND PLOTS         *
*      THE DATA ON THE GRAPH OF DETECTED DEVIATION AGAINST         *
*      SENSOR TRAVELLED DISTANCE. THE OBJECTIVE IS TO SHOW         *
*      THE SENSOR'S ABILITY IN DETECTING SEAM DEVIATIONS           *
*      WHEN MOVING ALONG A STRAIGHT LINE PATH (CHAPTER 6).         *
*********************************************************************

      DIMENSION ERR1(600),ERR2(600),ENUM(600),DIST(600)
      INTEGER HEIGHT
      CHARACTER TITLE*70,TYPE*70
      READ (7,'(A)') TITLE,TYPE
      READ (7,*) HEIGHT,SPEED
      J=0
      MAXN=0
  100 READ (7,*) (ENUM(I),I=(J*10)+1,(J*10)+10)
      DO 1 I=(J*10)+1,(J*10)+10
        IF (ENUM(I).EQ.9999.) MAXN=I-1
    1 CONTINUE
C     SEPERATE TWO SETS OF DATA.
      MIDNUM=MAXN/2
C     SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C     NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
      IF (MAXN.GT.0) GO TO 200
      J=J+1
      GO TO 100
  200 DO 2 I=1,MAXN
C     ONE SWEEP = 10MM IN 1S AND 256 SAMPLES
C     ERROR FROM SEAM = ERROR SIGNAL * (SWEEP RATE / SAMPLE RATE)
      J=I-MIDNUM
      IF (I.LE.MIDNUM) THEN
         ERR1(I)=ENUM(I)*16.5/256
         DIST(I)=I*SPEED
      ELSEIF (I.GT.MIDNUM) THEN
         ERR2(J)=ENUM(I)*16.5/256
      ENDIF
    2 CONTINUE

C     PRINTOUT INPUT PARAMETERS
      PRINT*,'END OF DATA FILE .'
      PRINT*,'NUMBER OF ERRORS =',MIDNUM
      PRINT*,'SENSOR HEIGHT =',HEIGHT,'MM'
      PRINT*,'SPEED OF TORCH =',SPEED,'MM/S'

C     THE GRAPHICS BIT
      CALL GINO
      CALL SAVDRA
      CALL DEVPAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
```

```
C     SET CO-ORDINATES
      XO=30.0
      YO=100.0
      XR=250.0
      YR=110.0
      TX=65.0
      TY=YO+YR+20.0
      YS1=90.0
      YS2=80.0
      YS3=70.0
      YS4=60.0
      YS5=50.0
      YS6=40.0

      CALL AXIPOS(1,XO,YO,XR,1)
      CALL AXIPOS(1,XO,YO,YR,2)
      CALL AXISCA(3,10,0.0,DIST(MIDNUM),1)
      CALL AXISCA(3,8,-8.0,8.0,2)
      CALL GRID(3,1,1)
      CALL CHAANG(90.0)
      CALL MOVTO2(15.0,130.0)
      CALL CHASTR('DETECTED DEVIATION (MM)')
      CALL CHAANG(0.0)
      CALL MOVTO2(110.0,85.0)
      CALL CHASTR('SENSOR TRAVELLED DISTANCE (MM)')
      CALL MOVTO2(TX,TY)
      CALL CHASTR(TITLE)
      CALL MOVTO2(XO,YS3)
      CALL CHASTR('TYPE OF WORK:    ')
      CALL CHASTR(TYPE)
      CALL MOVTO2(XO,YS4)
      CALL CHASTR('SENSOR HEIGHT: ')
      CALL CHAINT(HEIGHT,3)
      CALL CHASTR('MM')
      CALL MOVTO2(XO,YS5)
      CALL CHASTR('TORCH SPEED:    ')
      CALL CHAFIX(SPEED,5,2)
      CALL CHASTR('MM/S')
      CALL MOVTO2(XO,YS6)
      CALL CHASTR('NUMBER OF DEVIATION VALUES: ')
      CALL CHAINT(MIDNUM,4)
      CALL MOVTO2(XO,10.0)
      CALL CHASTR('FIG. 6.18  DEVIATION DETECTIONS ALONG A STRAIGHT LINE
     / PATH OF TORCH MOVEMENTS')
      CALL MOVTO2(XO+120.0,YS3)
      CALL CHASTR('(A)   --- SEAM PATH WITH 20 DEGREES ANGLE')
      CALL MOVTO2(XO+120.0,YS4)
      CALL CHASTR('(B)   --- SEAM PATH WITH 45 DEGREES ANGLE')
      CALL GRASYM(DIST,ERR1,MIDNUM,8,0)
      CALL GRAPOL(DIST,ERR1,MIDNUM)
      CALL GRASYM(DIST,ERR2,MIDNUM,6,0)
      CALL GRAPOL(DIST,ERR2,MIDNUM)
      CALL DEVEND
      CALL GINEND
      STOP
```

END

```
      PROGRAM ER4SET
*****************************************************
*        THIS PROGRAM IS USED TO PLOT 4 SETS OF     *
*     EXPERIMENTAL RESULTS FOR COMPARISON           *
*     PURPOSES. THE CORRESPONDING DATA FILE IS      *
*     SL1V (CHAPTER 6).                             *
*****************************************************

      DIMENSION ERR(600),ENUM(600),DIST(600)
      CHARACTER TITLE*60,TYPE*60,JOB*60,PATH*60
      INTEGER HEIGHT
      READ (7,'(A)') TITLE,JOB,PATH
      READ (7,*) HEIGHT,SPEED
C     SET UP GRAPHIC CO-ORDINATES
      XO=30.0
      YO=25.0
      XR=118.0
      YR=118.0
      TX=103.0
      TY=272.0
      CALL GINO
      CALL SAVDRA
      CALL DEVPAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
      CALL MOVTO2(TX,TY)
      CALL CHASTR(TITLE)
      DO 1000 ISET=1,4
         READ (7,'(A)') TYPE
         J=0
         MAXN=0
 100     READ (7,*) (ERR(I),I=(J*10)+1,(J*10)+10)
         DO 200 I=(J*10)+1,(J*10)+10
            IF (ERR(I).EQ.9999.) MAXN=I-1
            IF (MAXN.EQ.0) DIST(I)=I*SPEED
 200     CONTINUE
C        SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C        NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
         IF (MAXN.GT.0) GO TO 300
         J=J+1
         GO TO 100
 300     PRINT*,'END OF DATA FILE ...',ISET
         PRINT*,'NUMBER OF ERRORS =',MAXN
         PRINT*,'DISTANCE TRAVELLED=',DIST(MAXN)
         PRINT*,'OFFSET=',ISET-1
C
C THE GRAPHICS BIT
C
         IF (ISET.EQ.1) THEN
            XSHIFT=0.0
            YSHIFT=YR+4.0
         ENDIF
```

```
          IF (ISET.EQ.2) THEN
             XSHIFT=XR+4.0
             YSHIFT=YR+4.0
          ENDIF
          IF (ISET.EQ.3) THEN
             XSHIFT=0.0
             YSHIFT=0.0
          ENDIF
          IF (ISET.EQ.4) THEN
             XSHIFT=XR+4.0
             YSHIFT=0.0
          ENDIF
          ORX=XO+XSHIFT
          ORY=YO+YSHIFT
          XS1=XO+XR+4.0
          YS1=15.0
          XS2=XO
          YS2=YS1
          WX=ORX+10.0
          WY=ORY+10.0
          DX=XS2
          DY=8.0
          PX=XS1
          PY=DY
          HX=XS2
          HY=1.0
          SX=XS1
          SY=HY
          CALL AXIPOS(1,ORX,ORY,XR,1)
          CALL AXIPOS(1,ORX,ORY,YR,2)
          CALL AXISCA(3,16,0.0,DIST(MAXN),1)
          CALL AXISCA(3,10,-50.0,50.0,2)
          CALL LINCOL(3)
          CALL GRID(2,0,0)
          CALL LINCOL(1)
          CALL MOVTO2(WX,WY)
C         CALL CHASTR('TYPE OF WORK: ')
          CALL CHASTR(TYPE)
          CALL GRAPOL(DIST,ERR,MAXN)
 1000 CONTINUE
      CALL MOVTO2(XS2,YS2)
      CALL CHASTR('VERTICAL: DEVIATION (-5 TO +5MM)')
      CALL MOVTO2(XS1,YS1)
      CALL CHASTR('HORIZONTAL: DISTANCE (0 TO 160MM)')
      CALL MOVTO2(DX,DY)
      CALL CHASTR('JOB:')
      CALL CHASTR(JOB)
      CALL MOVTO2(PX,PY)
      CALL CHASTR('WELD PATH:')
      CALL CHASTR(PATH)
      CALL MOVTO2(HX,HY)
      CALL CHASTR('SENSOR HEIGHT: ')
      CALL CHAINT(HEIGHT,3)
      CALL CHASTR('MM')
      CALL MOVTO2(SX,SY)
```

```
      CALL CHASTR('TORCH SPEED: ')
      CALL CHAFIX(SPEED,5,2)
      CALL CHASTR('MM/S')
      CALL DEVEND
      CALL GINEND
      STOP
      END
```

```
      PROGRAM ORERR
************************************************************
*           THIS PROGRAM IS USED TO PRESENT THE RESULTS      *
*     OF SEAM DEVIATION ERROR SIGNALS ALONG THE ROBOT         *
*     TORCH PATH CONTAINING TWO CORNERS (CHAPTER 6).          *
*     DATA FILES ARE ANGL305 AND ANGL405.                     *
************************************************************

      DIMENSION ERR(600),ENUM(600),DIST(600)
      INTEGER HEIGHT
      CHARACTER TITLE*70,TYPE*70,FIGURE*70
      READ (7,'(A)') TITLE,TYPE,FIGURE
      READ (7,*) HEIGHT,SPEED
      J=0
      MAXN=0
  100 READ (7,*) (ERR(I),I=(J*10)+1,(J*10)+10)
      DO 1 I=(J*10)+1,(J*10)+10
        IF (ERR(I).EQ.9999.) MAXN=I-1
        IF (MAXN.EQ.0) DIST(I)=I*SPEED
    1 CONTINUE
C     SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C     NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
      IF (MAXN.GT.0) GO TO 200
      J=J+1
      GO TO 100
  200 PRINT*,'END OF DATA FILE ...'
      PRINT*,'NUMBER OF ERRORS =',MAXN,DIST(MAXN)
      PRINT*,'SENSOR HEIGHT =',HEIGHT,'MM'
      PRINT*,'SPEED OF TORCH =',SPEED,'MM/S'
C
C THE GRAPHICS BIT
      CALL GINO
      CALL SAVDRA
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
C
      XO=40.0
      YO=80.0
      XR=100.0
      YR=100.0
      XS=XO-(XR-XO)/5.0
      YS=YO+YR+10.0
      XS1=XO-(XR-XO)/5.0
      YS1=YO
      XS2=XO+(XR-XO)/3.0
      YS2=YO-10.0
      YS3=YO-20.0
      YS4=YS3-8.0
      YS5=YS4-8.0
      YS6=YS5-8.0
      YS7=YS6-16.0
      CALL AXIPOS(1,XO,YO,XR,1)
      CALL AXIPOS(1,XO,YO,YR,2)
```

```
      CALL AXISCA(3,10,0.0,DIST(MAXN),1)
      CALL AXISCA(3,10,-50.0,50.0,2)
      CALL GRID(3,1,1)
      CALL MOVTO2(XS1,YS1)
      CALL CHAANG(90.0)
      CALL CHASTR('SENSOR SIGNAL (ADC OUTPUT NUMBERS')
      CALL MOVTO2(XS2,YS2)
      CALL CHAANG(0.0)
      CALL CHASTR('SEAM LENGTH (MM)')
      CALL MOVTO2(XS,YS)
      CALL CHASTR(TITLE)
      CALL MOVTO2(XO,YS3)
      CALL CHASTR('TYPE OF WORK: ')
      CALL CHASTR(TYPE)
      CALL MOVTO2(XO,YS4)
      CALL CHASTR('SENSOR HEIGHT: ')
      CALL CHAINT(HEIGHT,3)
      CALL CHASTR('MM')
      CALL MOVTO2(XO,YS5)
      CALL CHASTR('TORCH SPEED: ')
      CALL CHAFIX(SPEED,5,2)
      CALL CHASTR('MM/S')
      CALL MOVTO2(XO,YS6)
      CALL CHASTR('NUMBER OF DEVIATION VALUES: ')
      CALL CHAINT(MAXN,4)
      CALL MOVTO2(5.0,YS7)
      CALL CHASTR(FIGURE)
      CALL GRAPOL(DIST,ERR,MAXN)
      CALL DEVEND
      CALL GINEND
      STOP
      END
```

```
      PROGRAM ANGSPEED

*********************************************************************
*       THIS PROGRAM READS THE DATA FILE C20 OR C45 AND            *
*     PLOTS THE DATA ON THE GRAPH OF DETECTED DEVIATION            *
*     AGAINST SENSOR TRAVELLED DISTANCE. THE OBJECTIVE             *
*     IS TO SHOW THE EFFECTS OF CHANGING TORCH TRAVELLING          *
*     SPEED (CHAPTER 6).                                           *
*********************************************************************

      DIMENSION ERR1(100),ERR2(100),ERR3(100)
      DIMENSION DIST1(100),DIST2(100),DIST3(100)
      DIMENSION ENUM(100)
      INTEGER HEIGHT
      CHARACTER TITLE*70,TYPE*70
      READ (7,'(A)') TITLE,TYPE
      READ (7,*) HEIGHT,SPEED1,SPEED2,SPEED3
      J=0
      MAXN=0
      NT1=40
      NT2=48
  100 READ (7,*) (ENUM(I),I=(J*10)+1,(J*10)+10)
      DO 1 I=(J*10)+1,(J*10)+10
        IF (ENUM(I).EQ.9999.) MAXN=I-1
    1 CONTINUE
C     SEPERATE THREE SETS OF DATA.
C     SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C     NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
      IF (MAXN.GT.0) GO TO 200
      J=J+1
      GO TO 100
  200 DO 2 I=1,MAXN
C     ONE SWEEP = 10MM IN 1S AND 256 SAMPLES
C     ERROR FROM SEAM = ERROR SIGNAL * (SWEEP RATE / SAMPLE RATE)
      J=I-NT1
      K=I-NT2
      IF (I.LE.NT1) THEN
         ERR1(I)=ENUM(I)*16.5/256
         DIST1(I)=I*SPEED1
      ENDIF
      IF (I.GT.NT1.AND.I.LE.NT2) THEN
         ERR2(J)=ENUM(I)*16.5/256
         DIST2(J)=J*SPEED2
      ENDIF
      IF (I.GT.NT2) THEN
         ERR3(K)=ENUM(I)*16.5/256
         DIST3(K)=K*SPEED3
      ENDIF
    2 CONTINUE

C     PRINTOUT INPUT PARAMETERS
      PRINT*,'END OF DATA FILE .'
      PRINT*,'NUMBER OF ERRORS =',NT1
```

```
C       THE GRAPHICS BIT
        CALL GINO
        CALL SAVDRA
        CALL DEVPAP(280.0,280.0,0)
        CALL WINDO2(0.0,280.0,0.0,280.0)
        CALL SOFCHA
        CALL CHASIZ(3.0,3.0)

C       SET CO-ORDINATES
        XO=30.0
        YO=100.0
        XR=200.0
        YR=90.0
        TX=50.0
        TY=YO+YR+20.0
        YS1=90.0
        YS2=80.0
        YS3=70.0
        YS4=60.0
        YS5=50.0
        YS6=40.0

        CALL AXIPOS(1,XO,YO,XR,1)
        CALL AXIPOS(1,XO,YO,YR,2)
        CALL AXISCA(3,10,0.0,DIST1(NT1),1)
        CALL AXISCA(3,8,-8.0,8.0,2)
        CALL GRID(3,1,1)
        CALL CHAANG(90.0)
        CALL MOVTO2(15.0,130.0)
        CALL CHASTR('DETECTED DEVIATION (MM)')
        CALL CHAANG(0.0)
        CALL MOVTO2(140.0,85.0)
        CALL CHASTR('SENSOR TRAVELLED DISTANCE (MM)')
        CALL MOVTO2(TX,TY)
        CALL CHASTR(TITLE)
        CALL MOVTO2(XO,YS3)
        CALL CHASTR('TYPE OF WORK:    ')
        CALL CHASTR(TYPE)
        CALL MOVTO2(XO,YS4)
        CALL CHASTR('SENSOR HEIGHT: ')
        CALL CHAINT(HEIGHT,3)
        CALL CHASTR('MM')
        CALL MOVTO2(XO,10.0)
        CALL CHASTR('FIG. 6.22  DEVIATION DETECTIONS AT VARIOUS SPEEDS')
        CALL MOVTO2(XO+120.0,YS4)
        CALL CHASTR('(A)    --- SPEED =  1MM/S')
        CALL MOVTO2(XO+120.0,YS5)
        CALL CHASTR('(B)    --- SPEED =  5MM/S')
        CALL MOVTO2(XO+120.0,YS6)
        CALL CHASTR('(C)    --- SPEED = 10MM/S')
        CALL GRASYM(DIST1,ERR1,40,1,0)
        CALL GRAPOL(DIST1,ERR1,40)
        CALL GRASYM(DIST2,ERR2,8,6,0)
        CALL GRAPOL(DIST2,ERR2,8)
        CALL GRASYM(DIST3,ERR3,4,8,0)
```

```
      CALL GRAPOL(DIST3,ERR3,4)
      CALL DEVEND
      CALL GINEND
      STOP
      END
```

APPENDIX IV

(Program listing for Chapter 7)

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```
0000            TITLE'The Ultrasonic Seam Tracker'
0000            TAB 10
0000            WIDTH 90
0000            "..........*..........*......................."
0000            ;**********************************************
0000            ;*    This program is used for the control of  *
0000            ;* the Ultrasonic Seam Tracker and real time   *
0000            ;* display of the sensed pattern. Data is      *
0000            ;* captured from the ZN427E ADC. The centre    *
0000            ;* of a seam is deduced by comparing the phase *
0000            ;* difference between the transmitting and the *
0000            ;* receiving signals. Seam deviation errors    *
0000            ;* are calculated for position correction via  *
0000            ;* the RS-423 serial port.                     *
0000            ;**********************************************
0000
0000            ;operating system equates.
0000
0000   (0220)   EVNTV  EQU &220         ;event vector
0000   (FFE0)   OSRDCH EQU &FFE0        ;read single character
0000   (FFEE)   OSWRCH EQU &FFEE        ;write character
0000   (FFF1)   OSWORD EQU &FFF1        ;read string
0000   (FFF4)   OSBYTE EQU &FFF4        ;OS operation
0000
0000            ;memory workspace.
0000
0000   (2710)   JOB    EQU &2710        ;metal thickness
0000   (278E)   MODEL  EQU &278E        ;command for modelling
0000   (278F)   LCST   EQU &278F        ;constant value
0000   (2790)   RCST   EQU &2790        ;constant value
0000   (2791)   SEAM   EQU &2791        ;seam position
0000   (2792)   AMIN   EQU &2792        ;average minimum
0000   (2793)   UMID   EQU &2793        ;upper range
0000   (2794)   MID    EQU &2794        ;min position
0000   (2795)   LMID   EQU &2795        ;lower range
0000   (2796)   GREG   EQU &2796        ;graphic register
0000   (2797)   REF    EQU &2797        ;reference
0000   (2798)   LBDC   EQU &2798        ;low byte delay counter
0000   (2799)   HBDC   EQU &2799        ;high byte delay counter
0000   (279A)   PRESM  EQU &279A        ;pre-seam position.
0000   (2800)   BLK1   EQU &2800        ;data block
0000   (2900)   BLK2   EQU &2900        ;graphic store
0000
0000            ;data capture equates.
0000
0000   (0070)   INPH   EQU &70          ;initial phase
0000   (0071)   INDT   EQU &71          ;initial data
0000   (0072)   STORE  EQU &72          ;data storage
0000   (0073)   DCTR   EQU &73          ;data counter
0000   (0074)   PHOS   EQU &74          ;off set phase
0000   (0075)   PRED   EQU &75          ;previouse data
0000
```

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```
0000                ;graphic display equates.
0000
0000        (0076)  VDU     EQU &76         ;VDU number
0000        (0078)  LENG    EQU &78         ;character length
0000        (0079)  LARGE   EQU &79         ;graphic enlargement
0000        (007A)  ESC     EQU &7A         ;interrupt key number
0000        (007B)  MULTR   EQU &7B         ;multiplier
0000        (007C)  MULTD   EQU &7C         ;multiplied
0000        (007D)  RES     EQU &7D         ;result
0000
0000                ;counter equates.
0000
0000        (0080)  LPCT    EQU &80         ;loop counter
0000        (0082)  NUM     EQU &82         ;number
0000        (0085)  IADD    EQU &85         ;input address
0000
0000
1400                        ORG &1400
1400
1400                ;********-- PROGRAM ENTRY --*********
1400                ; Prior to starting operation, the
1400                ; program requires to enter para-
1400                ; meters for setting up the screen
1400                ; and other initial procedures.
1400                ;************************************
1400
1400 201D1A          start:     JSR entry   ;enter parameters.
1403 205E16                     JSR screen  ;set up screen.
1406 20F014                     JSR init    ;initialisations.
1409 205D17                     JSR event   ;enable event.
140C
140C                ;******--MAIN PROGRAM--******
140C                ; This section shows the main
140C                ; structure of the program.
140C                ;****************************
140C
140C ADC5FC          sweep:     LDA &FCC5   ;read direction
140F 2904                       AND #4      ;from D2.
1411 F0F9                       BEQ sweep   ;wait for idle.
1413
1413 ADC5FC          idle:      LDA &FCC5   ;detect
1416 2904                       AND #4      ;falling edge.
1418 D0F9                       BNE idle    ;wait until change.
141A A965                       LDA #101    ;set no. of counts
141C 8573                       STA DCTR    ;for data storage.
141E 209814                     JSR data    ;read & store data.
1421 AD9627                     LDA GREG    ;check graphic register.
1424 F003                       BEQ comp    ;jump if not plotted.
1426 203015                     JSR plot    ;rub out priviouse plot.
1429
1429 20ED15          comp:      JSR offset  ;off set data.
142C 208117                     JSR postn   ;find average position.
142F 202202                     JSR send    ;send deviation error.
```

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```
1432 203015               JSR plot   ;plot graphic.
1435 A57A                 LDA ESC    ;if interrupt
1437 C91B                 CMP #&1B   ;stop scanning
1439 D009                 BNE ichk   ;and
143B 205714               JSR comd   ;get command.
143E 203015               JSR plot   ;clear plot.
1441 CE9627               DEC GREG   ;reset graphic register.
1444
1444 A579        ichk:    LDA LARGE  ;check
1446 F006                 BEQ rsm    ;counter.
1448 EE8E27               INC MODEL  ;increament counter.
144B 4C0C14               JMP sweep  ;repeat operation.
144E
144E A900        rsm:     LDA #0     ;reset model
1450 8D8E27               STA MODEL  ;counter.
1453 4C0C14               JMP sweep  ;repeat.
1456 60                   RTS
1457
1457             ;********--INPUT COMMAND--********
1457             ; This routine reads the keyboard
1457             ; buffer, indentifies the correct
1457             ; command and directs to the
1457             ; relevent routine.
1457             ;**********************************
1457
1457 A900        comd:    LDA #0     ;clear key
1459 857A                 STA ESC    ;number.
145B A00E                 LDY #14    ;rub out
145D 202519               JSR load   ;command message.
1460 A010                 LDY #16    ;display 2nd
1462 202519               JSR load   ;command message.
1465 A200                 LDX #0     ;flushes
1467 A915                 LDA #21    ;the keyboard
1469 20F4FF               JSR OSBYTE ;buffer.
146C
146C 20E0FF      incom:   JSR OSRDCH ;input command.
146F C90D                 CMP #13    ;if RETURN,
1471 F01A                 BEQ mess   ;continue.
1473 C920                 CMP #&20   ;if SPC,
1475 F013                 BEQ inposn ;store centre value.
1477 C909                 CMP #&9    ;if TAB,
1479 F00A                 BEQ mod    ;switch to modelling.
147B C987                 CMP #135   ;if COPY,
147D D0ED                 BNE incom  ;print
147F 20211B               JSR copy   ;screen.
1482 4C8D14               JMP mess   ;get message.
1485
1485 E679        mod:     INC LARGE  ;inc. counter.
1487 4C8D14               JMP mess   ;
148A
148A 202A18      inposn:  JSR centre ;track centre position.
148D
148D A010        mess:    LDY #16    ;
```

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```
148F 202519                     JSR load    ;change
1492 A00E                       LDY #14     ;messages.
1494 202519                     JSR load    ;
1497 60                         RTS
1498
1498
1498            ;*******-- DATA CAPTURE --*******
1498            ; This routine reads data from
1498            ; the A/D converter and fetches
1498            ; equivalent values from the
1498            ; look_up table for constructing
1498            ; a seam pattern.
1498            ;*********************************
1498
1498 AD9827     data:           LDA LBDC    ;save hold time.
149B 48                         PHA         ;LB.
149C AD9927                     LDA HBDC    ;
149F 48                         PHA         ;HB.
14A0 A204                       LDX #4      ;set delay.
14A2
14A2 A9FF       tmos:           LDA #255    ;load
14A4 8D9827                     STA LBDC    ;delay
14A7 8D9927                     STA HBDC    ;counter.
14AA 201E15                     JSR delay   ;direct to
14AD CA                         DEX         ;delay routine.
14AE D0F2                       BNE tmos    ;
14B0 68                         PLA         ;reload
14B1 8D9927                     STA HBDC    ;counter.
14B4 68                         PLA         ;
14B5 8D9827                     STA LBDC    ;
14B8 A000                       LDY #0      ;reset mem.location
14BA
14BA A900       sc:             LDA #0      ;command ZN427E
14BC 8DC2FC                     STA &FCC2   ;to START CONVERSION
14BF
14BF ADC0FC     eoc:            LDA &FCC0   ;check EOC from D7.
14C2 2980                       AND #&80    ;i.e. MSB only..
14C4 F0F9                       BEQ eoc     ;wait until EOC.
14C6 AEC1FC                     LDX &FCC1   ;read data from ZN427E.
14C9 E07E                       CPX #126    ;comp. with the
14CB B0ED                       BCS sc      ;max.counting no.
14CD 8672                       STX STORE   ;save data.
14CF 201215                     JSR phase   ;determine phase
14D2 C570                       CMP INPH    ;LEAD/LAG.
14D4 F006                       BEQ fetch   ;fetch data if same.
14D6 A9FA                       LDA #250    ;max. no.for data conv.
14D8 38                         SEC         ;set carry flag.
14D9 E572                       SBC STORE   ;A=250-X.
14DB AA                         TAX         ;X=A.
14DC
14DC BD1323     fetch:          LDA table,X ;look-up table.
14DF 990028                     STA BLK1,Y  ;store data .
14E2 8DC4FC                     STA &FCC4   ;output to X-Y recorder.
```

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```
14E5 C8                        INY         ;locate to next data.
14E6 201E15                    JSR delay   ;hold sample.
14E9 C673                      DEC DCTR    ;decrement data counter.
14EB F002                      BEQ retn_d
14ED D0CB                      BNE sc      ;read again
14EF
14EF 60           retn_d:      RTS
14F0
14F0              ;*****-- INITIALISATION --*****
14F0              ; This routine performs system
14F0              ; initialisation procedures.
14F0              ;******************************
14F0
14F0 201215       init:        JSR phase   ;store initial
14F3 8570                      STA INPH    ;phase
14F5 A900                      LDA #0      ;clear
14F7 8574                      STA PHOS    ;counters.
14F9 8D9027                    STA RCST    ;
14FC 8D8F27                    STA LCST    ;
14FF 8D8E27                    STA MODEL   ;reset modelling
1502 8579                      STA LARGE   ;counter.
1504 8D9627                    STA GREG    ;reset graphic
1507 A932                      LDA #50     ;register.
1509 8D9127                    STA SEAM    ;seam ref.
150C A01A                      LDY #26     ;defind
150E 202519                    JSR load    ;character.
1511 60                        RTS
1512
1512              ;******-- PHASE CONDITION --******
1512              ; This routine decides whether the
1512              ; phase condition is leading or
1512              ; lagging.
1512              ;*********************************
1512
1512 ADC3FC       phase:       LDA &FCC3   ;read phase
1515 2903                      AND #3      ;from D0 & D1.
1517 F0F9                      BEQ phase   ;read again if A=0.
1519 C903                      CMP #3      ;A-3,compare.
151B B0F5                      BCS phase   ;read again if A>=3.
151D 60                        RTS
151E
151E              ;******-- TIME DELAY --******
151E              ; This is a delay routine for
151E              ; the timing synchronisation
151E              ; of the A/D converter.
151E              ;****************************
151E
151E AD9827       delay:       LDA LBDC    ;set lower byte
1521 8D64FE                    STA &FE64   ;delay counter.
1524 AD9927                    LDA HBDC    ;set higher byte
1527 8D65FE                    STA &FE65   ;delay counter.
152A
152A 2C6DFE       wait:        BIT &FE6D   ;wait until
```

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```
152D 50FB                   BVC wait    ;delay executed.
152F 60                     RTS
1530
1530        ;******-- GRAPHIC PLOT --******
1530        ; This routine deals with the
1530        ; real time graphic displays of
1530        ; the sensed seam pattern on
1530        ; the screen.
1530        ;********************************
1530
1530 AD8E27  plot:          LDA MODEL   ;check
1533 D025                   BNE smpn    ;counter.
1535 A000                   LDY #0      ;set to origin.
1537 A965                   LDA #101    ;set 101 counts
1539 8573                   STA DCTR    ;for data counter.
153B A919                   LDA #25     ;VDU
153D 20EEFF                 JSR OSWRCH  ;number.
1540 A904                   LDA #4      ;PLOT
1542 20EEFF                 JSR OSWRCH  ;number.
1545 20AF15                 JSR cal     ;MOVE x,y coordinates.
1548
1548 A919    draw:          LDA #25     ;VDU
154A 20EEFF                 JSR OSWRCH  ;number.
154D A905                   LDA #5      ;PLOT
154F 20EEFF                 JSR OSWRCH  ;number.
1552 20AF15                 JSR cal     ;PLOT x,y.
1555 C8                     INY         ;move to next data.
1556 C673                   DEC DCTR    ;dec.data counter.
1558 D0EE                   BNE draw    ;repeat until 100 counts.
155A
155A AD9127  smpn:          LDA SEAM    ;check range.
155D C9FF                   CMP #&FF    ;compare with
155F D008                   BNE arw     ;max range.
1561 A01C                   LDY #28     ;display
1563 202519                 JSR load    ;warning
1566 4CA915                 JMP retn_14 ;message.
1569
1569 A919    arw:           LDA #25     ;draw an
156B 20EEFF                 JSR OSWRCH  ;arrow
156E A904                   LDA #4      ;pointing
1570 20EEFF                 JSR OSWRCH  ;at the
1573 AD9127                 LDA SEAM    ;seam
1576 857B                   STA MULTR   ;position.
1578 A90B                   LDA #11     ;
157A 857C                   STA MULTD   ;
157C 204816                 JSR mult    ;scale.
157F 18                     CLC         ;
1580 A57D                   LDA RES     ;
1582 695C                   ADC #92     ;
1584 9002                   BCC pt      ;
1586 E67E                   INC RES+1   ;
1588
1588 20EEFF  pt:            JSR OSWRCH  ;display
```

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```
158B 857D                   STA RES     ;graphic
158D A57E                   LDA RES+1   ;points.
158F 20EEFF                 JSR OSWRCH ;
1592 A9BC                   LDA #188    ;
1594 20EEFF                 JSR OSWRCH ;
1597 A903                   LDA #3      ;
1599 20EEFF                 JSR OSWRCH ;
159C A018                   LDY #24     ;
159E 202519                 JSR load    ;display arrow
15A1 AD8E27                 LDA MODEL   ;check
15A4 F003                   BEQ retn_14 ;counter.
15A6 207718                 JSR mol     ;
15A9
15A9 A901        retn_14:   LDA #1      ;indicate plotted
15AB 8D9627                 STA GREG    ;
15AE 60                     RTS
15AF
15AF                        extend 'ust2'
15AF             "..........*..........*........................"
15AF
15AF             ;***-- X and Y CO-ORDINATES --***
15AF             ; This routine calaulates the
15AF             ; relevent x, y co-ordinates of
15AF             ; each data for graphic plots.
15AF             ;**********************************
15AF
15AF 847B        cal:       STY MULTR   ;count.
15B1 A90B                   LDA #11     ;time scale.
15B3 857C                   STA MULTD   ;
15B5 204816                 JSR mult    ;X=count*11.
15B8 18                     CLC         ;
15B9 A57D                   LDA RES     ;LSB of
15BB 695C                   ADC #92     ;off-set X.
15BD 9002                   BCC offX    ;
15BF E67E                   INC RES+1   ;
15C1
15C1 20EEFF      offX:      JSR OSWRCH ;X co-ord.
15C4 A57E                   LDA RES+1   ;MSB of
15C6 20EEFF                 JSR OSWRCH ;X co-ord.
15C9 B90029                 LDA BLK2,Y ;fetch data.
15CC 20ED15                 JSR offset ;threshold.
15CF 857B                   STA MULTR   ;
15D1 A906                   LDA #6      ;amplitude.
15D3 857C                   STA MULTD   ;
15D5 204816                 JSR mult    ;Y=data*3.
15D8 18                     CLC         ;
15D9 A57D                   LDA RES     ;LSB of Y co-ord.
15DB 6980                   ADC #128    ;off-set Y.
15DD 9002                   BCC offY    ;
15DF E67E                   INC RES+1   ;
15E1
15E1 20EEFF      offY:      JSR OSWRCH ;
15E4 A57E                   LDA RES+1   ;MSB of
```

```
15E6 38                      SEC          ;
15E7 E902                    SBC #2       ;
15E9 20EEFF                  JSR OSWRCH  ;Y co-ord.
15EC 60                      RTS
15ED
15ED          ;****-- DATA OFFSET --****
15ED          ; This routine offsets the
15ED          ; data array for display.
15ED          ;*************************
15ED
15ED A006      offset:       LDY #6       ;select
15EF B90028                  LDA BLK1,Y   ;initial
15F2 38                      SEC          ;value.
15F3 E932                    SBC #50      ;
15F5 8571                    STA INDT     ;initial data.
15F7 8575                    STA PRED     ;previousdata.
15F9 A000                    LDY #0       ;clear reg.
15FB A965                    LDA #101     ;set data
15FD 8573                    STA DCTR     ;counter.
15FF
15FF B90028    locate:       LDA BLK1,Y   ;fetch data.
1602 38                      SEC          ;threshold
1603 E932                    SBC #50      ;data.
1605 8572                    STA STORE    ;store result.
1607 C575                    CMP PRED     ;data>=pre.data?
1609 9005                    BCC less     ;if yes,
160B E575                    SBC PRED     ;data-pre.data.
160D 4C1516                  JMP edge     ;
1610
1610 A575      less:         LDA PRED     ;if data<pre.data,
1612 38                      SEC          ;
1613 E572                    SBC STORE    ;pre.data-data.
1615
1615 C9B4      edge:         CMP #180     ;result>180?
1617 9013                    BCC small    ;if greater,
1619 A574                    LDA PHOS     ;check
161B D013                    BNE set      ;PHOS=0.
161D A901                    LDA #1       ;if zero,
161F 8574                    STA PHOS     ;reset PHOS=1.
1621
1621 A572      change:       LDA STORE    ;load data.
1623 38                      SEC          ;
1624 E571                    SBC INDT     ;
1626 38                      SEC          ;
1627 E932                    SBC #50      ;data-INDT-50.
1629 4C3B16                  JMP swap     ;
162C
162C A574      small:        LDA PHOS     ;check
162E D0F1                    BNE change   ;PHOS.
1630
1630 A900      set:          LDA #0       ;reset
1632 8574                    STA PHOS     ;PHOS.
1634
```

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```
1634 A9FA       0423  same:    LDA #250    ;max. phase
1636 38         0424           SEC         ;number.
1637 E571       0425           SBC INDT    ;
1639 6572       0426           ADC STORE   ;data+(250-INDT).
163B            0427
163B 990029     0428  swap:    STA BLK2,Y  ;store data
163E A572       0429           LDA STORE   ;for graphic
1640 8575       0430           STA PRED    ;plot.
1642 C8         0431           INY         ;
1643 C673       0432           DEC DCTR    ;
1645 D0B8       0433           BNE locate  ;
1647 60         0434           RTS
1648            0435
1648            0436  ;******-- MULTIPLICATION --******
1648            0437  ; This routine is used for 8-bit
1648            0438  ; multiplications.
1648            0439  ;*********************************
1648            0440
1648 A900       0441  mult:    LDA #0      ;clear result
164A 857D       0442           STA RES     ;register.
164C A208       0443           LDX #8      ;8-bit counter.
164E            0444
164E 467B       0445  loop:    LSR MULTR   ;shift first
1650 9003       0446           BCC zero    ;number right
1652 18         0447           CLC         ;and add
1653 657C       0448           ADC MULTD   ;second number.
1655            0449
1655 6A         0450  zero:    ROR A       ;rotate
1656 667D       0451           ROR RES     ;result.
1658 CA         0452           DEX         ;decreament
1659 D0F3       0453           BNE loop    ;counter.
165B 857E       0454           STA RES+1   ;store high_byte.
165D 60         0455           RTS
165E            0456
165E            0457  ;*******-- SET UP SCREEN --*******
165E            0458  ; This routine sets up the screen
165E            0459  ; for display.
165E            0460  ;**********************************
165E            0461
165E A00C       0462  screen:  LDY #12     ;set scrreen
1660 202519     0463           JSR load    ;mode.
1663 A000       0464           LDY #0      ;set origin
1665 A25C       0465           LDX #92     ;at 92,128.
1667 8473       0466           STY DCTR    ;set DB counter.
1669            0467
1669 A919       0468  vert:    LDA #25     ;VDU
166B 20EEFF     0469           JSR OSWRCH  ;and
166E A904       0470           LDA #4      ;PLOT
1670 20EEFF     0471           JSR OSWRCH  ;numbers.
1673 8A         0472           TXA         ;
1674 48         0473           PHA         ;save X.
1675 20EEFF     0474           JSR OSWRCH  ;
1678 98         0475           TYA         ;
```

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```
1679 20EEFF                 JSR OSWRCH ;
167C A96E                   LDA #110   ;MOVE x,110.
167E 20EEFF                 JSR OSWRCH ;
1681 A900                   LDA #0     ;
1683 20EEFF                 JSR OSWRCH ;
1686
1686 A673        hlab:      LDX DCTR   ;get counter
1688 E673                   INC DCTR   ;number.
168A BD9C25                 LDA scale,X ;detect
168D C9FF                   CMP #&FF   ;terminator.
168F F006                   BEQ next_1 ;
1691 20EEFF                 JSR OSWRCH ;draw.
1694 4C8616                 JMP hlab   ;
1697
1697 A919        next_1:    LDA #25    ;
1699 20EEFF                 JSR OSWRCH ;
169C A904                   LDA #4     ;
169E 20EEFF                 JSR OSWRCH ;
16A1 68                     PLA        ;return X.
16A2 AA                     TAX        ;
16A3 20EEFF                 JSR OSWRCH ;
16A6 98                     TYA        ;
16A7 20EEFF                 JSR OSWRCH ;
16AA A980                   LDA #128   ;MOVE x,128.
16AC 20EEFF                 JSR OSWRCH ;
16AF A900                   LDA #0     ;
16B1 20EEFF                 JSR OSWRCH ;
16B4 A919                   LDA #25    ;VDU number.
16B6 20EEFF                 JSR OSWRCH ;
16B9 A905                   LDA #5     ;PLOT number.
16BB 20EEFF                 JSR OSWRCH ;
16BE 8A                     TXA        ;
16BF 20EEFF                 JSR OSWRCH ;
16C2 98                     TYA        ;
16C3 20EEFF                 JSR OSWRCH ;
16C6 A978                   LDA #120   ;
16C8 20EEFF                 JSR OSWRCH ;DRAW x,888.
16CB A903                   LDA #3     ;
16CD 20EEFF                 JSR OSWRCH ;
16D0 8A                     TXA        ;
16D1 696E                   ADC #110   ;add interval.
16D3 B008                   BCS cyone  ;
16D5 C916                   CMP #22    ;
16D7 F00A                   BEQ reset  ;
16D9 AA                     TAX        ;
16DA 4C6916                 JMP vert   ;
16DD
16DD C8          cyone:     INY        ;inc. higher byte.
16DE AA                     TAX        ;
16DF C916                   CMP #22    ;x=1192?
16E1 D086                   BNE vert   ;
16E3
16E3 A000        reset:     LDY #0     ;reset high byte.
```

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```
16E5 A280               LDX #128     ;orig.at 92,128.
16E7
16E7 A919      horiz:   LDA #25      ;VDU number.
16E9 20EEFF             JSR OSWRCH   ;
16EC A904               LDA #4       ;PLOT number.
16EE 20EEFF             JSR OSWRCH   ;
16F1 A900               LDA #0       ;
16F3 20EEFF             JSR OSWRCH   ;
16F6 20EEFF             JSR OSWRCH   ;MOVE 0,y.
16F9 8A                 TXA          ;
16FA 48                 PHA          ;save X.
16FB 20EEFF             JSR OSWRCH   ;
16FE 98                 TYA          ;
16FF 20EEFF             JSR OSWRCH   ;
1702
1702 A673      vlab:    LDX DCTR     ;get scale .
1704 E673               INC DCTR     ;
1706 BD9C25             LDA scale,X  ;detect
1709 C9FF               CMP #&FF     ;terminator.
170B F003               BEQ next_2   ;
170D 4C0217             JMP vlab     ;
1710
1710 A919      next_2:  LDA #25      ;VDU number.
1712 20EEFF             JSR OSWRCH   ;
1715 A904               LDA #4       ;PLOT number.
1717 20EEFF             JSR OSWRCH   ;
171A A95D               LDA #93      ;
171C 20EEFF             JSR OSWRCH   ;
171F A900               LDA #0       ;
1721 20EEFF             JSR OSWRCH   ;
1724 68                 PLA          ;
1725 AA                 TAX          ;MOVE 93,y.
1726 20EEFF             JSR OSWRCH   ;
1729 98                 TYA          ;
172A 20EEFF             JSR OSWRCH   ;
172D A919               LDA #25      ;VDU number.
172F 20EEFF             JSR OSWRCH   ;
1732 A915               LDA #21      ;PLOT number.
1734 20EEFF             JSR OSWRCH   ;
1737 A9A8               LDA #168     ;
1739 20EEFF             JSR OSWRCH   ;
173C A904               LDA #4       ;
173E 20EEFF             JSR OSWRCH   ;
1741 8A                 TXA          ;DRAW 1192,y.
1742 20EEFF             JSR OSWRCH   ;
1745 98                 TYA          ;
1746 20EEFF             JSR OSWRCH   ;
1749 8A                 TXA          ;
174A 694C               ADC #76      ;add interval.
174C B008               BCS cytwo    ;
174E C9C4               CMP #196     ;
1750 F00A               BEQ back     ;
1752 AA                 TAX          ;
```

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```
1753 4CE716                 JMP horiz  ;
1756
1756 C8         cytwo:      INY        ;inc.higher byte.
1757 AA                     TAX        ;
1758 C9C4                   CMP #196   ;y=888?
175A D08B                   BNE horiz  ;
175C
175C 60         back:       RTS
175D
175D            ;******-- ENABLE EVENT --******
175D            ; This routine deals with event
175D            ; enable handlings.
175D            ;********************************
175D
175D A900       event:      LDA #0     ;low byte address
175F 8D2002                 STA EVNTV  ;for interrupt routine.
1762 A923                   LDA #&23   ;high byte address
1764 8D2102                 STA EVNTV+1 ;for interrupt routine.
1767 A206                   LDX #6     ;enable ESCAPE
1769 A90E                   LDA #14    ;pressed event.
176B 20F4FF                 JSR OSBYTE ;
176E A202                   LDX #2     ;enable character
1770 A90E                   LDA #14    ;entering event.
1772 20F4FF                 JSR OSBYTE ;
1775 A900                   LDA #0     ;
1777 857A                   STA ESC    ;clear key number.
1779 A201                   LDX #1     ;disable
177B A904                   LDA #4     ;cursor
177D 20F4FF                 JSR OSBYTE ;editing.
1780 60                     RTS
1781
1781
1781                        extend 'ust3'                          "
1781            "..........*..........*.......................
1781
1781            ;****-- FIND AVERAGE MIN --****
1781            ; This routine determines the
1781            ; the centre position of the
1781            ; seam.
1781            ;********************************
1781
1781 AD9027     postn:      LDA RCST   ;check for
1784 0D8F27                 ORA LCST   ;initialisation
1787 F03B                   BEQ retn_6 ;
1789 204019                 JSR mag    ;find turning points
178C AD9227                 LDA AMIN   ;determine
178F CD9427                 CMP MID    ;left or
1792 9006                   BCC less_6 ;right.
1794 20F017                 JSR right  ;go for right.
1797 4C9D17                 JMP scoff  ;
179A
179A 200A18     less_6:     JSR left   ;go for left.
179D
```

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```
179D C946       scoff:   CMP #70     ;max.seam co_ord.
179F B01B                BCS outrg   ;if greater, out of range.
17A1 C91E                CMP #30     ;min.seam co_ord.
17A3 9017                BCC outrg   ;if smaller, out of range.
17A5 E914                SBC #20     ;offset.
17A7 857B                STA MULTR   ;
17A9 A903                LDA #3      ;max-min.
17AB 857C                STA MULTD   ;
17AD 20081A              JSR div8    ;result return to MULTR.
17B0 A905                LDA #5      ;
17B2 857C                STA MULTD   ;MULTD=5.
17B4 204816              JSR mult    ;
17B7 A57D                LDA RES     ;SEAM=(Y-20)*5/3.
17B9 4CBE17              JMP reslt   ;
17BC
17BC A9FF       outrg:   LDA #&FF    ;out of range
17BE
17BE 8D9127     reslt:   STA SEAM    ;store result.
17C1 207419              JSR topcut  ;threshold.
17C4
17C4 60         retn_6:  RTS
17C5
17C5            ;*******-- DIVISION --********
17C5            ; This is a 16-bit division
17C5            ; routine.
17C5            ;*****************************
17C5
17C5 A900       div:     LDA #0      ;clear A (low byte rem.)
17C7 8580                STA LPCT    ;clear high byte rem.
17C9 A210                LDX #16     ;defind 16-bit division
17CB
17CB 0682       loop_3:  ASL NUM     ;shift one bit left to A
17CD 2683                ROL NUM+1   ;rotate higher byte
17CF 2A                  ROL A       ;rotate A
17D0 8572                STA STORE   ;temp. storage
17D2 2680                ROL LPCT    ;rotate high byte rem.
17D4 C57C                CMP MULTD   ;comp. low byte
17D6 A580                LDA LPCT    ;
17D8 E57B                SBC MULTR   ;comp. high byte
17DA 900E                BCC less_2  ;
17DC A572                LDA STORE   ;release A
17DE E57C                SBC MULTD   ;rem.(L)-divisor(L)
17E0 8572                STA STORE   ;
17E2 A580                LDA LPCT    ;
17E4 E57B                SBC MULTR   ;rem.(H)-divisor(H)
17E6 8580                STA LPCT    ;
17E8 E682                INC NUM     ;
17EA
17EA A572       less_2:  LDA STORE   ;
17EC CA                  DEX         ;
17ED D0DC                BNE loop_3  ;result in NUM
17EF 60                  RTS
17F0
```

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```
17F0           ;****-- RIGHT POSITIONS --****
17F0           ; This routine deals with the
17F0           ; seam positions shifted to
17F0           ; the right from the reference
17F0           ; centre.
17F0           ;*******************************
17F0
17F0 AC9227     right:    LDY AMIN    ;reference.
17F3
17F3 C064       loop_11:  CPY #100    ;check for
17F5 B00E                 BCS addy    ;data range.
17F7 88                   DEY         ;
17F8 B90029               LDA BLK2,Y ;
17FB CD9527               CMP LMID    ;comp. with
17FE 90F3                 BCC loop_11 ;lower case.
1800 CD9327               CMP UMID    ;comp. with
1803 B0EE                 BCS loop_11 ;upper case.
1805
1805 98         addy:     TYA         ;
1806 6D9027               ADC RCST    ;Y=Y+const.
1809 60                   RTS
180A
180A           ;****-- LEFT POSITIONS --****
180A           ; This routine deals with the
180A           ; seam positions shifted to
180A           ; left from the reference
180A           ; centre.
180A           ;*******************************
180A
180A AC9227     left:     LDY AMIN    ;reference.
180D
180D C000       loop_12:  CPY #0      ;check for
180F D005                 BNE ctu     ;data range.
1811 A900                 LDA #0      ;
1813 4C2918               JMP retn_15 ;
1816
1816 C8         ctu:      INY         ;
1817 B90029               LDA BLK2,Y ;
181A CD9527               CMP LMID    ;lower case.
181D 90EE                 BCC loop_12 ;
181F CD9327               CMP UMID    ;upper case.
1822 B0E9                 BCS loop_12 ;
1824 98                   TYA         ;
1825 38                   SEC         ;
1826 ED8F27               SBC LCST    ;Y=Y-const.
1829
1829 60         retn_15:  RTS
182A
182A           ;******-- CENTRE TRACK --******
182A           ; This routine deals with the
182A           ; centre position of the sensed
182A           ; pattern.
182A           ;*******************************
```

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```
182A
182A A579       centre:  LDA LARGE  ;check
182C F007                BEQ magn   ;counter.
182E A900                LDA #0     ;
1830 8579                STA LARGE  ;reset counter.
1832 4C7618              JMP retn_20 ;
1835
1835 204019     magn:    JSR mag    ;calculate
1838 AD9227              LDA AMIN   ;mid_point.
183B 8D9427              STA MID    ;
183E 8D9A27              STA PRESM  ;initial seam
1841 AC9427              LDY MID    ;position.
1844
1844 B90029     loop_10: LDA BLK2,Y ;reload data.
1847 C8                  INY        ;find
1848 CD9527              CMP LMID   ;lower case
184B 90F7                BCC loop_10 ;and
184D CD9327              CMP UMID   ;upper case.
1850 B0F2                BCS loop_10 ;
1852 98                  TYA        ;
1853 38                  SEC        ;left
1854 E932                SBC #50    ;reference.
1856 8D8F27              STA LCST   ;constant.
1859 AC9427              LDY MID    ;
185C
185C B90029     loop_16: LDA BLK2,Y ;reload data.
185F 88                  DEY        ;
1860 CD9527              CMP LMID   ;find
1863 90F7                BCC loop_16 ;lower
1865 CD9327              CMP UMID   ;and
1868 B0F2                BCS loop_16 ;upper
186A 8C9027              STY RCST   ;limits.
186D A932                LDA #50    ;right
186F 38                  SEC        ;reference.
1870 ED9027              SBC RCST   ;
1873 8D9027              STA RCST   ;constant.
1876
1876 60         retn_20: RTS
1877
1877            ;*********-- MODEL DISPLAY --*********
1877            ; This routine models seam dimension
1877            ; and position for experimental
1877            ; purposes.
1877            ;**************************************
1877
1877 A919       mol:     LDA #25    ;VDU
1879 20EEFF              JSR OSWRCH ;number.
187C A904                LDA #4     ;MOVE
187E 20EEFF              JSR OSWRCH ;code.
1881 A95C                LDA #92    ;low byte
1883 20EEFF              JSR OSWRCH ;x co-ord.
1886 A900                LDA #0     ;high byte
1888 20EEFF              JSR OSWRCH ;x co-ord.
```

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```
188B A982                   LDA #130    ;low byte
188D 20EEFF                 JSR OSWRCH ;y co-ord.
1890 A902                   LDA #2      ;high byte
1892 20EEFF                 JSR OSWRCH ;y co-ord.
1895 A919                   LDA #25     ;VDU
1897 20EEFF                 JSR OSWRCH ;number.
189A A915                   LDA #21     ;PLOT
189C 20EEFF                 JSR OSWRCH ;code.
189F A57D                   LDA RES     ;load
18A1 A47E                   LDY RES+1   ;data.
18A3 38                     SEC         ;get to
18A4 E96E                   SBC #110    ;display
18A6 B001                   BCS pt3     ;position.
18A8 88                     DEY         ;
18A9
18A9 20EEFF         pt3:    JSR OSWRCH ;low byte x.
18AC 98                     TYA         ;
18AD 20EEFF                 JSR OSWRCH ;high byte x.
18B0 A982                   LDA #130    ;
18B2 20EEFF                 JSR OSWRCH ;low byte y.
18B5 A902                   LDA #2      ;
18B7 20EEFF                 JSR OSWRCH ;high byte y.
18BA A919                   LDA #25     ;
18BC 20EEFF                 JSR OSWRCH ;VDU number.
18BF A905                   LDA #5      ;
18C1 20EEFF                 JSR OSWRCH ;
18C4 A57D                   LDA RES     ;low byte x.
18C6 20EEFF                 JSR OSWRCH ;
18C9 A57E                   LDA RES+1   ;high byte x.
18CB 20EEFF                 JSR OSWRCH ;
18CE A964                   LDA #100    ;low byte y.
18D0 20EEFF                 JSR OSWRCH ;
18D3 A901                   LDA #1      ;high byte y.
18D5 20EEFF                 JSR OSWRCH ;
18D8 A919                   LDA #25     ;VDU number.
18DA 20EEFF                 JSR OSWRCH ;
18DD A905                   LDA #5      ;
18DF 20EEFF                 JSR OSWRCH ;
18E2 A57D                   LDA RES     ;
18E4 A47E                   LDY RES+1   ;
18E6 696E                   ADC #110    ;
18E8 9001                   BCC pt2     ;
18EA C8                     INY         ;
18EB
18EB 20EEFF         pt2:    JSR OSWRCH ;low byte x.
18EE 98                     TYA         ;
18EF 20EEFF                 JSR OSWRCH ;high byte x.
18F2 A982                   LDA #130    ;
18F4 20EEFF                 JSR OSWRCH ;low byte y.
18F7 A902                   LDA #2      ;
18F9 20EEFF                 JSR OSWRCH ;high byte y.
18FC A919                   LDA #25     ;
18FE 20EEFF                 JSR OSWRCH ;
```

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```
1901 A915                    LDA #21      ;
1903 20EEFF                  JSR OSWRCH ;
1906 A9A8                    LDA #168     ;
1908 20EEFF                  JSR OSWRCH ;
190B A904                    LDA #4       ;
190D 20EEFF                  JSR OSWRCH ;
1910 A982                    LDA #130     ;
1912 20EEFF                  JSR OSWRCH ;
1915 A902                    LDA #2       ;
1917 20EEFF                  JSR OSWRCH ;
191A A2FA                    LDX #250     ;delay
191C A0FF                    LDY #255     ;counter.
191E
191E 88         delay2:      DEY          ;delay
191F D0FD                    BNE delay2 ;routine.
1921 CA                      DEX          ;
1922 D0FA                    BNE delay2 ;
1924 60                      RTS          ;
1925
1925                         extend 'ust4'
1925           "..........*.........*......................."
1925
1925           ;****-- LOAD VDU NUMBERS --****
1925           ; This rouitne fetches the VDU
1925           ; numbers for define word and
1925           ; define byte.
1925           ;********************************
1925
1925 B90E24     load:        LDA word,Y ;define word
1928 8576                    STA VDU      ;store lower byte
192A C8                      INY          ;
192B B90E24                  LDA word,Y ;
192E 8577                    STA VDU+1    ;store higher byte
1930 A000                    LDY #0       ;clear Y
1932
1932 B176       mem:         LDA (VDU),Y ;load VDU no.
1934 C9FF                    CMP #&FF     ;detect terminater
1936 F007                    BEQ term     ;
1938 20EEFF                  JSR OSWRCH ;
193B C8                      INY          ;
193C 4C3219                  JMP mem      ;
193F
193F 60         term:        RTS
1940
1940
1940           ;******-- MAGNIFICATION --******
1940           ; This routine is used for the
1940           ; display scale factor.
1940           ;********************************
1940
1940 A9FF       mag:         LDA #&FF     ;set min
1942 8572                    STA STORE    ;in temp. storage
1944 A900                    LDA #0       ;set max
```

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```
1946 8580                     STA LPCT    ;
1948 A064                     LDY #100    ;no. of data
194A
194A B90029      loop_7:      LDA BLK2,Y  ;fetch data
194D C580                     CMP LPCT    ;max?
194F 9002                     BCC min     ;
1951 8580                     STA LPCT    ;store new max
1953
1953 C572        min:         CMP STORE   ;min?
1955 B006                     BCS next_6
1957 8572                     STA STORE   ;if smaller, store new min
1959 98                       TYA         ;
195A 8D9227                   STA AMIN    ;
195D
195D 88          next_6:      DEY         ;
195E D0EA                     BNE loop_7  ;
1960 4672                     LSR STORE   ;min/2
1962 4680                     LSR LPCT    ;max/2
1964 A580                     LDA LPCT    ;
1966 6572                     ADC STORE   ;(max+min)/2
1968 6905                     ADC #5      ;
196A 8D9327                   STA UMID    ;upper value
196D 38                       SEC         ;
196E E90A                     SBC #10     ;
1970 8D9527                   STA LMID    ;lower value
1973 60                       RTS
1974
1974             ;******-- THRESHOLDING --******
1974             ; This routine set up a fixed
1974             ; threshold level for cleaning
1974             ; up unwanted noise signals.
1974             ;*******************************
1974
1974 A000        topcut:      LDY #0      ;clear counter.
1976
1976 B90029      cut:         LDA BLK2,Y  ;data elementes.
1979 C065                     CPY #101    ;check
197B B011                     BCS loref   ;amplitude.
197D C8                       INY         ;
197E CD9327                   CMP UMID    ;compare
1981 90F3                     BCC cut     ;with
1983 88                       DEY         ;threshold
1984 AD9327                   LDA UMID    ;level.
1987 990029                   STA BLK2,Y  ;
198A C8                       INY         ;
198B 4C7619                   JMP cut     ;
198E
198E AC9227      loref:       LDY AMIN    ;reference min.
1991
1991 B90029      usch:        LDA BLK2,Y  ;search
1994 C8                       INY         ;for
1995 C065                     CPY #101    ;upper
1997 B005                     BCS uesc    ;umid values.
```

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```
1999 CD9327                CMP UMID   ;
199C 90F3                  BCC usch   ;
199E
199E 8C9727       uesc:    STY REF    ;upper ref
19A1 AC9227                LDY AMIN   ;
19A4
19A4 B90029       lsch:    LDA BLK2,Y ;search
19A7 88                    DEY        ;for
19A8 C000                  CPY #0     ;lower
19AA F005                  BEQ lesc   ;umid values.
19AC CD9327                CMP UMID   ;
19AF 90F3                  BCC lsch   ;
19B1
19B1 98           lesc:    TYA        ;lower ref.
19B2 6D9727                ADC REF    ;
19B5 4A                    LSR A      ;(lower rf + upper rf)/2.
19B6 8D9727                STA REF    ;
19B9 CD9127                CMP SEAM   ;compare
19BC 9006                  BCC uoff   ;with
19BE 20C819                JSR lroff  ;centre
19C1 4CC719                JMP stop   ;position.
19C4
19C4 20E419       uoff:    JSR uroff  ;
19C7
19C7 60           stop:    RTS
19C8
19C8 ED9127       lroff:   SBC SEAM   ;consider
19CB 8D9727                STA REF    ;positions
19CE A200                  LDX #0     ;below
19D0 AC9727                LDY REF    ;center
19D3
19D3 B90029       ltran:   LDA BLK2,Y ;reference.
19D6 C8                    INY        ;
19D7
19D7 9D0029       letr:    STA BLK2,X ;
19DA E8                    INX        ;
19DB C065                  CPY #101   ;
19DD 90F4                  BCC ltran  ;
19DF E066                  CPX #102   ;
19E1 90F4                  BCC letr   ;
19E3 60                    RTS
19E4
19E4 38           uroff:   SEC        ;consider
19E5 AD9127                LDA SEAM   ;positions
19E8 ED9727                SBC REF    ;higher
19EB 8D9727                STA REF    ;than
19EE 38                    SEC        ;the centre
19EF A965                  LDA #101   ;reference.
19F1 ED9727                SBC REF    ;
19F4 A8                    TAY        ;
19F5 A265                  LDX #101   ;
19F7
19F7 B90029       utran:   LDA BLK2,Y ;
```

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```
19FA 88                       DEY         ;
19FB
19FB 9D0029      uetr:        STA BLK2,X  ;
19FE CA                       DEX         ;
19FF C000                     CPY #0      ;
1A01 D0F4                     BNE utran   ;
1A03 E000                     CPX #0      ;
1A05 D0F4                     BNE uetr    ;
1A07 60                       RTS
1A08
1A08             ;******-- 8-BIT DIVISION --******
1A08             ; This routine is used for 8-bit
1A08             ; divisions.
1A08             ;**********************************
1A08
1A08 A900        div8:        LDA #0      ;clear
1A0A A208                     LDX #8      ;counters.
1A0C
1A0C 067B        loop_8:      ASL MULTR   ;rotate first
1A0E 2A                       ROL A       ;number and
1A0F C57C                     CMP MULTD   ;compare with
1A11 9004                     BCC less_3  ;the second
1A13 E57C                     SBC MULTD   ;one.
1A15 E67B                     INC MULTR   ;
1A17
1A17 CA          less_3:      DEX         ;check
1A18 D0F2                     BNE loop_8  ;counter.
1A1A A57B                     LDA MULTR   ;reload first number.
1A1C 60                       RTS
1A1D
1A1D
1A1D             ;******-- TITLE PAGE --******
1A1D             ; This routine sets up the
1A1D             ; title page for program
1A1D             ; entry requests.
1A1D             ;*****************************
1A1D
1A1D A000        entry:       LDY #0      ;set up screen
1A1F 202519                   JSR load    ;mode.
1A22 A002                     LDY #2      ;print title.
1A24 202519                   JSR load    ;
1A27 A004                     LDY #4      ;move cursor.
1A29 202519                   JSR load    ;
1A2C A002                     LDY #2      ;
1A2E 202519                   JSR load    ;
1A31
1A31 A006        keyin_1:     LDY #6      ;enter metal
1A33 202519                   JSR load    ;thickness
1A36 20EF1A                   JSR line    ;from keyboard.
1A39 A000                     LDY #0      ;
1A3B
1A3B B185        tran:        LDA (IADD),Y ;transfer input
1A3D 991027                   STA JOB,Y   ;to memory.
```

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```
1A40 C8                          INY          ;
1A41 C90D                        CMP #13      ;detect end char.
1A43 D0F6                        BNE tran     ;
1A45
1A45 A008             keyin_2:   LDY #8       ;enter recording
1A47 202519                      JSR load     ;interval
1A4A
1A4A 20EF1A           DtoH:      JSR line     ;from keyboard
1A4D A900                        LDA #0       ;and convert
1A4F A202                        LDX #2       ;decimal to hex.
1A51
1A51 9582             spc:       STA NUM,X    ;clear space
1A53 CA                          DEX          ;for 24-bits no.
1A54 10FB                        BPL spc      ;
1A56 A000                        LDY #0       ;
1A58
1A58 B185             char:      LDA (IADD),Y ;load input char.
1A5A C90D                        CMP #13      ;detect end char.
1A5C F042                        BEQ check    ;go for overflow check
1A5E 20181B                      JSR mult2    ;mult.by 2.
1A61 A202                        LDX #2       ;
1A63
1A63 B582             stack:     LDA NUM,X    ;save number
1A65 48                          PHA          ;into stack.
1A66 CA                          DEX          ;
1A67 10FA                        BPL stack    ;
1A69 20181B                      JSR mult2    ;multiply
1A6C 20181B                      JSR mult2    ;by 4.
1A6F A200                        LDX #0       ;
1A71 A903                        LDA #3       ;set loop
1A73 8580                        STA LPCT     ;counter.
1A75 18                          CLC          ;
1A76
1A76 68               xten:      PLA          ;re-load number.
1A77 7582                        ADC NUM,X    ;calculate
1A79 9582                        STA NUM,X    ;2xNUM+8xNUM,
1A7B E8                          INX          ;i.e. 10xNUM.
1A7C C680                        DEC LPCT     ;
1A7E D0F6                        BNE xten     ;
1A80 7034                        BVS del_2    ;exit if bit_23 overflow.
1A82 B185                        LDA (IADD),Y ;load input char.
1A84 38                          SEC          ;convert it
1A85 E930                        SBC #&30     ;to a digit
1A87 902D                        BCC del_2    ;from 0-9.
1A89 C90A                        CMP #10      ;
1A8B B029                        BCS del_2    ;exit if not 0-9.
1A8D 6582                        ADC NUM      ;add the
1A8F 8582                        STA NUM      ;converted
1A91 900A                        BCC nocy     ;digit to
1A93 18                          CLC          ;
1A94 E683                        INC NUM+1    ;the current
1A96 9005                        BCC nocy     ;contents of
1A98 18                          CLC          ;
```

```
1A99 E684                      INC NUM+2  ;NUM.
1A9B 3019                      BMI del_2  ;exit if overflow.
1A9D
1A9D C8           nocy:        INY        ;go for
1A9E D0B8                      BNE char   ;next char.
1AA0
1AA0 A584         check:       LDA NUM+2  ;check overflow.
1AA2 D012                      BNE del_2  ;start again if ovreflow.
1AA4 A583                      LDA NUM+1  ;load high byte
1AA6 8D9927                    STA HBDC   ;for delay counter.
1AA9 A582                      LDA NUM    ;load low byte
1AAB 8D9827                    STA LBDC   ;for delay counter.
1AAE C900                      CMP #0     ;if NUM is not zero,
1AB0 D015                      BNE keyin_3 ;enter next parameter.
1AB2 C583                      CMP NUM+1  ;if NUM & NUM+1
1AB4 D011                      BNE keyin_3 ;are both zero.
1AB6
1AB6 A008         del_2:       LDY #8     ;
1AB8 202519                    JSR load   ;
1ABB
1ABB A920         spc_2:       LDA #32    ;backspace
1ABD 20EEFF                    JSR OSWRCH ;and delete.
1AC0 C678                      DEC LENG   ;
1AC2 D0F7                      BNE spc_2  ;
1AC4 4C451A                    JMP keyin_2 ;key in again.
1AC7
1AC7 A00A         keyin_3:     LDY #10    ;graphic plot
1AC9 202519                    JSR load   ;inquiry.
1ACC 20EF1A                    JSR line   ;
1ACF A000                      LDY #0     ;
1AD1 B185                      LDA (IADD),Y ;
1AD3 C959                      CMP #&59   ;Yes?
1AD5 F015                      BEQ rec    ;
1AD7 C94E                      CMP #&4E   ;No?
1AD9 F011                      BEQ rec    ;
1ADB A00A                      LDY #10    ;if not Y/N,
1ADD 202519                    JSR load   ;delete and
1AE0
1AE0 A920         spc_3:       LDA #32    ;key in
1AE2 20EEFF                    JSR OSWRCH ;again.
1AE5 C678                      DEC LENG   ;
1AE7 D0F7                      BNE spc_3  ;
1AE9 4CC71A                    JMP keyin_3 ;
1AEC
1AEC 8579         rec:         STA LARGE  ;store input.
1AEE 60                        RTS
1AEF
1AEF                           extend 'ust5'
1AEF              "..........*..........*........................"
1AEF
1AEF              ;******-- KEYBOARD ENTRY --******
1AEF              ; This routine detects the input
1AEF              ; characters for the keyboard.
```

```
1AEF            ;************************************
1AEF
1AEF A93F        line:   LDA #&3F    ;display
1AF1 20EEFF              JSR OSWRCH ;? prompt.
1AF4 A980                LDA #&80    ;&2780 MOD 256
1AF6 8585                STA IADD    ;LSB.
1AF8 A927                LDA #&27    ;&2780 DIV 256
1AFA 8586                STA IADD+1 ;MSB.
1AFC A905                LDA #5      ;max.length of
1AFE 8587                STA IADD+2 ;input char.
1B00 A900                LDA #0      ;min.ASCII value.
1B02 8588                STA IADD+3 ;
1B04 A97F                LDA #&7F    ;max.ASCII value.
1B06 8589                STA IADD+4 ;
1B08 A900                LDA #0      ;
1B0A A285                LDX #&85    ;LSB of input address.
1B0C A000                LDY #0      ;MSB of input address.
1B0E 20F1FF              JSR OSWORD ;
1B11 8478                STY LENG    ;store char. length.
1B13 E678                INC LENG    ;
1B15 E678                INC LENG    ;
1B17 60                  RTS
1B18
1B18            ;***-- MULTIPLY BY TWO --***
1B18            ; This routine doubles the
1B18            ; 24-bit number.
1B18            ;*******************************
1B18
1B18 0682        mult2:  ASL NUM     ;multiply
1B1A 2683                ROL NUM+1   ;by
1B1C 2684                ROL NUM+2   ;two
1B1E 30A7                BMI keyin_3 ;exit if overflow.
1B20 60                  RTS
1B21
1B21            ;***-- PRINT OUT SCREEN --***
1B21            ; This routine prints out the
1B21            ; display on the screen.
1B21            ;*******************************
1B21
1B21 A582        copy:   LDA &82     ;save NUM.
1B23 48                  PHA         ;
1B24 A583                LDA &83     ;
1B26 48                  PHA         ;
1B27 A584                LDA &84     ;
1B29 48                  PHA         ;
1B2A A012                LDY #18     ;enable and
1B2C 202519              JSR load    ;set up printer.
1B2F A9FF                LDA #&FF    ;set low byte for Y axis
1B31 8582                STA &82     ;at Y_low(&82)
1B33 A903                LDA #3      ;and high byte
1B35 8583                STA &83     ;at Y_high(&83).
1B37
1B37 A900        row:    LDA #0      ;set low byte for X axis
```

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```
1B39 8580                  STA &80    ;at X_low (&80)
1B3B 8581                  STA &81    ;and at X_high(&81).
1B3D 20701B                JSR duel   ;640 dots/line image mode.
1B40 A901                  LDA #1     ;next to printer.
1B42 20EEFF                JSR OSWRCH ;
1B45 A90D                  LDA #13    ;return.
1B47 20EEFF                JSR OSWRCH ;
1B4A 38                    SEC        ;
1B4B A582                  LDA &82    ;check minimum
1B4D E920                  SBC #32    ;value for
1B4F 8582                  STA &82    ;Y_low.
1B51 B002                  BCS Echeck ;
1B53 C683                  DEC &83    ;decrement Y_high.
1B55
1B55 A583        Echeck:   LDA &83    ;check for
1B57 C9FF                  CMP #&FF   ;finish.
1B59 D0DC                  BNE row    ;
1B5B A582                  LDA &82    ;
1B5D C9FF                  CMP #&FF   ;
1B5F D0D6                  BNE row    ;
1B61 A014                  LDY #20    ;reset and disable
1B63 202519                JSR load   ;printer.
1B66 68                    PLA        ;
1B67 8584                  STA &84    ;
1B69 68                    PLA        ;
1B6A 8583                  STA &83    ;
1B6C 68                    PLA        ;
1B6D 8582                  STA &82    ;
1B6F 60                    RTS
1B70
1B70 A016        duel:     LDY #22    ;set 640 dots per line
1B72 202519                JSR load   ;in bit image mode.
1B75
1B75 A900        Nbyte:    LDA #0     ;set bits
1B77 8586                  STA &86    ;at &86.
1B79 A980                  LDA #128   ;set byte
1B7B 8585                  STA &85    ;at &85.
1B7D
1B7D A280        pixel:    LDX #&80   ;set X coordinate.
1B7F A000                  LDY #0     ;set Y coordinate.
1B81 A909                  LDA #9     ;read current screen.
1B83 20F1FF                JSR OSWORD ;pixel details.
1B86 A584                  LDA &84    ;get result after
1B88 29FF                  AND #&FF   ;OSWORD call.
1B8A F006                  BEQ step4  ;
1B8C A585                  LDA &85    ;get byte
1B8E 0586                  ORA &86    ;byte OR bits.
1B90 8586                  STA &86    ;
1B92
1B92 38          step4:    SEC        ;
1B93 A582                  LDA &82    ;get Y_low.
1B95 E904                  SBC #4     ;step 4.
1B97 8582                  STA &82    ;store back.
```

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```
1B99 B002                  BCS rotate ;
1B9B C683                  DEC &83    ;decrement Y_high.
1B9D
1B9D 18        rotate:     CLC        ;sent byte by rotating it
1B9E 6685                  ROR &85    ;through carry flag into A.
1BA0 90DB                  BCC pixel  ;
1BA2 A901                  LDA #1     ;print
1BA4 20EEFF                JSR OSWRCH ;out
1BA7 A586                  LDA &86    ;bits.
1BA9 20EEFF                JSR OSWRCH ;
1BAC 18                    CLC        ;
1BAD A582                  LDA &82    ;get Y_low.
1BAF 6920                  ADC #32    ;check overflow.
1BB1 8582                  STA &82    ;
1BB3 9002                  BCC over   ;
1BB5 E683                  INC &83    ;increment Y_high.
1BB7
1BB7 18        over:       CLC        ;
1BB8 A580                  LDA &80    ;get X_low.
1BBA 6902                  ADC #2     ;
1BBC 8580                  STA &80    ;
1BBE 9002                  BCC frog   ;
1BC0 E681                  INC &81    ;increment X_high.
1BC2
1BC2 A581      frog:       LDA &81    ;
1BC4 C905                  CMP #5     ;
1BC6 D0AD                  BNE Nbyte  ;
1BC8 60                    RTS
1BC9
0222                      ORG &222
0222
0222           ;*********-- COMMUNICATION --*********
0222           ; This routine enables the tracker
0222           ; to communicate with the controller
0222           ; and sends out deviation errors to
0222           ; the controller for position error
0222           ; corrections.
0222           ;*************************************
0222
0222 48        send:       PHA        ;save flags.
0223 8A                    TXA        ;
0224 48                    PHA        ;
0225 98                    TYA        ;
0226 48                    PHA        ;
0227 A905                  LDA #5     ;select output
0229 A203                  LDX #3     ;type.
022B 20F4FF                JSR OSBYTE ;
022E A908                  LDA #8     ;set baud rate
0230 A207                  LDX #7     ;to 9600.
0232 20F4FF                JSR OSBYTE ;
0235 A906                  LDA #6     ;suppress
0237 A200                  LDX #0     ;linefeed.
0239 20F4FF                JSR OSBYTE ;
```

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```
023C A996          LDA #&96   ;check
023E A208          LDX #8     ;serial port
0240 20F4FF        JSR OSBYTE ;busy.
0243 98            TYA        ;
0244 2908          AND #8     ;CTS bit low?
0246 D020          BNE sx     ;no, so exit.
0248
0248 A996   outw:  LDA #&96   ;check
024A A208          LDX #8     ;serial
024C 20F4FF        JSR OSBYTE ;port.
024F 98            TYA        ;
0250 2902          AND #2     ;wait for
0252 F0F4          BEQ outw   ;6850 ready.
0254 AD9A27        LDA PRESM  ;retrieve character.
0257 ED9127        SBC SEAM   ;calculate
025A A8            TAY        ;deviation.
025B AD9127        LDA SEAM   ;renew position.
025E 8D9A27        STA PRESM  ;
0261 A997          LDA #&97   ;send
0263 A209          LDX #9     ;charater
0265 20F4FF        JSR OSBYTE ;from Y.
0268
0268 18     sx:    CLC        ;leave routine active.
0269 68            PLA        ;restore
026A A8            TAY        ;registers.
026B 68            PLA        ;
026C AA            TAX        ;
026D 68            PLA        ;
026E 28            PLP        ;
026F 60            RTS
0270
0270
2300               ORG &2300
2300
2300        ;***-- KEYBOARD INTERRUPT --***
2300        ; This routine detects input
2300        ; commands for interrupt.
2300        ;*********************************
2300
2300 08            PHP        ;save
2301 48            PHA        ;registers.
2302 8A            TXA        ;
2303 48            PHA        ;
2304 98            TYA        ;
2305 48            PHA        ;
2306 C01B          CPY #&1B   ;detect key.
2308 D002          BNE retn   ;if not ESC,return.
230A 847A          STY ESC    ;save key number.
230C
230C 68     retn:  PLA        ;restore
230D A8            TAY        ;registers.
230E 68            PLA        ;
230F AA            TAX        ;
```

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```
     2310 68           1377             PLA        ;
     2311 28           1378             PLP        ;
     2312 60           1379             RTS
     2313              1380
     2313              1381 ;******-- LOOK UP TABLE --******
     2313              1382
     2313 0011171C1F23 1383  table:     DB
0,17,23,28,31,35,38,41,45,48,51,53,56,58,62,65,68,72
     2327 50525356575A 1384             DB
80,82,83,86,87,90,92,93,95,96,100,101,103,104,105,10
     2338 6D6F70717273 1385             DB
109,111,112,113,114,115,116,117,118,119,120,121,12
     2346 7C7D7E808283 1386             DB
124,125,126,128,130,131,132,133,134,135,136,137,138,
     2355 8D8E8F919293 1387             DB
141,142,143,145,146,147,148,149,150,151,152,153,153,
     2364 9B9C9D9D9E9E 1388             DB
155,156,157,157,158,158,159,159,160,160,161,161,162,
     2373 A3A3A3A4A4   1389             DB 163,163,163,164,164
     2378 A4A5A5A5A6A6 1390             DB
164,165,165,165,166,166,167,167,168,168,169,169,170,
     2387 ACACADADAEAF 1391             DB
172,172,173,173,174,175,175,176,176,177,177,178,178,
     2396 B4B4B5B5B6B6 1392             DB
180,180,181,181,182,182,183,183,184,184,185,185,186,
     23A5 BBBBBCBCBC   1393             DB 187,187,188,188,188
     23AA BDBDBDBDBEBE 1394             DB
189,189,189,189,190,190,190,190,191,191,191,191,192,
     23B9 C0C0C1C1C1C1 1395             DB
192,192,193,193,193,193,193,194,194,194,194,194,195,
     23C8 C4C4C4C5C5C6 1396             DB
196,196,196,197,197,198,198,199,199,200,200,201,201,
     23D7 CACACBCBCB   1397             DB 202,202,203,203,203
     23DC CCCCCCCDCDCE 1398             DB
204,204,204,205,205,206,207,208,209,209,210,210,211,
     23EB D6D7D8D9DADB 1399             DB
214,215,216,217,218,219,220,221,222,223,224,225,226,
     23FA E5E6E6E7E7E8 1400             DB
229,230,230,231,231,232,232,233,234,235,236,238,240,
     2409 F6F7F8F9FA   1401             DB 246,247,248,249,250
     240E              1402
     240E              1403 ;******-- DEFINE WORD --******
     240E              1404
     240E 2C24         1405  word:      DW mode
     2410 4024         1406             DW hline
     2412 6624         1407             DW move
     2414 6A24         1408             DW par_1
     2416 8F24         1409             DW par_2
     2418 B424         1410             DW par_3
     241A D924         1411             DW disp
     241C 3325         1412             DW com_1
     241E 4E25         1413             DW com_2
     2420 8125         1414             DW print_1
     2422 8B25         1415             DW print_2
     2424 9325         1416             DW print_3
```

```
2426 BE25                          DW arrow
2428 CB25                          DW chara
242A E025                          DW warn
242C
242C               ;******-- DEFINE BYTE --******
242C
242C 16071F000385  mode:           DB 22,7,31,0,3,133,157,129,'
',31,0,6,133,157,129,' '
243C 1F0004FF                      DB 31,0,4,&FF
2440
2440 859D81208D83  hline:          DB 133,157,129,'
',141,131,157,129,'ULTRASONIC SEAM TRA
2461 859D8120FF                    DB 133,157,129,' ',&FF
2466
2466 1F0005FF      move:           DB 31,0,5,&FF
```

```
246A
246A 1F000C283129  par_1:    DB 31,0,12,'(1) Metal
thickness(mm)..........',&FF
248F
248F 1F0010283229  par_2:    DB 31,0,16,'(2) Recording interval(1-
65535)..',&FF
24B4
24B4 1F0014283329  par_3:    DB 31,0,20,'(3) Scale
enlargement(Yes/No)....',&FF
24D9
24D9 160005120401  disp:     DB 22,0,5,18,4,1,25,4,200,0,254,3
24E5 2D2D2D2D2D2D            DB '------ ULTRASONIC SEAM TRACKING GRAPHIC
DISPLAY ---
251B 1904B2034600            DB 25,4,178,3,70,0,'Sweep movement(mm)'
2533
2533 1904AA012000  com_1:    DB 25,4,170,1,32,0,'Press ESCAPE to
hold',&FF
254E
254E 1904B4002000  com_2:    DB 25,4,180,0,32,0
2554 507265737320            DB 'Press RETURN to continue or COPY to
printout',&FF
2581
2581 02011B014101  print_1:  DB 2,1,27,1,65,1,8,1,10,&FF
258B
258B 010C011B0140  print_2:  DB 1,12,1,27,1,64,3,&FF
2593
2593 011B014C0180  print_3:  DB 1,27,1,76,1,128,1,2,&FF
259C
259C 2D3130FF2D38  scale:    DB '-10',&FF,'-8',&FF,'-6',&FF,'-4',&FF,'-
2',&FF,'0',&F
25AE 2B32FF2B34FF            DB
'+2',&FF,'+4',&FF,'+6',&FF,'+8',&FF,'+10',&FF
25BE
25BE 08085345414D  arrow:    DB 8,8,'SEAM',10,8,8,8,224,225,&FF
25CB
25CB 17E00F0F0F0F  chara:    DB 23,224,&0F,&0F,&0F,&0F,&7F,&1F,&07,&01
25D5 17E1F0F0F0F0            DB
23,225,&F0,&F0,&F0,&F0,&FE,&F8,&E0,&80,&FF
25E0
25E0 19045C00B403  warn:     DB 25,4,92,0,180,3,'WARNING: Out of
range!',7,&FF
25FE
25FE                         END
```

No error(s) found

Symbol table:

AMIN---------2792	ARW----------1569	ADDY---------1805	ARROW--------25BE
BLK1---------2800	BLK2---------2900	BACK---------175C	COMP---------1429
COMD---------1457	CAL----------15AF	CHANGE-------1621	CYONE--------16DD
CYTWO--------1756	CTU----------1816	CENTRE-------182A	CUT----------1976
CHAR---------1A58	CHECK--------1AA0	COPY---------1B21	COM_1--------2533

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```
COM_2--------254E CHARA--------25CB DCTR---------0073 DATA---------1498
DELAY--------151E DRAW---------1548 DIV----------17C5 DELAY2-------191E
DIV8---------1A08 DTOH---------1A4A DEL_2--------1AB6 DUEL---------1B70
DISP---------24D9 EVNTV--------0220 ESC----------007A EOC----------14BF
EDGE---------1615 EVENT--------175D ENTRY--------1A1D ECHECK-------1B55
FETCH--------14DC FROG---------1BC2 GREG---------2796 HBDC---------2799
HLAB---------1686 HORIZ--------16E7 HLINE--------2440 INPH---------0070
INDT---------0071 IADD---------0085 IDLE---------1413 ICHK---------1444
INCOM--------146C INPOSN-------148A INIT---------14F0 JOB----------2710
KEYIN_1------1A31 KEYIN_2------1A45 KEYIN_3------1AC7 LCST---------278F
LMID---------2795 LBDC---------2798 LENG---------0078 LARGE--------0079
LPCT---------0080 LOCATE-------15FF LESS---------1610 LOOP---------164E
LESS_6-------179A LOOP_3-------17CB LESS_2-------17EA LOOP_11------17F3
LEFT---------180A LOOP_12------180D LOOP_10------1844 LOOP_16------185C
LOAD---------1925 LOOP_7-------194A LOREF--------198E LSCH---------19A4
LESC---------19B1 LROFF--------19C8 LTRAN--------19D3 LETR---------19D7
LOOP_8-------1A0C LESS_3-------1A17 LINE---------1AEF MODEL--------278E
MID----------2794 MULTR--------007B MULTD--------007C MOD----------1485
MESS---------148D MULT---------1648 MAGN---------1835 MOL----------1877
MEM----------1932 MAG----------1940 MIN----------1953 MULT2--------1B18
MODE---------242C MOVE---------2466 NUM----------0082 NEXT_1-------1697
NEXT_2-------1710 NEXT_6-------195D NOCY---------1A9D NBYTE--------1B75
OSRDCH-------FFE0 OSWRCH-------FFEE OSWORD-------FFF1 OSBYTE-------FFF4
OFFX---------15C1 OFFY---------15E1 OFFSET-------15ED OUTRG--------17BC
OVER---------1BB7 OUTW---------0248 PRESM--------279A PHOS---------0074
PRED---------0075 PHASE--------1512 PLOT---------1530 PT-----------1588
POSTN--------1781 PT3----------18A9 PT2----------18EB PIXEL--------1B7D
PAR_1--------246A PAR_2--------248F PAR_3--------24B4 PRINT_1------2581
PRINT_2------258B PRINT_3------2593 RCST---------2790 REF----------2797
RES----------007D RSM----------144E RETN_D-------14EF RETN_14------15A9
RESET--------16E3 RESLT--------17BE RETN_6-------17C4 RIGHT--------17F0
RETN_15------1829 RETN_20------1876 REC----------1AEC ROW----------1B37
ROTATE-------1B9D RETN---------230C SEAM---------2791 STORE--------0072
START--------1400 SWEEP--------140C SC-----------14BA SMPN---------155A
SMALL--------162C SET----------1630 SAME---------1634 SWAP---------163B
SCREEN-------165E SCOFF--------179D STOP---------19C7 SPC----------1A51
STACK--------1A63 SPC_2--------1ABB SPC_3--------1AE0 STEP4--------1B92
SEND---------0222 SX-----------0268 SCALE--------259C TMOS---------14A2
TERM---------193F TOPCUT-------1974 TRAN---------1A3B TABLE--------2313
UMID---------2793 USCH---------1991 UESC---------199E UOFF---------19C4
UROFF--------19E4 UTRAN--------19F7 UETR---------19FB VDU----------0076
VERT---------1669 VLAB---------1702 WAIT---------152A WORD---------240E
WARN---------25E0 XTEN---------1A76 ZERO---------1655
```

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```
      PROGRAM CHARAC
      DIMENSION ERR(2000),ENUM(2000),DIST(2000)
      HEIGHT=17
      SPEED=1.33
      J=0
      MAXN=0
  100 READ (7,*) (ENUM(I),I=(J*8)+1,(J*8)+8)
      DO 1 I=(J*8)+1,(J*8)+8
        IF (ENUM(I).EQ.9999.) MAXN=I-1
        IF (MAXN.EQ.0) DIST(I)=I*SPEED
    1 CONTINUE
C     SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C     NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
      IF (MAXN.GT.0) GO TO 200
      J=J+1
      GO TO 100
  200 DO 2 I=1,MAXN
         ERR(I)=ENUM(I)
    2 CONTINUE
      PRINT*,'END OF DATA FILE .'
      PRINT*,'NUMBER OF ERRORS =',MAXN,DIST(MAXN)
      PRINT*,'SENSOR HEIGHT =',HEIGHT,'MM'
      PRINT*,'SPEED OF TORCH =',SPEED,'MM/S'
C
C THE GRAPHICS BIT
      CALL GINO
      CALL SAVDRA
      CALL DEVPAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
C
      XO=30.0
      YO=100.0
      XR=200.0
      YR=100.0
      TX=100.0
      TY=YO+YR+10.0
      YS1=YO+60.0
      YS2=YO-15.0
      YS3=YS2-20.0
      YS4=YS2-30.0
      YS5=YS2-40.0
      YS6=YS2-50.0
      CALL AXIPOS(1,XO,YO,XR,1)
      CALL AXIPOS(1,XO,YO,YR,2)
      CALL AXISCA(3,5,0.0,5.0,1)
      CALL AXISCA(3,5,0.0,250.0,2)
      CALL GRID(2,1,1)
      CALL MOVTO2(XO-15.0,YS1)
      CALL CHAANG(90.0)
      CALL CHASTR('PHASE COUNT)')
      CALL MOVTO2(XO+150.0,YS2)
```

```
      CALL CHAANG(0.0)
      CALL CHASTR('SENSOR HEIGHT (MM)')
      CALL MOVTO2(XO,YS4)
      CALL CHASTR('SENSOR HEIGHT: ')
      CALL CHAINT(HEIGHT,3)
      CALL CHASTR('MM')
      CALL GRASYM(DIST,ERR,MAXN,6,0)
      CALL GRAPOL(DIST,ERR,MAXN)
      CALL DEVEND
      CALL GINEND
      STOP
      END
```

```
      PROGRAM DEPLOT
*******************************************************************
*        THIS PROGRAM PRODUCES A PLOT OF DETECTED SEAM          *
*      DEVIATION AGAINST SEAM POSITION OFFSET. IT IS            *
*      INTENTED TO ASSESS THE SENSING ABILITY OF THE            *
*      ULTRASONIC SENSOR (CHAPTER 7).                           *
*******************************************************************

      PARAMETER(NSAMP=30)
      DIMENSION YARRAY(NSAMP),XARRAY(NSAMP)
      INTEGER LAB(11)
      CHARACTER TITLE*70,TYPE*70,HEIGHT*70
      READ(7,100) TITLE,TYPE,HEIGHT
  100 FORMAT(A60)
      DO 200 J=0,3
         READ(7,*) (YARRAY(I),I=(5*J)+1,(5*J)+5)
  200 CONTINUE
      X=-8.0
      DO 300 J=1,17
         XARRAY(J)=X
         X=X+1.0
  300 CONTINUE
C
C THE GRAPHICS BIT
      CALL GINO
      CALL SAVDRA
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
C
      XO=100.0
      YO=110.0
      YL=YO-4.0
      CALL AXIPOS(0,XO,YO,115.0,1)
      CALL AXIPOS(0,XO,YO,115.0,2)
      CALL AXISCA(3,10,-10.0,10.0,1)
      CALL AXISCA(3,10,-10.0,10.0,2)
      CALL AXIDRA(2,1,1)
      CALL AXIDRA(-2,-1,2)
      CALL CHAANG(90.0)
      CALL MOVTO2(90.0,120.0)
      CALL CHASTR('DETECTED DEV. (MM)')
      CALL CHAANG(0.0)
      CALL MOVTO2(110.0,95.0)
      CALL CHASTR('POSITION OFFSET (MM)')
      CALL MOVTO2(30.0,190.0)
      CALL CHASTR(TITLE)
      CALL MOVTO2(60.0,40.0)
      CALL CHASTR('TYPE OF WORK:  ')
      CALL CHASTR(TYPE)
      CALL MOVTO2(60.0,30.0)
      CALL CHASTR('SENSOR HEIGHT: ')
      CALL CHASTR(HEIGHT)
      CALL MOVTO2(60.0,10.0)
      CALL CHASTR('FIG. 7.19 SEAM DEVIATION MEASUREMENTS')
```

```
      CALL GRAPOL(XARRAY,YARRAY,17)
      CALL GRASYM(XARRAY,YARRAY,17,6,0)
      CALL DEVEND
      CALL GINEND
      STOP
      END
```

APPENDIX V

(Program listing for Chapter 8)

```
*****************************************************************
*                                                               *
*      PROGRAM TO EVALUATE THE DEVIATION ERRORS FROM THE        *
*   SEAM TRACKER, AND TO MODEL THE BEHAVIOUR OF VARIOUS         *
*   FEEDBACK GAINS WITH RESPECT TO DIFFERENT SEAM PATHS         *
*   (CHAPTER 8).                                                *
*                                                               *
*****************************************************************


C MAIN PROGRAM ENTRY

      COMMON A1,A2,A3,A4,A5,A6

C DIMENSION MAIN POINT ARRAY

      DIMENSION PT(0:2000,5)
      DIMENSION TORCHX(2001),TORCHY(2001),DEVIAT(2001),
     1PATHX(2001),PATHY(2001)

C ELEMENTS ARE
C 1 = X POSITION
C 2 = Y POSITION
C 3 = ANGLE AT THAT POINT
C 4 = ERROR AT THAT POINT
C 5 = PERCIEVED ANGLE AT THAT POINT (SENSOR DEVIATION)

C SET UP VARAIBLES

C VELOCITY OF TRACKER = 1.0MM/S
      VELOC=1.0E-3
C TIME BETWEEN SAMPLES OR THE RATE SWEEP = 1S
      SAMTIM=1.0
C DISTANCE OF LINE IN FRONT OF TORCH = 20MM
      DFRONT=20.0E-3
C LENGTH OF SWEEP = 10MM
      SLINE=10.0E-3
C DEFINE STEP LENGTH FOR THE ITERATIONS
      STEPLE=1.0E-4

C DEFINE STARTING POINT

C START WITH PREVIOUS PERCIEVED ANGLE OF ZERO

      PT(0,1)=0.0E-3
      PT(0,2)=0.0E-3
      PT(0,3)=0.0E-3
      PT(0,4)=0.0E-3
      PT(0,5)=0.0E-3

C SET UP FUNCTION PARAMETERS
      A1=0.0
      A2=0.0
```

```
      A3=0.0
C PARAMETERS FOR CURVE: A2=1.0E-7, A3=-2.0E-6, A6=2.0E-3
C     A2=+0.1
C     A3=-0.02
      A4=0.0
      A5=0.0
      A6=+2.0E-3

C SET UP FEEDBACK GAINS
      PGAIN=15.0
      DGAIN=10.0

C START AT X = 0 MM
      PT(1,1)= 0.0E-3
C START AT Y = 2 MM
      PT(1,2)= 2.0E-3
C START AT ANGLE OF 00 DEGREES IN RADIANS
      PT(1,3)= 0.0E-3

C START OF PROGRAM

C     WRITE(7,*)' N  XPOS          YPOS          ANGLE          ERROR
C     1 PERCIVED'


C NUMBER OF STEPS
      NUM = 160
C OFFSET POSITION
      XOS = NUM/2
C OFFSET DISTANCE (MM)
      DOS = PT(1,2) + 3.0E-3

C  REPEAT FROM THE FIRST POINT N=1 UNTILL  ARRAY FULL

      DO 1000 N=1,NUM

      IF (N.LT.XOS) THEN
          A6 = PT(1,2)
      ELSEIF (N.GE.XOS) THEN
          A6 = DOS
      ENDIF

C     WRITE(6,*)N

C FIND THE ERROR FOR THIS POINT
C FIRST CHECK IF POINT ON LINE

      POINTY = EVALU (PT(N,1))
      E = PT(N,2)-POINTY

      IF (E .NE. 0.0) THEN

C  SET THE ERROR AT THAT POINT LARGE

        PT(N,4)=1E70
```

```
          TPX = PT(N,1)
          RNG = ABS(PT(N-1,4)) + (1.2*SAMTIM * VELOC)
          ESTEP = STEPLE
          CALL ERROR(TPX,RNG,ESTEP,PT(N,1),PT(N,2),PT(N,4))
          RNG = 1.0*ESTEP
          ESTEP = ESTEP/10.0
          CALL ERROR(TPX,RNG,ESTEP,PT(N,1),PT(N,2),PT(N,4))
          RNG = 1.0*ESTEP
          ESTEP = ESTEP/100.0
          CALL ERROR(TPX,RNG,ESTEP,PT(N,1),PT(N,2),PT(N,4))
          RNG = 1.0*ESTEP
          ESTEP=ESTEP/1000.0
          CALL ERROR(TPX,RNG,ESTEP,PT(N,1),PT(N,2),PT(N,4))

        ELSE

          PT(N,4) = 0.0

        ENDIF

        YPT=EVALU(PT(N,1))
        VALUE=YPT-(PT(N,2))
        IF (VALUE .LT. 0.0) THEN
          PT(N,4)=-1.0*PT(N,4)
        ENDIF

C EXIT WITH THE MINIMUM ERROR FOR THIS POINT STORED


C NEXT FIND THE POSITION OF THE LASER LINE
C POINT GIVEN BY POSITION AND ANGLE OF THE TORCH
        CLX=PT(N,1)+(DFRONT*(COS(PT(N,3))))
        CLY=PT(N,2)+(DFRONT*(SIN(PT(N,3))))

C       WRITE(6,*)'CLX,CLY',CLX,CLY

        IF ((EVALU(CLX)-CLY) .NE. 0.0) THEN


C REPEAT THIS LOOP TO FIND THE POINT ON THE LINE

          OLDDIF = 1.0E70
          BASEL = (DFRONT**2)
          TPX = CLX
          RNG = SLINE
          TSTEP = STEPLE
          CALL POINT(TPX,RNG,TSTEP,CLX,CLY,PT(N,1),PT(N,2),BASEL,
     C    OLDDIF)
          RNG = 1.0*TSTEP
          TSTEP = TSTEP/10.0
          CALL POINT(TPX,RNG,TSTEP,CLX,CLY,PT(N,1),PT(N,2),BASEL,
     C    OLDDIF)
          RNG = 1.0*TSTEP
```

```
      TSTEP = TSTEP/10.0
      CALL POINT(TPX,RNG,TSTEP,CLX,CLY,PT(N,1),PT(N,2),BASEL,
     C OLDDIF)
      RNG = 1.0*TSTEP
      TSTEP = TSTEP/100.0
      CALL POINT(TPX,RNG,TSTEP,CLX,CLY,PT(N,1),PT(N,2),BASEL,
     C OLDDIF)

C CALCULATE LENGTH BETWEEN SEAM AND CENTRE OF LINE
      X = TPX
      Y = EVALU(X)
      ALENGT=SQRT(((CLX-X)**2)+((CLY-Y)**2))

     ELSE

      X = CLX
      Y = CLY
      ALENGT = 0.0

     ENDIF

     PT(N,5)=ALENGT

C FIND GRADIENT BETWEEN TORCH AND POINT ON THE SEAM W.R.T.X
     GRAD1=((CLY-PT(N,2))/(CLX-PT(N,1)))
     GRAD2=((Y-PT(N,2))/(X-PT(N,1)))

     IF ((GRAD2-GRAD1).LE.0.0) THEN
       PT(N,5)=-1.0*PT(N,5)
     ENDIF


     TRAV = SAMTIM * VELOC

     PT(N+1,1)= PT(N,1)+ (TRAV * (COS(PT(N,3))))
     PT(N+1,2)= PT(N,2)+ (TRAV * (SIN(PT(N,3))))
     PT(N+1,3)= FEEDBA(PT(N,3),PT(N,5),PT(N-1,5),PGAIN,DGAIN)

 1000 CONTINUE

C PRINT OUT THE RESULTS

     DO 2000 N=1,NUM
C    WRITE(7,1050) N, PT(N,1), PT(N,2), PT(N,3),PT(N,4),PT(N,5)
     IF (N.LT.XOS) THEN
         A6 = PT(1,2)
     ELSEIF (N.GE.XOS) THEN
        A6 = DOS
     ENDIF
     PATHX(N)=N * SAMTIM * VELOC
C    DEVIAT(N)=PT(N,4)
     DEVIAT(N)=PT(N,5)
     PATHY(N)=EVALU(PATHX(N))
     TORCHX(N)=PT(N,1)
     TORCHY(N)=PT(N,2)
```

```
C1050 FORMAT(I4,5E13.6)

 2000 CONTINUE

      WRITE(7,191) (DEVIAT(I),I=1,NUM)
 191  FORMAT(4(E13.6,','), E13.6)
C THE GRAPHICS PART
C
      CALL GINO
      CALL SAVDRA
      CALL DEVPAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
      CALL AXIPOS(0,30.0,190.0,118.0,1)
      CALL AXIPOS(0,30.0,190.0,60.0,2)
      CALL AXISCA(3,16,0.0,PATHX(NUM),1)
      CALL AXISCA(3,6,0.0E-3,6.0E-3,2)
      CALL LINCOL(10)
      CALL GRAPOL(PATHX,PATHY,NUM)
      CALL BROKEN(2)
      CALL LINCOL(1)
      CALL GRAPOL(PATHX,TORCHY,NUM)
      CALL BROKEN(0)
      CALL MOVTO2(30.0,220.0)
      CALL CHASTR('SEAM PATH')
      CALL MOVTO2(100.0,200.0)
      CALL CHASTR('TORCH POSITIONS')
      CALL MOVTO2(30.0,150.0)
      CALL CHASTR('SIMULATED SEAM PATH AND TORCH POSITIONS')
      CALL AXIPOS(0,30.0,70.0,118.0,1)
      CALL AXIPOS(0,30.0,70.0,60.0,2)
      CALL AXISCA(3,16,0.0,PATHX(NUM),1)
      CALL AXISCA(3,6,-3.0E-3,3.0E-3,2)
      CALL AXIDRA(1,1,1)
      CALL AXIDRA(-1,-1,2)
      CALL LINCOL(1)
      CALL GRAPOL(PATHX,DEVIAT,NUM)
      CALL CHAANG(90.0)
      CALL MOVTO2(5.0,30.0)
      CALL CHASTR('SENSOR DEVIATION (M)')
      CALL CHAANG(0.0)
      CALL MOVTO2(80.0,30.0)
      CALL CHASTR('SEAM DISTANCE (M)')
      CALL MOVTO2(50.0,90.0)
      CALL CHASTR('ZERO LINE REPRESENTS THE SEAM')
      CALL MOVTO2(5.0,10.0)
C     CALL CHASTR('FIG.8.1  SEARCHING FOR A STRAIGHT LINE SEAM')
C     CALL CHASTR('FIG.8.1  TRACKING OF A DISTORTED SEAM')
      CALL CHASTR('FIG.8.1  TRACKING OF AN OFFSET SEAM')
      CALL DEVEND
      CALL GINEND
      STOP
```

```
      END
C
C
      SUBROUTINE ERROR(X1,X2,D,X0,Y0,E0)
C SET SAMPLING RANGE
      EMIN = X1 - X2
      EMAX = X1 + X2
C FIND ERROR
      DO 30 X=EMIN,EMAX,D

      Y = EVALU(X)
      E = SQRT(((Y-Y0)**2) + ((X-X0)**2))
      IF (E .LT. E0) THEN
         E0 = E
         X1 = X
      ENDIF
   30 CONTINUE
      END

      SUBROUTINE POINT(X1,X2,D,CX,CY,X0,Y0,BL,OD)
C SET SAMPLING RANGE
      TMIN = X1 - X2
      TMAX = X1 + X2
C FIND POINT ON THE SEAM
      DO 40 X=TMIN,TMAX,D

      Y=EVALU(X)

      RX = X0-X
      RY = Y0-Y
      RLENGH = (RX**2) + (RY**2)

      SX = CX-X
      SY = CY-Y

      SLENGH = (SX**2) + (SY**2)

      DIF =ABS(RLENGH - BL - SLENGH)

      IF (DIF .LT. OD) THEN
        OD = DIF
        X1 = X
      ENDIF
   40 CONTINUE
      END
C

      FUNCTION EVALU(X)

      COMMON A1,A2,A3,A4,A5,A6

C THE FUNCTION THAT DESCRIBES THE LINE OR PATH TO TRACK
      EVALU=(A1*X**3)+(A2*X**2)+(A3*X)+(A4*SIN(A5*X))+A6
      RETURN
      END
```

```
C THIS ROUTINE CALCULATES THE NEW ANGLE

      FUNCTION FEEDBA(OLD,PER,OLDPER,PGAIN,DGAIN)
      FEEDBA=OLD+PGAIN*(PER)+DGAIN*(PER-OLDPER)
      RETURN
      END
```

```
**************************************************************
*                                                            *
*       THIS PROGRAM PRODUCES PLOTS FOR THE COMPUTER        *
*    SIMULATIONS AND EXPERIMENTAL RESULTS.                   *
*                                                            *
**************************************************************
C
      PROGRAM OSROT
      DIMENSION ERR(600),ENUM(600),DIST(600)
      CHARACTER TITLE*60,TYPE*60,JOB*60,PATH*60
      INTEGER HEIGHT
      READ (7,'(A)') TITLE,JOB,PATH
      READ (7,*) HEIGHT,SPEED
      PRINT*,TITLE
      PRINT*,JOB
      PRINT*,PATH
      PRINT*,HEIGHT
      PRINT*,SPEED
C
      XO=30.0
      YO=25.0
      XR=118.0
      YR=118.0
      TX=103.0
      TY=272.0
      CALL GINO
      CALL SAVDRA
      CALL DEVPAP(280.0,280.0,0)
      CALL WINDO2(0.0,280.0,0.0,280.0)
      CALL SOFCHA
      CALL CHASIZ(3.0,3.0)
      CALL MOVTO2(TX,TY)
      CALL CHASTR(TITLE)
      DO 1000 ISET=1,4
         READ (7,'(A)') TYPE
         PRINT*,TYPE
         J=0
         MAXN=0
  100    READ (7,*) (ERR(I),I=(J*5)+1,(J*5)+5)
         DO 200 I=(J*5)+1,(J*5)+5
            IF (ERR(I).EQ.999.) MAXN=I-1
            IF (MAXN.EQ.0) DIST(I)=I*SPEED
  200    CONTINUE
C        SINCE ERROR PER SWEEP TAKES ONE SECOND, THUS,
C        NUMBER OF ERRORS * SPEED = DISTANCE TRAVELLED.
         IF (MAXN.GT.0) GO TO 300
         J=J+1
         GO TO 100
  300    PRINT*,'END OF DATA FILE ...',ISET
         PRINT*,'NUMBER OF ERRORS =',MAXN
         PRINT*,'DISTANCE TRAVELLED=',DIST(MAXN)
         PRINT*,'OFFSET=',ISET-1
C
```

```
C THE GRAPHICS BIT
C
        IF (ISET.EQ.1) THEN
           XSHIFT=0.0
           YSHIFT=YR+4.0
        ENDIF
        IF (ISET.EQ.2) THEN
           XSHIFT=XR+4.0
           YSHIFT=YR+4.0
        ENDIF
        IF (ISET.EQ.3) THEN
           XSHIFT=0.0
           YSHIFT=0.0
        ENDIF
        IF (ISET.EQ.4) THEN
           XSHIFT=XR+4.0
           YSHIFT=0.0
        ENDIF
        ORX=XO+XSHIFT
        ORY=YO+YSHIFT
        XS1=XO+XR+4.0
        YS1=15.0
        XS2=XO
        YS2=YS1
        WX=ORX+10.0
        WY=ORY+10.0
        DX=XS2
        DY=8.0
        PX=XS1
        PY=DY
        HX=XS2
        HY=1.0
        SX=XS1
        SY=HY
        CALL AXIPOS(1,ORX,ORY,XR,1)
        CALL AXIPOS(1,ORX,ORY,YR,2)
        CALL AXISCA(3,16,0.0,DIST(MAXN),1)
        IF (ISET.LT.3) THEN
        CALL AXISCA(3,10,-5.0E-3,5.0E-3,2)
        ENDIF
        IF (ISET.GE.3) THEN
         CALL AXISCA(3,10,-50.0,50.0,2)
        ENDIF
        CALL LINCOL(3)
        CALL GRID(2,0,0)
        CALL LINCOL(1)
        CALL MOVTO2(WX,WY)
        CALL CHASTR(TYPE)
        CALL GRAPOL(DIST,ERR,MAXN)
 1000 CONTINUE
      CALL MOVTO2(XS2,YS2)
      CALL CHASTR('VERTICAL: SENSOR DEVIATION (-5MM TO +5MM)')
      CALL MOVTO2(XS1,YS1)
      CALL CHASTR('HORIZONTAL: DISTANCE (0 TO 160MM)')
      CALL DEVEND
```

```
      CALL GINEND
      STOP
      END
```