DEVELOPMENT OF A REAL-TIME ULTRASONIC SENSING SYSTEM FOR AUTOMATED AND ROBOTIC WELDING

by

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DECLARATION

No part of the work described in this thesis was performed in collaboration with anyone else, except where specifically stated. Although advice and help was sought and received from a number of people, all the work described herein is my own.

Acknowledgements have been given to the people whose advice and aid was sought.

This work has not been submitted before for any other award to this, or any other, University.

E. Siores

Dedicated to my wife Dawn.

For myself, I am interested in science and in philosophy only because I want to learn something about the riddle of the world in which we live and the riddle of man's knowledge of that world.

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ABSTRACT

The implementation of robotic technology into welding processes is made difficult by the inherent process variables of part location, fit up, orientation and repeatability. Considering these aspects, to ensure weld reproducibility consistency and quality, advanced adaptive control techniques are essential. These involve not only the development of adequate sensors for seam tracking and joint recognition but also developments of overall machines with a level of artificial intelligence sufficient for automated welding.

The development of such a prototype system which utilizes a manipulator arm, ultrasonic sensors and a transistorised welding power source is outlined. This system incorporates three essential aspects. It locates and tracks the welding seam ensuring correct positioning of the welding head relatively to the joint preparation. Additionally, it monitors the joint profile of the molten weld pool and modifies the relevant heat input parameters ensuring consistent penetration, joint filling and acceptable weld bead shape. Finally, it makes use of both the above information to reconstruct three-dimensional images of the weld pool silhouettes providing in-process inspection capabilities of the welded joints.

Welding process control strategies have been incorporated into the system based on quantitative relationships between input parameters and weld bead shape configuration allowing real-time decisions to be made during the process of welding, without the need for operation intervention.

1. INTRODUCTION

Welding is the most widely used metal joining technique in the fabrication of structures today. Conventionally, however, welding fabrication has been a labour-intensive manual operation that requires high levels of operator skill and dexterity. Furthermore, since welding technique may vary widely from welder to welder, the repeatability and consistency of manual welding has been rather low. Due to the significant degree of human involvement, automation of welding fabrication is essential to improve productivity, reduce costs and assure repeatable high-quality welds.[1] Effective automation of welding is, however, more complicated than attaching a torch to a mechanical manipulator and simply providing means for following a pretaught path.[2]

Specifically, the potential for fixturing inaccuracies requires some parts locating capability and appropriate offsetting of pre-taught paths before welding starts. This process is typically referred to as part finding. In additon, part-to-part dimensional variations, edge preparation tolerances and in-process thermal distortions produce the requirements for some means of real-time corrections to the pre-taught welding path. Such corrections are possible by sensing the actual seam location during welding. This process is typically referred to as joint or seam tracking.[3]

Simple corrections to the welding path alone are not sufficient for truly automated welding. Initial welding conditions (current, wire feed rate, travel speed, torch position and orientation in the joint etc.) may need to be corrected to compensate for variations in the joint geometry (including fill volumes, root opening, edge preparation and penetration).[4] Additionally, for complete automation of the welding fabrication process, process selection problems and post weld inspection and quality assurance, must also be considered.

Modern automated and robotic welding systems employ some kind of sensory devices of which most are capable of locating the joint and following the seam and some of measuring the dimensions of the weld joint.[5] More recent research efforts in the area are orientated towards the development of sensors to provide suitable information to guide the welding head along a seam, determine the extent of any random or systematic joint variations and modify the weld parameters accordingly. Such adaptive systems (Figure 1), will form the basis for the development of new robotic generations which will possess increasingly high levels of artificial intelligence.[6]

Major objective of the present work was to develop a fully automated welding system with a level of artificial intelligence. Requirements that such a system must fulfil included the following:

1. It must withstand the harsh environment of the welding process.
2. It should be usable by non-specialist personnel.
3. It must operate in real-time.
4. It ought to provide three-dimensional information on the seam geometry and joint fit-up.
5. It should be versatile and applicable to various weld geometries, welding techniques and different materials.
6. Its cost must constitute a small fraction of the total cost of the arc welding system.

Work described in this thesis is the development of such a system using ultrasonic sensors, possessing all the above required functions. Experimental investigations and theoretical developments are described all of which revolve around the welding process monitoring and control. A detailed descussion on the above mentioned sensory system is included and further work required as well as future developments are contained. Finally, the protype system is assessed and evaluated and its potential uses are outlined.

2. LITERATURE SURVEY

2.1 BACKGROUND

In the early days of mechanised arc welding it was usual for the operator to play an active part in controlling the process. At this time the responsibilities may have included tasks such as head steering, height adjustment and resetting parameters, (such as wire feed rate, current, voltage etc) as necessary. Over the last few years, the degree of mechanisation in welding has steadily increased to improve both quality and productivity and many systems are steadily automated to the point where the operator's function is mainly supervisory during welding.[7] Arc welding an increasingly updating process lately received an automating treatment and today is generally regarded as an automatic process where the welding parameters are preset or controlled during the welding operation. The intention of automation in welding was to extend beyond the capabilities of human welder in terms of speed, accuracy, consistency, resistance to fatigue and cost of production.[8]

With the vigorous increase of automated systems and their applications into much demanding welding production lines, the urge for robotisation flourish. Important factors contributing to these were; a desire to manufacture products with high and even quality, shortage of skilled operators, the strive to increase productivity and a growing concern for the working environment.[9] Use of these flexible manufacturing systems for welding is still limited to workpiece misalignments whose tolerances lie within very narrow limits.[10] This is a major technical drawback on the automation of the entire welding process. On the other hand if it was possible to detect succesfully the out of tolerance workpiece variations occurring in practice, suitable corrections could be made automatically in the welding path and/or welding parameters.

Answers to this dilema were supplied with the development of process detection sensors[11] which enhanced both the intelligence of this automation and application horizons for robotic welding. Corrections for both weld path deviations and inappropriate welding variables are now possible through various types of adaptive controls. Each workpiece can be measured prior to and during welding. Welding data being determined can then be processed in the robot controller and its basic input programme being overridden and corrected as necessary.

In this chapter, difficulties associated with automated arc welding are outlined along with developments in welding equipment hardware. Employment of microcomputer control for welding is reviewed and its dependence on feed-back control for successful applications examined. Problems unique to weld sensing are identified and sensor requirements are categorised. The most common current approaches of weld sensing are covered and their advantages and disadvantages considered. Some elements of the theory of ultrasound as a means of inspection are presented and attention is focused on the automated process inspection developments. The importance of ultrasonic inspection in welding is outlined and updated techniques are considered all of which concentrate on specialised transducer design and various sources of generating ultrasound.

2.2 WELDING AUTOMATION

2.2.1 Automatic Versus Automated Welding

With respect to modern fabrication techniques, the notions of "automatic" and "automated" welding give rise to mixed feelings in today's production and conditons.[12] It is therefore, worthwhile to study objectively these matters in the light of the facts, to estimate the possibilities and limitations involved.

Automated welding and automatic welding have much in common.[13] There are many similarities but there is a major difference. Automatic welding involves elaborate dedicated fixturing with tooling, work holding devices, and accurate part location and orientation. It also involves elaborate welding arc movement devices with predetermined sequences of welding parameter changes and the use of limit switches or timers to form the weld joints. Automated welding is being employed in high volume of production industries where the cost of equipment is justified by the large number of pieces to be made. Automation in welding reduces manpower requirements, repeatably produces consistent welds, maintains production schedules, and reduces the cost of parts welded. One major disadvantage is the high inititial cost of welding machine involved. Another disadvantage is the need to keep automatic equipment occupied continuously. A further disadvantage, when used for lower volume of production is the need to provide numerous dedicated fixtures for various parts.

Automated welding eliminates elaborate, expensive fixtures, and the automatic timer or limit switch input necessary to control the arc with respect to workpiece. It incorporates a program which replaces the complex fixturing and sequencing devices. Automated welding provides the same time saving and precision welding as automatic welding, yet can be applied to small-lot production even to production of a single part. In addition, it has quick change capability and can accommodate products without the necessity of redesigning and reworking the expensive fixtures.

Automated welding utilizes programs coupled to a welding arc travel device of extreme capabilites. The arc motion device can be capable of moving in three directions: longitudinal, transverse, and vertical. Additional welding positions can be obtained if the work is mounted on a positioner that rotates and tilts if required. However, if arc travel in all of these directions is accomplished within the range of the equipment and adjustments to the welding parameters are being made during process then full control is achieved.

This is flexible automation[14] and it reduces tooling and fixtures to a minimum (Figure 2). It allows welding of complex parts for small lot production and provides welding accuracy and speed with repeatable quality and cost. Weldments are located and held at the correct position with respect to the torch. Dedicated programming is then initiated and the weld is made completely without human assistance. Human element is involved during loading and unloading of the weldment from its locating fixture.

Automation aims to employ a universal automated machine (Figure 3) which will weld various weldments.[15] Coupling a robot welder to either a numerically controlled or microcomputer command unit provides an answer. Employing a robot arm and providing a work-holding fixture, programs can be developed to weld each part whenever needs be manufactured.[16] Various locating fixtures may be brought to it in preparation for welding the parts in question. Process control is available for each part and is used for correctly welding the part. Set up time is minimal and robot arm is kept busy on a full-time base capable of doing different types of "jobs". It only needs a positive locating point to align the robot welding torch with the part being welded and then utilising a microcomputer/controller to program it accordingly. Working on "teach mode" and traversing the welding torch along the welding joint by human control the motions are built into the machine, these manouvres being represented by analogue signals and subsequently stored in the controller's memory to be reproduced at a later stage when welding commences. In addition, a computer controller is used to change welding parameters during the welding operations if required.[17]

2.2.2 Problems Associated with Automated Welding

A universally applicable automated welding system must accommodate a great many variations in welding tasks.[18] It should handle a wide range of materials prepared in a variety of ways and also being capable to carry out repairs.[19] Different thicknesses of the parts impose different constraints on the welding process. For thin sheet, high accuracy and repeatability is required to achieve a small weld size, whereas for thick sheet, controlling the welding parameters to cope with variations in gap width is regarded as the first priority. Not only must the automated system satisfactorily handle complicated weld patterns, it must also be adaptable to the various joint types, execute multiple pass welding where appropriate and follow the seams even if previous tack welds are present.

Welding process is demanding of equipment and, if an automated system is to prove acceptable in practice, it must be sufficiently robust to perform reliably and continuously.[21] Welding requirements can be classified in three broad areas; manipulation and positioning, weld placement and weld quality.

Automated welding systems are capable of manipulating either or both the torch and the workpiece to achieve a satisfactory weld. The mechanical structure (robot) which manipulates the torch must have the necessary working volume mobility (degree of freedom) to access all the weld points without colliding with the workpiece while maintaining the appropriate attitude of the torch relative to the seam. Manipulators, also must be capable of performing weave patterns and meet various requirements such as positional accuracy, repeatability and travel speed.[22] Jigs and fixtures should also be controlled so that a wide range of parts can be accommodated with minimum set-up and change-over time. However, even if the manipulator positioning system is pre-programmed for the weld sequence and even if one had perfect fixtures which would ensure repeatability of component placement, satisfactory welding would not be assured. Workpiece and dimensional tolerance variations are inherent in welding.[23]

Automated welding systems must be able to detect and compensate for such variations in the working environment. Product quality requires both that the weld is correctly placed and that itself meets quality requirements (such as penetration, porosity inclusions, appearance, etc.).[24] These two aspects of joint tracking and weld sensing are process interelated issues. Weld quality is controlled by sensing either directly or indirectly the various welding parameters involved in the process.[25]

Welding variables for arc welding are well established and categorised. Electrode type and shielding methods are usually the basic considerations and are dictated by the required weldment mechanical properties. Electrode size is related to weld joint geometry, the current recommended for a particular job and additionally the number of passes. Electrode polarity is established initially and is based on whether maximum penetration or maximum deposition rate is required.[26]

Weld pool size depends on the heat input involved, which in turn, depends on process parameters (i.e. welding current, arc voltage, travel speed and wire feed speed.). For single pass welds current and travel speed dominate the penetration depth. Selection of current and choice of travel speed are based on electrode size. Furthermore, arc voltage dominates the bead width and has an influence on penetration since it controls arc shape.[27]

Secondary variables include: angle of electrode to the workpiece, angle of workpiece itself, amount of shielding means and, most important, distance between current pick up tip and the arc. This is called electrode "stickout" and has a considerable effect on the weld pool shape.[28]

It can be therefore clearly visualised that close control of the above mentioned interelated welding variables should be applied in a form of monitoring and feeding back into the process to achieve full automation.

2.2.3 Developments in Welding Power Sources

Power sources are based on two types of process control:[29]

A) Synergic Control, where the power source and wire feed unit is linked together in such a way that the mean current is determined by the wire feed speed or vice-versa. As the wire feed speed is matched by the burn off rate, stable conditions are achieved, with the voltage varying according to the arc length used.

B) Voltage Control, where a reference voltage is normally chosen to correspond to a given arc length. As the arc length changes during welding, the mean current is also varried to maintain optimum burn off and hence restore the original voltage.

As modern power supplies are capable of direct control by electronic means, the overall output of the power supply is essentially capable of closed loop feedback control. When current feedback is used, the output characteristic is nominally constant current (C.C.), whilst when voltage feedback is employed, the output characteristic is nominally flat or constant potential (C.V.). Voltage/current characteristics of intermediate slopes are obtained by combinging current and voltage feedback in suitable proportion.

With regard to electrical design and operating characteristics, power supplies for arc welding are categorised into three groups (Figure 4):

A) Transistor Series Regulator which are characterised by banks of transistors acting as variable resistors on the DC side of a transformer/rectifier power source. Additional smoothing is often provided by capacitors to allow operation at high rates of current change. These power sources normally provide the highest accuracy and repeatability together with the highest frequency response. Substantial power is dissipated in the regulator, which therefore requires water cooling.

B) Switched - Mode which are essentially similar to the above. However, few transitors are used and hence are generally operated in a switched mode, either conducting or turned off allowing a considerable reduction in power dissipation. An additional smoothing circuit comprising inductance and flywheel diode is necessary to allow current continuity. Accuracy and repeatability are generally good with high frequency response.

C) Primary Invertor which are lightweight and compact power supplies with the normal values frequency transformer/rectifier design. Mains supply is first rectified and stored by a capacitor. Switching transistors or thyristors are then used for converting the medium voltage DC to high frequency AC. This high frequency AC is subsequently transformed down and rectified to provide DC operation at welding current and voltage levels. These relatively new systems are accurate and highly energy efficient.

It is envisaged that the progress of solid state controlled power sources has been advancing rapidly. As the reliability and availability of electronic hardware has improved, the accuracy and repeatability of the new power sources and wire feed mechanisms have also improved, resulting in high performance and inexpensive welding process equipment.[30]

2.2.4 Robotic/Flexible Manufacturing Welding

A robotic manipulator may be defined as a multidegree of freedom open-loop chain of mechanical joints and it is designed to perform mechanical operations which normally require the manipulative skills of humans (Figure 5).[31] Robots normally consist of a power supply, a robot arm and a controller. This controller is capable of initiating and terminating arc motions in a desired sequence and at desired points and store these data in a memory array. All controllers are microprocessor based and their complexity reflects upon the robot's capabilities.

Robots can be either non-servo or servo controlled. Non-servo controlled robots move their arm in an open loop fashion between determined trajectories in accordance with fixed limits. Servo controlled robots incorporate feedback devices that continuously monitor the position of each axis and therefore enable the arm to be positioned anywhere within the total working range. According to the level of sophistication, servo controlled robots can be subdivided into three main groups:

A) Point-to-point control where each joint is monitored by an independent position servo system with all axes moving from position to position independently.

B) Continuous path control where each joint is moved a minimum amount to achieve a desired final position, thus giving the end of the robot arm, a controlled predictable path. All the axes variables are interpolated to make all the joints move simultaneously, thus giving a coordinated joint motion. This type of control is the basis of to day's industrial robots.

C) Cartesian motion control where locations are expressed in terms of cartesian coordinates (X,Y,Z) and orientation angles of the end effector relative to a reference frame fixed in the base of the manipulator arm. Cartesian motions are achieved by applying an interpolating function to the cartesian location of the manipulator's tool tip and transforming the interpolated tool tip location to joint commands. Kinematic equations of motion requires solving in real time to enable the operator to concentrate on the desired end effector motion rather than the motion required at the axes.

Due to increased sophistication in industrial robots, programmable mechanised welding is now possible. Robots are fast becoming a strong influence in a field that previously was largerly manual or mechanised.[32] Robotic systems offer increased productivity, product quality, safety and economic return and have proven track record in many applications. Industrial welding robots available have different specifications and capabilities and to select the appropriate, one has to know their characteristics. Robot's working volume and it's axes of freedom must be matched to the welding preparation sizes and shapes. Repeatability should be evaluated against weld size, expected quality level, part fit-up, location tolerances and also process used. Many industrial robots are now interfaced directly to the welding power supplies and therefore welding parameters pre-programmed directly during the robot teach period. Additionally, robots should be equipped with adequate input/output capabilites together with interfaces to other computers for off-line programming or sensory feedback.[33]

Considering the above requirements, however, complex jigging and accurate joint preparations may still be necessary. To overcome this problem, more sophisticated robot units are equipped with sensory feedback to permit seam following and adaptive process control to be achieved.[34-40]

2.3 COMPUTER AIDED WELDING

To simplify the setting of the welding process, the use of one knob control system is desirable. The most used method to implement the control circuitry is by means of analogue components like operational amplifiers and resistor network. The main problem with this solution is inflexibility and high cost if many synergic relationships are required.[41] Use of a microprocessor (micro controller) (Figure 6)with adequate auxiliary components is often the way to go (Figure 7).

Applications of microcomputers to welding control systems include:

Power Source Control.
Welding System control.
Process Monitoring.
Process Control.

2.3.1 Power Source Control

The way in which the microprocessor is used to control a welding power supply varies widely. However, it is interesting to consider the basic requirements of such a system in an attempt to classify its potential applications.

Operator interfaces, comprising analogue to digital and vice versa (A/D, D/A) converters, translate the welding parameters sellected into a form understood by the control system. In electronically controlled power sources a signal voltage is generated whilst for microprocessor control systems the signal input is digital.

Data storage units used are of magnetic tape, floppy disk or alternatively of non-volatile memory devices such as EPROMS.[42]

Waveform generators process the information collected by operator interface and data storage units to provide appropriate instructions for the power source output. In a simple unit this may only involve the translation of data stored on EPROM into an appropriate form to control output levels by providing a reference voltage. This is accomplished in the machine interface stage. Output is then maintained at the level required by conventional electronic circuitry (feed back and control by a comparator). In more sophisticated units a high speed microprocessor is incorporated in this section to enable the output sequence and output levels to be monitored and controlled by the microprocessor.[43] The accuracy of the output in this situation is obviously dependent on the processing speed and resolution of the control processing unit. Output signals from the waveform generator are adapted to the requirements of the power control system by the machine interface. Two main types of power sources have emerged based on the above principles:

i) EPROM memory pre-programmed.
ii) Fully programmable.

Recent welding units incorporate an EPROM memory in the control system which is used to store optimum welding parameters for the selected current values. The operator selects a wire type and size from the control panel. From this information the control unit selects an appropriate table of welding parameters from the EPROM. In the simplest case the EPROM may be "read" by conventional electronic logic devices and it may not be necessary to use a central processor at all. When the welding current is adjusted an optimised set of values of pulse parameters and wire feed speed are produced. Simplicity of control is the main advantage of this type of power supply and reduces the possibility of incorrect settings and consequent defective welds.

In fully programmable devices the operator may set up a table of parameters, and an interval for which these parameters should be maintained. Alternatively the system may be set to wait for an input signal. Once set, the table of parameters may be identified with a "job" number and may be reselected by simple remote control.[44] Offline storage of welding parameters may be achieved with floppy disks or EPROM devices. This type of system may be interfaced with a wide range of power source types the main requirement being a method of controlling the output from a low power electronic signal (0-10 Volts).

2.3.2 Robotic System Control

Principles of the fully programmable power source control discussed above may be extended to cover the manipulation systems used in automatic welding. In this case the microprocessor needs to control the speed and position of several drive motors in addition to the welding parameters. With dedicated welding heads such as orbital or linear tractors this may utilise the technique described above (i.e. welding, speed and position parameters are preset in a tabular form via the controller). To simplify data entry a second microprocessor may be incorporated in the operator interface. For example in a welding system, one microcomputer may be used to provide "menu driven" data entry facility while a second computer configured as a waveform generator controls the welding system; this includes control of different axes of motion, together with facilities for process monitoring The system may be built in a modular basis and scaled up to increase the number of control functions. If it is necessary to program movement directly, this may involve driving each axis around the weld path by means of a joystick or cursor type control buttons and the positioning data are stored separately.

2.3.3 Process Monitoring

Use of microprocessor controlled data acquisition devices (data loggers) has been common in the process control area and computer based devices dedicated to the collection of welding data have become available.[45] These devices fall into three groups:

i) Average parameter monitoring
ii) Output waveform analysis
iii) Transient parameter monitoring.

Mean values of arc current, voltage, wire feed speed and plate temperature may be required during the development, cost analysis and control of a welding procedure or during investigation of process problems. These parameters may be measured with conventional meters but the use of microprocessor based system offers the additional capability of raw data manipulation, data storage, facilities to set alarm levels and hard copy of data.

Several workers[46] have attempted to quantify the stability of welding processes by examining the regularity of transient events in the process. This entails analysis of the welding waveform and calculation of statistical criteria. Simple software can be derived to enable data to be displayed as a stability criteria or graphically as a relationship between a specified variable and a stability factor.

2.3.4 Process Control

Despite the growing use of automation, commercial welding today is far from being an exact science. Automated and robotic systems generally fail to compensate adequately for random variations in the workpiece or the welding conditions (Figure 8) and quality control depends largerly on the non-destructive testing of completed welds.

The difficulty facing conventional automated welding systems is the sheer number of variables that need to be controlled (Figure 9). A typical arc welding process, for example, may be subject to variations in arc efficiency, arc voltage, traverse rate, filler-wire position and feed rate, electrode geometry, thickness and alignment of the joint, surface contamination and many other factors.[47] Monitoring and control can be usefully applied only to features of the operation that can be clearly identified and precisely measured.[48] *Herein has lain a major difficulty facing all* attempts to devise effective schemes for in-process quality control. Traditionally weld quality has been judged on the basis of identifiable defects, such as porosity, inclusions, over-or under-penetration by the weld bead etc. In any welding procedure, the average weld should be free from this kind of defects. In the absense of a complete knowledge of weld failure mechanisms or even the precise conditions a weld meets in service, the choice of suitable control parameters must be guided largerly by common sense and intuition.

Clearly, sensory measurement capabilities are necessary for automated welding systems to operate effectively. Collected data from sensors must be processed and analysed and the results be introduced into the control system in real-time so that the response is good direct, reliable and efficient (Figure 10).[26] Command and control structure for such systems is invariably a hierarchy wherein goals or tasks, selected at the highest level are, decomposed into sequences of sub-tasks which are passed to the next lower level in the hierarchy.[49] This same task is repeated at each level until, at the bottom of the hierarchy, there is a sequence generated of primitive actions each of which can be executed with a single operation. Sensory measurements are fed back into this hierarchy at many different levels to alter the task decomposition so as to accomplish the highest level goal inspite of uncertainties or unexpected conditions in the environment.

For all joint types a mimimum requirement for all arc weld sensors is that they must be capable of controlling the proper tracking position.[50] For unprepared fillet welds, for example, this is the intersection of the plate faces, while for butt and prepared joints it is related to the plate edge or the preparation faces. A second requirement for weld sensors, and one that is much more difficult to achieve, is that they must be capable of ensuring that welds are placed accurately and that are of the required size and shape.[51] This second function may be performed by a combination of information gathered from the sensing devices and knowledge of the welding process itself. An alternative and more desirable approach, would take measurements from the weld bead and use these to modify the welding parameters to maintain weld quality.[52]

The nature and expected extend of component imperfections indicates the complexity of the required sensing approach. In making the sensor assessment the following aspects have to be considered:

1. Welding design requirements, i.e., those features necessary to satisfy service functions.
2. Joint imperfections, i.e. those deviations from the ideal seam.
3. Weld shape deviations and other defects induced by joint imperfections or inadequate bead penetration.
4. Influencing features; i.e., those items from 2) and 3) which might be usefully sensed for process feedback control.

2.4 ROBOTIC WELD SENSING TECHNIQUES

2.4.1 Applications of Sensors to Welding.

Early robots could only weld in a predetermined fashion. That is, they possessed only the ability to repeat preprogrammed welding sequences exactly. Successful implementation, therefore, required consistently fixtured component parts whose joints would not wonder during welding. To solve these problems adaptive control coupled appropriately in a closed loop control (Figure 11) with sensing devices was required to 'assure' or improve weld quality and increase productivity in automated fabrication.[53]

Control of arc welding can generally be regarded as the combination of two tasks:

i) To ensure the oriented movement of the working instrument (electrode) along a given spatial trajectory (control of geometry).
ii) To control technological parameters (welding speed, current, arc voltage, wire feed rate, etc.) and the welding cycle (control of technology).

Corrections for both weld path deviations and welding variables are, possible, but with the numerous welding processes and joint configurations currently employed no one type of sensor can provide a universal solution.[54] Three major classifications have emerged as a family of adaptive control technologies, through-the-arc, preview, and direct arc.

This section describes each of the major types of joint tracking systems that are paving the way for higher utilisation of robotics in industry.

2.4.2 Through-the-Arc Sensing

Through-the-arc sensing[33] is the most prevalent form of joint tracking today.[55] In operation, this tracking technique makes use of an oscillating torch. It's weaving motion causes changes in the voltage sensed at the joint walls. These voltage changes are directly proportional to the fluctuations in distance between the surface of the weldment and the tip of the welding electrode. Fluctuations in voltage readings are monitored and feedback signals are sent to the robot controller, which then centers the oscillating torch in the joint.

To track the joint in a direction normal to the welded part's surface, a preset voltage value that represents the desired welding electrode extension is programmed into the robot controller. Feedback signals originating at the welding electrode tip constantly sense this voltage value and adjust the torch position accordingly via commands from the robot controller. This way, a constant arc length is maintained. By combining cross-joint guidance and torch height control, through-the-arc joint tracking is always being counted on to keep the arc in the root of the joint and the torch at the proper stand-off distance.

This form of welding guidance, to be trully effective, requires an additional feature called seam finding. This sensing feature uses the welding electrode tip as a high voltage, low amperage probe to define the centreline of the joint through a preprogrammed search routine.[56,57] After both joint sidewalls have been sensed by the welding wire, the torch automatically positions itself over the joint centreline. This feature requires that an initially programmed start point for the robot's welding sequence be contained within the joint sidewalls.[58] Thus, fairly repeatable weldment joints are needed if seam finding is to operate succesfully. Figure 12 depicts the above functions.

A few robot companies[59,60] have developed more sophisticated software to enhance this seam finding function Through dedicated software, the robot is programmed not only to find the joint centreline, but to find the joint start via a user-defined search routine. The welding electrode is thus used to probe for the appropriate joint characteristics in all three dimensions. With this advanced sensing capability, the weldment's joint do not need to satisfy the stringent repeatability requirements associated with robotic arc welding. In addition, the first programmed point of the welding sequence may be several centimeters away from the actual joint start location, in any direction. After finding the start of the joint, the through-the-arc joint tracking function takes over to follow the weld path.[61]

Advantages of through-the-arc joint sensing far outweigh its limitations for a distinct range of applications. Benefits of this joint tracking technology include:

1. Ability to track and weld simultaneously.
2. Real-time compensation corrections for heat distortion during welding.
3. Not affected by smoke, weld spatter or the arc itself.
4. Relatively low cost in comparison to other joint tracking alternatives.

Together, though, the combined through-the-arc tracking and seam finding sensors have certain limitations.

1. Welding electrode extension must be strictly maintained at a controlled length during the seam finding operation. Incorrect extension results in erroneous sensing of the joint track.
2. All welds must include a weave V preparation for the system to work effectively.
3. Joint sidewalls must be well-defined and have at

least 6.5 mm leg length and 6.5 mm wall thicknesses.

4. Standard touch sensing for finding the joint start location assumes that the joint only deviates in the directions normal to both joint sidewalls. Any displacement of the torch in the plane parallel to the joint centreline is usually not compensated for.
5. Cannot track around sharp corners or turns.
6. Heavy rust or mill scale affects the joint tracking ability of the welding torch.
7. Some joint trackers exhibit electrical signal problems in flux cored arc welding applications.
8. Limited ability in the tracking of weld joints for nonferrous materials.

The present through-the-arc welding guidance systems offer primarily joint tracking capabilities. Recent developments, however, by a few robot vendors[62] have enabled this joint tracking technique to perform an adaptive weld fill operation. Using the welding wire as a probe, joint geometries are profiled by touching the weldment joints on all sides with the welding wire prior to arc initiation. This way, weld sizes for specified joint configurations are calculated. Likewise, appropriate sets of welding variables to match the joint size are selected from the robot controller memory.

Through-the-arc sensing is a well-established reliable joint tracking technolgy. Its present range of successful installations and future potential open the doors to a diverse range of robotic welding applications.

2.4.3 Preview Sensing

Preview sensing is a joint tracking approach that generates information about the joint before it is welded. This type of sensing is performed either through contact type sensors such as mechanical probes or through non-contact sensors such as solid-state camera and optical laser combinations.

A) Contact Sensing.

Contact style of sensors utilises the joint preparation or part geometry as a mechanical guide.[63] Preview sensing by the contact method typically involves mechanical probes equipped with electronic sensing devices.[64] In operation, signals proportional to the positional deflections of the probes are generated by the electronic sensor. These signals, in turn, generate both cross-joint and normal direction corrections of the welding torch over the joint. This variety of weld guidance exhibits advantages of relatively low cost, simultaneous tracking and welding ability, and universality of both welding process and weldment material type. However, major disadvantages are encountered with this joint tracking approach when applied to robotics.

1. Not adaptable to suit a variety of joint geometries.
2. Tendency for the probe to loose contact with the joint.
3. Contact sensors limit the welding speed.
4. Probes cannot follow complex contours.
5. Probes are subject to wear.

Despite the advantage of some contact-type of preview sensors, they are not viable for most robotic welding applications that require adaptive control sensing.[65-68]

B) Non-Contact Sensing.

Non-Contact version of preview sensing is the joint tracking method currently receiving most attention. With this joint sensing approach, a number of alternative techniques[69] (using area array cameras, fibre optics, structured lighting, eddy current probes,[70] and other equipment) have been successfully employed to generate three-dimensional profiles of weld joints.[71] From digitised images of welded joints, non-contact sensor technologies derive two valuable pieces of information.

i) Tracking data:- relative positon of joint with respect to sensor.
ii) Weld fill data:- geometric profile of joint which provides appropriate welding variables for constant weld fill.

One of the most popular style of non-contact preview sensing is the structured lighting/solid-state camera approach (Figure 13). Combined with machine vision technology, this electro-optical sensing method reduces three-dimensional information from two-dimensional camera images. Projected planes of laser light produce illuminated stripes on the weld joint that are viewed by a solid-state camera. Three-dimensional coordinates of each point on the stripe can be calculated from the intersection of the plane of structured light illumination and the optical path along the solid-state camera axis, using optical triangulation mathematics. Although most joint tracking systems of this type use a similar concept they vary substantially in both hardware and software design of their final productions models.[72-75]

Capabilities of non-contact preview sensing are impressive. They include:

1. Locate the start of a weld joint in any plane, within a distance of at least 25 mm from the preprogrammed welding torch position.
2. Sensing system is independent of the welding process.
3. Used prior to or during the welding process.
4. Compensate for distortion during welding.
5. Tracking T-, lap and butt joint configurations and groove welds.
6. Tracking on ferrous and non-ferrous materials.

As with any new, emerging technology, there are drawbacks to the first generation production models. Limitations of non-contact preview sensing in its current evolutionary stage include:

1. Workpiece surface variations can play havoc with sensor hardware.
2. Sensing is affected by smoke, spatter and the arc, to varying degrees.
3. Sophisticated image processing is required.
4. Space-intrusive hardware located near the welding head affects joint accessibility and is vulnerable to damage.
5. Technology is relatively expensive, in comparison to other joint tracking alternatives.

Non-contact variety of preview sensor has made great progress in its relatively short history. First joint trackers were two-pass systems.[76] In the first pass, they sensed the true joint position by transversing its entire length with the torch disabled. With the joint location stored in memory, welding was then conducted by the robot in a second pass. From this initial two-pass preview joint tracker evolved the single-pass variety. Real-time guidance systems of this type project a laser beam of structured light which can vary in location from several millimeters to several centimeters in front of the actual point of the weld. In more advanced tracking systems,[77-81] the imaging system is also used to profile the weld joint for adaptive fill control purposes. The cross-sectional area of the joint is calculated using optical triangulation mathematics. At this point, the set of welding variables matching the joint size is selected from preprogrammed tables in the robot controller memory.

In the future, all of the hardware required for preview sensing may be housed in compact welding head assemblies as Figure 14 illustrates.[82] Preview sensing promises much more for future welding applications. Additionally to weld guidance and adaptive fill control, current research efforts in preview sensing are directed towards, providing weld quality control information. Through additonal analysis performed on the digitized image of the weld joint, several features of the joint geometry can be identified and located. These features include:

a) Joint centreline
b) Weld wetting points
c) Joint edges
d) Joint angle
e) Root opening
f) Joint sidewalls or weld faces
g) Tack welds.

With this data, the sensing system will provide the inspection ability to produce a permament record of the weld profile for certification or quality control purposes. Non-contact preview sensing is generally expected to be the most important ingredient in the growth and expansion of robotics in the welding industry over the next few years.

2.4.4 Direct Arc Sensing

Direct arc sensing is being investigated to achieve real-time joint tracking and weld pool control for both the gas metal arc and gas tungsten arc welding processes. Like the non-contact preview sensing, direct arc sensing uses such technologies as area array cameras, structured lighting, and machine vision to produce artificially three-dimensional profiles of weld joints from two-dimensional camera images.[83] Unlike preview sensing, direct arc sensing monitors the active welding scene and provides real-time corrective action to both joint tracking and weld fill control, a process similar to the hand-eye coordination of the human welder (Figure 15).[84]

Heart of the direct arc sensing is its ability to monitor both the joint profile and weld pool in real-time so that the appropriate corrective actions are taken. Mechanism used to provide this real-time weld inspection is the coaxial viewing system. This system integrates the weld viewing optics inside the torch barrel in such a manner that the optical axis of the system is coaxially aligned with the welding electrode.

This concept has been applied to the gas metal arc welding process to achieve a similar form of process control and arc light is used to illuminate the weld scene.[85] The image of the active welding area is transmitted to a solid-state camera via a series of lenses, mirrors and filters. At this point, a solid state camera digitizes the analogue image and a machine vision system connected to the camera is employed to analyse the weld scene and extract the pertinent features. Some of these weld features include, periphery of the entire weld pool, boundary between solid and liquid, solidified weld bead and joint geometry. This information is transmitted to the robot controller, which, in turn, supplies the robot with appropriate corrective actions for welding path and/or joint fill modifications.

Successful results have been obtained for both welded butt joints and fillet weld applications.[86]. In the case of butt joints, unstructured lighting (illumination from the arc) is suffient to illuminate the welding scene so that the joint tracking system can function properly. In the case of fillet welds, however, a structured lighting source has to be integrated into the coaxial viewer system to profile the joint type image. Unlike butt joints, fillet welds may not have the distinct features or contrast sufficient to provide the necessary third dimension for joint following and weld fill control. To compensate, a source of structured lighting, such as a laser beam, is projected onto the joint to achieve artificially a three-dimensional joint representation. Laser projection location with direct arc sensing is at a point just in front of the weld pool and within the field of the coaxial viewing system.

Important potential benefits of direct arc sensing using coaxial viewing include:

1. Joint tracking and weld fill corrective actions performed at point of welding, avoiding the travel delay required for preview systems which precedes the point of welding.
2. Real-time adaptive welding process sensing.
3. Sensor system is contained within the welding torch housing and considered to be non-intrusive in terms of space constraints and also essentially protected.
4. Real-time weld bead inspection capability is a potential future sensor enhancement.

It is evident that this technology is still gradually updated. Production versions of laboratory models have already been applied in the jet aircraft and aerospace industries.(87) These applications use modified versions of the original coaxial viewer concept in which the sensor is packaged in a welding torch housing, with fibreoptics, being used to transmit the images of the weld scene to a remote camera. These viewer system enhancements remove the camera electronics from the harsh welding environment whilst maintaining any joint accessibility problems due to bulky sensor hardware. This joint tracking technique will undoubtedly make the largest impact on future welding applications once the sensor has been fully developed and debugged. Potential drawbacks of direct arc sensing include:

1. Cannot be used for submerged arc or plasma arc welding processes.
2. Long-term horizon for availability from vendors.
3. Hardware is at the present very expensive.

2.5 QUALITY EVALUATION IN AUTOMATED WELDING

Although the meaning of quality can be very broadly defined (Figure 16),[88] the section here focuses on the most immediate manufacuturing concern, namely conformance to technical performance requirements. Conformance in welding is directly determined through comparison of the measured characteristics of weldments and their design specifications. Based on this criterion, quality of a welded product is controlled by means of techniques which have evolved over the years with changes in the control philosophy.

Major approaches and techniques of product quality control are summarised in Figure 17. An early idea of quality control was essentially one of fault detection. A manufactured product is inspected; if it fails to meet the quality requirements it is rejected; if it does meet them it is released to the product user since inspection of entire batches of production is not always feasible or desirable. Techniques of sampling inspection,therefore,were developed. Acceptance sampling plans and schemes have been commonly accepted and implemented in a wide spectrum of industries including the welding industry.[89]

Detection approach to quality, however, suffers from one serious drawback. By the time defective products are detected, the damage has already been done. No amount of inspection can salvage a batch of defective product hence quality cannot be inspected into the product. The function of a sampling plan lies in its ability to limit the spread of such damage to the customer, not its ability to improve quality.[90] Inspection is thus the most passive form of quality control.

A better philosophy for quality improvement is clearly that of prevention, i.e. not to allow defective products to be generated in the first place (Figure 18). To achieve this, the focus of control is shifted from the product to the process that gives rise to the product.[91] Processes denote productive operations involving combinations of resources of men, machines, materials and methods. The mechanics of welding process control entail the continuous monitoring of process output; the moment any indication is received suggesting that defective units have been produced or are about to be produced, the procedure is brought to a halt for trouble shooting or adjustments.[92] Information feedback can be achieved on a real-time basis. Success depends on the judicious intervention of the welding process. Over-reaction to slight fluctuations in weldment property leads to frequent and unnecessary parameters adjustments or production stoppages, while untimely reactions result in frequent runs of defective weldments. Again, theories of probability and statistics are essential, as they help to distinguish between systematic and random shifts in product characteristics and process performance.[93]

It is realised that elaborate welding inspection and process control procedures prevent deterioration of quality, but by themselves cannot bring out the best in welding manufacturing. Detection and prevention techniques applied aim only at maintaining the status quo and are meant to be applied on a routine basis. When new situations arise involving changes, more versatile and powerful techniques are needed. Some circumstances in which changes are called for are as follows:

i) Product quality is stable but improvement is desired.
ii) Process output or yield has been sustained at a certain level but is still considered low.
iii) Process is found out of statistical control and adjustments are needed.
iv) Process is new and operating parameters have not been accurately determined.

v) Product is new and design parameters have to be finalised or refined for the best expected performance.

All above cases applied to welding share a common characteristic, namely the need for performance optimisation (Figure 19). A welding process is, therefore regarded as "under control" if it is consistently giving a yield of, say, 97 per cent, but it is not considered to be optimised if no effort is made to extract the remaining 3 per cent. Modern welding quality requirements are very demanding and high quality level is achieved only if both welding product and process are inherently capable of attaining it. With this understanding the saying "Quality has to be designed into the product" becomes an important guiding principle for real quality breakthroughs.[94]

This latest overall quality can be attempted theoretically or empirically.[95] Theoretical approaches entail fundametal analysis and synthesis, based on available welding knowledge and technology. What many design and quality welding engineers may not be aware of is the importance of an empirical approach aided by statistical tools in optimisation studies. Just as theories of probability and statistics are essential for formulating sampling inspection plans and process control procedures, the application of a set of methodologies known as statistical design experiments drastically enhance the productivity of virtually any kind of welding process - parameter relationship studies.[96] While sampling inspection and process control are recognised as established quality control techniques, optimal design via statistics is often regarded as a recent one in quality engineering, although its theoretical foundation was developed more than half a century ago.[97]

Once quality is "designed into" the product; process, process control product inspection and particularly acceptance sampling, is relegated to supplementary roles. The most important difference between the traditional and new approaches is that the former is passive, relying on control tactics based upon available data on the performance of existing welding products and processes. On the other hand the latter is active, systematically probing and engineering the behaviour of the welding product or process of interest through purposeful generation of data.[98] Data information from specially designed experiments, being richer than that in routinely available data, is instrumental to optimisation studies for quality and productivity.

With the introduction of automation in manufacturing, the importance of active quality engineering bears further elaboration. One of the most important features of automated welding manufacturing is the fast generation of products of consistent quality. It does not follow, however, that as a result there is less need for quality engineering. Reasons for this are simple. Product quality may be consistent, but there is nothing to guarantee that it is consistently good and meets performance requirements.[99] It might actually be consistenlty bad, and, what is worse, consistently bad units are produced and losses incurr at much faster rates than before. As a consequence, a damaging impact rather than a beneficial one arises. A less obvious consideration is that, even if product quality seems to be consistent and acceptable at the production stage, there is no assurance that such consistency persists at the product use or deployment stage. If welding automation is regarded only as a means of enhancing production capability and is implemented without the integration of ideas of quality and reliability engineering, then its full potential is not being appreciated and will not be realised.[100]

Statistical design of experiments, should be relied on to:

A) Achieve the best quality at the time of manufacuture.

B) Extract the highest level of performance during the product's useful life.

C) Obtain the least amount of variability in this performance.

Optimisation in design ensures that a product not only can function as required, but also is united for automated manufacturing.[101] Welding automation results in faster and higher volume production therefore, as pointed out before. Quality has to be designed into the product right from the start and additionally attained through process or product monitoring. To this end, the "robot design" approach[102] is useful in meeting the challenges of automation as it ensures to a certain extent that quality is unaffected even when there are variabilities in the welding conditions and additionally that such quality is sustained when conditions of product usage are changed or become unfavourable.

All the above considerations have far-reaching implications in the economics of automation. Since welding automated systems are invariably capital intensive and mostly used in high volume production, any unproductive system stoppage due to poor design, either in the manufacturing hardware or in the manufactured product, means greater losses than in the case of manual welding systems.

2.5.1 Ultrasonic Inspection / Assessment.

Engineering products must be inspected during and after manufacture and often during their service life, to ensure that they remain fit for purpose.[103] Non-Destructive Testing (N.D.T.) is the name given to the various processes of inspection which do not render the item examined unfit for further use. Accurate methods are required to determine the location, size and type of flaw such as a crack or inclusion of foreign material. At a still more sophisticated level, there is interest in being able to measure the presence of residual stress in a weld, near a crack, or in a stressed part so as to be able to use fracture mechanics to predict the breaking point and useful life of a structure.[104]

A second type of problem which arises in such non-destructive evaluations of structures is the time and hence the cost of carrying out such assessments.[105] It is vital therefore, to be able to carry out inspection as accurately and as quickly as possible, and it is important to be able to evaluate and position the flaws reliably at every stage of manufacture and while in service.

Standard techniques employed for non destructive testing inspection of solid parts have involved X-ray and radiographic methods, eddy current testing, use of dye penetrants and accoustic methods. Radiographic techniques require bulky apparatus and furthermore, when large metal parts are being examined, very high energy beams are employed which involve clearing the area where the inspection is to be carried out. On the other hand, however, they provide familiar easily recognisable data and do not need any direct contact with the material being tested.

Eddy current techniques provide very useful information on near surface defects in metals and will, no doubt, be further improved in the next few years. Fluorescent dye penetrants is often a simple and effective way of detecting surface defects.

Acoustic techniques have the major advantage that they measure the elastic properties of the material. As we are normally interested in mechanical properties, acoustic measurements provide data most closely related to a determination of the viability and useful life of a material sample.[106] In the past, the main thrust of acoustic measurement techniques was to evaluate the position and size of defects such as cracks or debounded regions. It is only recently that acoustic techniques are beginning to be applied to measure the shape of a defect, the strength of a bond, or the residual stress in a weld region or near a crack.[107]

Basic acoustic techniques employed in N.D.T. are very similar to those used in sonar and in medical applications. A simple single piezoelectric transducer is used to excite an acoustic wave in the object being examined (Figure 20). This acoustic wave propagates through the object of interest whilst the transducer is held directly against the solid material to be examined. Contact between the transducer and the sample is enabled with the use of water, grease, oil or a thin layer of rubber.

Suppose the acoustic transducer is excited by a short electrical pulse, it then emits an acoustic pulse of length to be determined by its bandwidth ($\tau_p = 1/\Delta f$ where Δf is the bandwidth of the transducer), which in turn passes into the object and finally being reflected by the acoustic impedance discontinuities caused by the presence of flaws. This return echo signal arriving at the transducer is then received by the transducer and amplified and displayed as a functon of time on an oscilloscope (ultrasonascope) (Figure 21). Echo time delay is:

$$T = 2z / u_w$$

where: z is the distance of the flaw from the surface.
u_w is the acoustic wave velocity in the material.

Consequently, from the time delay of the observed pulse on the ultrasonascope screen one can determine the distance of the flaw from the surface. Furthermore, it is expected that the amplitude of the return echo to depend on the size of the flaw, so that rough information can be extracted on the size of the flaw by measuring the amplitude of the return echo. This technique is known as the A-scan (amplitude scan) technique (Figure 22).

By moving the transducer along the surface of the object being examined various flaws are detected while the A-scan information is being obtained. Therefore, the transverse position of the flaws can be detected, although the definition of the system in transverse direction is dictated basically by the size of the transducer. If the distance z is such that:

$$z \gg \alpha^2 / \lambda$$

where: α is the transducer radius.
and λ is the wavelengh of the pulse center frequency.

then flaws are located at the far field of the transducer and the beam diameter is larger than the transducer's. Accordingly, if flaws are in the near field of the transducer, the transverse definition is camparable to the transducer's radius. The best definition is being obtained when the transducer diameter is chosen so that flaws are located roughly at the boundary of near and far field of the transducer (Figure 23).

Range definition of such A-scan systems are relatively accurate because they are dictated by the pulse length and is of the order of: $u_{\tau p} / 2$, where: τ_p is the pulse length. Such devices are used at baseband with transducers whose bandwidth is camparable to their center frequencies. At low frequencies, the definition is obviously poor. As the frequency is increased, however, to improve the definition, signal attenuation in most solid materials typically increases as the square of the frequency, so that there is a limit to the upper frequency which can be used. Therefore, the larger the structures, the lower the frequency and the poorer the definition employed.

A disadvantage of this A-scan method is that is slow and tedious. One line of amplitude information is observed at a time and although the transducers can be moved rapidly, large amounts of information have to be deconvoluted and subsequently interpreted by the operator.

An alternative technique is to use the so-called B-scan method in which return echo signals are used to modulate the intensity of an oscilloscope spot. Time delay is represented horizontally and the mechanical position along the surface of the object vertically. By this means, a crude picture of the structure within the material is presented as illustrated in Figure 24. Most structures are not flat, however, and it is difficult to make contact over very large regions therefore, limiting its applications.

A third technique, illustrated in Figure 25, is to employ transmission imaging in a so called C-scan method. Here, a focused transducer is used to transmit an acoustic beam through the object of interest. If the object is relatively thin it is placed on the acoustic beam focus and a second confacial focus receiving transducer is used to receive the acoustic beam. The object of interest is then mechanically scanned across the beam while the beam itself is moved back and forth to create a raster scan. Results are displayed and recorded either on a T.V. screen or on paper. Advantages of this method include that a good definition is obtained and a high quality transmission image is observed.

From the three techniques mentioned above the A-scan is the most widely used. Reflected pulses are received either by the same transmitting crystal or by a separate receiving one. It is a very sensitive and convenient method of inspection for cracks, voids and inclusions. Results interpretation, however, requires both skills and reference to standard blocks containing known defects. Used in the pulse-echo mode, it also provides a convenient and widely used thickness measuring gauge, accurate to about 2 per cent and requires access to one side only.

There are three types of ultrasonic wave propagation; longitudinal, transverse, and surface. The transmission of ultrasonic energy depends on particle vibration. These particles are displaced as the wave travels through the medium. Longitudinal or compressional waves are waves in which the particles of the transmitting medium move in the same direction as the wave is being propagated. In transverse or shear waves the particles of the transmitting medium vibrate at right angles to the direction of wave propagation. Under correct conditons ultrasonic waves of considerable amplitude are propagated on the material surface. Surface waves are divided into three classes. Rayleigh waves which propagate over the surface of a solid whose thickness perpendicular to the surface is large compared to the wavelength of the wave. Vibrations occur in the plane containning the direction of propagation and the normal to the surface of the body. Lamb waves which propagate in the body of a solid whose thickness comparable to the wavelength of the waves and the velocity of propagation is determined by the product of the thickness of the plate and the frequency. Lamb waves travel on the surface without any vertical component and propagate with velocities which are dependent upon frequency, the velocity decreasing with increasing frequencies.

Due to their short wavelength, ultrasonic waves travel essentially in straight lines. As the wavelength becomes shorter, the waves more closely approach the ideal condition of rectilinear propagation. There is always some spreading of the beam as the waves travel from the source. When a wave strikes an interface between two media, part of the energy is reflected and part is transmitted. The amount of energy reflected is determined by the specific acoustic impedance of each of the two media. Ultrasonic waves obliquely crossing the boundary separating the two media undergo abrupt changes in the direction of propagation and beam refraction takes place. Finally the loss of energy in an ultrasonic wave propagated through material is attributed to four different mechanisms: heat conduction, viscous friction, elastic hysterisis and scattering.

Various defect types possible in butt welds have been described frequently (Figure 26). For the majority of butt weld testing it is more convenient to use angle probes, the wave angle being selected mainly to suit the part thickness. Single probe inspection is generally employed. There are, however, certain defects which cannot be detected in this way, so double probe arrangement is necessary. When examining butt welds with angle probes it is impossible to cover the whole weld thickness at once with probes currently available having a small beam angle. Probes with sufficiently large beam angles are designed for examination of welds by means of single scan, thus reducing the time required for preliminary tests. Any flaws located could then be re-examined using narrow beam probes in order to estimate the position and type of flaw. Employing narrow beam probes of conventional design, a zig-zag scan is required if the whole cross-section of the weld is to be examined.[108] The skip distances and the beam path lengths are easily calculated and depend on the type, geometry, thickness and angle of incidence of the ultrasonic beam in the medium. For flaw location, it should be remembered that most flaw detectors are calibrated from compression waves in a particular material, and any corrections must be made for shear waves and also changes in velocity owing to specimens of other material type. Part of the whole beam path length trace covers the beam path in the Perspex shoe at the angle probe itself. For accurate work, allowance should be made for this, and it is easily done if the size of the shoe and the velocity of compression waves in perspex are known.

Accurate flaw location also relies on the fact that the maximum echo from a flaw is received when the flaw lies on the axis of the beam. It is obvious that the narrower the beam the easier it is to locate the defect on the beam axis.[109] It is essential therefore, that the beam spread and exact beam angle of the probe to be known for the material being examined. This can be easily checked by using standard calibration blocks (Figure 27).

Initial considerations of these points appears to make ultrasonic inspection a method rather unsuited to the application of automation, but with a full knowledge of the factors involved automatic methods can be used in weld testing.

2.5.2 Developments in Ultrasonic Inspection

An experienced operator can gleam a considerable amount of information about the characteristics of ultrasonic displays on a manual flaw detector screen. To the inexperienced eye, scanning comprises a single line trace showing pulse echo amplitudes at various distances along the thickness. By observing more closely, however, it might be seen that a smooth reflector such as a uniform crack could produce a smooth rising edge to the echo whilst a rough reflector produces a jagged rising edge. Depending on whether or not the deflection moves sideways on the screen, and in which direction, when the transducer is scanned across the material surface, the operator can tell if the deflection is at an angle to the beam. Otherwise, its size and nature is also assessed from how quickly or slowly a pulse echo rises and decays.

All the time, the operator is building up a mental image of the flaw. This mental process requires considerable training and it is time-consuming. Computerised testing methods (Figure 28) have the advantage that all received data are stored and subsequently processed - not necessarily in real time - to produce a complete and totally reliable picture of the deflector.[110] As this information is processed and inspection progresses, results are obtained in real-time. This this is an additonal bonus. Speed of automatic scanning is still limited by the ability of the electronics to handle the data, but this situation has gradually improved.[111] At present, in the hands of a skillful operator the manual method is arguably faster than automatic testing. It has to be remembered, however, that important information can be missed, through boredom or fatigue on continuously moving probes across welds. The introduction of monitor controls with audible alarm has alleviated this problem, but where inspection is repetitive a fully automated system is to be preferrred. If the application warrants it, the automatic scanning facility can then be linked into a computer. Consequently, manufacturers are now supplying instruments having an increasing variety of analogue outputs, which can be used in automatic systems typically with oscilloscopes, paper tape recorders and X-Y plotters, or converted to digital output for computer processing.[112]

In the latter case, the signal outputs are used to create graphic displays, for fault location and diagnosis, on a VDU screen. These displays can be of a B-scan (cross-sectioned) or C-scan (plan-view), or it is possible to build up an isometric picture of the weld from which any faults are accurately pinpointed in both depth and surface distance from the probe emission point.

Over the past several years, improved design of ultrasonic flaw detectors has led to various practical advantages appropriate to weld inspections and other test requirements. From the controls aspect, notable improvements include:

1. Progressive reject applied linearly to small signals ("grass") down the time base without affecting the amplitudes of the remaining signals.
2. An increasing use of the bar gate monitor which

unlike the stepped or pedestal gate facilitates easy identification of fault pulse echoes.

3. Use of broader amplifier frequency bandwidths for imrproved resolution of the received signal.
4. Introduction of Automatic Pulse Rate Frequency (APRF) which adjusts to the highest PRF consistent with test range, material sound velocity and delay selections without exceeding the operator selected value.
5. More accurately calibrated gain controls.
6. Wider use of calibrated delays.

Improved resolution of received signals (Figure 29) has made it easier to determine, for example, whether a weld area giving rise to a conglomerate of defect signals actually signifies porosity or slag inclusions. It is also possible to be more accurate with distance measurement and in differentiating between a reflection caused by a weld bead and one resulting from a small crack along the edge of the bead.[113] Digital output and read-out of distance measurement along the timebase makes the variable calibration method of determining surface distance and depth of reflection even easier to use. This digital output is used also to measure the distance between two echoes in the same beam path.

During the years that such equipments have been in use several shortcomings have become apparent, mainly in the mechanical scan systems resulting in difficulties keeping scanning equipment and recorders synchronised. This resulted in offset of traces laid down in opposite directions. There was also a need to control retardation and acceleration of probe carriage rigs at scan reversal points and to maintain constant probe contact pressure. It was then proposed that all movements on rigs and recorders shall be by stepping motors, driven by a digital controller having variable programme features.[114].

Increase in automatic ultrasonic inspection resulted in a demand of larger areas inspection which in turn produced huge quantities of data. Data recording systems were incapable of handling the information so it was proposed that a digital data processing for their practical implenentation must be used. Such processing, if done on-line, is accomplished in a time-sharing arrangement with a remote general purpose computer, or with a microcomputer especially adapted for process control and on-line data reduction.[115-117]

Signals to be processed digitally must first be converted to digital form through the use of analog-to-digital (A.D.C.) converters (Figure 30). Such converters employ sampling techniques without sampling intervals long enough to allow conversion and storage of data plus any real-time computing that is required. Sampling requirements also make it absolutely essential that high frequency noise is absent, since sampling on the peaks and valleys of such noise can greatly bias the results. Therefore, signals were pre-filtered with low-pass filters before conversion to digital form.[118]

Next natural step was the possibility of an advanced imaging system. It was thought, that the information available at the transducer-material interface having been processed, element by element, could produce an image of an area of interest within the material. This, required sampling the aperture at less than half wavelength intervals at the highest frequency of operators and the development of a data processing system to handle the information.[119] Difficulties were overcome using high perfomance digitizers and faster computer programming facilities.

Until about a decade ago, the major efforts to improve N.D.T. concentrated on increasing instrumentation resolution. Emphasis was on improved electronics for analogue signal processing and transducers to detect the smallest possible defects. In the past ten years tremendous emphasis has been directed towards identifying procedures and processes that enhance both the reliability as well as to guarantee informational content of signals obtained from conventional N.D.T. Large portion of this emphasis has currently being centred on the application of advanced signal processing concepts already successfully applied in other scientific fields.[120]

Digital signal processing is a widely used engineering term that, in a broad sense, is described as a transformation converting signal data into useful information using digital computers. An analysis of the current application of digital signal processing techniques and the existing ultrasound interative showed that a variety of N.D.T. problems are solved by applying signal processing and, specifically, digital signal processing to ultrasonics (Figure 31).[121] Further analysis showed that goals for digital signal processing are clearly defined. They are as follows:

1. Improve inspection reliability.
2. Improve defect detection.
3. Improve defect characterisation.
4. Generate valuable information determining the remaining life of structures.
5. Generate information about processes such as welding etc.

The first goal, improved ultrasonic inspection reliability, is of major interest of all industries. Typically, ultrasonic methods are employed in a manual or semi-automatic mode where human operators making accept/reject decisions are subject to error. Furthermore, most manual data recording and analysis methods are primitive, making reliability a major concern. Use of digital signal processing minimises operator dependence because it uses automated data acquisition as well as analysis, which are highly repeatable compared with manual inspection systems.

The second goal of providing increased resolution capability is associated with inspection of homogeneous and isotropic materials as well as those that pose difficulties when inspected using conventional techniques. These include materials with large grain size, impedance mismatch, and so forth. Digital signal processing techniques such as averaging, beam forming and matched filtering are employed to improve the signal-to-noise ration (SNR) for increased detection capabilities.[122]

The third goal of providing detailed definition of the defect has acquired great significance lately because of its need for implentation of such methodologies as retirement-for-cause and remaining-life analysis. Several signal processing methods, broadly classified into imaging, inversion and pattern recognition have been extensively used to determine type, shape and size of defects.[123]

The fourth goal, application of digital processing to ultrasonic data, is to determine mechanical properities of the material such as grain size and fracture toughness.[124,125]

Lastly, but very importantly, tremendous gains in product quality and producitvity are possible through process monitoring and control.[126]

Determination of the response signal, however, given the excitation source, often involves the solution of complex, coupled partial-differential equations with difficult boundary conditions while the solution of the forward problem, as it is usually called, is very difficult. A number of techniques have been developed to model the interation process.[127].

Empirical approaches, on the other hand, are not related to the physical mechanism. While arguably not as elegant an approach as those involving phenomenological models, empirical models are simpler to formulate. Absence of a link between the physical process and the model allows the feasibility of using a wide variety of models to be investigated. Most techniques aim at accomplishing tasks of defect characterisation by mapping the large dimensional signal space into a smaller dimensional feature space. One of several pattern recognition techniques is then used for classifying or characterising the defect by examining the feature space. Figure 32 depicts the defect characterisation scheme whilst Figure 33 shows a typical pattern classification scheme.

The process of mapping the signal into the parameter space does not usually provide the user with an intuitively satisfying understanding of the defect characterisation scheme and often a physical picture of the defect conveys much more information. Acoustic imaging approaches range from intensity mapping, pulse-echo time-of-flight methods to holographic and tomographic imaging. An excellent tutorial paper covering the basics of various imaging techniques and a state-of-the-art review of digitial acoustical imaging is available in reference.[128] Imaging techniques such as time-of-flight and the Synthetic Aperture Focusing Technique (SAFT) have successfully determined defect characteristics.[129] Pattern recognition methods such as the Adaptive Learning Network (ALN) and Fisher Linear Descrimination Analysis (FLDAS) have also successfully identified defect types.[130]

2.5.3 Problems Associated with Ultrasonic Evaluation.

Ultrasound transmission through a material is dependent on the temperature of that material since the elastic constants (and hence the velocity of sound) is a function of temperature. As the temperature of a material increases, the velocity of sound decreases resulting in longer transit times to traverse the material (Figure 34). In a material of uniform temperature this poses no problem as long as the velocity of sound in that material at that temperature is known. In situations where the temperature of the material varies spatially, it is more difficult to relate distances to ultrasound transit times.[131] If the temperature and hence the velocity gradient, is known, it is then possible to determine distances from transit times by measuring the velocities along the path traversed. The path followed by ultrasound, however, also depends on the velocity of sound gradient.

Elevated temperatures also result in an increase in ultrasound attenuation in most materials (Figure 35). As attenuation in a medium increases, more and more ultrasound energy must be injected to obtain a measurable return singnal. Ultrasound attenuation is more pronounced at higher frequencies than at lower registered.[132] Thus, if signal strength is a problem, a lower frequency transducer may provide a large signal amplitude.

Finally, increased temperatures cause problems in the transduction of ultrasound. It has been mentioned that an ultrasound transducer is generally coupled to the medium to be tested by a thin layer of liquid. At elevated temperatures, this liquid may evaporate rapidly resulting in lack of coupling. To maintain acoustic coupling of the transducer a high temperature material is required or a continuous flow of light couplant. Additionally, the piezo-electric crystal element of an ultrasound transducer is sensitive to high temperature. It should not be allowed to get too hot, otherwise its piezo-electric properties are lost. During welding very large temperature gradients are present in the parent material and all attempts to measure weld pool dimensions using ultrasound must address the influence of these gradients on ultrasound transmission. Attenuation is a problem and requires a combination of higher pulser strength and reduced transducer frequencies to make the desired measurements.(133) Additionally, it is necessary to develop a way of providinig pressure contact between the ultrasound transducer and the weldment besides simultaneously enabling some cooling of the transducer to occur.

Ultrasound path from the transducer to the weld pool traverses steep temperature gradients resulting in an increase of ultrasound transit times and possibly some path curvature.(134)

Fundamentally, the physical properties of metals demand that heating to some elevated temperature is required for their successful production and fabrication at one stage or another. Processses such as hot rolling, welding and heat treatment are typical examples. Control of these processes is largerly empirical in nature and destructive and non destructive post-process tests are employed to ensure that the required standards have been achieved.

Non-destructive testing unquestionably plays a vital role in quality control for such processes. It is unfortunate, that techniques such as ultrasonics are employed mainly post-process for the detection of defects. This situation is undesirable in terms of both cost effectiveness; and reliability.(135) Non-destructive techniques which can monitor and control high temperature processes, detect or present the occurence of flaws are required. Real-time radiography, in this context, would have been ideal, but very expensive. Lack of penetration depth limits the use of the eddy current test whilst ultrasonics do not have these drawbacks. In conjunction with microprocessor technology,it has proved a possible to develop automatic systems to monitor and locate flaws accurately at an early processing stage.

Welding, with its inherent problems of quality control is an area where such a system would be of great value. A high proportion of defects which arise in weldments are intrinsic to the process and result from inadequate process control. In nuclear, offshore and aerospace industries weldments are required to be of very high standards. Non-destructive testing in this area is necessarily rigorous and intense.

There are additional problems associated with the use of ultrasonics for high temperature applications of which the more important are; transducer coupling and arc effects on propagation constants of an acoustic wave.

Transducer cooling and coupling are problems associated primarily with contact techniques, not appropriate for dynamic monitoring of high temperature processes. This is not to be undertaken because acoustic coupling would not readily be possible, since surfaces become roughened i.e.with a series of protrusions and pits. This is probably an extreme example where the conditions for contact ultrasonics would be extremely aggresive.

Modern transducers are made of polycrystalline ceramics (e.g. lead zirconate titinate, lead metaniobate and barium titinate) rather than naturally occuring crystals (e.g. quartz, tourmaline, Rochelle salt).[136] These ceramics are made of randomly orientated crystallites and have to be "polarised" before they exhibit the piezo electric effect. Polarisation is achieved by heating to the Curie temperature and applying an intense electrostatic field and maintaining it during cooling. At temperatures of the order of 850-1250 °C transducers of the crystal oscillator type are above their Currie temperature and hence their piezo electric properties destroyed. The most logical approach is probably a water cooled housing for the probe, but since this has to surround the front of the transducer additional interfaces between the transducer and material are introduced.[137]

Transducer cooling and coupling under dynamic conditions is not so severe at high temperatures. There are many situations in welding where transducers are coupled to the propagating medium at a point where the temperature is low, thus aleviating the above mentioned problems. Vacum evaporated thin film acoustic transducers have been found to be very useful for high temperature work (e.g. sulphide works well up to 600 °C).

Instead of using commercially available ultrasonic probes, wheel shaped transducers filled with couplant can be employed which are rolled along the material under inspection. Sensors of this type alleviate any difficulties associated with acoustic coupling (Figure 36).

To what degree the acoustic wave is attenuated depends upon the material frequency, temperature and grain size.[138] The higher the frequency employed the greater the attenuation. Attenuation also increases with increasing grain size, temperature and beam path.[139-143] An acoustic wave travelling through a relatively large grained structure at an elevated temperature, is attenuated severely so that complete absorbtion occurrs before exit to the detecting transducer. In large sections where this is a problem, transmission techniques offer the greatest chance of success. A reason for this is that the distance traversed by the acoustic wave in the transmision technique is only half of that in the pulse echo and reflection techniques.

Calibration of an ultrasonic system for dimensional measurement and defect location are dependent on the velocity of the acoustic wave. Indication of defect size is dependant upon the attenuation of the acoustic wave. To develop automated high temperature ultrasonic systems it becomes necessary to have a deeper understanding of the effect of temperature on attenuation and velocity. Velocity and attenuation measurements as a function of temperature have been used to study the physical and structural properties of a variety of polycrystalline materials. Early work with velocity measurements clearly demonstrated the value of ultrasonics as a method for the detection of physical and structural changes occurring as a function of temperature.[144] In later work velocity measurements have been used to study the effect of temperature on elastic moduli. Velocity measurements are thus being used for both the computation of these modulus (e.g. Poison's ratio, Young's modulus) and the derivation of expressions relating these modulus to temperature. Attenuation measurements have also been used to detect temperature dependant changes. For this purpose attenuation appeared to be more sensitive than velocity measurements. Both measurements have been employed to study the effects of material structure on an acoustic wave, with the objective of extending the theory and understanding of acoustic energy losses in polycrystalline metals.

When considering the progress and development of automated ultrasonic systems for use in high temperature processes, it is noticeable that little work has been published. Dimensional measurements, defect location and size are examples were variations in temperature affect the accuracy of the system. Loss of accuracy is caused by variations in velocity and attenuation, which alter the delay and amplitude of returned signals. Programming microcomputers with the relevant data allow the effects of temperature, or any variations, to be automatically accounted for before presentation of any measurements.

2.5.4 Ultrasonic Sensors in Automated/Robotic Welding

Previous experimental approaches[134] using skipped shear wave ultrasound showed that some signals could be monitored during welding. At that time, it was possible to identify and record the observed amplitude and beam path length pertubations (Figure 37). Post weld analysis has indicated that the weld bead centre columnar zone was the ultrasound return area.[145] Accepting this apparent limitation, the approach seemed to offer potential for further investigation and development and the next stage of the work concentrated on automating the welding process. Many various transducer/receiver modes were investigated as were also transducer positions, frequency, attenuation and type. Various material dimensions and conditions were examined, although the majority of the work was conducted on high and low strength ferritic steels.

When wedge mounted compression probes were employed, and scanning normal to the welding direction was applied, it was found that weld penetration depth could be determined. Return signals originated from the weld bead centreline columnar grains in all cases. Compression wave scanning down the weld joint with the weld pool advancing towards the transducer showed that the weld pool width did not remain constant but pulsed wider/narrower in an almost cyclic manner. This, latter arrangement was under investigation quite independently to locate occureness of lack of inter-run fusion during multi-run weld deposition. These experiements were continued for only a short time and were used to derive much basic information on the metallurgy of weld beads.

As the monitoring function was thought to be more easily attained using skipped shear waves, the experimental work took this approach. Experimental findings indicated that the apparent ultrasound reflector was within the weld puddle but neither the weld bead centreline grains nor the liquid/solid interface.[146] Multiple experiments reproduced this finding but continued that the independent variable was beam path length and not amplitude.

Up to this point, investigations were using static ultrasonic transducers and 'driving' the weld through the established ultrasonic beam to validate the initial concept. To measure weld penetration dynamically, it was necessary for the transducer probes to travel alongside the welding head and yet retain acoustic contact with the plates being joined.[147] These requirements were easily and simply fulfilled by bolting the ultrasonics carrying cradle to the welding head (Figure 38). Selection of the best shear wave angle was found to be related directly to plate thickness but usually either 45° or 60° transceivers were used. A data bank was produced to enable rapid calculation of the beam path length for any given shear wave angle and welding heat input.

When arranging the equipment for dynamic monitoring of weld penetration, the point of maximum weld pool depth had obviously to be located. Numerical analysis indicated that this point would occur directly under the arc, thus the probes were initially positioned with their centrelines on the centreline of the electrode. This approach proved to be flawed and it was quickly established that the true point of maximum penetration occurred some 3 mm behind the electrode centreline (Figure 39). It was easy to understand this retardation in qualitative terms, for heat takes time to flow from the arc region to melt the plate, thus, being behind, rather than directly under the arc.[148] Once the operational arrangements were understood and correctly established, dynamic monitoring during automatic welding proved easy to accomplish. After correction for apparent thermal gradient beam path lengthening, these path lengths were plotted onto macro sections of the relevant welds. Such was the confidence engendered by this system that the move from dynamic monitoring to dynamic control was underway.

Control work began by selecting a desired weld penetration depth and desiring retention of this dimension. Success was readily obtained, although a major problem was highlighted as being the sluggish response of the power source to changes in welding current. Although this part of the work proved that the control system worked, there were justifiable questions asked about the accuracy of the system. This was because submerged arc welding technique used is renowned for its consistency in penetration performance. To test the system further, a series of desired weld penetration profiles were selected and programmed into the control device. During the creation of a symmetrical curve, the desired penetration increased and then decreased steadily with no sudden step function changes. When step function changes were desired, results were less accurate than previously. It was found from the welding current records that although the command signal came at the correct moment, the fastest possible response of the power source was slow. This current increase transmitted itself to the weld pool in a dramatic fashion on both incremental and decremental current changes.

During the course of this work, the occurence of extra return signals had complicated understanding on many occasions. These extra signals were reqarded as secondary harmonics from the ultrasonic transducers operating in excess of 100 dB. In one analysis, the extent of the beam spread from each crystal was drawn and it became immediately apparent that the 'harmonics' were infact primary return signals. Two extra return signals existed, one from the leading edge, the other from the trailing edge of the broadened ultrasonic beam. What had been happening was that the leading edge signal read the plate edge in advance of the weld pool whilst the trailing signal scanned the freshly solidified weld metal.

3. EXPERIMENTAL PROCEDURES AND RESULTS

Submerged arc welding (S.A.W.) was chosen for this application for its high quality welding capabilities and also for its distinct "submerged" features (Figure 40). Because flux covers the seam, the only possible way to sense the joint is through the material or from the back side provided it is accessible. Furthermore, the process is inherently controlled automatically and seemed to offer the best route to achieve optimum metal deposition. A systematic selection scheme of optimum welding parameters combination, however, required some carefull feasibility study to achieve desired welding conditions. Detailed relationships between each of the welding parameters and their effects on metal transfer and weld bead characteristics had to be established.

This section describes the theoretical basis and its experimental confirmation for a series of weld parameter relationships which were postulated to provide optimum metal transfer conditions. Additionally attempts were made to produce a submerged arc welding model for bead shape control purposes and subsequent penetration control by ultrasonic sensors. Although, submerged arc welding was used throughout and experiments carried out on mild steel specimens, preliminary assesment to another welding process namely Metal Inert Gas (M.I.G.), workpiece type and configuration were also examined to enhance the sensors capabilities.

Experiments were carried out to fulfil the following requirements:

1. Assess the suitability of the ultrasonic sensors in automated welding.
2. Identify the welding parameters that control joint tracking.
3. Identify the welding parameters that control weld bead penetration.

4. Develop a systematic approach for the selection of welding parameters.
5. Develop a prototype sensing unit.
6. Assess the systems features in welding.
7. Use the results as a background for future system development.

3.1 BASIC AIMS OF THE EXPERIMENTS

Attempts to produce high accuracy and high quality welds highlighted the need for self-correcting control of both guidance systems and welding parameters. The overall aim of this investigation was to develop such an automated welding system using ultrasonic sensors, driving positional linear devices and a transistorised welding power supply. To accomplish these objectives the following had to be achieved:

1. Interface the welding power source to the microcomputer to control process input parameters.
2. A mechanical manipulator system needed to be linked to an external microcomputer so that the coordinates could be updated in real time.
3. Develop an ultrasonic timing device which would accurately distinguish and measure beam path lengths of signals in terms of time-of-flight.
4. Link the ultrasonic timing system to the microcomputer and develop algorithms to recognise both various bead penetrations and seam deviations.
5. Develop "intelligent" software to compensate for both corrective actions to driving system and power source.
6. Test the theoretical model developed for submerged arc welding and other arc welding processes.
7. Assess systems suitability for different types of parent materials and welding positions.

8. Assess the potential capabilities of such a system and future work orientation.

As the system was considered to be a prototype, initial work concentrated on designing and constructing not only the essential hardware but also the software to drive and control the entire welding operation. Preparatory work was, therefore, wholly dedicated in building up the necessary facilities to automate the welding sequence and achieve high accuracy and repeatability.

3.1.1 Welding Equipment and Consumables

Major equipment components required for submerged arc welding are (Figure 41):

1. Welding machine (power source).
2. Wire feeding mechanism and controls.
3. Welding torch.
4. Flux hopper and feeding mechanism.

Welding power supply was specially designed for the process with DC power used. Power source was rated at 100% duty cycle, because submerged arc welding operations are continuous and the legnth of time in operation normally exceeds the 10 minutes base period used for determining duty cycle.

The power source used throughout this programe was 1000 Amps, transistorised controlled unit using feedback techniques to enable output accuracies better than 1% to be achieved (Figure 42). This source was specified and purpose build for this research work. It was based on the series regulator principle using a number of transistors connected in parallel and mounted on water cooled heat sinks. Control of output charactersistics was achieved by means of employing either current or voltage feedback or any combination of the two to achieve intermediate slopes. The output level was controlled by means of a front panel level control or by an external analogue signal source.

Power supply comprised the following:

1. Three phase transformer and rectifier bridge for the supply of direct current (DC).
2. A capacitor bank for the reduction of supply ripple and to lower the supply impedance. This was required only when the system had to carry out pulse welding with short pulse times.
3. A series of transistor banks consisting of water cooled heat sinks each with a number of transistors connected in parallel. Each transistor was balanced in terms of gain to ensure the output current was shared equally between each device. A fuse was connected in the common emitter output of each bank for protection in the event of failure.
4. A feedback shunt measuring the output current of the power supply and fed it back to the control electronics, compared the actual output to the specified output level and continously corrected if required.
5. A voltage divider network providing voltage feedback from the machine's output. This was required when using constant voltage output conditions or any intermediate slope.
6. An error amplifier unit monitoring the machine's output.
7. An output slope control unit providing constant current or constant voltage output or alternatively by mixing the feeback signals provided any intermediate slope.

Wire feed was provided by a capstan driven wire feed unit powered by a 5-phase stepping motor (Figure 43). The drive unit for the stepping motor was mounted on the power supply itself. Reference signals for wire feed speed were provided from a front panel control or by means of an external pulse chain derived from the computer. This feeder provided a continous wire feed speed from 0 to 10 metres per minute and accepted electrode wire diameter up to 5mm.

Bead on plate was initially used for obtaining optimum process input parameters. Mild steel plates were of 19 mm thickness and of the following percentage composition C:0.08, Mn:1.4, Si:0.8, S:0.015, P:0.012, Cu:0.12. Filler wire employed was of composition C:0.06 %; Mn:0.5 %, while the flux used was of CaO:18.4%, SiO_2:15.2%, Al_2O_3:0.015%, MgO:30.2%, Na_2O+CaO:2.04%.

3.1.2 Computer Integrated Welding

To achieve a fully automatic welding system, the welding power source was interfaced and controlled by an external computer (B.B.C.) which was required to perform three main tasks:

1. Started the power supply, commenced welding and finally shut down the welding process.
2. Generated the welding parameters and wire feed speed required for any particular welding trial and also altered them during welding when necessary.
3. Monitored current, voltage and wire feed speed and took corrective action when required.

This computer was linked to the power source using a specially built interface. Welding pulse parameters were generated via a digital-to-analogue converter circuit (D/A) Figure 44, 0-10 Volts analogue output corresponding to 0-1000 Amps welding current. The main welding parameters were monitored using a welding parameter monitoring system (Figure 45).

The power source (Figure 46) was primarely controlled by three operating parameters:

1. Current level control.
2. Wirefeed speed control.
3. Slope characteristic control.

Slope characteristic control unit had a range of settings from 1 to 11. Setting 1 resulted in a constant voltage mode, the level control being directly related to the welding current (0-1000 Amps). Setting 11 was the constant current setting, the level control being directly related to the welding voltage.

Intermediate settings resulted in different slope characteristics being chosen, the level control being related to a position on the slope, as opposed to specific voltage or current level. For development purposes of the control system, slope characteristic setting 1 was used (constant voltage setting).

Wire feed speed (metres/minute) was controlled by the power source when the "External Mode" was used (Figure 47). This control was governed by a straight line relationship existing between the current and wire feed settings (Figure 48). S.A.W. system (steady DC open arc operation) was therefore characterised by two basic equations:

$$I = \alpha_1 V + C_1 \qquad (1)$$

$$V = \alpha_2 I + C_2 \qquad (2)$$

Where: I is the current, Amps

V is the wire feed rate, m/min

α_1, α_2 are the slopes, A/m/min or m/min/A.

and C_1, C_2 are the intercepts, A or m/min.

Once this satisfactory straight line relationship had been established (Table 1), the software allowed a scaling system to be imposed on the current/wire feed relationship. This reduced operator input to a single value in the range of 1-10. Output signals for the microcomputer were then converted to a suitable format allowing their accurate interpretation by the power source.Current values were subsequently held as an 8 bit number (255 decimal) and placed in the output register "B" of the 6522 VIA chip. Data direction register "B" was set to output mode and 8 bit values were sent from the user port B (bus interface).

Three input signals were required by the S.A.W. power source; "START", "STOP" and "CURRENT LEVEL". "VOLTAGE LEVEL" was also incorporated into the system which was used at a later stage for weld bead modelling purposes. Entry for these signals was provided by a 15 pin D plug on the front panel of the power source. It was worth noting that the 15 pin D plug on the power source was opto isolated from the power source high energy circuits ensuring that the interface at computer could not be overloaded.

The basic program used to communicate with the S.A.W. power source is shown in Appendix I. Purposes of this program were:

1. Calculation of the current setting for a specific welding range setting.
2. Calculation of the wire feed setting for a specific welding range setting.
3. Transmission of the current and wire feed speed values to the interface.
4. Control of the interface board i.e. enabling or disabling the correct portions of the interface circuit as required.

The operational sequence of the software is displayed in

Figure 49. Both analogue and digital outputs were tested using prepared data values in the software so that output values were accurately predicted and then compared to actual values. This way, a large number of errors was traced and solved.

Programs were written to send, receive, encode and decode signals between computer, welding rig and welding power source. The computer, had the ability through these programs and the calibration equations held in core to modify:

1. Welding speed by controlling velocity in the (X,Y) plane.
2. Electrical settings by controlling current and/or arc voltage.

To produce a satisfactory weld, the controller lacked at this stage details to generate welding procedures. In this experimental situation, it needed to be told the welding speed, current, and length of weld. One method of supply was immediately obvious. These values were preset. Thus the microcomputer tripped the necessary switches, sent appropriate signals, guided the head along the weld seam by using subroutines and terminated by completing the required weld length. Additionally, since the keyboard remained live during welding, the operator was given the facility to stop the welding procedure during the welding run.

3.1.3 <u>Ultrasonic Monitoring and Control Equipment</u>

Ultrasonic inspection equipment used, included two 2.5 MHz shear wave ultrasonic angle probes and their high temperature shoes. Comparisons were made between 45°, 60° and 70° angle probes on 19.0 mm thick plate. It was observed that the longer beam path lengths of the 60° and 70° transducers increased signal attenuation unacceptably, consequently an index angle of 45° was selected for all ensuing examinations. Variations of skip or stand-off distance were similarly examined, the most favourable echoes being obtained between 40-42 mm stand off from the weld centre line. This was as would be expected from geometrical considerations of the liquid/solid interface in relation to the central axis of the ultrasonic signal. Considering ultrasonic beam spread effects (Figure 50) the leading edge signal was so arranged as to provide seam tracking capabilities. Selection of ultrasonic frequency, crystal size, approach angle, stand-off distance and material thickness ensured that the ultrasonic leading edge signal was millimetrically in front of the weld pool. Therefore, distances between electrode tip and centres of the transducer crystals were calculated accurately. It was found, that using 2.5 MHz shear wave ultrasonic angle probes (45°) with one skip distance away from the weld centreline on 19.0 mm thick plate, the beam spread was 6°. This allowed for exact positioning of the transducer centres, 3mm back of the electrode tip and where the maximum penetration point lies.

Using two ultrasonic probes did not, in any way, cause complexity problems. On the contrary the available information was well worth the extra system as due to surface roughness if one probe temporarily lost contact, the second probe still remained intact and also both sides of the seam were interrogated. Some consideration was devoted to electronic measurement equipment since its limitations would affect the overall performance. It is well known that most measurement errors are introduced on the analogue side.

The time intervalometer/analyser/digitizer employed was compatible with standard auxiliary ultrasonic equipment and was linked with the computer to measure ultrasonic wave transit times in real-time in the material. It was to display and quantitatively differentiate between the two critical ultrasonic signals concerned in this work. Such an electronic system was thought to comprise two counters, one enabling measurements between the initial pulse (transit) and the first reflection, the other between the inital pulse and the second reflection.

An electronic device was then designed and constructed to fulfill all above requirements (Figure 51). The resulting amplified electrical signal was passed through an active electrical network which identified the exact positions of the two signals using an adjustable threshold level (Figure 52). Midpoints of these pulses were taken for reasons of accuracy (Figure 53). Through all this filtering, signal fidelity was preserved without adding or subtracting any frequency components. The two principal values of these timings were displayed and constantly updated, unless manually overriden by a "hold" switch on the equipment front pannel. Finally the counters provided 16 bit binary which was in a suitable format for interfacing to the computer. Figure 54 details the electronics. It's resolution depended on the velocity of the wave in the medium and it was found to be ±0.03 mm for shear wave velocity.

Careful consideration was paid to the purely practical problems associated with ultrasonic monitoring of a mobile workpiece. These were and remain:

1. Constant ultrasonic coupling between the probe and the surface of the material must be maintained.
2. Constant stand-off distance between the probes centres and the seam centreline must be maintained, but allowing for initial skip calibration.
3. The weight of the resultant fixturing device for holding the probes should be minimal.

A probe positioning device used in earlier work for weld bead penetration control was redesigned, fulfilling as far as possible all the above criteria. Probe to plate contact was maintained by four coil springs exerting pressure on the probe mounted platform vertical sliders. An extra smaller pair of coil springs acting as "probe shock absorbers" prevented "kick-up" of the transducer trailing edges caused by plate irregularities. The same configuration also carried the welding torch centrally placed between the two probes. Distance between each probe and electrode tip could be easily altered. It was fabricated from mild steel and had the non-moving parts made from aluminium for obvious minimum weight requirements. Figure 55 illustrates the whole assembly.

Coupling was provided by using oil (Tellus 27) delivered underneath each high temperature probe shoe. Couplant reservoirs (Figure 56) were machined directly into the "soles" of the acrylic probes so that the thin oil was flowing from a peristaltic pump (Figure 57) to the oil supply pipe drilled into the transducers rear edges, at low pressure. Flow was adjusted to maintain sufficient coupling without hydraulically lifting the shoes from the parent plate. Finally, excess oil escaped round the lower end of the transducer as the whole assembly moved along.

The high output impedance of piezoelectric transducers required the output signal to be fed through a preamplifier with low output imdedance, before being fed to further measuring or analysing instruments. This preamplifier was also an important component not only for the amplification of low signal amplitude events but it had the ability to drive long cables from remotely located sensors. Its main value lied in improving marginal sensitivity and resolution conditions and in establishing a precise frequency band-pass.

Bearing in mind the above consideration the electronic circuity for such an amplifier (Figure 58) was designed and constructed to provide the following functions:

1. Increased signal levels and mimimized interference and ringing introduced in cables and elsewhere by

using a preamplifier at or near the transducer.

2 Removed interfering noise and signals and accurately controlled the received signal bandpass through the use of a bandpass filter.

3. Allowed transducer signals to be set in the best "operating window" of the instrument and reduced the need to use instrument controls to calibrate signal amplitude by using the external controls on the front pannel of the preamplifier for system gain adjustments.

4. Provided selectable amplitude-limiting action when desired to reduce overload in the instrument.

"Flaw" detection equipment utilised for this reasearch work comprised of a standard commercially available ultrasonascope flaw/thickness test system. Apparatus consisted of a basic mainframe ultrasonascope with standard functions (reject, gain and delay.) as Figure 59 depicts. Its pulser/receiver section was used to generate electrical pulses to excite the transducers and to receive and amplify ultrasonic signals. An electrical pulse was generatedwhich excited the piezoelectric transducers, causing them to emit an ultrasonic pulse. In "pulse-echo" application this pulse travelled through the test material until it was reflected from an interface. Reflected pulses were received and converted into electrical signals by the same transducer. Signals were then amplified and conditioned by the receiver section and were made available for further analysis.

Monitoring welds using two probes connected to a single ultrasonascope display unit necessitated a method of switching from one probe to the other. A multiplexor was designed and constructed (Figure 60), having variable frequency and pulse width adjusted electronically via the microprocessor. The unit was self contained and included not only switching capabilities between two identical probes but also was capable of multiplexing ultrasonic wave mode propagation (through transmission/pulse echo).

A video camera recorder was employed for continuously monitoring ultrasonascope details. The system comprised a colour camera with macro lens and a built in microphone which was not only used for its still frame by frame advance features but also for recording the "arc sounds" during welding. This video/audio recording proved to be indispensable when post-weld analysis of ultrasonic displays was performed. Figure 61 shows the video camera and its accessories.

3.2 ULTRASONIC DATA ACQUISITION AND PROCESSING

Incoming ultrasonic signals were acquired in a manner which played a crucial role in the success of signal processing scheme. Failure to dovetail the signal acquisition system characteristics with the transducer lead to irretrievable loss of information, and subsequent attempts of recovery via signal processing techniques were usually not fruitful. Critical issues in signal acquisition such as filtering, sampling and averaging were therefore, examined closely.

3.2.1 Information Retrieval.

Information retrieval aimed to extract as much relevant information as possible from signals. This work addressed only edge detection and weld bead shape characterisation. Before proceeding further to discuss the signal processing technique it is useful to examine the typical edge characterisation scheme as shown in Figure 62. Energy was transferred to the material under test, via an excitation transducer. It interacted with the material edge and returned energy was then received via a receiving transducer. Material/energy interaction was governed by the underlying physical process, type of excitation source and properties of the material under test. Typical response signals reflecting material/energy interaction were viewed as the system's output shown in Figure 63.

Principal elements of the data collection system were the two identical shear wave angle transducers, an X-Y scanning frame and a computer based system for data recording and scan control. The 12 mm diameter transducers gave narrow bandwidth pulses with a centre frequency of 2.5 MHz and mounted on the holder maintained a separation of about 20 mm between the transducer face and scanned surface. X and Y transducer movement was controlled independently by stepper motors. Signals from the transducers were fed through an amplifier to a variable frequency multiplexer before reaching an eight-bit signal digitizer and finally collected by the microcomputer through its Input/Output (I/O) board facility. A software signal averager, also employed, reduced random electrical and acoustic noise. Time intervals between transducer driven pulse and first digitized sample of each waveform were adjusted so that the edges to be recognised were centrally placed in the digitized section. Before and after scanning each test block, a calibration scan was recorded from actual test block using a 5 mm "auto calibration window".

Ultrasonic signals were often corrupted by noise and/or artifacts introduced by the transducer instrumentation and other elements in the measurement set-up. These influences were mimimised by further conditioning the signal appropriately. When the noise spectrum was known precisely and lied outside the signal spectrum it was relatively simple to apply the electronic filter to enhance the Signal to Noise Ratio (S.N.R.). Averaging process, also significantly contributed on improving this ratio. In practice, however, both these simple techniques by themselves were often inadequate and consequently additional sophisticated techniques were needed. When known spectral characteristics of the artifacts were introduced, deconvolution techniques then appropriatelly restored the signals. Quantitative interpretation of A-scans was limited due to distortion, caused by the band-pass nature of the ultrasonic transducers and sound propagation paths involved in the experiments. This distortion could be so severe that the images produced contained very little quantitative information. Therefore, when a narrow electrical impulse was applied to an ultrasonic transducer, the sound field produced was broad in time duration and range, or oscillated. If the experiments were ideal sharp impulses would represent scattering from the hot surfaces and molten weld pool.

Methods to compensate for this distortion and subsequently enhance the resolution of ultrasonic images had to be adopted. Signal restoration meant the recovery of a signal that had been distorted. This mathematically is expressed as:

$$\mathbf{y} = \mathbf{D}\ \mathbf{h} \ldots\ldots\ldots\ldots \{3\}$$

where: y is the measured or known output singal.

h is the unkown signal.

and D is a known transformation that produces distortion.

The restoration problem is that of recovering h given y and D. Obvious approach to solving for h was to find the inverse operator D^{-1} such that:

$$\mathbf{h} = \mathbf{D}^{-\mathbf{y}} \ldots\ldots\ldots\ldots \{4\}$$

The solution for the above equation required that the inverse must exist and be unique. In practice, determination and implentation of the inverse operator was very difficult or impossible, so it was approximated. Often, the problem is ill-posed. To be well-posed, the problem of solving the first equation must satisfy all the following conditions:

i) Solution h exists for each element y in the range space Y.

ii) Solution h is unique.

iii) Small perturbations in y result in small perturbations in the solution h without the need to impose additional constraints.

In the pulse-echo mode of ultrasonic testing, if the interrogating signal is denoted x(t), then under various simplifying assumptions, the reflected signal y(t) is expressed as a convolution integral:

$$y(t) = h(a)\ (t-a)\ d\ a \text{.....................} \{5\}$$

where: h(t), called the impulse response, is a function of time related to the reflections that occur in the direction along the beam.

System identification is called the problem of calculating the impulse response calculating h(t) given the measurements x(t). If we want to find x(t),given h(t) and y(t), the problem is called deconvolution. Taking Fourier transforms from both sides of the above equation, it is noted that:

$$H(f) = Y(f)\ /\ x(f) \text{........................} \{6\}$$

where: h(t) is the inverse Fourier transform of H(f).
and f is the continuous temporal frequency variable.

Weld bead ultrasonic measurements were always band - limited and often noisy. Therefore, a meaningful way to generate an input or reference signal x(t) was found to estimate the impulse response. Reference signals were generated by measuring the reflection of an ultrasonic pulse from flat top and corner of mild steel specimens in an area of the block not containing any flaws. These references had the desired property that most of the ultrasonic energy was reflected back to the transducer. For this purpose the reference signal, x(t) is written as:

$$x(t) = u(t)\ T_1(t)\ P_1(t)\ \delta(t)\ P_2(t)\ T_2(t) \ldots\ldots\ldots (7)$$

where: u(t) is the electrical impulse driving the transducer.

$T_1(t)$ is the forward transducer impulse response.

$P_1(t)$ is the forward propagation path impulse response.

$P_2(t)$ is the return propagation path impulse response.

$T_2(t)$ is the backward transducer impulse response.

$\delta(t)$ is the Dirac delta function (an impulse).

and t is time and denotes the convolution operation.

Clearly, by taking the Fourier transforms from both sides it was observed that even though the reference signal did not occur simultaneously with the measured signal, it was interpreted as an input to the linear system h(t) the impulse response of the scatterer of interest (weld pool).

3.2.2 Scanning Procedure and Data Collection.

When the system was scanning, collecting test data, the display shown in Figure 64 appeared on the ultrasonascope screen. Hard copy of data was kept by employing a video camera to record the incoming signals. Scans provided a "live" display where echoes from reflectors lied and fall at the correct position along the timebase as the transducer was scanned on the workpiece. Time of flight measurements were further processed into a more desirable digital format. In the above mentioned figure, transmission pulse and returned echoes were clearly seen at the ultrasonascope screen and their respective digitized values on the computer monitor. Tests were always conducted at near maximum gain so that no information was lost. Typical reference signals for calibration purposes using the 5mm "window" approach are shown in Figure 65. Although threshold levels varied electronically they were set at 60% mimimum amplitude level and signals below this level were not reported. No crucial information recorded during tests was lost by imposition of the threshold as observed from video recordings. During scanning, displays were continuously updated and time measurements were compared with those extracted from previous points. Their values were recorded if their respective times were within predetermined limits, otherwise were ignored. Unlike the conventional test, however, all data collection and storage was carried out automatically by the system so that data collection was more comprehensive and objective. When a scan was considered complete it was given a reference number and all accompanying data were stored on a floppy disk.

The system's scanner device shown in Figure 66 comprised of an X-Y movement and an aperture of 100 x 100 mm, designed for scanning research specimens. It was also possible to incorporate z (linear) and θ (rotational) movements. Stepping motors ensured positional accuracy better than 0.1 mm. A probe suspension mechanism incorporated, accepted a variety of single probe sizes. Programs for control and setting up, concerning all aspects of a test, were contained within the microcomputer. Setting up and control was achieved by simple alphanumeric neumonic instructions, therefore, eliminating the need for machine level programming at this development stage.

Internal analogue to digital converter and the ultrasonic digitizer was sufficient for capturing the salient features of the signals, i.e. collected similar information to that available in conventional ultrasonic test, but was unable to cope with signal sampling or averaging. Data were therefore, further processed in the microcomputer ("autocalibration envelope").

Human eye-brain combination is excellent for pattern recognition. During the course of this investigation it was learned to discriminate between the above mentioned signals by looking at the A-scans on an oscilloscope. It was therefore, decided to try a similar tactic of a pattern recognition system based on cues humans use to identify sounds.

First, cues to discriminate the two types of signals (penetration and seam tracking) from A-scans were identified. In general, seam tracking signals observed were of greater amplitude than those of penetration and were a replica of the original waveform from the transducer. Penetration signals, on the other hand, consisted of several reflections from the moving weld pool which overlapped resulting in many cycles in the waveform.

A preliminary set of features was subsequently developed to attempt to discriminate amongst signals using the intuitive cues described above. This set was preliminary in that the features did not quite fit the intuitive cues, but were the results of a brief side investigation in this area.

Two of the output ultrasonic parameters were related to the actual monitoring system gain for a particular test run. Threshold level was used to eliminate noise signals from the analysis. Small amplitudes in the A-scan were ignored if they were below this value. The same threshold discriminated also low amplitude porosity or geometric reflector signals. The gain factor on the ultrasonascope front panel was then used to weight these two amplitude features (penetration and seam tracking), so that different test runs were compared even if the amplifier gain settings of the two probes were different. Both these two output values were preset and stored as constants, with reference to the ones exrtracted during weld bead modelling. The system therefore, was consistently calibrated prior to use and this required a set of standards for calibration. Ultrasonic data acquisition and processing software is given in Appendix 1.

A-scan data were stored as a series of numbers, each number representing the time-of-flight measurement of each peak from the initial pulse. The data acquisition system obtained this timing and sampled the A-scan data every 0.5 seconds (Figure 67).

3.2.3 Beam Path Length Measurements

Ultrasound pulses in an elastic solid were just high frequency strain waves propagating through the material with all the characteristics of strain waves. Elastic strain waves propagate in two modes:

- Longitudinal waves, in which the direction of strain disturbances is the same as the direction of wave motion.
- Shear waves, in which the direction of strain disturbances is perpendicular to the direction of wave motion.

The velocity of sound of an ultrasound pulse in a solid is a function of the elastic constrains of the solids and the mode of wave motion. For the longitudinal wave:

$$C_l = \frac{E(1-v)}{\rho(1-2v)(1+v)} \qquad (8)$$

while for the shear wave:

$$C_t = \frac{E}{2\rho(1+v)} \qquad (9)$$

where: C_l is longitudinal wave velocity.
C_t is shear (transverse) wave velocity.
E is elastic modulus.
v is Poisson's ratio.
and ρ is material density.

For steel at room temperature, C_L is 5.9 x 10^6 mm/sec while C_t is 3.22 x 10^6 mm/sec. Additionally the velocity of sound in a material is a function of the material temperature since the values of E, v and ρ change with temperature.

Currently, the most common device for producing an ultrasound pulse is the piezoelectric transducer. The sensors used throughout contained a quartz plate which produced an electric charge when it experienced strain in certain preferred directions. Alternatively, when an electric voltage was placed along the preferred axis it caused the crystal to deform along that axis. When the piezo electric transducer was placed in contact with the material and a voltage pulse was fed into the transducer, an ultrasound pulse entered the material. If this pulse was reflected back to the transmitted transducer, the voltage produced was measured.

Piezoelectric ultrasound transducers generally have disc shaped or square quartz plates as a trasmitter/receiver element. Stress distribution originating from a finite size source is a finite disturbance with size and shape determined by the size and shape of the crystal. Ultrasound intensity produced by each transducer varies in a predicatable manner with distance from the transducer. This ultrasound variation intensity can be described by characterising two regions, the near field and the far field. In the near field, ultrasound pulses are subjected to interference effects and their intesity goes through a series of maxima and minima. In the far field, the interference effects virtually disappear and pulses can be described by a cone with a constant beam angle and an amplitude that decreases monotonically with distance. Transition between nearfield and farfield effects is characterised by the nearfield length, N. For a disk shaped quartz plate:

$$N = (D^2 - \lambda^2) / 4\lambda \qquad (10)$$

where: D is plate diameter.
and λ is pulse wavelength.

In the far field region, the beam angle was described by:

$$\sin\gamma_o = 1.2\ (\lambda/D) \qquad (11)$$

where: γ_o is beam half angle.

Alternations of the ultrasound amplitude in the welded material was the result of two effects. The first was a direct result of energy conservation. As distance from the transducer increased, the constant beam angle of the transducer resulted in a larger region of material being disturbed. Since the inital pulse had a fixed energy content and more material was being searched, the amplitude of the disturbance along the transducer axis in the farfield region is described by:

$$A = \frac{A_o(\pi D^2)}{(4\lambda l)} \qquad (12)$$

where: A is amplitude at distance l from transducer.
l is distance from transducer.
and A_o is initial amplitude at the transducer.

Attenuation also occurred as a result of the scattering processes within the material. For a given material the attenuation resulting from internal scattering was described by:

$$A = A_o \exp(-\alpha l) \qquad (13)$$

where: α is an experimentally measured scattering coefficient.

The last two equations (12 ,13) combined gave the centreline ultrasound amplitude at a given distance l from the transducer with the result:

$$A = \frac{A_o(\pi D^2)}{(4\lambda l)\exp(-\alpha\lambda)} \text{........................} \{14\}$$

For material testing purposes, the characteristics of ultrasound at the interface between two materials were of great importance. At the interface, ultrasound energy was reflected back into the material in which it had been travelling, while the same was transmitted into the second material. It was possible for the energy being transferred by an ultrasound pulse to be converted from longitudinal mode of propagation to shear mode of propagation at an interface. This energy exchange is known as mode conversion. As a result, an ultrasound pulse incident upon the interface between the two materials was divided into two reflected and two refracted (transmitted) pulses, one longitudinal and one shear in each case (Figure 68). The angles of incidence, reflection and refraction of an interface were related to each other by Snell's law:

$$(\sin\theta_{ij}) \;/\; C_{ij} = \text{constant} \text{..................} \{15\}$$

where: θ_{ij} and C_{ij} are the angle and ultrasound velocity for material i and mode j.

At the interface, an incident longitudinal pulse at angle θ_{il} with velocity C_{il} was reflected into a longitudinal pulse with angle $\theta_{\alpha l}$ and velocity $C_{\alpha l}$ and a traverse pulse with angle $\theta_{\alpha t}$ and velocity $C_{\alpha t}$. It was then refracted into a longitudinal pulse with angle $\theta_{\alpha\lambda}$ and velocity $C_{\alpha\lambda}$ and a traverse pulse with angle $\theta_{\alpha t}$ and velocity $C_{\alpha t}$. The relationship between angles and velocities is:

$$\sin\theta_{il}/C_{il} = \sin\theta_{it}/C_{it} = \sin\theta_{\alpha l}/C_{\alpha l} = \sin\theta_{\alpha t}/C_{\alpha t} \text{....} \{16\}$$

Amplitudes of the reflected and refracted pulses are functions of the densities of ultrasound velocities of the two materials. Coefficients of reflection and/or refraction were defined to describe the amplitude of ultrasonic reflections. Reflection coefficient is the ratio of reflected ultrasound to incident ultrasound amplitude, while coefficient of refraction is the ratio of transmitted ultrasound to incident ultrasound amplitude. Generally, there are two reflection and two refraction coefficients namely longitudinal and shear. Reflection at the interface between the solid and air exhibited virtually no energy coupling between the two media. This meant that both refraction coefficients were zero. For an incident longitudinal pulse on the boundary between solid and air, the longitudinal and shear reflection coefficients are:

$$R_{ll} = \frac{(C_t/C_l)\sin(2\theta_l)\sin(2\theta_t) - \cos^2(2\theta_t)}{(C_t/C_l)\sin(2\theta_l)\sin(2\theta_t) + \cos^2(2\theta_t)} \quad \ldots\ldots (17)$$

$$R_{tl} = \frac{2(C_t/C_l)\sin(2\theta_l)\cos(2\theta_t)}{(C_t/C_l)\sin(2\theta_l)\sin(2\theta_t) + (\cos^2(2\theta_t)} \quad \ldots\ldots (18)$$

where: R_{ll} is the reflection coefficient from an incident longitudinal pulse.

and R_{tl} is the reflection coefficient from an incident longitudinal pulse to a reflected shear pulse.

Quantity of ultrasonic energy reflected or transmitted at an interface between two media was determined by using their respective acoustic impedances. Acoustic impedance for any media being defined by the product of velocity of ultrasound (C) in that media and its density (ρ). Ratio of reflected to incident energy was calculated using the following expression provided that the thickness of the reflecting surface (transducer) was greater than the wavelength of the ultrasound in couplant:

$$\frac{E_r}{E_i} \quad \frac{(\rho_1 C_1 - \rho_2 C_2)^2}{(\rho_1 C_1 + \rho_2 C_2)^2} \quad \ldots\ldots (19)$$

where: E_r is reflected energy.

E_i is incident energy.

ρ is the density of a particular medium.

and C is the velocity of a particular medium.

When the thickness of medium 2 was less than one wavelength of ultrasound in that medium (e.g. couplant and test plate), the following expression was used to calculate the ratio:

$$\frac{E_r}{E_i} \qquad \frac{[(\rho_1C_1)/(\rho_2C_2) - (\rho_2C_2)/(\rho_1C_1)]^2}{4\cot^2(2\pi\lambda) + [(\rho_1C_1/\rho_2C_2)+(\rho_2C_2/\rho_1C_1)]^2} \ldots\ldots (20)$$

where: t is the thickness of medium 2.
and λ is the wavelength of ultrasound in medium 2.

To determine the size of a "defect" within a material, it was necessary that the mechanisms by which ultrasound was reflected from an arbitrarily shaped three-dimensional surface were well understood. In the procedure to follow, Snell's law and the equations of reflection and refraction at an interface were used to construct a series of straight line beam paths which followed the direction of an ultrasound disturbance.

Figure 69 depicts a test piece plate of 19.0 mm thickness with a three hemisphere shaped weld pool, two of which have the same radius. Weld pool was considered to be axisymmetrical along weld centerline. An angle beam transducer (transmitter/receiver) was used as the ultrasound source and was placed at distance x_o from the weld pool centerline. This ultrasound transducer produced a finite width cone of ultrasound which illuminated the weld pool with ultrasound. As distance x_o was varied so that the transducer was moved backward or forward on the plate, the area illuminated by the ultrasound beam was shifted. Shifting of the transducer location altered the reflections from the weld pool since different portions of the weld pool were illuminated. Greater and sharper peaks were received on the ultrasonascope when the transducers line of sight was normal to the region of interest i.e. the seam and weld pool. As this action was taking place, it was possible for the beam to miss the weld pool and continue travelling until it reached the plate edge. Ultrasound beam was also reflected from the bottom of the plate once before it reached the weld pool. For the purposes of weld pool dimensional measurement, transducers were positioned either at one skip distance away from the weld centerline or two, depending on the thickness of the material and the angle of incidence.

Only reflected ultrasound rays at certain preferrred angles returned to the transducer. Occasionally, however, large number of reflected pulses returned to the transducer all at the same time and made the task of extracting weld pool dimensions from ultrasonic time traces rather cumbersome (Figure 70). The much extraneous information was decoded so only useful information was analysed.

Investigations were also performed primarily to determine the effect of temperature on the velocity of transversed waves in mild steel specimens. Intentions were to improve the systems sensitivity and accuracy since beam path length/time-of-flight measurements were affected by the velocity of acoustic waves in the medium.

Attenuation is sensitive to the elastic properties and microstructural features of the medium in which they propagate. For strain free materials where no structural changes occur, velocity decreases with increasing temperature due to changes in elastic modulus and density of the propagating medium.

Thermally activated physical and structural changes during welding (e.g. Curie point, phase chance etc.) can modify this trend, producing peaks, troughs or inflexions, occuring where these changes were taking place. In general, the prominence of these superimposed features depended on the degree of change. Sharp changes in velocity took place where marked changes in the physical or structural properties occurred.

Representations of the velocity/temperature curve (Figure 71) produced by Wootton,[133] were similar in both character and quantatively with the results obtained by Papadakis[129] for low Cr, N, medium carbon alloy steels. Although materials and prior treatments used by Wootton were different from Papadakis, no changes in velocity gradient occurred within the A_1-A_3 temperature region. With the radical changes in physical and structural properties which occurred within this region, a change in the gradients of velocity/temperature curves was anticipated. This apparent lack of sensitivity in Papadakis procedure probably originated from the large temperature intervals at which measurements were made (i.e. every 200 °C). Slow heating and holding can mask the effects of diffusion controlled processes on velocity. Wootton's measurements, however, were taken an average every 45 °C and heating and holding periods were much faster due to the mode of heating employed (i.e. modified muffle furnace was used as opposed to Papadakis technique using a ceramic tube wound with a heating element).

To examine the features of velocity/temperature curves closely, three zones corresponding to the three phase regions of the Fe/C phase diagram were analysed (Figure 72).

As mentioned previously, the velocity of an accoustic wave propagating through a solid is dependant upon the elastic moduli and density of the solid. For a longitudinal wave the velocity is given by:

$$C_l = [(E/\rho)(1-v)] / [(1+v)(1-2v)] \ldots\ldots\ldots\ldots \{21\}$$

where: C_l is the longitudinal velocity.
E is Young's modulus.
ρ is the density of the material.
and v is Poisson's ratio.

E decreases with increasing temperature as did ρ, but the decrease in E was considerably larger than that of ρ. Velocity therefore, decreased with increasing temperature, since the right hand side of equation 21 decreased, primarily because of the effect of temperature on the ratio E/ρ.

Between room temperature and Ac_1, velocity decreases fairly uniformly up to 570 °C , at which point an inflexion occurs probably due to ferritic recrystallisation. Although there is little change in E or v, at an atomic level, there is a great deal of activity during recrystallisation and grain growth in welding to justify the above probability. This is due to the dynamic changes which inhibited the propagation of acoustic waves and thus, increase the gradient of the curve at this temperature from - 3m/s/°C to - 12m/s/°C, before the rate decreased again at 620 °C.

Strain energy resulting from plastic deformation is released during recovery, but a large portion remains and acts as the driving force for recrystallisation. The overall process appears to be the nucleation of strain free grains and their subsequent growth. Electron microscopy studies, however, suggest that the fundamental process in recrystallisation is the migration of boundaries separating regions relatively free from dislocations from regions with a greater dislocation density. These mobile boundaries, migrate through the matrix creating behind them a recrystallised structure. In mild steels there are vast numbers of these boundaries moving through the structure, hence atomic migration on a large scale occurs. At the instant an acoustic wave impinged on one of these moving particles the energy was not necessarily transmitted to the nearest neighbour in relation to the direction of propagation. It is quite probable that the acoustic energy was transmitted to the nearest neighbour relative to the position that the atom was moving to, as the acoustic wave was struck. In turn the vector path of the acoustic wave travelling through the lattice was increased. This resulted in an apparent decrease in velocity, since the greater distance traversed resulted in longer transit times. It was mainly the dynamic process of recrystallisation which lead to the modification of the curve gradient between 570 and 620 °C. Assuming the above is correct, the temperature where the gradient of the curve started to decrease (620 °C) represented the region where recrystallisation had been largerly completed and the curve was returning to its original course.

Between Ac_1 - Ac_3 and at 740 °C, another inflexion point occurs. It was anticipated since in this region $\alpha + Fe_3C \rightarrow \gamma$ phase change commenced. The decrease in gradient at 740 °C was explained on the basis of the change in the ratio E/p for the crystal structure transformation B.C.C. --> F.C.C. Austenite with its more closely packed structure is denser than Ferrite. In addition all of the carbon present was dissolved interstitially in the F.C.C. lattice, leading to a further increase in density. Young's modulus also increases as a result of the B.C.C. - F.C.C. transformation (Figure 73). In comparison with the increase in ρ the increase in E was quite large. Therefore, the right hand side of equation 21 increased, resulting in a relative increase in velocity. In addition the effect of the dynamic processes of crystallisation and grain growth of the austenite phase played a role in this region. On these basis, velocity decreased during these dynamic processes and masked the effect of the ratio E/ρ on velocity.

Between Ac_4 - 1140 °C and at 920 °C, the gradient becomes slightly more negative and marks the completion of the phase change to austenite. At this point the ratio E/ρ becomes solely dependant on temperature. Therefore, it was anticipated that the change in gradient was negative with respect to the gradient within the Ac_1 - Ac_3 region.

According to the above observations and the discussion on the predetermined results above, isotherms were constructed according to temperature gradients occured (amplitude ≈ 50 °C) and velocity changes were estimated (Figure 74). Subsequently, the angles of incidence entering each isotherm were calculated using Snell's law which in turn allowed beam path length constructions and time of flight measurements (Table 2). Finally the base sweep of the ultrasonascope display was recalibrated according to known weld pool sizes and heat inputs involved during the welding process.

In an attempt to determine the transit times concerned, a set of geometric equations to predict transit times between transducer and weld pool and back, were constructed.[146] Transducers were made in two parts, the crystal element and the electrodes in a housing. Refraction wedge underneath the crystal used to direct the ultrasound beam to the desired angle. It required finite time for ultrasound to pass through the refraction wedge and into the weldment. Transit time predictions must therefore, include an estimate of the transit time through the wedge. Transducer beam angle was characteristic and defined the ultrasound beamwidth. Transducers were sitting upon the wedge at some fixed angle θw_n, relative to the normal to the plate surface (Figure 75). Transit times through the wedge are calculated by using the following equation:

$$t = \frac{b}{Cw_l \cos\theta w (1 + \alpha \tan\theta w_o)} \quad \text{.....................} (22)$$

where: b is the z intercept of a linear equation defining the angled surface of the wedge.

α is the slope of the angled wedge surface.

θw is the angle of a ray leaving the ultrasound. transducer and is equal to $\theta w + \delta\theta$, where $\delta\theta$ is a small angle.

and Cw_l is the velocity of sound of a longitudinal wave in a wedge.

The wedge surface can be defined by:

$$z = b - \alpha\ (x_I - x_o) \qquad \{23\}$$

where: z is the height of the angled surface of the wedge above the plate.

x_I is the x position of a point on the angled section of the wedge.

and x_o is a fixed reference position on the wedge.

A ray originating at the centre of the angled portion of the wedge with angle θw, entered the plate at a position given by:

$$x_t - x_o = \frac{b(\tan\theta w_o - \tan\theta w)}{1 + \alpha\tan\theta w_o} \qquad \{24\}$$

If the plate and the wedge were acoustically coupled via pressure or liquid couplant, ultrasound was refracted into the plate at the interface. Angle at which ultrasound entered the plate, θ_t, is, from Snell's law:

$$\theta_t = \sin^{-1}[\ (Cp_t/Cw_1)\ \sin\theta w\ ] \qquad \{25\}$$

where: Cp_t is the velocity of sound of shear waves in the plate.

It was assumed that transit time through acoustic coupling was very small and therefore negligible.

An ultrasound ray of angle θ_t was now travelling through the plate towards the weld pool. The path taken by the ultrasound ray, reflected from top and bottom of the plate n_t times (generally) before it reached the weld pool surface. Assuming that the point of intersection of the ray with the weld pool surface was (x_i, z_i), the transit time required for ultrasound to travel from the transducer to the weld pool is given by:

$$t = \frac{2n_t d - z_i}{Cp_t \cos\theta_t} \quad \{26\}$$

and the ray path had to satisfy the condition:

$$x_i - x_o = (2n_t d - z_i) \tan\theta_t \quad \{27\}$$

Intersection points determined between weld pool and an ultrasound ray were a function of the weld pool shape. Assuming again that weld pool shape is of a three hemisphere shape and that the centre of the two identical hemispheres did not lie along the plate surface, but rather were offset by some distance h above the plate (Figure 76), the weld pool surface is defined by:

$$x^2 + z^2 + 2hz = r_p^2 - h^2 \quad \{28\}$$

and

$$dz/dx = x / \sqrt{r_p^2 - x^2} \quad \{29\}$$

Weld pool surface intersection with an incident ultrasound ray was found from the simultaneous solutions of the last three equations. This resulted in a guadratic equation which was solved to find the reflection point as follows:

$$x_i - x_o = (2n_t d - z_i) \tan\theta_t$$
$$x^2 + z^2 + 2hz = r_p^2 - h^2$$

Let $\alpha = 2n_t d \tan\theta_t$

$\beta = \tan\theta_t$

$A = 1 + \beta^2$

$B = \alpha\beta + \beta x_o - 2h$

$\Gamma = \alpha^2 + x_o^2 + 2\alpha x_o - (r_p^2 - h^2)$

Then z_i and x_i are given by:

$$z_i = (B \pm \sqrt{B^2 - A\Gamma}) / A \quad \{30\}$$

and

$$x_i = \alpha - z_i\beta + x_o \quad \{31\}$$

(N.B. Only positive real solutions were considered.)

Angle of incidence of the ultrasound ray is (Figure 76):

$$\theta_i = \alpha - \theta_t \quad \{32\}$$

where: $\alpha = \tan^{-1}[x_i / \sqrt{r_m^2 - x_i^2}]$ the tangent angle to the weld pool.

Angle of reflection θ_r is then:

$$\theta_r = \begin{cases} \theta_i, \text{ for shear wave reflections} & \{33a\} \\ \sin^{-1}[(Cp_i/Cp_t)\sin\theta_i] & \{33b\} \\ \text{for longitudinal waves from Snell's law.} & \end{cases}$$

For convenience, the reflection angle was defined with reference to the normal plate as:

$$\theta_R = \alpha + \theta_r \quad \{34\}$$

The reflected ray was now pointing in the direction of θ_R (Figure 77). For, θ_R negative, the ray was reflected away from the transducer and was not of interest. For θ_R less than 90° angle, the ray is pointing towards the bottom of the plate and follows a reflection path bouncing between the bottom and top of the plate at angle θ_R and heading back towards the transducer. There is the possibility that mode conversion could take place along this path resulting in a longitudinal wave return to the transducer. Additionally, if θ_R = 90°, the ray heads down the interior of the plate without approaching either top or bottom of the plate. Finally, if θ_R is greater than 90°, the ray heads towards the top of the plate and continuous bouncing back towards the transducer again with the possibility of mode conversion taking place. Return path to the top of the plate through r reflections from top to bottom to top without occurence of mode conversion ended at the point x_r, where:

$$(x_r - x_r) = 2\, n_r\, d\, |\, \tan\theta_R\, | - z \tan\theta_R \quad \text{......(35)}$$

Transit time for this path was:

$$t = \frac{2\, n_r\, d \tan\theta_R - z\, |\, \tan\theta_R\, |}{C \cos\theta_R} \quad \text{..........(36)}$$

where: C is velocity of sound of the reflected pulse.

If x_r is a value that corresponds to the location of the refraction wedge, then ultrasound ray entered the wedge and travelled back through it to the transducer. Angle of entry back into the wedge was found using Snell's law and transit time to the transducer face is:

$$t = \frac{b - \alpha(x_r - x_o)}{C_{w1}(\cos\theta w + \alpha \sin\theta w)} \quad \text{..................(37)}$$

It was observed that the position of the ray which did not correspond to the wedge location, was not received by the transducer. Additionally there were some preferred positions at which ultrasonic reflection maxima occurred. These maxima were separated by distance $\Delta x = 2d / \tan\theta_n$, where d is the plate thickness and θ_n the nominal wedge angle.

3.3 OPERATIONAL CHARACTERISTICS OF THE MANIPULATOR ARM

The purpose of the manipulator arm was to carry the welding torch and probes. The objective was to provide simultaneous movements along either of two cartesian co-ordinate axes in order to position the desired welding bead along the seam with minimal positional error. To achieve this, high stiffness lead screw positional tables were employed having lead screw diameter 10 mm and pitch 1.0 mm.

Also backlash and pitch errors in the lead screws were reduced to a minimum by using an adjustable split drive nut. Fixture tables were configured in a standard gantry arrangement with adjustable vertical support posts. Maximum travel distances were 100 mm or 10.000 steps. Figure 66 illustrates the described configuration.

3.3.1 Stepping Motor Driven Positioning Assembly.

Stepping motors (4-phase) used were electromechanical transducers that converted sequences of digital pulses into angular displacements. They were originally employed to rotate a fixed angular displacement each time a pulse was applied to their controllers and were succesfully used to follow arbitratry positions with low speeds and small accelerations. To obtain the timing (in the start-stop motion at every step) pulses were supplied as a direct replica of the desired position-time relationship. Stepping motors used had certain desirable feautures, such as being inherently pulse driven devices, easily interfaced with pulse generating digital systems and under mild condition, the shaft position is independent of load. Reliable positioning was therefore, achieved with open or closed loop control. Motion accuracy was measured to be ± 0.3 mm.

They were continuously excited by direct current and hence had a high holding torgue even when the motor was not rotating. To have the rotor progress by one step, the currents in the stator coils were switched on, switched off or reversed in a suitable manner. Such switching processess occurred in a certain sequence corresponding to the design principle of the motor. All stepping motors were operated in a full step mode. Figure 78 shows the design principles of a 4-phase stepping motor, whith its typical performance curves.

Stepping motors used, were highly compatible with the microcomputer. Ultimate system flexibility was a product of the two devices, with a simple relationship shared between control input and motor shaft rotation. Motor response and reliability were easily enhanced by capitalising on:

i) Specific perfomance charcteristics of an individual stepping motor as applied to a specific load.

ii) Correct match to a logic-based controller.

iii) Inherent noise immunity gained by digital transmission between the two.

Other advantages were traced to the dynamics of the stepping drive itself. Rotor shaft position at the conclusion of an input pulse train was highly predictable and based upon motor damping, friction, and inertial load factors. In the overall line, countless steps were delivered with low total angular error. Thus, at optimum speeds the stepping motor served as both a high speed drive and a high-resolution positioning tool.

Motor stiffness was a prime consideration in choosing the optimum motion-control system for a specific application. Unique to its overall design, this value was inherently high in the permanent-magnet stepping motor. Response to a sudden load surge was immediate, instantaneously approaching maximum holding torgue without the time lag typical of feedback-oriented servomotor systems. This additional torgue enhanced output response reliability was one of the most important consideration in employing the stepping motors for automating the welding process and specifically moving the welding head laterally across non-linear seams.

Motors were driven in a random manner at speeds up to 200 steps/sec., without missing a step and therefore, provided an ideal incremental shaft positioning device compatible with solid state digital methods. Pulses at the input produced 1.8° angle movement of the motor shaft or 200 steps per revolution. Motors were controlled by digital commands, translated into pulses through IEEE 488 control interface and motor drives. The absolute velocity values determined motor speeds and consequently welding head resolution along the appropriate axis. Digital signals were applied to motors and the actual distance through which the head moved were recorded.

Experience in using the above configuration to follow the seam showed that system calibration was quite adequate and that overall tracking accuracy measured was as high as ± 0.3 mm over the full travel length.

All stepping motors required one or more drive modules to supply power to the motors. Power was in the form of carefully controlled currents switched in sequence which thereby caused the motor to rotate. Drive module, in turn, required two input signals, one for each motor step and a direction input which determined the direction of rotation. Internal drive logic and power amplifiers set and maintain output current levels.

Employing chopper regulation high overall efficiency was achieved and the use for ballast resistors was eliminated whilst power consumption was minimised. Motor drives delivered nominal currents of 3 Amps and operated from a 24 Volts power supply. Motor pulses were derived from the external source (microcomputer) and could achieve speeds from 40 to 10,000 steps per second. A centre-tapped system was employed which enabled multiple drives to be fed from the same winding without the current-sharing problems encountered in bridge circuits. Stepping motor drives and their power supplies are illustrated in Figure 79.

3.3.2 Interfacing with an External Microcomputer

Linking together the computer with the controls of the manipulator system required data paths. IEEE-488 (Figure 80) specification defined a communication network by which data and commands were transferred between IEEE-compatible devices. IEEE-488 defined the electrical connections and signal levels together with a "handshake" procedure by means of which the required data transfer was achieved. This bus system was based on a highway which was connected to all devices in parallel. There was normally one controller (microcomputer) together with other devices which were "talkers" or "listeners" depending on whether they sent or received data. Often both functions were performed, as in the case of the stepper interface. This controller had overall supervision of the system and decided who would talk and who would listen. Additionally, it acted as a talker and listener itself.

This highway comprised 8 data lines and 8 central lines which were dedicated to specific functions associated with the management of the systems and the transfer of data or commands. Figure 81 depicts the arrangement and functions of the control lines. Since the bus was connected to all devices in parallel, there was a way of identifying each device so that the controller sent information to or from the right place. This was achieved by giving each device a different "primary address" which was set up on switches within the unit. This address was only a number by which that particular device was identified. Controller handshake procedure was initiated by telling all devices to expect some data. It accomplished this by taking the ATTENTION (ATN) line low and sending out an address, called MY LISTEN ADDRESS (MLA), on the data liner.

MLA comprised the primary address of the device together with a two-bit code showing that the device was required to listen. The device with that address code then set itself up to receive data; the ATN line returned high and all other devices ignored what meant or for the time being. The controller then proceeded to transmit data in the form of ASCII characters with the most significant character first. It used the 8 data lines and 3 handshake control lines DAV, NRFD and NDAC. The receiving device used NRFD to show that it was ready to receive data; having placed the information on the data lines, the controller signified valid data by means of DAV. When the listener had captured the data it told the controller so by means of NDAC, after which the control lines reversed to their previous state ready for the next character. After all the data had been transferred, the controller sent out a general "UNLISTEN" (UNL) command on the data lines, again with the previous listener.

When the controller wished to receive data from a remote device, a similar procedure was followed; this time the controller sent out "MY TALK ADDRESS" (MTA) to tell the addressed device that it was expected to send some data. Again MTA consisted of the primary address together with the "talk" code. This was usually followed by a SECONDARY COMMAND GROUP (SCG) code which defined the type of data required i.e. status or position information. The roles of device and controller were now reversed, with the addressed device now sending back data bytes using the same handshake lines DAV, NRFD and NDAC. On completion of the data transfer the controller sent out the "UNTALK" (UNT) command to disconect the talker.

The only other control line of interest in this context was the SERVICE REQUEST (SRQ) line which was used by any device to ask for attention from the controller. If there was more than one connected device then the controler interrogated each one to find out which of them made the request e.g. when motion was completed or if a fault condition arose.

Facilities included:

1. Indexing - incremental indexing programmed in motor steps and translated in to mm.

2. Speed Control - speed programmed in steps per second and then translated in to mm.
3. Acceleration and decelaration - linear acceleration and deceleration ramps generated automatically.
4. Run/Stop operation. The motor was run at a pre-programmed speed, stopped as required or stoppped on the next zero-phase position of the translator. Speed could be changed whilst the motor was running if required.
5. Cancel facility - used to terminate a run, remove boost, de-energise or abort an index.
6. Stall defections - used on one related axis in the multiplexed mode, or on any axis in the simultaneous mode.
7. Emergency stop - hardwired connection which halted all axes driven by the controller interface.

3.3.3 Monitoring and Controlling Joint Configurations.

As presently constituted, the welding configuration presented a mixture of closed loop and adaptive control. Welding current, arc voltage and welding speed were set by computer at the start of welding and any deviations, as sensed by the ultrasonic monitoring system, were directly corrected until output and input agreed. Corrections were made by computer software but could equally well be achieved by independent microprocessor control or independent circuitry.

Welding head and weld seam relative positions were sensed by ultrasonic means. This was performed in three stages:

i) Verified that the head was where it should be in relation to the seam.
ii) Estimated the distance travelled between each sampling period and the next.

iii) Estimated the width of gap between the plates.

Software developed (Appendix 1) made all three tasks dependent of real dimensions. In case the head had wandered from its correct position on the seam, correction was a matter of calculating the distance in mm which would return it to its correct position before the next sampling period. If the angle of seam to horizontal plane changed and was smaller than the angular beam spread of the crystal, distances along X and Y axis were recalculated. It was found more efficient to perform each of these tasks at each sampling point as that if the head had not wandered. A zero correction was made to the head and distances were recalculated. This recent addition meant that the time intervals between sampling periods were always of the same length and therefore constant.

3.4 PROCEDURE OPTIMISATION FOR WELD BEAD MODELLING

Experimentally, the first step in welding process was the optimisation of subsidiary process variables and their control over the welding sequence. This technique enabled an objective view of the factors making up the welding process to be taken into consideration and showed the likely effect of procedural changes to productivity.

Although the current process parameter range covered in the present work has been strictly limited, a number of interesting trends had previously been identified. All the welding variables considered, affected one or more of the weld bead dimensions. In each instance, where sufficient results were available the variation did not appear to be linear. Therefore, when the current was varied at a a fixed voltage and welding speed, the increase in weld bead width was most marked at currents below 500 Amp. On the other hand, the increase in penetration for a given rise in current was greater at current levels above about 550 Amp.

At the same time, the height of the reinforcement did not appear to be affected by changes in current. Results obtained on different wire diameters indicated that this was in reality a current density effect. Voltage affected only bead width and cross-sectional area, which increased with voltage. Additionally all the bead dimensions varied inversely with the welding speed although the effect on bead width was mostly marked.

It has been recognised that the presentation of data in two-dimensional diagrams was in reality much too simplified a format, although their value in helping to visualise the significance of the variables concerned was acknowledged. In practice it was expected that several interacting variables must be accounted for in any decision.[149] To best cope with this problem statistical analytic techniques were used to construct equations capable of relating the process variables to the weld bead geometry. The most useful way to select and present the relevant information for a particular application was through an interactive computer program.

These models were used either to predict bead geometry from any combination of welding parameters within the ranges studied or to determine relationships within the range of parameters to obtain desired bead geometry dimensions from ultrasonic beam path length measurements. Primary intentions were for use in an automated production system for adaptive control of welding conditions.

3.4.1 Effect of Welding Variables on Bead Geometry

Weld bead modelling was primarily intended to help select proprietary welding parameters in view of production of acceptable, "sound" welds. Alongside with the main aims, weld bead modeling aided the analysis of weld defects, thus, consulting before and correcting during the welding procedure. Experiments were designed to identify important welding parameters whose effects were investigated using half factorial experimental designs and subsequently use these results for welding process parameter monitoring and control.

Once flat mild steel material was selected as the workpiece the appropriate wire and flux type were chosen for the particular application. Plate edges were cleaned and freed from contaminants such as oil, rust, paint etc., which, if in contact with the molten pool and the flux, could cause porosity, slag inclusions and in severe cases cracking. Joint configuration angles and the selection of other forms of edge preparation such as V, etc., were avoided for simplicity. Flux movement was always static relative to the solid lying molten weld pool to avoid any distortion of the weld bead shape. Flat workpiece welding position was chosen so that the flux was supported by the parent material and also flux spillage was avoided by secluding it within the parallel plates in the lower part of the probe holder. This way, flux depth control was maintained throughout the welding sequence. Also, the effectively flat workpiece position was thought to give the best possible control conditions for bead shape and easy slag removal and also to alleviate any gravitational effects.

Preliminary considerations showed that, the location of the earthing point, relative to the direction of welding wire travel was important. Welding away from the earth produces smoother, even bead profile, and normal penetration depth in comparison to welding towards or across the earth position.

Electrode polarity was chosen to be DC positive since it has been proved to give the deepest penetration and the best bead surface appearance and shape. Angle between the electrode and plate, relative to the direction of travel can determine the point of application and direction of the arc force. To obtain the best practical combination of bead shape and penetration it was advisable to weld with the wire pointing forwards, leading by approximately 10° angle rather than normal to the workpiece surface. Additionally, experimental results have showed that electrode extension or "stick out", which is the unmelted wire extending beyond the end of the contact jaw, had to be held between 25-30 mm for the mild steel application.

Keeping all the above welding variables constant at their predetermined limits, a series of close fit butt welds on 19.0 mm thickness of workpiece were made, to determine the effect of welding current, arc voltage, travel speed and wire diameter on bead shape geometrical characteristics. Since those were the major variables that affected the shape of any submerged arc weld, individually identified and previously discussed theoretically, experimental work started in order to assess the effect of these parameters on weld bead shape.

Large welds, particularly those that have long narrow configuration, i.e. a high depth/width ratio, exhibits the typical solidification pattern of large columnar grains growing inwards and at near right angles to the weld centre line.

Generally a depth/width ratio of 1/1½ was thought to provide this more favourable grain growth pattern and thus gave better more "sound" welds. Following this assumption, the target of the welding experiments was to produce welds wider than deeper, the grains to grow upwards and provided that the profile was smooth and convex the best possible condition would have been achieved.

3.4.2 Determination of Weld Pool Dimensions

In specifying weld bead dimensions, it is general practice to give the width (W) at the level of the plate surface, the depth (P) below the surface to which the bead has penetrated and the height (H) of the reinforcement dimension tolerances:

$55\% \leq P \leq 100\%$ $W \leq 40$ mm $H \leq 7$ mm $P/W \leq 0.75$ $H/W \leq 0.3$

Dimensions after the welding run were readily determined on etched vertical sections of the weld bead cut transversely to the direction of welding. Three sections were taken from each plate and the mean of the three values for each weld bead was recorded Figure 82. The effects of welding parameters on weld bead dimensions are outlined below:.

A) Welding Current (I): Throughout the current range examined, 300-1000 Amps, bead width, penetration and area increased directly with current, but the reinforcement was unaffected (Figures 83-85). Closer examination of the weld bead profiles showed further points of interest. Between 300 and 400 Amps, penetration and reinforcement were similar in size, but above this current penetration increased and developed the familiar cup shape. At most currents, reinforcement blended smoothly into the plate but at 600 and 700 Amps, the transition was sharp (Tables 3-5).

B) Arc Voltage (V): Bead width and cross-sectional area increased with increasing arc voltage, but penetration and reinforcement remained constant (Figure 86). At lower voltages reinforcement tended to give a sharp junction between bead and plate (Table 6).

C) Welding Speed (S): As was expected, all weld bead dimensions decreased as speed increased, but the effect was most marked with the bead width (Figure 87). Penetration tended to be more uniform at higher speeds (Table 7).

D) Wire diameter (D): It was difficult to observe any major variation over the small range of wire diameters used (Table 8). Bead width, penetration and cross sectional area all appeared to decrease slightly with increase in wire diameter whereas the reinforcement exhibited the opposite trend (Figure 88)

3.4.3 Weld Bead Shape Control - A Mathematical Approach

It was thought that a formalised approach to procedure optimisation could succesfully establish combinations of welding parameters which would produce welds of a given quality standard. While the experimental approach was being formalised a mathematical approach to correlate welding parameters with weld geometry was also proceeding. This experimental work, combined with an investigation of tolerances in welding, was used to put forward a new approach to procedure developments which potentially required considerably less experimental data. The data base used 2 x 3[illegible] factorial experimental procedures and its limits are shown in Table 9.

Method of analysis for each output variable was identical and as follows:

1. An analysis of variance quantified the actions and interactions of input variables (I,V,S,D) on each weld dimension in turn (Table 10). Mean squares for each effect were compared with the indpendently assessed error for the most complex interaction thus quantifying the effects relative importance.
2. A function based on the analysis of variance was fitted to the data base by multiple analysis (Table 9).
3. Since experimentation in welding is generally highly specific and both input and output variables are susceptible to differences in interpretation, physical considerations about the logical shape of the equations were also taken into account.

Throughout the analysis, the multiple correlation coefficients, v and Fisher's - ratio, F, at the 1% level of confidence, were employed to measure goodness of fit. Table 10 shows the results of this analysis of variance in penetration as a function of welding current, arc voltage, travel speed and wire diameter and all possible interactions. This led to a search for an equation capable of evaluating penetration mainly as a function of all four input variables in combination.

Representing the weld bead parameters and shape relations by (Y), the response function is expressed as:

$$Y = (I, V, S, D) \quad \ldots \quad (38)$$

where: I is current.
V is voltage.
S is welding speed.
and D is wire diameter.

Y could be: penetration, width, reinforcement height, aspect or percentage dilution.

Different models were considered but giving preference to the simplest, the relationship selected was a portion of the power series - algebraic polynomial, expressed as follows:

$$Y = C_0+C_1I+C_2V+C_3S+C_4D+C_5IV+C_6IS+C_7ID+C_8VS+C_9VD+C_{10}SD \quad \ldots \quad (39)$$

where: C_0 - C_{10} are constants.

This model included the main effects of variables and first order interactions. To determine the main and interaction effects the following formula was used:

$$e_j = \frac{2\Sigma\ x_{ij}y_i}{N} \quad \ldots \quad (40)$$

where: x_{ji} is value of factor or interaction in the coded form.

y_i is output parameter.

and N is total number of observations.

Coefficients were determined by dividing the effects of the variables and interactions of the variables by 2 and the constant C_o obtained by the following formula:

$$C_o = [Y_1 + Y_2 + Y_3 + \ldots + Y_n] / n \ldots\ldots\ldots\ldots\ldots\ldots \{41\}$$

where: Y_1, Y_2, Y_3, ... Y_n are the outputs of n trials.

Constants and coefficients are presented in Table 11 and ensuing evaluations led to an equation of the general form:

$$\ln P = C_o + C_1 \ln I + C_2 \ln V + C_3 \ln S + C_4 \ln D \ldots\ldots\ldots \{42\}$$

Richter[150] estimated the values of C_o - C_n such as:

$$\ln P = -6.05 + 2\ln I + 0.21\ln V - 0.4\ln S - \ln D \ldots\ldots \{43a\}$$

Studies at the Welding Institute[151] evaluated the coefficients such as:

$$\ln P = -7.15 + 1.61\ln I + 0.21\ln V - 0.27\ln S - 0.53\ln D \ldots \{43b\}$$

which at first sight looked very different from the previous equation. The second equation correlates 0.97 with the observation of penetration in the Welding Institute experiments; the first correlates 0.95. The descrepancy was probably caused by differences in welding speed and current ranges, the Institute's steps being smaller than Richter's. Additionally, equation 43b had the advantage that the sign of the coefficent of ln V is negative, a finding expectable on physical considerations. Equation 43b was therefore, accepted as adequate to predict penetration on close edge square butts. It was modified, however, for reasons of better accuracy to:

$$\ln P = -7.1482 + 1.55586\ln I + 0.213918\ln S - 0.26663\ln D \quad \{44\}$$

Similar analyses were carried out for the other weld bead dimensions:

$$\ln W = C_0 + C_1\ln I + C_2\ln V + C_3\ln S + C_4\ln D \quad \{45\}$$

with C_1 much smaller than the other coefficients.

Bellchuck's equation:[152]

$$\ln W = 0.18 + \ln V - 0.5\ln S + 0.3\ln D \quad \{46a\}$$

seemed suitable and the best estimate of coefficients was:[151]

$$\ln W = 0.38 - 0.08\ln I + 1.05\ln V - 0.48\ln S + 0.44\ln D \quad \{46b\}$$

Coefficients were so alike that no further discussion was necessary; equation 46b was therefore, accepted as an adequate prediction of width, with slight modifications for higher accuracies:

$$\ln W = 0.382095 + 1.04577\ln V + 0.436533\ln D - 0.020533\ln I - 0.48228\ln S \quad \{47\}$$

Similarily a search for an equation to predict the reinforcement height found that the nearest published equation wass that proposed by Jackson and Shrubsall:[153]

$$\ln H = k + \ln I - \ln S \quad \{48a\}$$

where: k = constant

Multiple corrrelation study retained all four input parameters for the sake of completeness.[151]

$$\ln H = -2.6 + 1.4\ln I - \ln V - 0.5\ln S - 0.5\ln D \qquad \{48b\}$$

Since this gave a good correlation and made physical sense, equation 48b was accepted as a prediction of bead height. To obtain better accuracies the following equation was used:

$$\ln H = -2.5854 + 1.41961\ln I - 0.91861\ln V - 0.49421\ln S - 0.47391\ln D \qquad \{49\}$$

As data were now held in a form of algebraic equations the process procedure selection was more flexible. The method consequently adopted was that of an interactive computer program which first prompted the user for the required information and then listed acceptable procedures. An example is given in Table 12 while listing of the actual software is included in Appendix 1.

To see wheather the system would generalise easily to processes other than submerged arc welding, some figures reported by Nogaev and Mazouko's[154] were studied. The authors, reported the results of gas shielded welding of steel at currents and speeds compatible with those assessed previously. Since they record four input parameters I, V, S, D, and three output parameters P, W, H a direct comparison was made.

The three output parameters as predicted by the equations and as recorded in Nogaev and Mazouko's paper arerelated linearly to within 0.5 mm at most. There were two strategies therefore which made the submerged arc equations predict gas shielded results. One was to rework the form of the original equations on gas shielded data base as to produce a new set of coefficients and the second was to establish the linear relations between equations and predictions:

$$P\ (\text{gas-shielded}) = a_o + a_1\ P\ (\text{submerged-arc}) \quad \text{.......} \{50\}$$

Since the last strategy required far fewer experiments and since the limits on accuracy were realistically set by sampling and measurement problems on the welds, it may be naturally preferred. Effects on penetration, width and height of bead of a change in shielding medium were therefore rapidly assessed.

Published standards, where they mention undercut, define a permitted maximum in terms of depth and extension in a unit length of weld. In fact the amount of undercut permitted was so small that the samples of the data base were coded with zero (no trace of undercut) or one (any trace of undercut). However, it has been shown that a satisfactory equation could be obtained even when none had been reported to give the investigation a start of analysis.

To show that the system was capable of expansion to include other input variables, welding *gap could be included* in a small 2^{-} x 3 factorial experiment design. Richter's analysis of penetration made it vary directly with gap, that was:

$$P = P_o + k\ G \quad \text{.............................} \{51\}$$

where: Po is the predicted penetration.
and k is 1.65 as suggested by graphic analysis.

On Belchuk's analysis on width, gap was considerd to have no effect:

$$W = W_o \quad \text{..................................} \{52\}$$

Jackson and Shrubsall made no direct study of the effect of gap but an inspection of results and a consideration of the physics of welding at a constant deposition rate suggested:

$$H = H_o - k\,G \qquad \{53\}$$

where: $k > 0$.

Graphical analysis suggests that k = 0.79. Results of such experiments in which observed and predicted are shown to be close enough to obviate the need for statistical testing.

It has been recognised, however, that by setting parameters so finely, some of the resulting welds may lie outside the limits of acceptability. Additionally, by selecting so conservative procedures an uduly low output rate may be achieved. Their production, however, require some consideration to layout and ease of use. It would be a pity to lose the facility of explanation by relying on algebraic rather than geometric techniques. Results of predicted and observed weld bead dimensions, however, show are in good agreement as Figure 89 illustrates.

3.5 AUTOMATED CONTROL PROCEDURES

Control during welding was implemented in real-time by two closed loops, that of seam tracking and of penetration control, which can be found in Appendix 1. Ultrasonic time of flight was the governing factor. In case of joint-tracking, relative positions of the electrode and weld seam were monitored and subsequently controlled by the leading signal. If the torch deviated from the seam, corrections were made instantly before the next sampling period. Sampling periods dictated the systems accuracy, and time intervals between sampling points were always of the same length. The microprocessor torch positioning system received instructions from the computerised system which also controlled the welding process. The torch position controller then became a sub system of the overall system (Figure 90). There were eight instruction codes which were reserved for the torch control, these were interpreted as:

0, Move to absolute X co-ordinate.
1, Move to absolute Y co-ordinate.
2, Set the X axis origin.
3, Set the Y axis origin.
4, Move relative to the current position along X axis.
5, Move relative to the current position along Y axis.
6, Reset torch position system.

The first two position instructions read new absolute co-ordinates from the computer and position the torch accordingly. The next four read a displacement from the current position, positive or negative, and used this to position the torch; instructions 2 and 3 simultaneously redefining the new position as the zero point on their respective co-ordinate axis. The 'reset' instruction drove the torch to the centre of its range; this position was determined by the pulse timer which monitored the sensor position on the specimen. The centre position was important because the control software was seeing it as a reference point to check that every requested position of the torch was within the range. It was of outmost importance that the axes of measurement were adjusted to be mutually orthogonal.

To drive and control in the plane parallel to the workpiece surface it was necessary to know the angle θ made by the seam and the longitudinal axis X, in the (X-Y) plane, and the width of the gap between the plates. Experimental procedures showed that the angle θ depended on the beam spread of each individual crystal. Angles θ greater than the beam spread caused signal loss and experiments were restricted to angular changes less than the angle of "sight" of individual crystals. Information about the dynamic changes in shape and dimensions was of extreme interest; if a real-time control was to be achieved during welding. To detect the edge of the seam, a two-dimensional edge detection algorithm was applied (Figure 91). The algorithm was a sequential search such as:

A) Pick an initial boundary: It was essential to begin the search for a boundary at a location where the likelihood of making an error was the smallest. Moved probes to a location to give the algorithm a location which appeared to be near the boundary. The algorithm then found the initial boundary based on a symmetrical location on either side of the seam.

B) Look ahead: If the algorithm was successful in finding the next boundary, the new one was stored in a file from which the look-ahead routine took the new current boundary next time around. If the algorithm failed to find a boundary (due to loss of coupling) the backtracking routine was called. This way, a global threshold to guide local search and to detect error was employed. Also, when a reliable echo was not received, the sensor co-ordinate was kept at its current position and to look-ahead several samples. This look-ahead procedure translated the sensor horizontally (one sampling distance) and attempted to perform a distance measurement.

C) Back tracking: Whenever this routine was called, the current boundary was a false one. Looking back from the previous boundary data, it took present value from current boundary and calculated the value of one step before to guide local search before the look ahead routine was recalled. If another boundary was found, then the algorithm continued following that new path, otherwise the backtracking routine was called again.

D) Termination: This procedure was used to determine that the algorithm had found the boundary. One way to implement this routine was by using a logical function whose value was TRUE, when the current boundary point satisfied the termination criterion, and FALSE, otherwise. The algorithm terminated whenever the logical function yielded the value TRUE.

The leading pulse showed the relative depth of penetration. If monitored penetration fluctuations differed from preset values instant corrections were made before the next sampling position. Sampling periods were identical to both loops. Instruction codes reserved for fusion control were (Figure 92):

0, Set P zero level.
1, Move P to preset value.
2, Reset P level.

The first instruction set absolute coordinate of penetration and the move instruction energised the current controller to accomplish a preset level. Finally, the reset level subsequently controlled the fluctuation in current according to changes in beam path length.

3.5.1 Adaptive Welding Process Control

Welding variables needed to provide a good weld depending on the type of material to be welded, part size, joint type and dimensions, shielding flux and several other variables. In "blind" welding applications, where no measurement of joint geometry and dimensions takes place, an approximate set of welding variables are developed and used over a particular batch of parts, based on an average of expected joint dimensions. In advanced welding systems, joint recognition and modelling capabilities are used to continuously measure joint dimensions along the seam of each part to be welded. Given the joint measurements, welding variables could then be appropriately set in real time while welding each individual part. This way, the welding process is adjusted to compensate for joint dimensional variations along a single part, and from part to part within a batch of parts.

Joint characteristics that were measured with the ultrasonic system typically included, joint cross-sectional area (fill volume), and joint geometry. These variables were referred to as observables. In addition to joint dimensions, modelling software was capable of determining the seam space coordinate system, relative to which torch position was specified. For each particular part to be welded, geometric joint features that influenced weld quality were selected as the observables. For instance, in the case of butt joint, cross-sectional area. Therefore, the cross-sectional area had to be selected as an observable. If part thickness was known to be constant, on the other hand, the distance between the joint sidewalls was selected as the observable.

Submerged arc welding process was regulated by controlling travel speed, torch position, welding curent and arc voltage. To perform adaptive welding control, these variables, referred to as controllables, were set according to the joint characteristics described by the observables. For initial implementation of the adaptive weld control system, welding current, arc voltage, wire feed speed, torch position and welding speed were regulated. Torch position was specified with respect to the space referrence frame ("window") described previously. This, was used to displace the torch relative to the joint in out-of-position welding.

A-scans recorded were correlated to weld pool depths and the result was a linear plot. Figure 93 illustrates the trend of larger transit times for greater pool depths. Torch position control could also be used to provide multipass welding without requiring a new path to be taught, providing that the number of passes was decided beforehand during the design stage. Each pass could be treated as a different seam space offset from the joint, rather than as an entirely different welding path. Since ultrasonic processing can permit determination of the joint even under an existing weld bead, joint tracking for multipass welds could well be made possible.

3.5.2 Real-Time Ultrasonic Inspection

This section describes the work conducted to show the feasibility of using automated ultrasonic examination with computer-based techniques to inspect completed welds on a single-pass basis. During tests welds were inspected, as they were being made.

The ultrasonic sensory system was applied, while the video camera was monitoring the ultrasonascope screen. Completed welds, had several geometric reflectors which were distinguished from possible flaw detectors. Reflections from the bottom of the test piece were usually specular, and little energy was sent back to the transducer except when the sound beam intersected the weld root, where the irregularities in the surface resulted in a significant reflection back to the transducer.

Data collected while the search head was moving down the workpiece, during welding (Figure 94). However, with the transducer moving in a direction perpendicular to the weld joint, data from a number of different transducer positions enabled to be determined. Concurrent quality inspection depended on the amplitude and position of the echoes from the flawed weld relative to that from sound welds. Producing an image took time and its interpretation extended beyond the proposed sensory system. Additionally, distinguishing the flaws from close geometric reflectors was very difficult in the images.

One potential solution, however, was to use pattern-recognition techniques on the scan. If the pattern of the scan signal from a flaw is signifficantly different from that of the geometric reflectors, that pattern can be distinguished by a computer algorithm. Such a method provides facilities to work in real-time, thus alleviating difficulties concerning imaging techniques. The basic procedure in a pattern-recognition system is given in Figure 94. A set of numbers, called features, is calculated for each incoming scan. These are then compared with a reference set of features which had been obtained from scans of known flawed areas and known unflawed areas. A decision is then made as to whether the features of incoming scan best matches those of the flawed or unflawed areas. Decisions are based on the Euclideans distance between the features of the test scan and the centroid of each reference set. Scans can then be classified as belonging to the set to which they are closest.

Porosity signals consist of several reflections from the bubbles in the porosity, which overlap resulting in many cycles in the waveform. Scan signals from a good weld have a low amplitude signal similar in shape to porosity. A preliminary set of features was therefore, developed to attempt to discriminate types of signals extracted from quite distinguishable defects. The set was preliminary in that the features were the results of a brief side investigation in this area.

This pattern recognition system was an attempt to discriminate different types of flaws. This was done to assume that unecessary repairs were not made, and necessary ones were. Some porosity was, however, acceptable, depending on the distance between bubles and the overall length of the defect. First steps had been made towards distinguishing types of flaws but the task was carried up to the point where it was possible to discriminate between acceptable and rejectable flaws. One solution was through artificial intelligence combined with pattern recognition techniques.

A host of other, easily solved problems would also be addressed by demonstration of the system on a specific commercial application. These included calibration, operating procedures, tolerances, noise and electrical interference isolation, real-time analysis and transducer configuration. It was believed, that all these, while important to the success of the system in commercial applications, were straight forward engineering problems which did not require new technology development, but required some time for integration into the complete system.

3.5.3 Limitations of Experimental Equipment

Welding current control and wire feed motor speed changes, demonstrated a sufficiently fast response when used in conjunction with the equipment and software previously described. Although a sophisticated wire feed mechanism was used, wire damage was unavoidable. Since weld bead profile depended on smooth feeding the need for alternative mechanisms was urged. A system which will comprise a motor powered capstan with a lightweight step drive supported on the end of the manipulator similar to the push-pull wire feed system could be adequate. However, friction forces would still exist and systems promoting easier and smoother wire feeding which would deform the wire to the smallest degree are required. Recently, research work is undertaken in this field and experimental investigations consider the feasibility of a non-contact wire feeder employing an electromagnetic field as a "swallowing action" mechanism.[155]

Guns for robotic welding should be water cooled, particularly at the contact tip to reduce burnback and adhesion of spatter to the wire tip and nozzle. This selection of welding torch and contact tips should also be considered.

During the investigations poor flux control was noticed allowing flux to leak and foul the sensors by causing kick-up. A simple system can be devised so that it will control the flux flow by simply measuring the weight of the granules and feeding the flux in short comings. Alternatively a welding process e.g. M.I.G. would completely alleviate the difficulty.

The manipulator system used throughout the experimental work comprised weld bead guidance in two directions on a plane parallel to the surface of the material to be welded. More degrees of freedom are obviously needed e.g. motion Z direction, rotational and tilt to align the sensors line of sight normal to the weld centreline and control the process. Therefore, a robot would be ideal for handling more complicated weld geometries.

To achieve probe holder flexibility and adaptability into different geometrical weld plate configurations the following should be considered:

1. Ability to adjust for different stand-off and trailing distances.
2. Ability to hold different probe sizes and configurations.
3. Ability to rotate each probe around its axis using small light weight stepping motors.
4. Ability to measure the spring force using pressure sensors for multiaxis control purpose.
5. Ability to keep the torch in position using ball bearings while the whole probe holder is rotating.
6. Ability to use the same jig configuration into different weld preparations.

Main design inadequacies associated with the recording ultrasonic equipment were:

1. Multiplexed signals from sensors can delay substantially the sampling rate and thus slow the welding process.
2. Provision for more signal analysis should be made.
3. Advance signal amplification and conditioning is required.

Any system that is computer controlled is relying on the computer's software for its efficiency. Programs written in "Basic" were adequate to control and thereby demonostrate the viability of the system. However, the introduction of more degrees of freedom to the system will necessitate a change of software design. Programs would either have to be written entirely in "Machine Code" or in any other high level languages e.g. "FORTRAN", "PROLOG","C" etc. This will also enable faster sampling rates of the received sensory data thus achieving higher acuracy and welding speeds and finally increased productivity.

Employment of a robot for seam tracking purposes implies that instead of using (IEEE 488) parallel interface, a serial interface (RS 232) should be used since robots communicate with the controller or external computer through this device.

4. DISCUSSION

4.1 AUTOMATION IN WELDING

In all production processes, including *welding, there* is a strong tendency towards increased automation. Important factors contributing to this are:

1. A desire to manufacture products with high and even quality.
2. A shortage of skilled operators.
3. The strive to increase productivity.
4. A growing concern for the working environment.

Arc welding is one man-like task for which robots present attractive means for mechanisation. As might be expected, however, the lack of sensing capability and intelligence of a human operator has made their application very difficult. An attempt is made to identify all of the elements of the "manual adaptive welding control system to help establish the overal needs for "artificial adaptive welding" control.

4.1.1 Automated Arc Welding Capabilities

Arc welding process like most manually intensive tasks, requires that the process conforms to the workpiece which is made to conform to the process. This necessity for conformance by the process is identified as the essential problem in welding automation. Producing conformance between the arc welding process and the workpiece is difficult because of the inherent variability of the process itself and equipment used. Process variability results from the instability of the arc, arc melting process and metal transfer. Process equipment variability results from the inherent imprecision of the welding torch, contact tip, welding wire etc. All these can be compensated for by manually interactive control, but are difficult to deal with for robotic applications.

Workpieces are the greatest source of variability and this results from the imprecision of processes utilised to prepare weldment components. Within the above context, it must be recognised that one of the distinct advantages of manual arc welding is its ability to join metals using minimal fixturing and low-precision assembly of component parts into a welding fixture at low production costs.

Present robotic technology applications to arc welding have been accomplished to the present extent primarily by recognising and controlling the variabilities discussed previously. Provisions or improvements in robotic welding, however, increase the overall cost but this is more than balanced by increase in productivity. Even with the implementation of various provisions problems persist relative to broad and generic applications. Applications must be carefully selected to ensure suitability and economy. Redesign of components for robotic welding is not feasible, at least in the short term. Time taken to program and reprogram robots to maintain precision relative to the component consumes man hours and interferres with production.

An essential element of any control system is one means for observing and measuring the output or process performance. It is this information that allows control to be implemented and its effect evaluated. Ir the human control system, this observation is performed by one of the five senses of hearing, sight, smell, touch and taste, with the sight or vision being by far the most important in welding. Given a three-dimensional part, the welder recognizes key features and their locations in the weld scene, such as edges of the joint, edges between the molten weld pool and solid base metal, arc features, electrode tip appearance electrode silhouette against background and metal transfer. From these basic abreviations, deduces the relative location and size of key features. Using feedback control by firstly observing and comparing the "output" of the process with what is desired, if there is a difference, process inputs are changed in such a way as to cause the error to be reduced. This results in a mental perception of the output quantity, which is compared with some preconceived mental conception of what the output should be. A response is then performed to reduce the differences. This control is primarily spontaneous, in that it occurs without need for conscious thought or decision making.

For joint tracking, the location of joint edge is mentally compared with the molten weld pool location. From the stand-point of fusion control, weld pool size is also perceived, and is mentally compared to a preconceived size that is envisaged as allowing sufficient penetration. Any difference between the two, causes welding process input parameters to be changed.

Recent technological advances in automated welding have been concentrated on the development of sensory systems and their associated feedback controls.[156] Systems must be provided with the desire value to control welding variables. For instance:

a) Where should the weld be relative to the joint features?
b) How big should the weld pool be?
c) What should its shape be?

Although this seems straight forward on the surface, the situation may be complicated by the nature of the weld joint, its variation and particular conditions or occurences as the weld progresses. This element of control is being considered as providing the preconceived notions as to the desired values of the process outputs, based on knowledge of welding conditions, joint types etc. Additonally, it has more basis in knowledge possessed by the individual and requires recall and thoughtful, but rapid, decision making. In the most simple of implementations, this control is derived from a programable controller or a microcomputer. Supervisory control is provided from a knowledge base which makes decisions concerning process control. This accumulated knowledge is associated with the experience of a manual welder and assimilates the expertise necessary to increase process tolerance of the total welding system.

Adaptive welding control in a human allows individuals to be very flexibe and adaptable to various welding conditions and circumstances. This more general characteristic of flexibility or adaptability is very important because to be viable in the full range of applications, the robot welding control system must be as flexible as the robot itself.

Integrated electronic/microprocessor technologies, have lately allowed for great strides in development and implementation of sensory systems and feedback controls to substitute human welders. Even so, present sensor capabilities are limited and integration with a total welding system is still incomplete making broad applications difficult. Sensor technology is currently in a period of considerable development and flux.

4.1.2 The Significance of Flexible Welding Automation

Increasing complexity of welded parts and the desire to increase productivity of welding processes and simultaneously improve and control quality of the deposited weld metal have made welding an ideal candidate for automation and in-process monitoring. However, since the welding process itself is composed of several interdependent functions, any control techniques that seek to improve weld quality and productivity must consider all these functions. For the type of welding considered here (submerged arc welding) locating or fixturing of subcomponents to be joined, position control and velocity of the torch motion, and type and repeatability of the joint edge preparation must be considered in addition to control of the heat source itself (i.e., metal transfer, arc characteristics and stability). In general, these functions can be divided into two major categories; torch position and arc process related. Such, problems related to repeatability of joint edge preparation, joint location and torch velocity are included in torch positioning. Consequently, problems related to arc stabilty melting and solidification of weld and base metal are included in the arc process category.

In many situations in which a large quantity of identically shaped work pieces are to be welded, unavoidable variations of the weld seam from one work piece to another normally exist. These variations,are mainly dependent upon the accuracy of edge preparation and the thermal effects during the welding operation. These, govern the on-line detected weld path to be desired, and the actions to be taken which are based on measured data.

Successful adaptive closed loop control in automated welding plants, particularly in welding with robots, contains two essential elements:[157]

1. Seam tracking to ensure correct positioning of the welding head relative to the joint preparations.
2. Joint recognition with sensing of the joint geometry and real time modification of relevant process variables to ensure consistant penetration, joint filling and acceptable weld bead shape.

To accomplish that the weld is placed accurately and is of the required size, shape and quality advanced adaptive control is required. This involves development of adequate sensors for seam tracking and joint recognition with highly intelligent signal processing and interpretation.

Additionally, developments in the fields of welding equipment, workpiece positioners, manipulators and suitable programming, control and documentation systems are also essential. Microcomputer applications are easily suited to all decision making operations required in welding process control. Further, they offer the ability to handle and control multi-variable processes, like welding, in real-time with maximum flexibility. This flexibility is achived with the aid of sensors, which can offer welding parameter control and optimisation when integrated with microcomputers. Development of highly intelligent, programmable welding controllers first take account of system approaches for exact presetting of relevant welding conditions depending on the requirements of the welding process itself.

To achieve high flexibility, process systems are designed to be modular and to distribute the essential control tasks to each sub-system in use. According to master/slave control principles, the master controller is responsible for the sensor controlled torch positioning, supervising functions and effecting operation modes. Microcomputer based welding control is connected directly with the welding equipment for process control and for information interchange with the sensor controller. Depending on the sensor information the controller makes a decision on what actions are required to stabilise the welding process by modifying its input parameters. Sensor controller maintains in constant contact with the master control to allow corrections in both seam tracking and gap width irregularities.

The integration of Sensor Guided Welding Robots (S.G.W.R.) into Computer Aided Manufacturing (C.A.M.) requires suitable interfaces on the process level for information exchange. One control problem in the field of technical planning is the missing connection between available C.A.D. systems and welding robots. It has been shown that adaptive welding requires:

1. A technique for relating data about the workpiece to the welding process.
2. A knowledge of how variations in workpiece geometry require variation in welding procedure.
3. A technique for altering welding procedures and monitoring that the alterations have been done.

The widespread industrial use of submerged arc welding, or any welding process for that matter, does not guarantee that the procedures used are the most productive. For a given application there is generally little information regarding tolerances governing weld quality or the possibility of improving productivity by altering welding procedures. For a given application there may be a large range of possible welding conditions, each altering a different level of weld quality, process tolerances and production rates. Procedure optimisation techniques when employed enable an objective view of the factors making up the welding process to be taken and show the likely effect of procedural changes in productivity. The first step in optimisation is to stabilise subsidiary variables and obtain control of the welding process. Once basic reproducibility is achieved, the next step is to choose boundary conditions and establish relevant process fields.

Successful use of optimised procedures in industry demands much the same approach in understanding and controlling the production welding process. Productivity is closely related to the amount of control applied and the tolerances on important variables. Welding conditions in this study were intended as a starting point for industrial procedure optimisation trials. This does not imply that the production rates achieved in the laboratory will be attained at every instance; rather that the knowledge of limitations of a given production situation enable the best use of the equipment available. It is hoped that these procedural methods will allow a balance to be struck between production rate and the incidence of defects in a given situation. At the same time they allow a rational approach to the cost of improving equipment and standards of work compared with the benefits from likely production rate increases. Derived "data" utilising the above mentioned approach can clearly show to a potential user of the process the alternative advantages of a tolerant but slow procedure and a fast but tightly toleranced procedure. Alternatively, comparisons with particular production situations can be made.

It is additionally recognised that the presentation of data in two-dimensional diagrams is in reality much too simplified a format, although their value in helping to visualise the significance of the variable concerned is acknowledged. In practice it is expected that several interacting variables are accounted for in decision making. To best cope with this problem computer analysis techniques are used to construct equations capable of relating process variables and weld bead geometry. The most useful way to select and present relevant information for a particular application is through an interactive computer programme.

4.1.3 <u>The Importance of In-Service Inspection</u>

Methodologies of retirement-for-cause, remaining-life analysis and life extension, essential for evaluating quality of welds, require three basic inputs:

a) Detailed weld defect characteristics.
b) Weldment material property data.
c) Defect analysis considering operating parameter ranges.

Tremendous gains in product quality and productivity are possible through process monitoring and control. This in-process control inspection has an inherent advantage in that quality is built into the product rather than inspected into it.

Welds in critical components are frequently evaluated non-destructively to industrial standards. Welds greater than 50 mm thick are usually evaluated volumetrically after the weld has been completed. If a defect is located deep within the weld, a large quantity of otherwise acceptable weld deposit is removed to eliminate the defect, and complete defect removal is not always assured. Components are then rewelded and welds are inspected once again. If an unacceptable defect still exists, the repair process is repeated.

Energy costs of the repair process include one or more of the following:

1. Removal of material around the defect.
2. Preheat of the base metal.
3. Consumption of additional filler materials.
4. Heat input during rewelding.
5. Post weld processing including stress relief, heat treatment and grinding.

Many of these costs can be either significantly reduced if weld bead defects are detected and repaired soon after they are produced or eliminated if in-process inspection is built into the system. This latest idea forms the basis of this work; to reduce energy consumption and increase productivity in automated/robotic welding through use of automated ultrasonic inspection of welds.

Automated process control and rapid inspection techniques are used to keep production errors from generating large numbers of faulty products. Welds are inspected along the joint to be sure that welding defects will not weaken the final product in service. Ultrasonic methods are the most promising of the possible non-destructive evaluation techniques for these inspections because they can interrogate internal structures at production line speeds.[158]

One of the most important characteristics of a fusion weld is that it should show complete and uniform penetration. The fact that lack of root or side penetration can either statically or dynamically result in failure due to the formation of notchlike defects becoming the site for crack propagation is well documented. Due to the high cost of down time and method of testing, many welded structures are not inspected as often as they should be. For an efficient application of the methods for weld quality and in-process control in welding, sensors must provide accurate information of the weld condition, especially data on the depth of undercut, extent of penetration, height and shape of the underbead, structure of weld metal etc. Such a system of sensors combined with controlling computers can ensure the formation of welded joints with the required geometrical characteristics and service properties.

4.2 AUTOMATED ULTRASONIC IN-PROCESS INSPECTION

The purpose of an ultrasonic inspection system is to detect defects in products to maintain established quality levels in them. Inspection of product quality for defects both in manufacturing and in-service, is an important, common and general requirement. Human inspection is, to a large and increasing extent, being replaced by automatic instrumental methods. Fully automatic methods have important advantages as outlined below:

1. Great potential for consistency.
2. Capable of very high speed interrogation.
3. Capable of handling highly monotonous tasks which demand continuous concentration.

The main tasks of ultrasonic inspection are:

i) Reliable detection of all defects with a large safety margin to relevance.
ii) Location and classification, whether further analysis is necessary.
iii) Sizing and characterisation of these defects.

These criteria and characterisation are valid for manual as well as mechanised ultrasonic inspection. It is a testing system that does not involve potential health hazards and work disruption. Weld inspection may be divided broadly into two classes:

a) Inspection for the purpose of ensuring that products comply with given specifications.
b) Inspection on a fitness-for-service basis.

The goal is effective process control for economy, failure prevention and operational safety of the finished product.

During this work, principal contributory factor in the automated ultrasonic inspection has been the development of two orthogonal linear tables, carrying the probes, with motorised drives. This aided the computer assisted inspection and hence the automatic co-ordinated inspection.

Designers would naturally prefer to have no defects in their materials, but in the general run of production it is difficult to produce metals completely free from defects or discontinuities. The problem of inspection therefore, becomes one of deciding which defects or discontinuities will have an effect on the behaviour of the material in service. Before this can be done it is necessary to have information not only about their location but also about their size, shape, type and orientation. Defects which are large compared with the cross-section of the ultrasonic beam present little difficulty since their boundaries can be traced out to determine size and orientation. Furthermore, defects of such magnitude usually cause large material rejection. When it is required to obtain information other than location, it is the small defects which present problems and the principal method at present in use is one where the pulse-echo technique is employed. In this technique the amplitude of the echo from the defect is compared with that from a standard known defect.

Current work orientation towards in-process weld monitoring and adaptive control forms the basis for an intelligent welding system. An expert data base using information acquired can make intelligent decisions concerning process control without human intervention. Two major areas are addressed. Firstly, the ability to select the correct solution to a welding problem is developed. That is, sensors must not only be able to detect an out-of-limits event, but also to diagnose the cause and correct the situation, or determine that a human operator must be alerted. Secondly, a fitness-for-purpose criterion is included. That is, when a potentially defective length of weld is formed, the significance of the defect is assessed based on the ultimate service conditions so that an appropriate reaction (continue welding, record defect location, stop welding, etc.) is executed. Utilisation of machine intelligence, as on expert systems, is feasible because ultrasonic sensors are capable of forming a computer integrated recognition system.[153]

Ultrasonic systems for in-process inspection have been the subject of research and development during the investigations conducted in this work. They include computerised "X and Y" linear (stepper-motor driven) transducer holder assembly, ultrasonascope unit, reflective pulse timer, gated peak detector, A/D converter, VDU, printer, floppy disk and multiplexer. Amplitude, time and position are the measurands. The electronic gated peak detector is used to determine the signal amplitude within a preset gate and the pulse reflective timer to measure the time-of-flight of each ultrasonic signal. A feature of the ultrasonic hardware is the possibility of thresholding (i.e. the level of signal can be varied) using the flaw-signal amplitude discriminator applied to the display. Here, only the flaws with signal amplitude above 60% percent of the full range are displayed (Figure 95). Mechanical scanning is employed in order to speed up inspection and to ensure total coverage of the materials. Processing of these signals consists of the following operations:

1) Defect detection - the determination that the signal relates to an unacceptable departure from the target functional properties of the object. All other signals being ignored.
2) Defect delineation - the determination of the extent of the defect.
3) Defect parameter extraction and classification - the characterisation of the defect through parameters, extracted from the delineated defect signals and the further processing of these parameters to identify the defect by name or type. It is this stage of signal processing where the most sophisticated methods are likely to be encountered.

The role of signal acquisition is crucial in automated ultrasonic evaluation and governs the performance and accuracy of the whole system. Failure to deconvolute the incoming data results to loss of vital information concerning the welding and inspection process. Sampling period times must be closely controlled so that the information contained in the signal is not corrupted. Sampling rates largely depend upon multiplexing frequency, Increasing this frequency allows higher sampling rates to be achieved. At the same time signal to noise ratio (S.N.R.) should be kept at maximum level. Ultrasonic signals are often disrupted and very noisy due to artifacts inherently present in the transducer instrumentation and also scattering due to high temperatures involved during welding. Attempts to minimise the above effects by conditioning the signal proved to be fruitful when special special electronic filters are employed to enhance S.N.R. Additionally, signal repetition suggests that averaging would adequately improve S.N.R.

Signal amplification also solves some of these problems associated with ultrasonic signal amplitude fluctuations. The amplification process is aided by an adjustable peak detector capable of capturing fast transient signal recordings within a predefined envelope. As the position of the probes is fixed with respect to weld centre-line, transducer position is thus uniquely defined. The peak detector deconvolutes the incoming signals by identifying their origins from a background of unwanted signals ("grass"). This way, collected data lie in an expected set envelope which eliminates the need for random signal correlation techniques to be employed. Clearly, the adapted data acquisition procedure followed can be regarded as producing high integrity results by restoring the ultrasonic signals.

Adequate signal restoration was consequently followed by a data interrogation process of analysis and retrieval. The aim was to extract as much relevant information as possible concerning weld pool dimensions. Examining both sides of the weld, the energy transferred to the material interacts with the solid/liquid interface of the material being welded. Due to beam spread effects, the whole area of fusion zone can be interrogated. The three signals present are direct responses from seam sidewalls, bottom of the weld and the weld pool itself appearing in sequencial order. For all three signals to appear, accurate positioning of the probes along the seam, and with respect to electrode tip position was needed. Multiplexed variations of ultrasonic time within the predefined envelopes are easily measured using the timer device. Genuine weld pool signals, previously identified, and portraying the various parts of the weld pool can then be interpreted in a suitable digital format and acknowledged by the microprocessor. Time-of-flight measurements are logged in memory, arrayed in a form of file. Dedicated software was then developed to categorise these data and to related time-of-flight to weld pool position by taking into account material thickness ultrasonic velocity and probe separation. For reasons of clarity, ultrasonascope outputs can be displayed in analogue format and their digital signal counterparts viewed at the same time on the VDU screen.

4.2.1 Ultrasonic Real-Time Data Processing:

Image analysis and processing of an ultrasound beam reflected from a weld joint are performed by the processing sequence system. This was accomplished by:

1. Detecting the ultrasound beam path lengths under a variety of conditions (different material preparations, profile orientations, etc.) and discriminating them from other possible interference sources (inclusions, voids, etc.).
2. Recognising features on the beam path length that correspond to significant features of the joint or weld surface (joint edges and sides, weld faces etc.).
3. Describing the three-dimensional geometry of the weld joint and obtaining cross-sectional measurements and dimensions (such as weld opening, joint sidewall angles, fill volume, etc.).

During time of flight digitization, a discrete array of intensities is computed and stored in memory after sampling and quantifying video signals appearing on the ultrasonascope screen. During beam path length extraction, ultrasonic signals are detected and translated into actual distances in mm. During feature recognition, the shape of the contour is analysed and significant contour features are recognised. During profile modelling, a three-dimensional model of the joint surface can be developed from computed cross-sectional dimensions.

The first step in ultrasound processing is to extract each beam path length corresponding to signals appearing on the ultrasonascope screen. During guided welding, the arm's position is known, where the part is supposed to be located and the geometric description of the beam and ultrasound images are generated after equipment calibration. From all these information, ultrasonic signal position and appearance are approximately determined. Processing algorithms are worked in a "windowed" region that surrounds the expected beam path location. "Windowing" significantly reduces processing time by reducing the amount of image data processed.

The "window" is searched according to a scan pattern that originates at an optimal seam region. This pattern is chosen because it simplifies the ultrasound processing operations needed to extract the beam path length. In addition, scanning improves the noise rejection characteristics of the system, since welding arc and noise typically emanate from the torch. Time of flight extraction software dynamically selects a threshold for processing on each scan line to improve noise rejection and reduce the sensitivity of the ultrasonic system to material finish. Images are scanned for all patterns of ultrasound that are above the threshold and that satisfy certain line thickness constraints. All such candidates are filtered and the most likely beam path length description is selected from the set of line candidates.

To recognize significant features on the weld joint, corresponding features on each signal are identified. Such signal features can be classified as either:

A) Points of significant orientation change (convex or concave joint edges, joint clearance, end points, weld melting points, etc.).

B) Surfaces (workpiece surfaces adjacent to the joint, joint faces weld profiles, etc).

The general shape and orientation of the ultrasonic image of any given weld joint is invariant for that weld joint and can be described as a set of feature points and surfaces. However, the specific geometry and orientation of the signal varies significantly, depending on the actual part dimensions and orientation of the sensor relative to the joint. Welding arc noise can further abscure parts of the signal. The objective of the signal deconvolution and recognition process is to identify and locate the expected feature points and surfaces in the processed ultrasonic images.

Rather than performing recognition on the basis of shape alone, the joint recognition scheme tries to match the dimensions and geometry of ultrasonic paths with values obtained on a sample part. Joint parameter training can be achieved by an interactive process in which the operator teaches the ultrasonic system the correct feature points and surfaces ("window"). A set of parameters that completely describe the joint is then learned in this process. In addition, a set of tolerances is established, describing how much the joint parameters change. During real-time ultrasonic processing, incident beam geometry varies slightly. Beam variation history is used to update joint parameter expectations to account for these changes in orientation and actual joint dimensions.

Robust recognition of joint features is provided by using multiple representations of the beam. These include representations in terms of orientation changes along the beam and in terms of elementary line segments. This redundancy, significantly reduces the likelihood of misrecognition. Former representation are used to determine the approximate location of the major feature points and to describe the joint shape at a coarse level of detail. The latter is used to accurately define surfaces and points.

All the path features (surfaces and points) found previously refer to the section of the weld joint defined by ultrasonic echoes. To obtain the features and dimensions on a cross-section perpendicular to the weld line, further geometric modeling of the surface defined by a series of path points along the weld joint is peformed. To this one, information computed during recognition of the features on each picture is used and the joint configuration is modelled.

4.2.2 Ultrasonic Image Interpretation

Three data points: amplitude, time and position were collected. The gated peak detector was used to determine the amplitude of the signal within a preset envelope and the reflective pulse timer to measure the time-of-flight of the ultrasonic signals. As seen, the scanning motion of the transducer is under complete computer control. A detected A-scan output of the ultrasonic receiver is obtained from the pulse echo wave form of the transducer. The ultrasonic A-scan interface digitizes the time-of-flight delays and amplitudes of up to three consecutive echoes appearing on a single trace. Digitized data are passed to the host computer along with position coordinates of the transducer through the suitable interface. Preprogramming of the RAM and the preamplifier echo signal at regular intervals is accomplished by the host computer through the internal timing and interface module. Control procedures establish the code for passing data from the host computer to the ultrasonascope and modules and set the internal logic for an external sync and execute command. This configuration allowed fast, real time programming just prior to reception of the sync pulse of the external timer.

The digital scan converter was used to translate analogue echo representations into a digital format suitable for further analysis. Data recorded are subsequently processed by the microprocessor using relatively simple computational algorithms. The stages followed for each ultrasonic indication recorded are based on time of flight calculations. Initially, the transducers position is determined according to reference points on both sides of the seam prior to welding. Calculations take into account material thickness, ultrasound velocity within the media, transducer frequency, angle of incidence and finally stand-off distance from the seam. Due to beam spread phenomena, seam sidewalls are interrogated and additionally, when welding commences, weld pool geometry reflections are estimated. Displays are generated after signal processing and conditioning which assist weld pool representations in real-time.

Scanning procedure follows specimen and transducer positioning, based on a pre-calculated distance from the plate edge. Ultrasonic set parameters,such as the gain, frequency, reject level, gate delay and gate range are adequately selected. Transducers are moved to the scan's starting position and then initialize the scan program. The program immediately enters its dialog section, prompting for parameter settings and computer displays. Operation parameters are; scan increment sizes, position limits and amplitude threshold levels. Instructions are subsequently send to the computer to begin the scanning, sampling and averaging routines. From this point on, the system is under the complete control of its microcomputer. Computer stores all of the operator's dialog responses on the floppy disk, and then it begins the inspection loop. Basic steps within the loop are:

i) Computer reads the specified number of peak amplitude values from the ultrasonic search unit, and averages them.

ii) If the average is greater than the specified threshold level, then the average, the reflection depth and the transducer position are recorded.

iii) If the scan is complete, the loop is exited. If the scan is incomplete, the computer moves the transducer to the next data sampling position, and the inspection program returns to step (i) above.

After leaving the inspection mode, a program on the microcomputer then reads the floppy disk and transfers the data to a DATA file wherein they are subsequently analysed to produce weld images. Acumulative real time plots of the data are made during scans in order to allow the operator a preview of the data collected. Although the technique started as relatively being an approach to automation, subsequent ideas enhanced the system's response. These involved attempts to construct weld images from ultrasonic representations allowing for displays whilst the weld pool is being formed. Advances in development work resulted in computer graphic representation of weld silhouettes as Figure 95 depicts.

Initially it was envisaged that the ultrasonic digitizer should be capable of capturing, digitizing and subseqeuently processing the data. The digitizer, however, performed the two former tasks adequately and only analysis of incoming signals needed to be considered. Using probes with centre frequencies of up to 2.5 MHz implied that there are probably frequency components in the signal of up to 3.0 MHz. Theory suggests that the required sampling rate must be greater than twice this frequency. This is fast even for many present day analogue to digital converters but one shot captures is desirable if tests are not to be slowed down excessively by the need to sample repeatedly. Since signals are digitized before analysed and sampled, this leads to consistency in programming style in the final system and maintains flexibility of system configuration. An oscilloscope incorporated in the system, not only displayed the detector output conventionally, but also confirmed that the digitized signals, when displayed in an analogue manner, correspond to the input ultrasonic frequency signal.

One of the system's pricnipal attributes is that the test data are re-analysed without the necessity of actually repeating the test. Variation of the display time level on a set of stored data yields much useful information. For example, if the display level is preset and calibrated according to the average value of the "window", all the signals having shorter or longer time intervals indicate welding process variations and irregularities. If test pieces are scanned completely, the two projected images are completely full of these indications, apart from signals that lie outside the acceptable tollerance limits region. Any region which does not contain indications and has no signal gain in its vicinity is, therefore, not adequately scanned during the test, resulting from either poor coupling or too coarse scanning pattern. It is possible to monitor recorded signals captured in this manner during scanning to ensure that all regions are adequately covered. The ability to alter the display threshold level of returned echoes is very useful in examining the effect of imposing different amplitude thresholds on the same test data, ensuring that the imposition of such thresholds does not cause significant points to be ignored.

Facilities for examining simultaneously amplitude of videoed signals and reflector position data from both sides of the weld on paper -hard copies of scans- is of great assistance, especially in determining welding process parameters and conditions. Also the ability to compare scans of different portions of welds made at different times using the same welding parameters can be of considerable use in the field of in-service inspection of structures. Additionally, the ability to compare scans of the same portion of weld made at different times is of specific importance as far as quality assurance is concerned because subtle changes in responses between inspections can signify the occurrence or growth of a service defect.

4.2.3 Factors Affecting Ultrasonic Time Measurements

Although the systems behaviour was quite successful there were still anomalies in monitoring beam path lengths that required more detailed examination. Beam path lengths measured electronically are larger than the distances revealed by micro-sectioning and subsequent microetching. This was expected from the theory. Mode of ultrasound used, welding current levels, rate of weld pool solidification and velocity changes due to temperature gradients are responsible for the apparent differences between monitored and measured distances.

From ultrasound propagation principles, the velocity of ultrasound reduces as the temperature of the test material increases. The rate of decrease is small below 600 °C but increases rapidly above 600 until 850 °C where the rate reduces once again. It is thus reasonable to assume, that some artificial elongation of the measured beam path length occcurres at elevated temperatures adjacent to the weld pool formation; the equipment having been initially calibrated using velocities at room temperature.

It was shown clearly that at a typical electrode/beam travelling distance of 3.0 mm the recorded temperature 4.0 mm away from the liquid/solid interface was 150 °C. Below this temperature there was little velocity change consequently only the last 4.0 mm of beam path were closely examined. Each 0.25 mm of this area was considered as an individual temperature zone for ultrasound velocities and angles of incidence calculations.

Velocities at each zone temperature were transposed from the data. Angles of incidence through these temperatures were recalculated and thus the beam path lengths within the various temperature gradients. Subsequently the total beam path lengths were estimated.

Since it was assumed that the isotherms geometric shape is regular and of quarter sphere shape small compensations had to be made. Additionally, due to actual weld pool shape irregularities the returned path was thought to be taking more time than the incident. Clearly the effect of temperature on beam path length is compensated for by pre-calibrating the expected beam path lengths on the ultrasonascope and is considered majorly responsible for the apparent beam path inaccuracies.

Inclination angles of the liquid/solid interface in relation to the beam axis vary with the weld bead shapes generated by differing welding currents and voltages. When, for example, welding at currents in excess of 550 Amps, the liquid/solid interface is at an angle greater than 75° degrees. When working at currents below 550 Amps this angle is considerably reduced to 65° degrees. Therefore, ultrasound wave propagation is rarely normal to the liquid/solid interface and assumptions on ultrasound propagations are made that they follow a path along or channelled between the dendritic formations in the solidifying weld pool.

The continuously changing topography of the liquid/solid interface, caused by solidification, appears to be also responsible for the peculiar nature of returned echoes. Dendritic growth of the liquid/solid interface additionally presents a perpetually altering reflecting surface of the incident beam of ultrasound. More ultrasound is therefore, scattered and less returned at one moment in time when compared with the next. Returned signals present vary accordingly. In this case the amplitude changes but not necessarily the beam path length.

4.3 ULTRASONIC SENSORS IN ADAPTIVE WELDING

Equipment used for control of the welding process were engaged in a closed loop control fashion and the two ultrasonic sensors were used to "view" the weld seam, as Figure 95 illustrates. Multiplexed signals obtained from sensors were fed and displayed onto an ultrasonascope screen and in turn captured in a digital format by the time of flight measurement unit. Modified signals were finally channelled into the microprocessor, where processed and relevant welding process information was obtained.

Interrogating both sides of the weld seam, the area of interest in the digitized signal is identified by using the target locator to work within an electronic signal auto-calibration "envelope". Within this envelope, the reported to the microcomputer two alternating items of information are the two sides of the joint.

To provide data for fusion control, weld liquid/solid interface is also interrogated and results are transformed into commands suitable for the purpose built microprocessor current controller. Parameters of interest are weld-width and penetration; these are correlated with current in terms of its effect on net heat input, such that dynamic changes in beam path length can be made. These fluctuations in time of travel result in an increased or decreased depth of penetration. The latter function is controlled by using further software specially tailored to relate current and beam path length and taking into consideration the phenomena of ultrasound propagation.[160]

The recognition scheme obtained, uses weld bead modelling techniques to standardise the welding process and at the same time correlate the expected ultrasonic reflections with the actual weld bead dimensions.

4.3.1 Welding Process Control Strategies

Main goal of the sensing system was to build a three-dimensional characterisation of the joint geometry. Two dimensional sampling can provide data for joint tracking algorithms. Such a data base is created by sampling periodically every second the time of flight of the ultrasonic measurements along the width and length of the workpiece centreline. Sampling in the third dimension supplies values, extracted from the bottom of the weld pool and provides data for weld bead penetration algorithms. Intentions were for the sensing system to repeat periodically a cross-section sampling procedure.[191]

Control strategies and process procedures adopted are as follows; When the manipulator arm reaches the workpiece and sensors are placed assymetrically along the seam, a search for the starting point is executed. Alternating return signals received from both sensors (translated from time of flight measurements into beam path length and this in turn into actual distance in mm between the sensor's crystal centre and weld centre line) are compared with the preset values chosen for the particular weld application. Manipulator arm then takes a set of corrective actions and places the sensors symmetricallly along the weld centreline with the electrode tip located precisely on top of the seam at a predetermined height from the surface of the material to be welded. Having located the seam the sensors controller locks the manipulator onto the seam, by scanning the sensor back and forth over the seam in a narrow window of approximately 5mm. Data collected over the mentioned window are subsequently stored in the computer's memory with the intention to be used as reference values for future scanning data comparisons.

Averaging of the singnals is achieved through a suitable processing algorithm where high and low acceptable limits are also set. The "window" gives the sensory controller a form of vision of the workpiece seam, mimizes data interpretation and results in high path resolution. After back tracking to the negative direction until measured distance is greater than the preset, the starting point is located. As the axis of sensing system is fixed 3 mm in front of the electrode tip there is a delay between the moment when the displacement is measured and when welding torch is situated in the place where the measurement is taken. Delay was, however, minimal and therefore ignored. Having located the starting point the device backtracks once more for 3 mm distance and the manipulator arm locks itself into this position. The starting point is stored in the computer's memory and coordinates are given to this point (0,0,0) representing reference distances in horizontal, transverse and vertical directions. Sensors are held by the manipulator in this reference position for 10 seconds which is the time taken for prepurge (water flow) and final adjustments before welding commence.

Subsequently, the control programme for feedback positioning supervises the reading of alternating data from both sensors and controls the stepping motors running at a preprogrammed speed, for accurate positioning of the welding head. Welding starts according to preset current, wire feed and beam path length values. Process control algorithms perform a periodic sampling of the measured data every 0.5 sec. If the seam variations do not exceed the sensors angular range of operation which is equal to the beam spread angle of the particular sensor then the three-dimensional scanning sequence is straight forward.

This procedure is as follows; Repeated actions of obtaining distance measurements from both sensors, are compared and adjusted when necessary maintaining control of both joint tracking and weld bead penetration until the end of the cross section is reached. This is marked by a sudden large increase in beam path length because the sensors leading signal picks up information from the workpiece unwelded edge.

Corrective actions taken during the process of welding are; If the monitored weld bead penetration value is greater than the preset - shorter penetration depth - then current and wire feed speed are increased until the desired beam path on the other hand, the monitored value indicating depth of penetration is reached. If, however, the monitored value is smaller than the preset - deeper penetration - then the current and wire feed speed are decreased accordingly. Finally, if the monitored values from both sensors are equal to the preset penetration depth value then welding proceeds normally.

Scanning procedures become more complicated when the leading signal is lost either due to inadequate coupling or when the seam or weld bead slope exceeds the sensors angular range of operation. An additional routine is therefore, followed: Continue welding using the same parameters as in the last sampled point of the seam until the signal reappears allowing, however, 3 seconds without any data flowing into the computer controller. If, however, after this mentioned predetermined time there is still no signal gain from the multiplexed sensors then the welding power source is switched off, the tracking manipulator stopped and the welding procedure ended. This was a precausitive action, before the welding sequence continuoued with the welding head wandering on the material. If signal is regained within the time limit, firstly corrective actions to the path are immediately made by placing again the welding electrode tip in its precise position and secondly corrective actions to the process parameters commence by readjusting the weld bead penetration if needed at the predetermined level. If signal gain from one probe only is lost for less than 5 seconds work continues with the other sensor and only half of the weld bead profile is monitored. If signal is not gained within this predetermined time the welding process is stopped immediately.

At the end of the welding process the opposite situation is experienced. The controller switches off the welding power source and the wire feeder unit thus, terminating the welding sequence and immediately afterwards while post-purge takes place for 10 seconds the manipulator is moving the welding head with the sensory devices away from the molten metal zone following the direction of the last three interrogated points on the seam.

The algorithm developed repeats the following sequence:

1. Translates forward the sensors sampling point on the workpiece surface (a constant horizontal distance) to assure periodic sampling.
2. Alters the sensors position to align their line of sight to be normal to the seam at the sampling point according to amplitude - gain - and simultaneously places them symmetrically along the weld centre line.
3. Computes the actual distance travelled and the distance between sensors centre points and weld centre line after translating the measured time of flight into beam path length, into motor steps and finally into actual distance in mm.
4. Stores both the joint tracking values representing distance travelled and weld bead penetration values.

To maintain a constant sampling distance, the position of the sensors is compensated for. Iterative approaches are described which fulfill this requirement. The iterative compensation technique uses a sequence of checking and correcting steps to approach the desired sampling point. Range information is obtained after translating horizontally the sensors one sampling distance (≃ 1mm). If the sensors angular degree of freedom is suppressed or if the current distance measurement is equal to the previous distance measurement then the sampling point is corrected. A similar procedure is applied in the vertical direction for the depth of penetration measurements, otherwise, the horizontal distance between the desired and the actual sampling points is computed. Sensor position is translated horizontally by this correction distance and the check and correct procedure is repeated for the next distance measurement. This procedure terminates when the two consecutive distance measurements are equal. This approach has the disadvantage that two or more distance measurements are required for each sampling point. Processing takes place in a number of stages; For each ultrasonic indication recorded, the following calculations are performed:

1. Probe position is calculated. The scanner always operates with one end of its arm in contact with the surface. Workpiece surface geometry is known and flat, so once the basic scanner cordinates are calculated the arm position is uniquely defined on the surface.
2. Ultrasonic beam directions are calculated, the surface position defining the surface normal vector from which the beam direction vector is calculated using the probe beam angle, beam spread angle and a knowledge of the particular weld pool geometry.
3. Positions of the ultrasonic indications are calculated. For pulse-echo probes the preferred reconstruction method is to extrapolate along the beam direction vector from the probe position and position a point at the range of the ultrasonic signal as measured.
4. Displays are generated. Ultrasonic data are displayed in a table format and subsequently in two-dimensional projections to assist visualisation of weld bead profile.

Close fit butt welds are not the only weld joint format likely to be encountered. In "thick" materials (i.e. over 10 mm), the major other type is a fillet, whilst on "thin" material (below 10 mm) both fillet and lap joints are widely used. Fillet joint morphology offers some interesting ultrasonic problems, such as defining the beam path position on the continous member.[162] In both plate types, the ultrasonic wave modes, as defined in the butt weld work, were utilised and preliminary results showed the applicability of the ultrasonic sensory system to control both seam tracking and weld bead penetration simultaneously.

With thin plate materials distortion during arc welding is a major concern and is usually noticed as an opening or closing of the gap. Work is currently in progress to monitor this gap movement and to correct the arc/electrode position so as to ensure sound fusion on both plates.[163,164] To be able to examine thin plates, one requires to use either plate (Lamb) or surface (Rayleigh) waves and during use, the whole thickness of the section is reviewed. The tested system proved not only to monitor welding torch position but also penetration using Tungsten Inert Gas (T.I.G.) welding facilities.

Aluminium had also been investigated and the technique was found to be equally as applicable to these alloys as to steels provided that the analogous precalibration steps are followed.[165]

The ultrasonic sensory system described is capable of measuring positon and dimensions of a weld joint from a "picture" of beam-path lengths reflected from a joint. These capabilities are integrated into a manipulator control process so that the ultrasonic sensors provide feedback to the manipulator controller to follow a fixtured weld joint. Real-time guidance of manipulator consists of ultrasonic processing to analyse pictures of the joint and locate its position in space, and also arm control algorithms that redirect the robot to follow the joint. These operations take place concurrently in a multiprocessing computer system.

Control algorithms employed for torch positioning are an enhancement of the seam following algorithms used for blind welding. In blind welding applications, the operator leads the arm through the trajectory required to weld a part and trains a set of points through which the torch is required to pass. The torch trajectory between taught points is typically specified to follow a straight line or a circular arc. Since the arm controller requires a position update at some small fixed time rate, intermediate positions between the taught points are determined. To generate a straight line path, the distance between two taught points is divided into a number of points separated by the distance that is travelled in that time interval at the requested speed. Positions are determined by straight line interpolations between the two taught points. Arm motion, in principle, consists of commanding the arm to go to consecutive interpolation points at a fixed time interval. The ultrasonic guided arm performs in a similar fashion, by leading the arm through the points on the part. In this case the ultrasonic system is used to look for the seam as the path traverses.

Sensory guidance algorithms described are a highly integrated part of the arm control algorithm. Basic operations such as ultrasonic measuring and path offset generation require intimate knowledge of the workings of arm control algorithms and large amounts of shared data. This is readily accomplished because the arm controller and ultrasonic processor are connected to the same microcomputer bus and function under the same operating system. While the joint tracking control algorithm is tightly coupled to the arm control algorithm, it is independent of the particular manipulator system or robot arm being used. Operations of path planning and joint tracking control are performed in a general Cartesian coordinate system, independent of arm configuration. The kinematics of the particular arm used, are described by a modular "arm solution" which is loaded separately from the joint filling software. Therefore, any manipulator with an existing software arm solution can be used for joint tracking provided it is (4-phase) stepping motor driven.

4.3.2 Three-Dimensional Weld Pool Silhouette Analysis

Ultrasonic testing has been used effectively as a non-destructive evaluation technique for locating subsurface defects of a wide range of materials. It is a well established technique for locating cracks, lack of fusion and porosity in welding.

Computer imaging methods currently used in ultrasonics fall under the general category of pulse-echo ranging techniques. Within this category is a plethora of subcategories. The A-scan, however, does not actually produce an image in the usual sense of the word. A brief discussion of the principle should serve as a convenient springboard to explain the advanced methods. The basic idea is "time-of-flight" accurate monitoring. By transmitting a short pulse of sound into an object and then recording the echoes as a function of time, one can determine both range and size inforamtion. On the screen, the horizontal axis yields range as the vertical echo amplitude. Because the echo amplitude is proportional to the emitting object, one can infer the object location. Also, as the A-scan traces give only one dimensional spatial information, they are not traditionally thought of as producing an image. Combining the A-scan concept with careful synchronized scanning of a transducer, one can generate two-dimensional spatial information, and obtain a trace that is suitably termed an ultrasonic image (Figure 97).

A typical application of the pulse-echo method is the measurement of thickness of a steel plate. Data such as probe position, time-of-flight of the echo while the probes automatically and sequentially scan the surface transmitting acoustic pulses through the thickness, are recorded. Although A-scans may not usually be considered to provide an image, a map of thickness of a steel plate certainly qualifies as a two-dimensional map of a physical quantity. In a sense such a map qualifies as a "synthetic aperture" image, because it is constructed by sequentially gathering thickness information point-by-point over a two dimensional region.

A newly developed weld pool constitutes a change in phase and material properties relative to the rest of the weldment and is an ultrasound reflector. To make use of this concept to measure weld pool dimensions in real-time, the following transducer arrangement was adopted. Two identical transducers mounted equidistant alongside a welding torch holder were aligned in such a way that the transducers field of view was centred on the weld pool. Placed "millimetrically" in front of the welding torch and positioned on opposite sides of the joint they are capable of determining if the weld is moving off centre and therefore, to initiate corrective action. This guaranteed that the transducers observe the weld pool action at all times. Having properties similar to that of light the ultrasound beam starts from a source and propagates in a cone fashion. This cone, filled with ultrasound, illuminates the whole weld pool area, provided that transducer stand-off distances from weld centre line are appropriately selected. The recognition scheme is obtained using weld bead modeling techniques to standardise the welding process and at the same time correlates the expected ultrasonic reflections with the actual weld bead dimensions.

The procedure for image formation is as follows; Joint tracking and weld pool data are collected, then manipulated at high speed in real-time. The sensory system extracts all necessary information from various parts of the weld pool to recognise the specific joint characteristics. A database is then established for data interpolation which is analysed and compared with the initial preprogrammed welding process requirements and design data. Routines are produced allowing for the database expansion during welding. The software package incorporates elements of artificial intelligence capable for adequate real-time computer imaging of weld pool shapes.[illegible]

After significant features are extracted, the "object" is further discriminated by filtering the necessary information. This involved a recognition shceme based on decision making, within the microprocessor's software, which was defined in a hierarchical manner so that the seam was recognised first, followed by penetration depth and then weld pool spatial location. Overall data selection run concurrently with data interpretation which means that the total cycle time for area recognition plus weld process handling cannot be reduced. This creates software limitations which do not allow for real-time weld pool geometrical shape formation in three dimensions. However, post-welding silhouettes representing weld pool boundaries along the seam can be plotted in 3-dimensional image representations in a "Head-up Display" mode. This proves to be an invaluable tool in product quality assessment as it allows the user visually to view the fusion zone and modify as appropriate.

4.3.3 Ultrasonic Information Controlled Welding

Developments to accomplish adaptive control are based on information gained from variations in beam path length of the ultrasonic signals. Sampling of these signals for arc guidance control is synchronised with weld bead dimensions control but prevented conflict between the two operations since sampling was carried out after signal deconvolution.

In addition, algorithms in the microcomputer software also performed digitally all the required filtering, processing and estimation of the sampled signals.

Selection of ultrasonic frequency, crystal size, approach angle and stand-off distances ensures that the ultrasonic leading edge signal is millimetrically in front of the weld pool, for a particular material and its thickness and achieves joint tracking with minimal delay between the joint and the weld pool. Beam path length is the controlling factor; depending on the position of each probe, distinct beam path lenghts define the joint edge and the weld pool. Once in operation, variations from these values causes corrective action: either movement of the manipulator arm (i.e. joint tracking) or welding current pertubations (i.e. joint recognition and weld recognition). The prototype device therefore, concominantly monitors and controls both tasks.

The set of equations described in the previous Chapter were used to find the transit time for an ultrasound pulse leaving the transducer at a certain angle, reflecting from the weld pool as a shear or longitudinal wave, and returning to the transducer without mode conversion along the path. Examining the transit time equations, it is clear that the transit time and the path taken by an ultrasound pulse in travelling to the weld pool and back is sensitive to the stand-off distance, angle of incidence of the ray, acoustic characteristics of the material, and weld pool size.

For a finite ultrasound beam width, it is possible to take several different paths between the transducer and the weld pool each with different transit time. Distinct ultrasound rays that return to the transducer are most likely reflected from different locations on the weld pool surface. Ultrasonic time traces contain the potential to provide measurements of several points on the weld pool surface. To date, a technique for determining weld pool dimensions from ultrasound transit time measurements has not been developed.

The approach taken, to determine weld pool dimensions from ultrasonic traces is as follows: Pattern recognition, which involves ultrasonic time traces obtained from sample welds after being produced. After welds are made, they are sectioned and measured, in accordance with advance weld bead modelling and the ultrasonic reflections are correlated with the measured dimensions. Results are stored in memory and during welding ultrasonic reflections are compared with reference values to determine directions. Equations are used to generate a series of typical reflections from the modelled weld pools. The dominant characteristics of these reflections are isolated and approximate ray paths are fitted to them after microsectioning. Transit time equations, however, are inverted to get an estimate of weld pool dimensions. Necessary adjustments to primary process parameters are made by automated compensation devices to eliminate weld defects in real-time. Secondary information about weld quality such as heat input and penetration are also computed. Data generated in real-time are used to stop welding, or alert an operator when an out-of-limits event occurs and also to drive the feedback control system.

A) The Detection Subsystem.

The purpose of the detection was to indicate the presence of defects, without indication of severity or type. To achieve a performance compatible with a human inspector it is necessary to detect 95% of defects at low speed without wasting good material. Instrumentation is further required to replace the subjective but flexible judgement of a human inspector with the objective but inflexible judgement of a machine. Specifications and requirements for detection require some care if the quality designation of each specimen is to be compatible between man and machine. A specimen is to be considered defective if it contains one defect indication. Adequate detection does not require that the whole area of a defect trigger the detector. Provided that at least some of the defects are detected, detection may be considered successful.

The detector is presented with an analogue signal which always contains a noise component which is unwanted and is largely stochastic and which sometimes also contains a message component indicating the presence of a defect. This detector is required to state whether the signal within each interval of observation represents noise only, or whether a message is also present. The essential component is block 2 in which the basic decision is taken. This output is binary - at level '1' when a defect is considered to be present, and at level '0' otherwise. Decisions are implemented by comparing the signal amplitude to a threshold level. A defect is considered to be present when this threshold is exceeded. Two erroneous outcomes are possible: a 'missed detection' when the signal amplitude does not exceed the threshold, although a defect is present and a 'false alarm' when the signal crosses the threshold due to noise alone. The effeciency of the decision process in terms of minimising these error probabilities depends on the contrast for the message signal. Message contrast is improved by a filter which selects message energy from the background noise.

B) The Delineation Subsystem.

Delineation of a defect is the process of locating a boundary which encloses the defect and separates it from the background surface. This boundary is used to control the extraction of defect parameters (such as width, length, etc.) and so need to be only as accurate as parameter extraction demands. With the scanner producing line-scan data, boundaries of detected defect signals within each scan are located. The peak of the response signal serves to locate the detected defect signal along the scan. Location together with duration give the estimated signal boundaries, as required.

C) The Identification Subsystem.

Parameter extraction goes hand-in-hand with defect delineation. Automated inspection requires a large amount of design data for its system construction. Such data take the form of defect samples on the steel plate, and the collection scanning and book-keeping associated with even a modest number of samples calls for considerable effort over an extended period of time. In the pulse-echo mode technique, the dimensions of a defect are determined by comparing the amplitude of the echo given by the unknown defect with that given by a reference defect. At present it is difficult to avoid a method which uses the comparison of the amplitude of the defect echo with that of a reference echo. An improvement in the present position is dependent on the solution of two problems:

i) Identification of a defect from its ultrasonic responses.

ii) Knowledge of the relectivity of the various defects likely to be encountered, in terms of their shape, orientation and surface condition.

4.4. CLOSING REMARKS AND FUTURE DEVELOPMENTS

This work illustrates that for the first time it is possible to achieve fully automated welding and inspection employing a manipulator arm, a transistorised power source and ultrasonic sensors. The system is fully operational using a microprocessor controlling all the various tasks involved.

Ultrasonic sensing system was developed as a tool in the following five fields:

1. Joint tracking.
2. Weld recognition.
3. Quality control and quality assurance.
4. Welder training.
5. Welding research and development.

The system can be used to provide welders with monitored views of welds that otherwise cannot be seen, because it works through the material and not through direct-line of sight. It can also be used for welds made in an environmental enclosure. These welds may be visually obscured by the enclosure itself, welding apparatus, or the manipulator arm.

Using ultrasonic sensors in the pulse-echo mode, joint tracking and torch adjustment is proven. This set up provides a coaxial view of the joint sidewalls without any parallax effects. In trying to monitor all tracking variables two sensors are employed in order to interrogate the seam from both sides. The more sensors that are used, the more information there is on which the controller can base decisions. With more than two, *however, the system* would become increasingly complex and simultaneous monitoring of all sensors would be probably confusing.

When two sensors are used, they can be on two separate monitors, or on a single, split-screen monitor. The split screen effect can be achieved in various ways; Two video signals from two ultrasound excitation sources electronically merged into a split-screen format and displayed on one monitor. A bifurcated ultrasonic receiver, or two ultrasonic receivers going into a beam splitter used to transmit two images to a single camera in a split-screen format.

Remote viewing also provides operator safety, which is a particularly sensitive issue with regard to robots and manipulators. Automated arms have an inherent element of danger in that they do not necessarily repeat the same movement at the same speed. Therefore, it is considered unsafe to have an operator within an arm's work envelope when it is operating, regardless of how slow it is moving or how predictable its movements seem to be. Using the ultrasonic sensory system, the operator remains safely out of the work envelope, while still monitoring the seam and making any necessary corrections in tracking variables. The operator is also kept safe from hazzards of the welding environment, such as arc flash, burns and toxic fumes when various arc processess are used.

To successfully manipulate the welding *process*, *the* operator needs to control not only the joint-tracking but also the welding variables. Some, if not all, of these controls can be preset and/or made to function automatically as part of the start up sequence.

The system is used to provide a "view" of the backside of a part being welded to see when full-joint penetration is achieved. This is provided by the readily access to the back side of the part with an "optical" path to the location where penetration is to be monitored. It is also used to maintain a permanent videotape record of each weld being made, as well as its inherent inspection capabilities. Additionally permanent records are kept in the floppy disk and are compared with the videotape. If a flaw is discovered in a weld during or after the process both monitoring accessories are reviewed to try to ascertain the cause of the flaw and prevent such flaws from occurring again.

Permanent records are also made of visual inspections during or after a weld is completed by drawing the actual weld profiles in three dimensions using either three dimensional image analysis and/or graphically plotting the weld profile points from the recorded beam path lengths accordingly.

The system can be used also in many different aspects of welder and quality inspector training. Examples are, series of training films for teaching the proper techniques and procedures that must be followed to get sound welds. These films can also show poor techniques and their associated welding procedures. Training films can also be directed forward broadening the skills of experienced operators and for retaining or recertifying them. Generally, they could only benefit by gaining a greater understanding of welding processes and quality inspection.

Another potential application of the system is as a tool for welding research and development. Ultrasound provides an ideal view for studying weld pool surfaces and arc plasma dynamics, pool shape and size, melting and solidification phenomena, bead contour, sidewall fusion, wetting, undercutting characteristics, defect cause-effect relationships etc.

The sensory device model developed, has been fully checked and evaluations indicate that it will soon become a commerically viable unit in welding automation and quality inspection. Industrial world has shown great interest on developing the system very quickly using the existing knowledge accumulated from this work. Several specific questions, however, can be addressed by testing the system on specific, realistic applications. First the time probability of weld bead detection and seam following for that application could be determined and compared with other sensory guided systems. Additionally its inspection capabilities should be extended to lack of fusion and porosity in process detection. These would then provide the basis for a cost analysis to determine the economic feasibility of the system since the direct savings due to energy reduction and productivity improvements have already been established. Second, the hardware requirements for a commercial application could be established.

This search unit used in the laboratory investigations, while very versatile, would probably not be appropriate for a commercial field application yet due to its complexity. A field system would have to be durable, robust and easy to operate. It would be used in weld shops and yards under significantly dirtier conditions rather than those of the laboratory demonstration. Personnel operating the system would not be researchers committed to making the system work, but rather workers committed to producing welded products as easily and quickly as possible.

Two specific hardware requirements must be addressed. One concerns couplant, the medium between the search unit and the part being welded/inspected that assures good sound transmission. Many welds on high strength steels require the weld to be free of contaminants that can cause hydrogen embrittlement and delayed cracking. Therefore, the search unit must be designed so that the couplant use is minimized and the solution to this problem must be demonstrated. The second requirement concerns the systems range of operating temperatures. In the laboratory demonstration, the search unit travels about 3 mm in front of the welding torch, where the maximum temperature is approximately 21 °C (Room Temperature). This was below the design temperature range for that unit and so no damages were encountered. Some welding procedures, however, require that the base metal be preheated to as much as 150 °C. For these applications a search unit must be desinged that accounts for all the problems of operating at such temperatures, including couplant, mechanical expansion, transducer operation and sound path distortion due to temperature gradients.

A third area of concern is the relationship of the system to current acceptance codes. The system is not meant as a replacement for the current N.D.E. methods of determining acceptance. Rather it is a method of improving productivity by finding and repairing defected welds. In time, however, if the system proves to be as reliable as current acceptance practices, it could be used in place of these methods, resulting in further improvements in productivity and in safety.

A second relationship to the acceptance codes is more complex. The recognition system must additionally be able to distinguish types of flaws such as lack of fusion and porosity accurately. This must be done to enhance the systems capabilities and to assure that necessary repairs are not made and necessary ones are. The first step has been made toward discriminating types of flaws but the task must be carried further to be able to discriminate between acceptable and rejectable flaws.

A host of other easily solved problems would also be addressed by a demonstration of the system on a specific comercial application. These include calibration, operating procedures, operator training alignment maintenance and tolerances, noise and electrical interference, isolation, etc. All of these, while important to the success of the system in a commercial application, are straight forward engineering problems which do not require new technology development, but some time for integration into the complete system.

Temperature/Velocity data were of great importance and value in the development of this automated ultrasonic system for both flaw detection and control of process parameters. Additionally, they can make possible to monitor attenuation trends during heat treatment operations to determine the exact time at which processes such as age hardening, tempering and stress relief are completed. With a knowledge of attennuation trends, in relation to the previous example, automatic ultrasonic systems can possibly be developed to control process parameters such as temperature and throughput in continuous heat treatment operations. When temperature is uniform throughout the material, however, accurate ultrasonascope calibration estimates can be achieved by pretreating the calibration blocks to the required temperatures accordingly.

In the area of automated ultrasonic inspection and real-time flaw detection in welding, this system has given greater control over the process, rather than just locating and marking defective sections. It makes possible for such systems to be developed and detect bulk defects. This results significantly in a reduction of waste materials and prevents unnecessary processing of defective material. To achieve high accuracy in such a system, timing was very critical and variations in velocity with temperature were accommodated within the system.

Additionally, use of attenuation measurements as a non-destructive test technique were investigated on its own right. Attenuation sensitivity is related to physical properties and structural features of metals. This suggests many uses in metallurgy as well as in quality control. It seems possible that attenuation measurements can be used in when non-destructive tests in heat treatment applications are required. Therefore, it is thought that attenuation measurements could reduce the proportion of hardness tests, or indeed other mechanical tests such as tensile tests, that are required.

Yet a further area where attenuation measurements could be of use is in condition monitoring. With this technique, elastic waves created by energy release during plastic deformation and fracture during service can be detected by transducers. It is therefore, feasible that attenuation measurements in susceptible components in service could detect structural changes associated with plastic deformation and fracture, thereby, giving early warning of impending failure. Since the acoustic waves would be generated externally, problems associated with background noise and frequency would be eliminated.

Ultrasonic inspection techniques using piezoelectric transducers are established and widely accepted methods on non-destructive testing. Nevertheless, piezoelectric devices have a number of disadvantages which are sufficient in some applications to warrant the introduction of alternative means of generating waves.

An important development in the field of ultrasound generation has been the use of lasers. Their wave propagation in solids is caused by interaction of the optical wave trains with the material. Interactions take place at the materials surface and its principles are based on the rapid generation of thermal expansion or ablation. More than one mechanism exists by which the interaction of a laser beam with a material surface gives rise to ultrasonic pulses.[16,7] One occurs at relatively low laser powers in which the mechanical vibration is induced by a sudden expansion of a laser-heated region of the surface. As the power increases the deposition of heat becomes sufficient to boil off (ablate) a thin surface layer and the ultrasonic source nature changes from a rapid radical expansion to an impulse in the normal direction (Figure 98).

Acoustic waves generated may propagate directly from the source at the solid surface, or may be the result of a shock front which at first changes the material phase and at a later stage of propagation, weakens to become an acoustic wave. Two extreme situations are identified, characterised by the laser intensity used. At very low power densities the light causes only a rise in temperature by conduction below the surface with no change of phase material. If, on the other hand, the power density is very high, multiphoton ionisation takes place on the surface within a few light cycles, causing a plasma to be formed. Between these two extremes, there is a wide variety of intermediate situations in which changes of phase, pressure due to vaporisation, thermionic emission and shock wave generation may be important in forming the acoustic source.

As there is no inverse of the mechanism of elastic wave production using lasers, a different mechanism for detecting the ultrasonic energy must be employed.[109] It seems essential that the laser generator be backed up with an optical technique for elastic wave reception so that full advantage can be taken of the completely non-contact potential of the laser technique. The most useful approach for detection is by laser interferometers. The basic principle is that a coherent optical beam reflected from the object under examination is allowed to interfere with another part of the beam split-off and reflected from a fixed target. Small motions in the surface can then be detected by changes in the interference conditions between the beams and magnitude of displacements inferred by counting fringes.[16,4]

The outstanding feature of laser-generation is that no physical contact with the material is required. This is in marked contrast with conventional ultrasonic techniques where the piezoelectric trnasducer element must be bounded to the material surface. Problems associated with couplant response, wear and tear of transducers etc. are, therefore, immediately eliminated with an optical technique.

It is unfortunate that at the present time these interferometric systems which maintain suitable pulse response and bandwidth are relatively inefficient when compared with alternative acoustic receivers. For this reason the "all laser" generation and reception of ultrasound remains an inefficient process. If this problem could be overcome laser-generated ultrasound could make a valuable contribution to non-destructive evaluation.

In summary, the feasibility of the system has been demonstrated. The next step is to apply the technology developed in this reasearch program to a specific application and thereby demonstrate commercial feasibility.

5. CONCLUSIONS

Adaptive control of a manipulator arm and welding process parameters is essential and offer considerable advantages for high quality automated welding. Such a system was developed and the following is a summary of activities undertaken and conclusions reached by this work.

5.1 DEVELOPMENT OF AN AUTOMATED JOINT TRACKING SYSTEM

1. A scanning ultrasonic system has been upgraded and used as a prototype guidance system integrated with a host microcomputer.

2. Algorithms have been developed to fulfil the requirements of joint characterisation and include:
   - a) Simple filtering, averaging and conversion techniques to remove any unwanted signals.
   - b) Segmentation techniques for feature extraction followed by image understanding.

3. A 2-axis manipulative arm has been designed, constructed and integrated with a host microcomputer to achieve seam tracking through stepping motor driven control.

4. A global strategy based on ultrasonic signal deconvolution for totally automated welding procedures has been proposed and implemented into the system through software design.

5.2 REAL-TIME PROCESS MONITOR AND CONTROL

1. The same control equipment have also been used as a prototype weld bead penetration system integrated with the power source.

2. Algorithms have been developed to fulfil the requirements of weld bead penetration depth.

3. The transistorised power source interfaced with the host microcomputer enable control of both process parameters and subsequently weld bead profiles.

4. A weld bead profile model has been developed to maintain consistent and adequate metal transfer over a wide range of fluctuating currents.

5. The systematic selection of arc welding parameters has been suggested following weld bead profile modelling to make successful operation of the ultrasonic sensors a much straight forward task.

5.3 IN-PROCESS ULTRASONIC INSPECTION USING 3-D IMAGE ANALYSIS

1. Resulting control equipment are capable for both storage and processing of ultrasonic data.

2. Metal transfer characteristics and weld bead shape is controlled independently.

3. The system can also be used for any material provided that the appropriate ultrasonic constants and welding parameters are changed.

4. Work carried out on different workpiece thicknesses using different ultrasonic sensory techniques and process variables proved the universality of the system.

5. The system's potential capabilities can be extended to accomodate different welding processess.

6. In-process weld inspection inherent of the system makes its potential commercially more desirable.

7. 3-dimensional image structures can be formed from data collected from the pool dimensional assessments have indicated that the system is an extremely "powerful tool" not only for in-process visualisation of weld pool profiles but also for on-line inspection and quality assessment.

8. Finally the resulting equipment are suitable for both automated and robotic welding and also for automatic weld inspection, and is equally valuable in both roles.

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TABLES

WELDING CURRENT, A	WIRE FEED SPEED, m/min	
	ARC VOLTAGE, 30 V	ARC VOLTAGE, 35 V
350	0.72	0.64
400	0.84	0.93
450	0.92	1.00
500	1.25	1.99
550	1.24	1.33
600	1.39	1.32
650	1.61	1.45
700	1.63	1.73
750	1.92	1.83
800	1.99	1.92
850	2.01	2.18
900	2.34	2.22
950	2.53	2.30

TABLE 1. Conditions to establish the relationship between wire feed speed and welding current.

WELD POOL DEPTH, mm	ULTRASONIC TRANSIT TIME, ms
10.5	2.63
11.0	2.75
11.5	2.80
12.0	3.14
12.5	3.23
13.0	3.48
13.5	3.55
14.0	3.57
14.5	3.60
15.0	3.75
15.5	3.83
16.0	4.10
16.5	4.15
17.0	4.33
17.5	4.37
18.0	4.48
18.5	4.74
19.0	4.81

TABLE 2. Recorded ultrasonic time-of-Flight values at different weld depths.

WELDING CURRENT, A	PENETRATION, mm	
	ARC VOLTAGE, 30 V	ARC VOLTAGE, 35 V
350	2.49	4.25
500	4.63	2.74
550	4.25	5.72
650	6.23	5.62
750	9.02	9.58
850	9.87	10.25

TABLE 3. Effect of welding current on penetration depth.

WELDING CURRENT, A	BEAD WIDTH, mm	
	ARC VOLTAGE, 30 V	ARC VOLTAGE, 35 V
350	13.6	11.5
450	14.5	13.6
550	16.9	16.0
650	18.5	19.6
750	16.1	19.6
650	15.0	18.0

TABLE 4. Effect of welding current on bead width.

WELDING CURRENT, A	REINFORCEMENT HEIGHT, mm	
	ARC VOLTAGE, 30 V	ARC VOLTAGE, 35 V
350	123	1.75
450	1.62	2.18
550	1.79	2.15
650	1.92	2.97
750	2.18	2.40
850	3.74	4.19

TABLE 5. Effect of welding current on reinforcement height.

	ARC VOLTAGE, V	WELDING CURRENT, 400 A	WELDING CURRENT, 700 A
PENETRATION, mm	25	4.82	8.18
	30	5.73	8.02
	35	4.30	7.13
P/W RATIO	25	2.31	9.63
	30	3.33	6.72
	35	4.28	5.24
H/W RATIO	25	0.16	0.17
	30	0.12	0.30
	35	0.14	0.56

TABLE 6. <u>Effect of voltage on:</u>

A) Weld penetration.

B) P/W ratio.

C) H/W ratio.

WELDING CURRENT, A		WELDING VOLTAGE, V	WELDING SPEED m/min
	700	25	0.5
		25	0.6
		30	0.7
		30	0.8
		35	0.9
		35	1.0
	800	25	0.5
		25	0.6
		30	0.7
		30	0.8
		35	0.9
		35	1.0
	900	30	0.5
		30	0.6
		30	0.7
		35	0.8
		35	0.9
		35	1.0

TABLE 7. Effect of welding speed on acceptable welding procedures.

WIRE DIAMETER, mm		WELDING CURRENT, A	WELDING VOLTAGE, V	WELDING SPEED, m/min
	3.2	500	2.5	0.4
		500	30	0.6
		500	35	0.8
		600	25	0.4
		600	30	0.6
		600	35	0.8
		700	25	0.4
		700	35	0.6
		700	35	0.8
	4.0	650	25	0.4
		650	30	0.7
		650	35	0.9
		700	25	0.4
		700	30	0.7
		700	35	0.9
		800	25	0.4
		800	30	0.7
		800	35	0.9
	5.0	700	30	0.6
		700	30	0.7
		700	35	0.8
		800	30	0.6
		800	35	0.7
		800	35	0.8
		900	35	0.6
		900	35	0.7
		900	35	0.8

TABLE 8. Effect of wire diameter on acceptable welding procedures.

PARAMETER	SYMBOL	UNIT	LOW	MIDDLE	HIGH
Current	I	A	400 500	500 700	700 900
Voltage	V	V	25	30	35
Travel speed	S	m/min	0.24	0.36	0.48
Wire diameter	D	mm	3.2	-	5.0

TABLE 9. Limits of factorial design.

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
I	7.02410	2	3.51205
V	0.42313	2	0.21156
IV	0.75336	4	0.18834
S	66.50606	2	33.25303
IS	1.18870	4	0.29717
VS	5.15034	4	1.28759
IVS	2.97144	8	0.37143
D	228.41340	1	228.41340
ID	4.26351	2	2.13176
VD	1.47293	2	0.73647
IVD	16.18516	4	4.04629
SD	28.23924	2	14.11962
ISD	3.22511	4	0.80628
VSD	9.50089	4	2.37522
IVSD	19.99316	8	2.49914
Total	395.31053	53	
Error (from replication)	1.23440	7	0.17630
Levels of factors			
I = 3			
V = 3			
S = 3			
D = 2			

TABLE 10. Analysis of variance for penetration.

Correlation coefficient = 0.970

Determination index = 0.94

Variance analysis

Source	Sums of squares	Degrees of freedom	Mean squares	F-ratio
Regression	8.0581E 00	4	2.0145E 00	
Error	5.0357E-01	49	1.0277E-02	1.96E 02

T-test = 28.846 DF = 52

Coefficients and 95% confidence limits

Lower	Mean	Upper	DR	Variable
-8.1651E 00	-7.1482E 00	-6.1313E 00	0.00	0
14.3868E-01	15.5586E-01	16.7303E-01	0.97	1
13.2924E-03	21.3918E-02	41.4543E-02	0.29	2
-3.6367E-01	-2.6663E-01	-1.6959E-01	-0.62	3
-6.7443E-01	-5.3186E-01	-3.8929E-01	-0.73	4

TABLE 11. Multiple correlation logarithm of penetration.

INPUT PARAMETERS AND TOLERANCES.

Thickness of plate (mm) 19.0 mm
Tolerances on penetration 55%
Maximum travel speed 1.0 m/min
Maximum current 1.000 Amps
Tolerance on travel speed $\pm$ 1
Tolerance on current $\pm$ 10
Tolerance on voltage $\pm$ 1
Preferred wire diameter 5 mm
Upper limits on width and height 40 mm
Upper limit on P/W ratio 0.7
Upper limit on H/W ratio 0.3

COMPUTED PROCEDURES

D	S	I	V	P	H	W
5.0	0.66	800	30	7.0	3.0	12.00
5.0	0.60	800	30	7.0	3.0	13.00
5.0	0.60	825	30	8.0	3.0	13.00
5.0	0.54	775	30	7.0	3.0	13.00
5.0	0.54	800	30	7.0	3.0	13.00
5.0	0.48	750	30.	7.0	3.0	14.00
5.0	0.42	725	30	7.0	3.0	15.00
5.0	0.42	850	30	9.0	4.0	15.00
5.0	0.36	725	30	7.0	4.0	16.00
5.0	0.36	750	35	7.0	3.0	19.00
5.0	0.36	800	30	9.0	4.0	16.00
5.0	0.36	825	35	8.0	4.0	19.00
5.0	0.30	700	30	7.0	4.0	18.00
5.0	0.30	750	30	8.0	4.0	18.00

TABLE 12. Procedure optimisation for weld bead modelling.

FIGURES

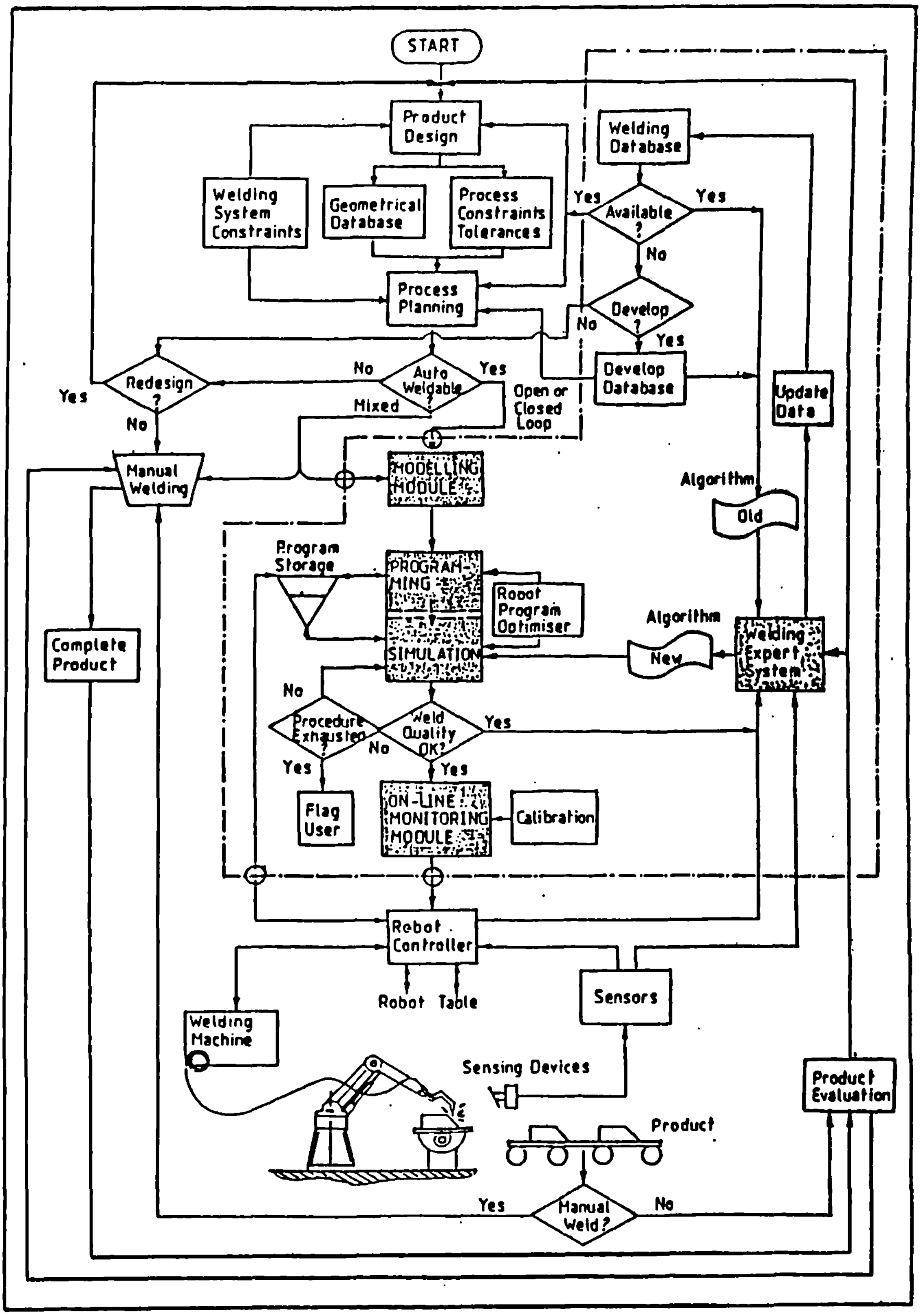


FIGURE 1. OVERVIEW OF ADAPTIVE WELDING SYSTEM.

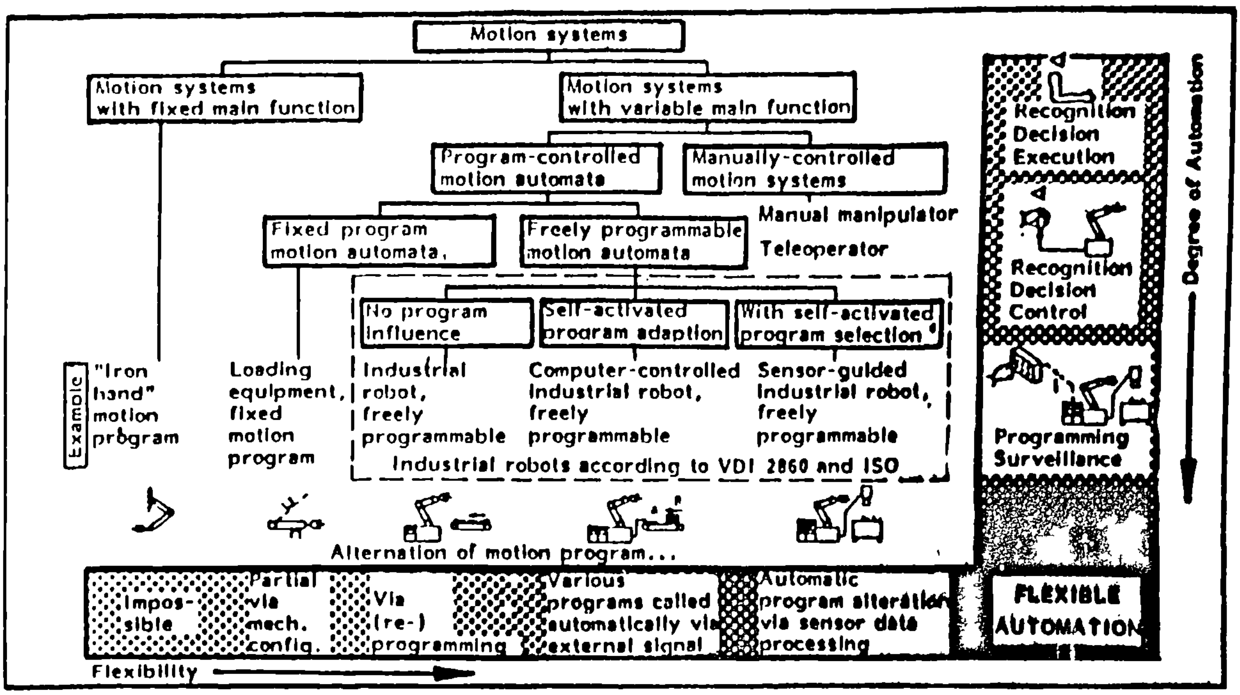


FIGURE 2. FLEXIBLE AUTOMATION.

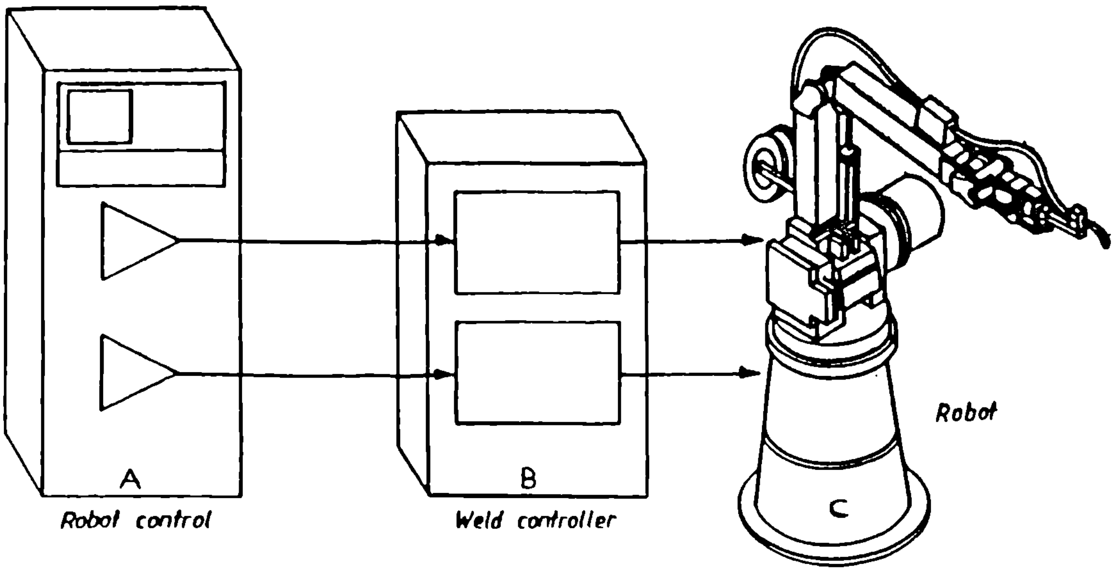


FIGURE 3. UNIVERSAL AUTOMATED WELDING SYSTEM:

A) CENTRAL MICROPROCESSOR.
B) PROCESS PARAMETERS CONTROLLER.
C) SEAM TRACKING CONTROLLER.

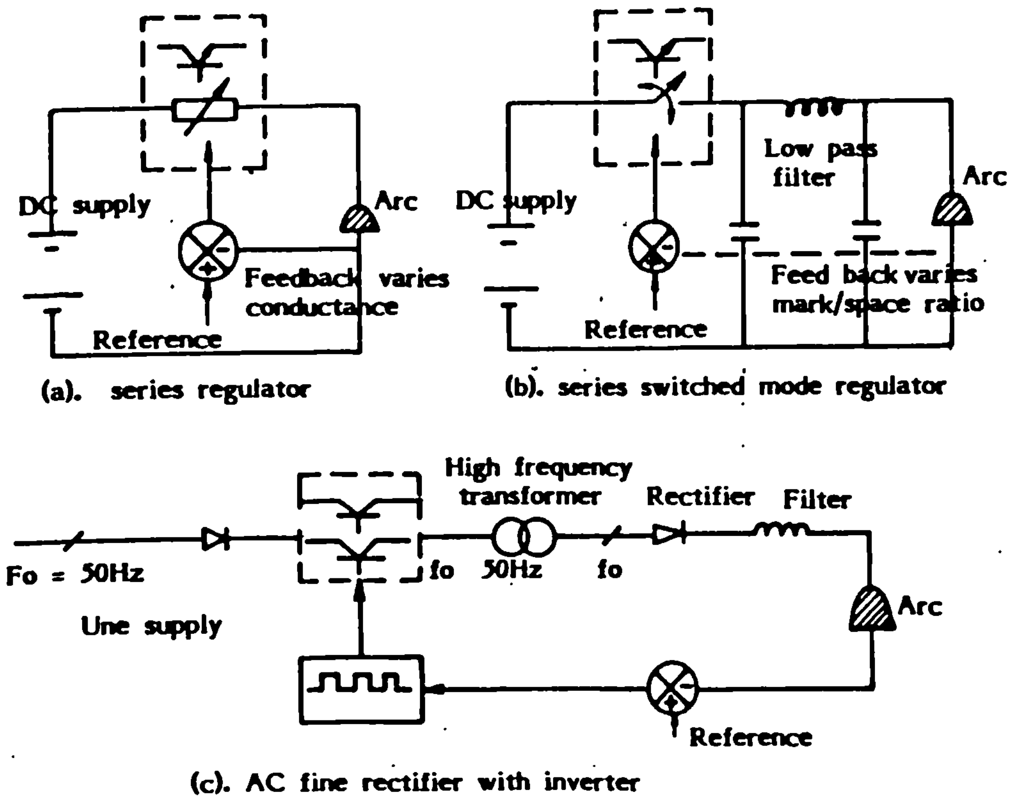


FIGURE 4. POWER SUPPLIES FOR ARC WELDING.

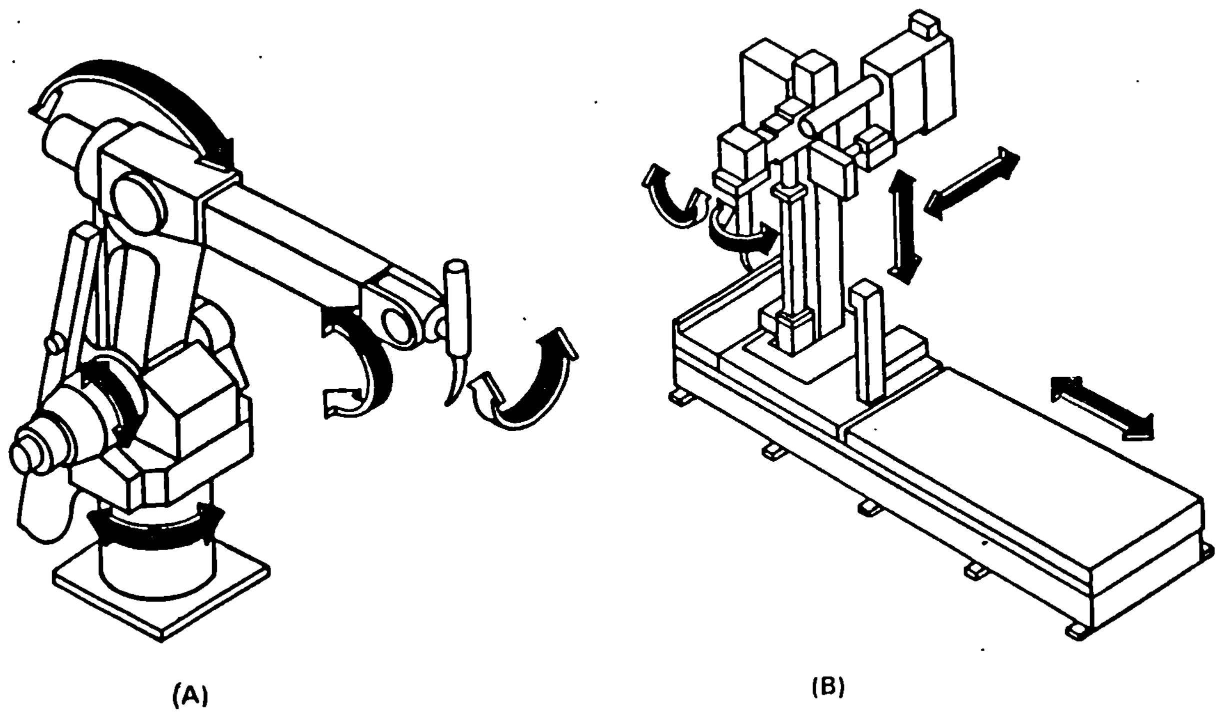


FIGURE 5. ROBOTIC MANIPULATORS:

A) ARTICULATED.
B) RECTILINEAR.

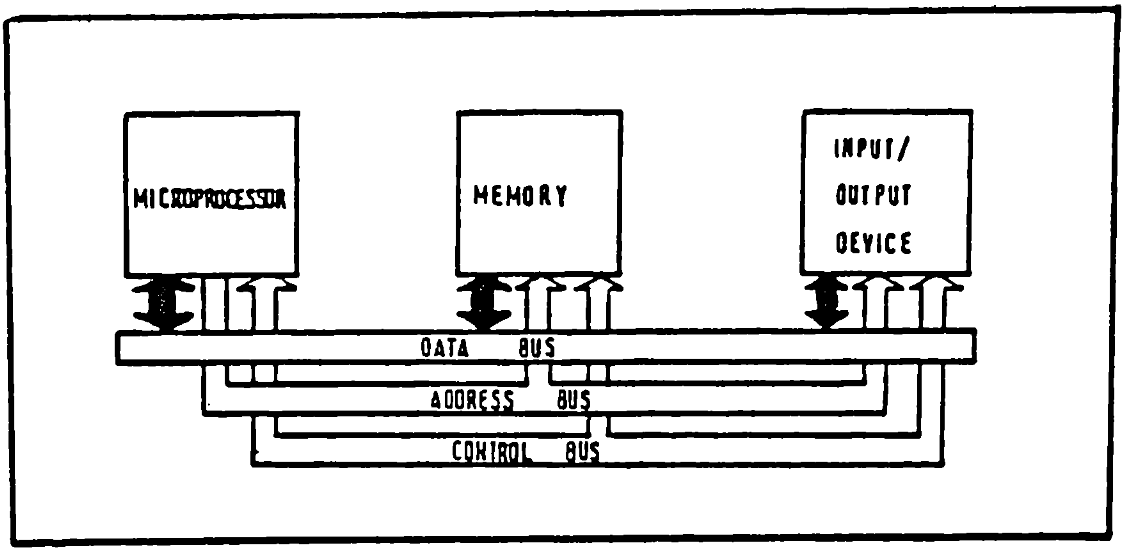


FIGURE 6. BASIC COMPONENTS OF A MICROCONTROLLER.

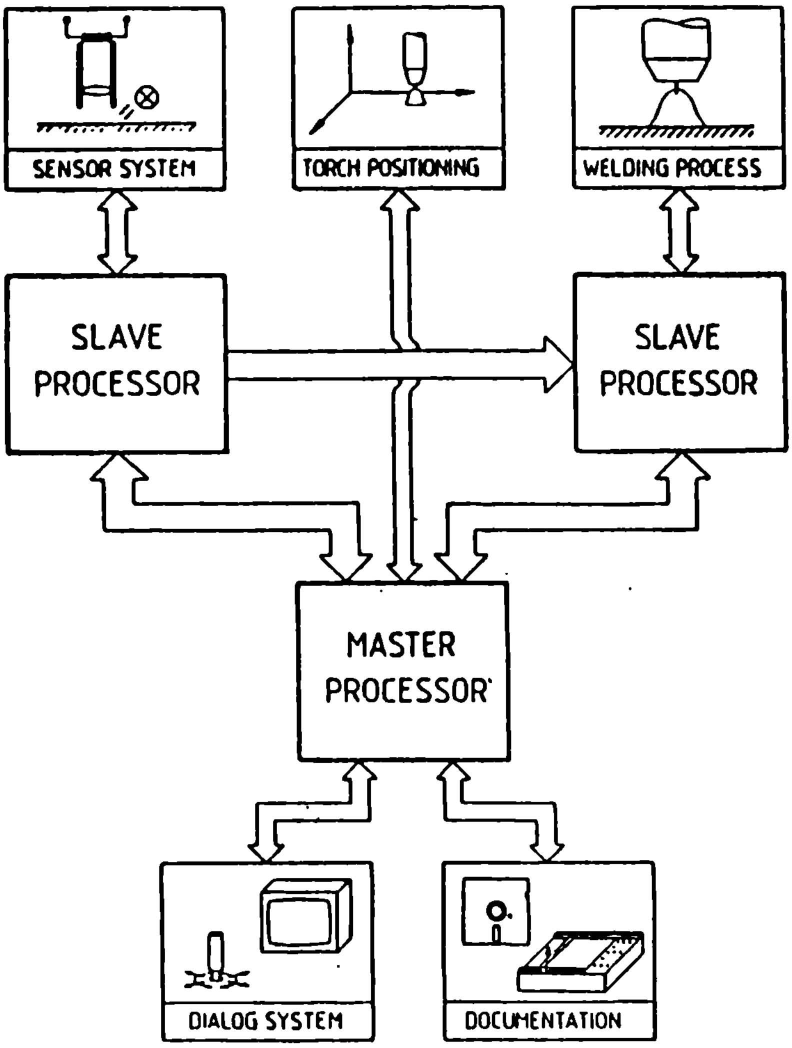


FIGURE 7. COMPUTER AIDED WELDING SYSTEM.

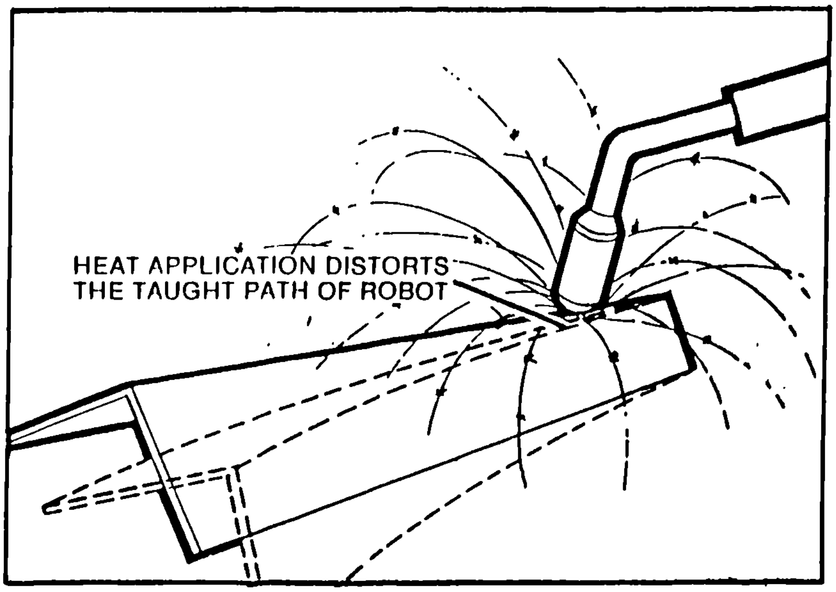


FIGURE 8. WORK PIECE VARIATIONS DUE TO HEAT INPUT.

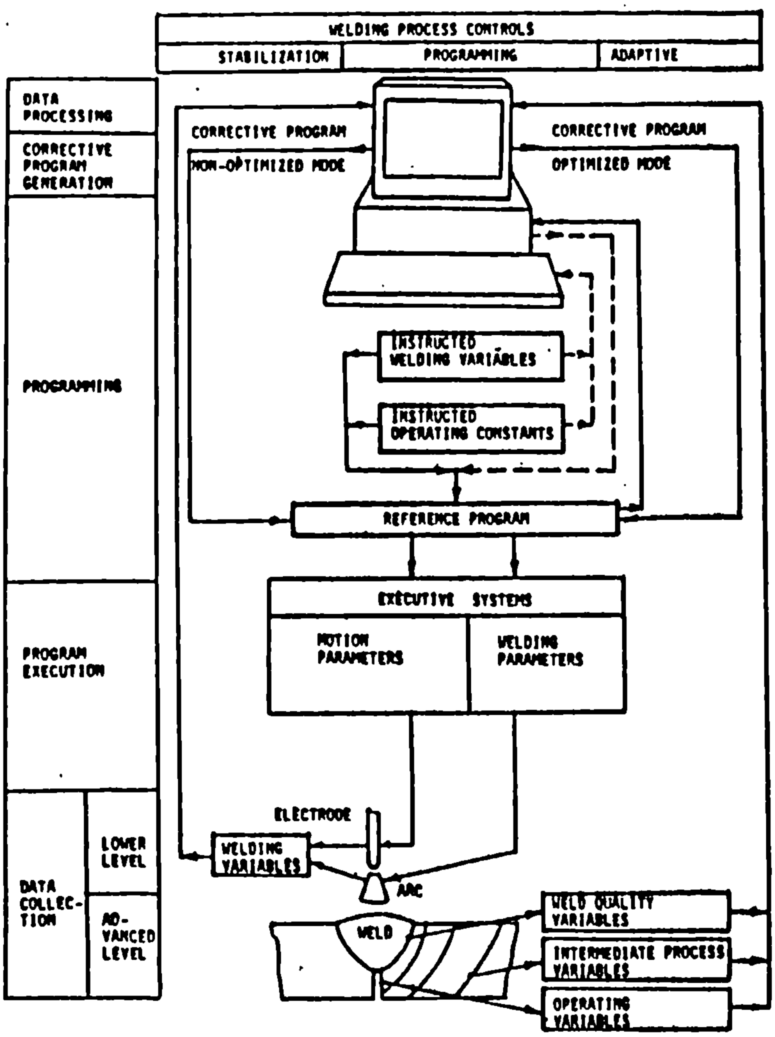


FIGURE 9. CONVENTIONAL AUTOMATED WELDING AND ITS CONTROL VARIABLES.

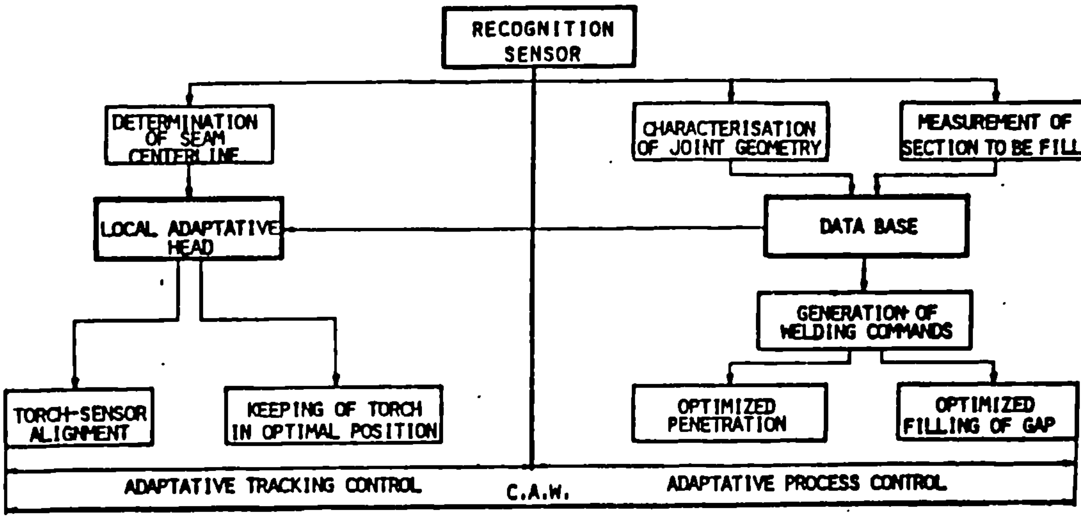


FIGURE 10. SENSORS IN AUTOMATED WELDING.

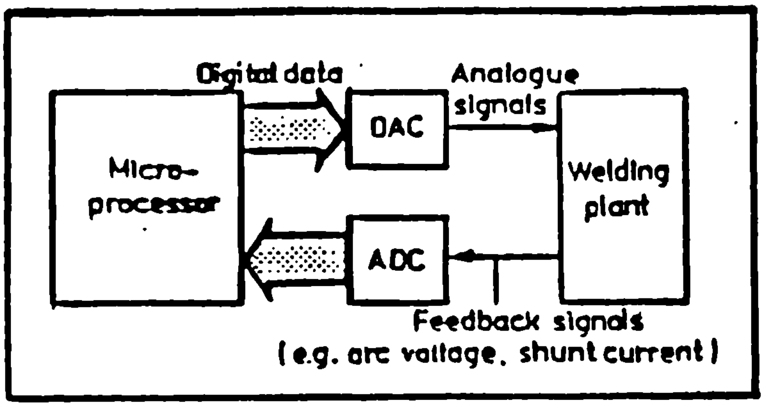


FIGURE 11. CLOSED LOOP CONTROL SYSTEM.

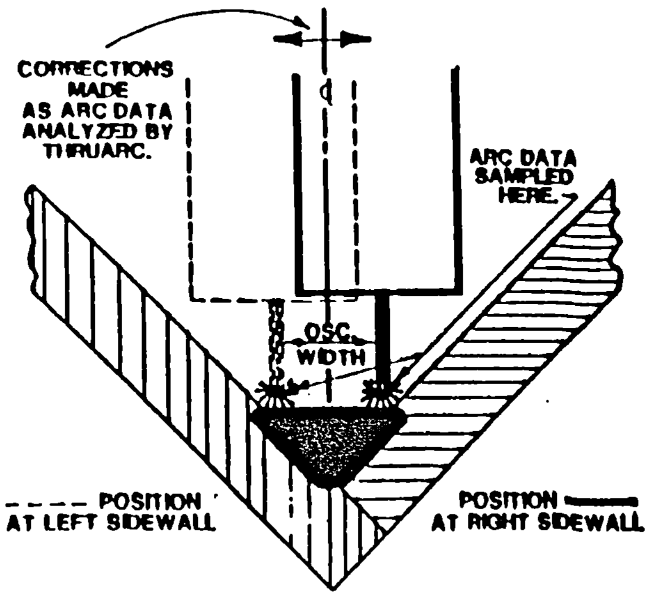


FIGURE 12. THROUGH-THE-ARC SENSING.

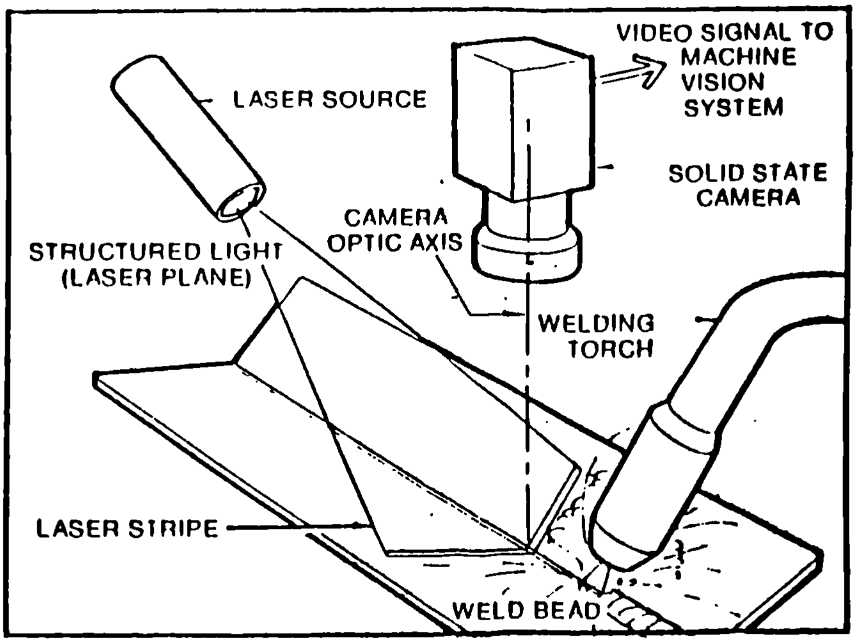


FIGURE 13. NON-CONTACT PREVIEW SENSING.

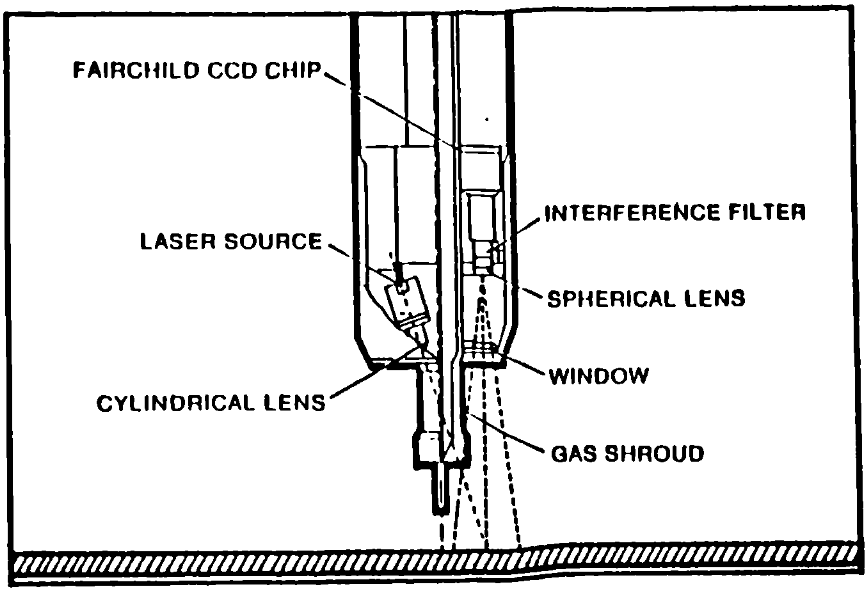


FIGURE 14. META-TORCH.

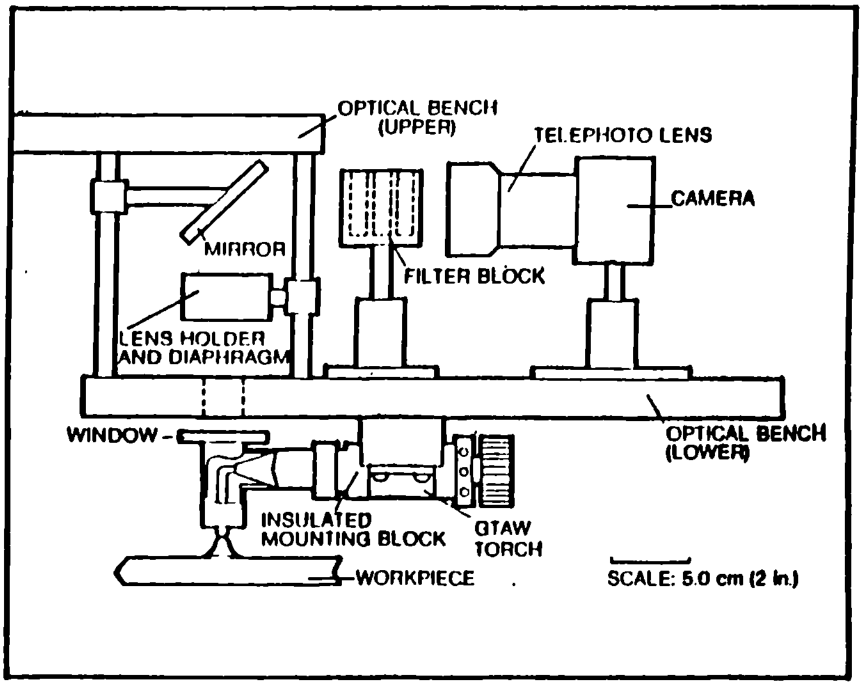


FIGURE 15. DIRECT-ARC-SENSING.

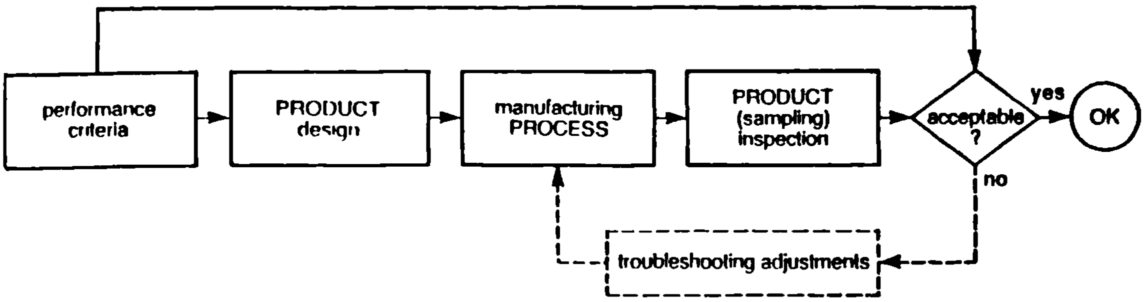


FIGURE 16. QUALITY CONTROL SEQUENCES.

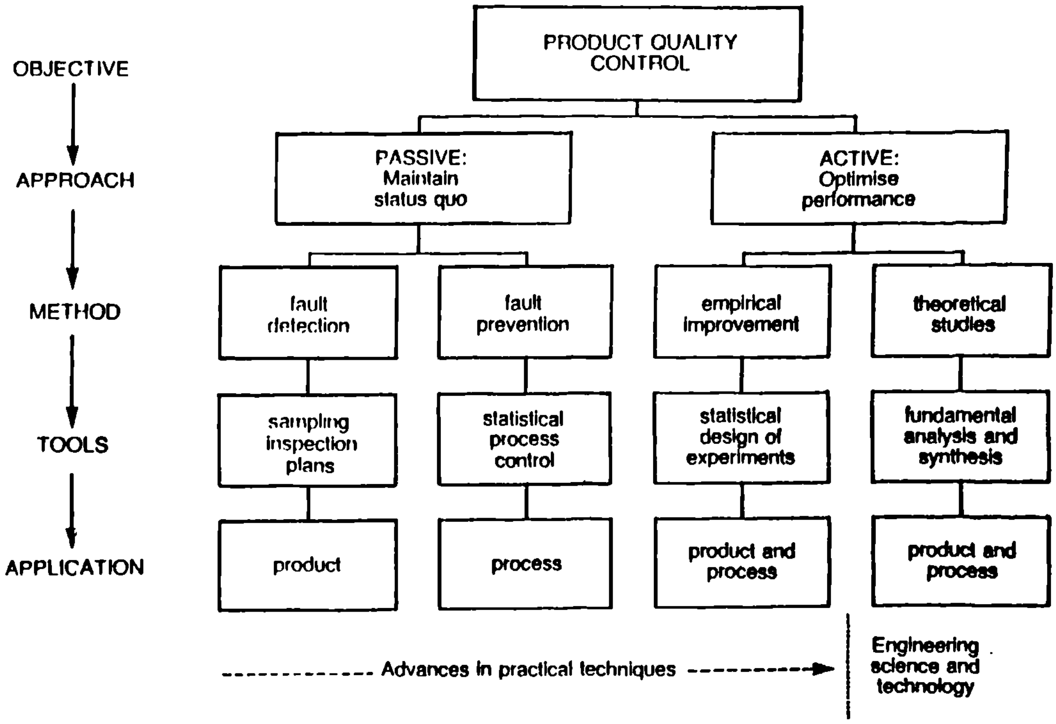


FIGURE 17. QUALITY MONITORING AND CONTROL TECHNIQUES.

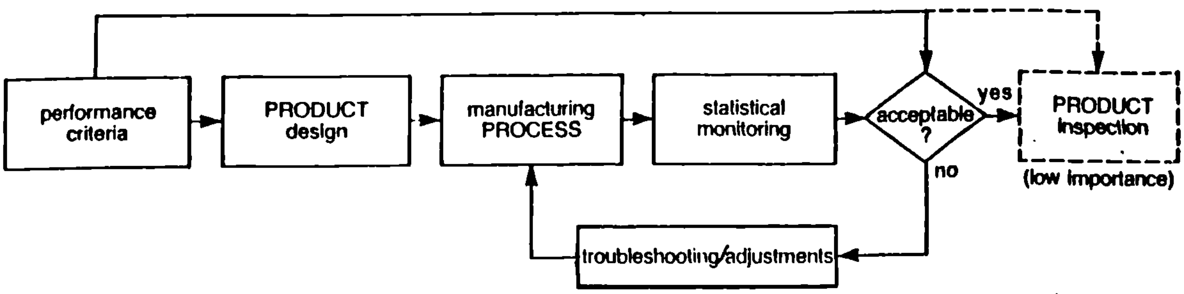


FIGURE 18. QUALITY BY FAULT PREVENTION.

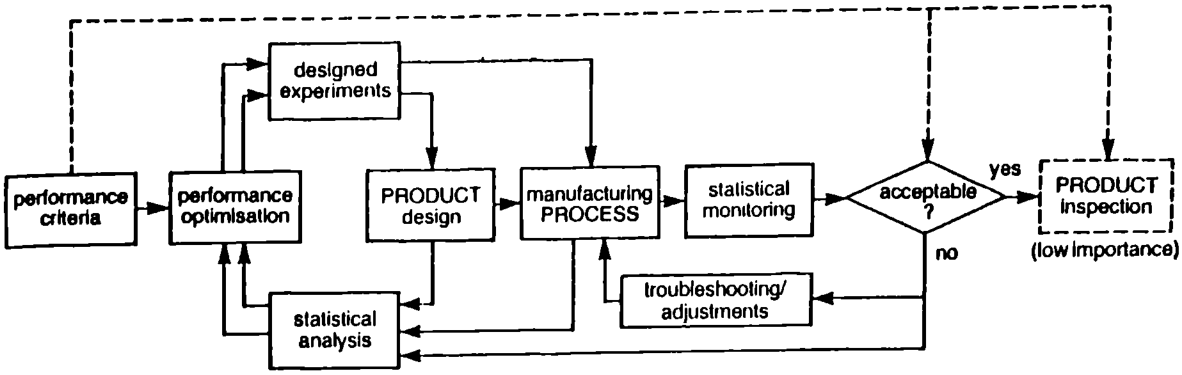


FIGURE 19. QUALITY BY OPTIMISED DESIGN.

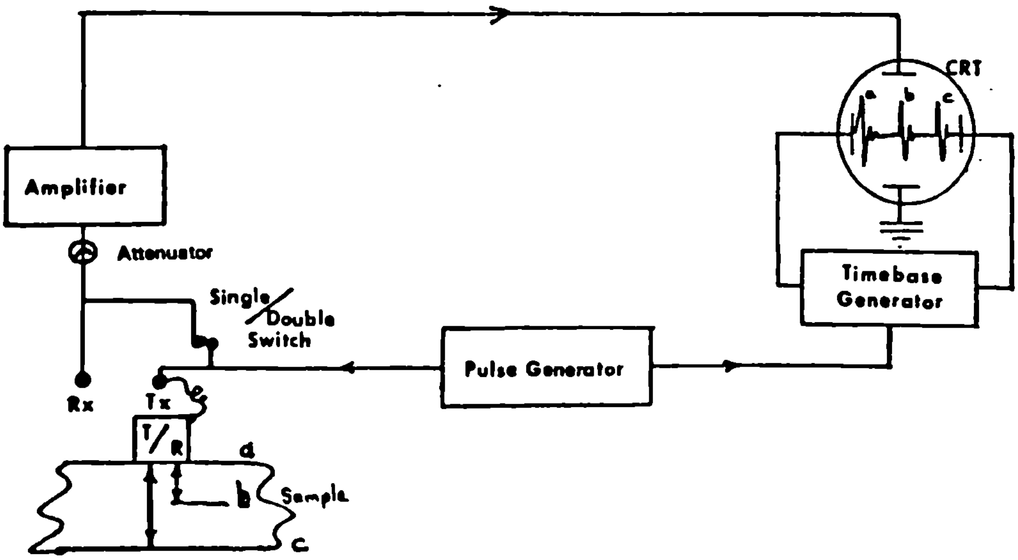


FIGURE 20. TYPICAL ULTRASONIC INSPECTION SYSTEM.

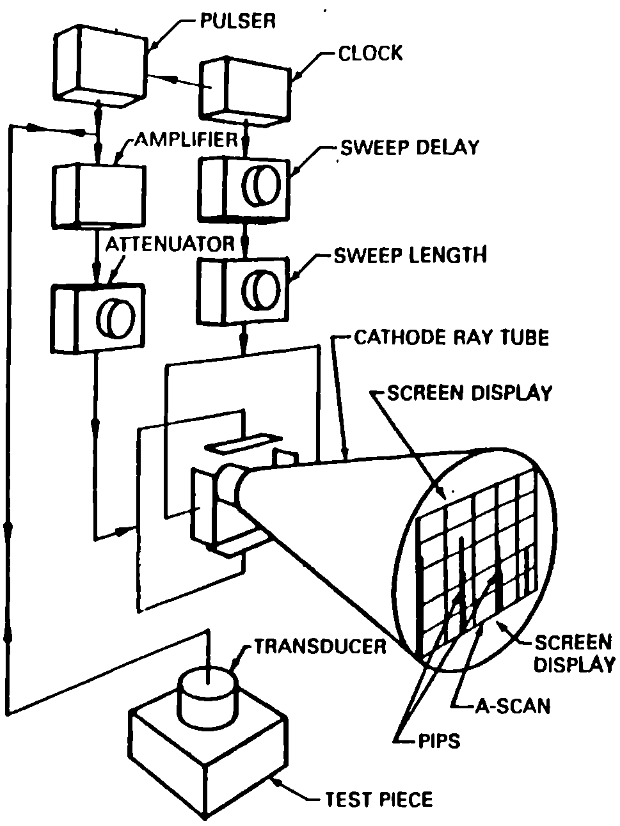


FIGURE 21. ULTRASONOSCOPE UNIT.

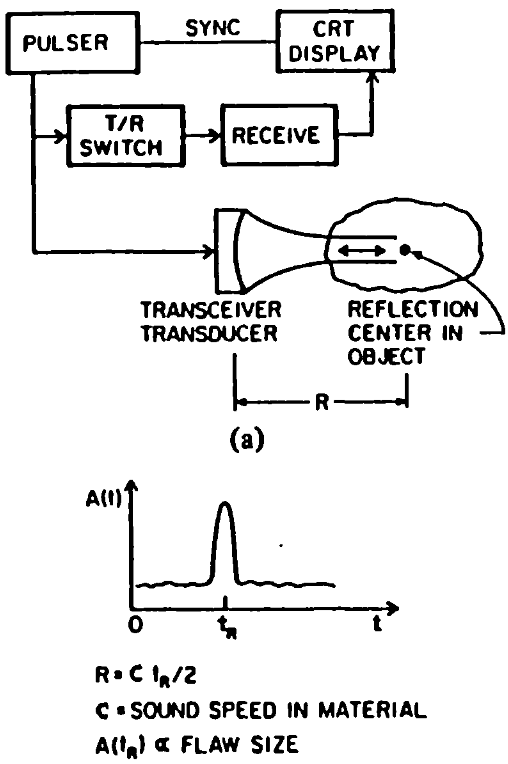


FIGURE 22. A-SCAN.

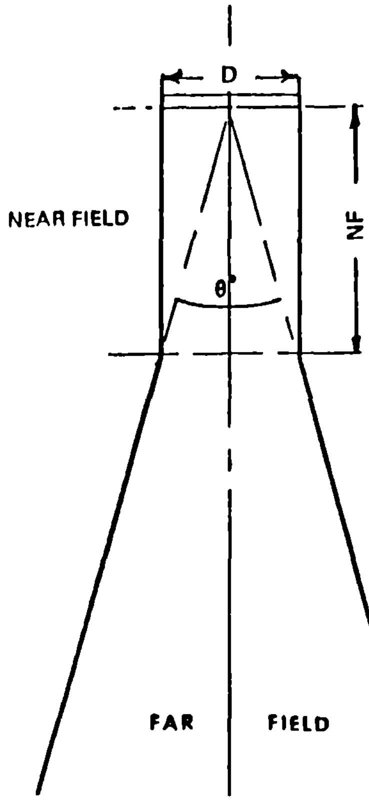


FIGURE 23. NEAR AND FAR FIELD OF A TRANSDUCER.

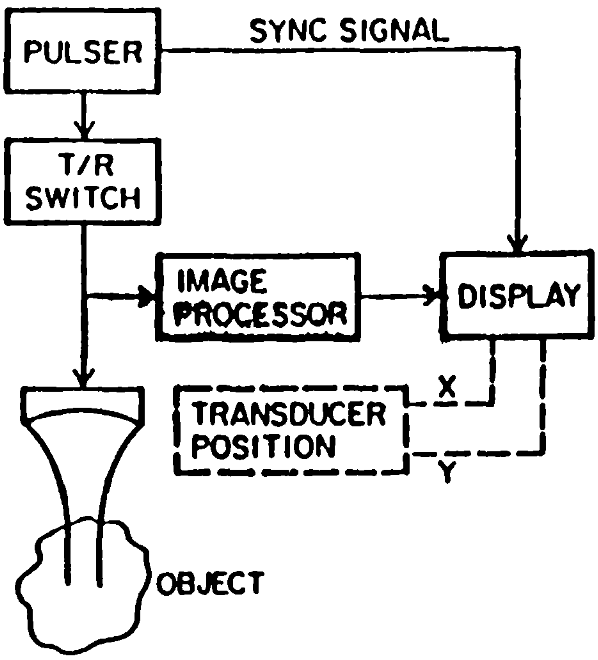


FIGURE 24. B-SCAN.

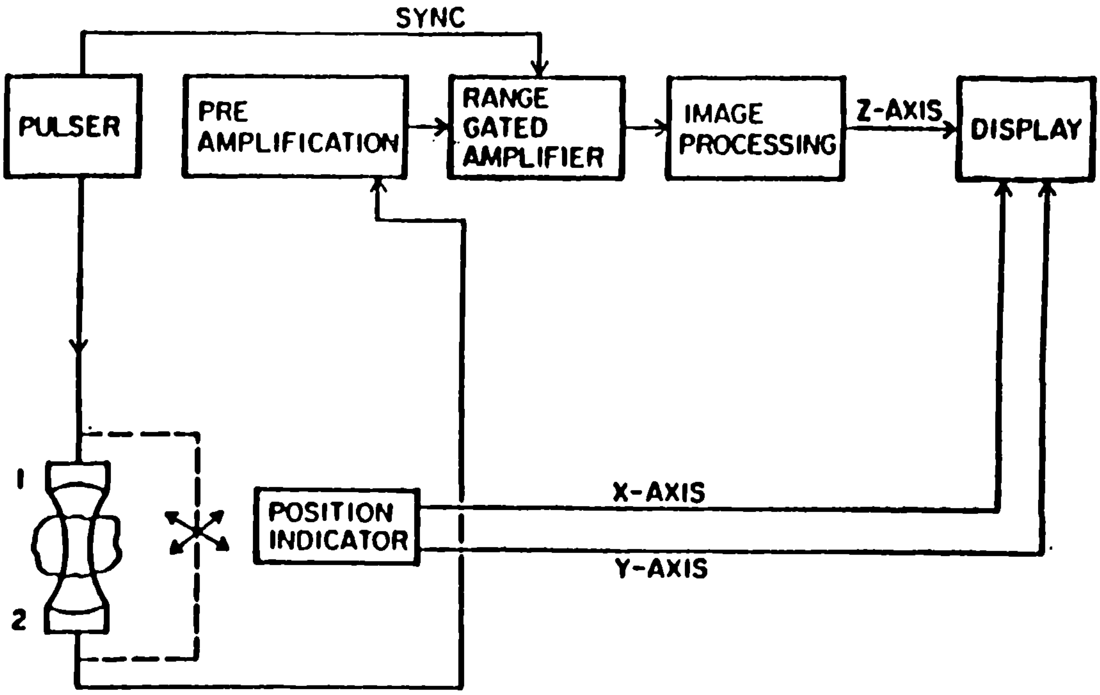


FIGURE 25. C-SCAN.

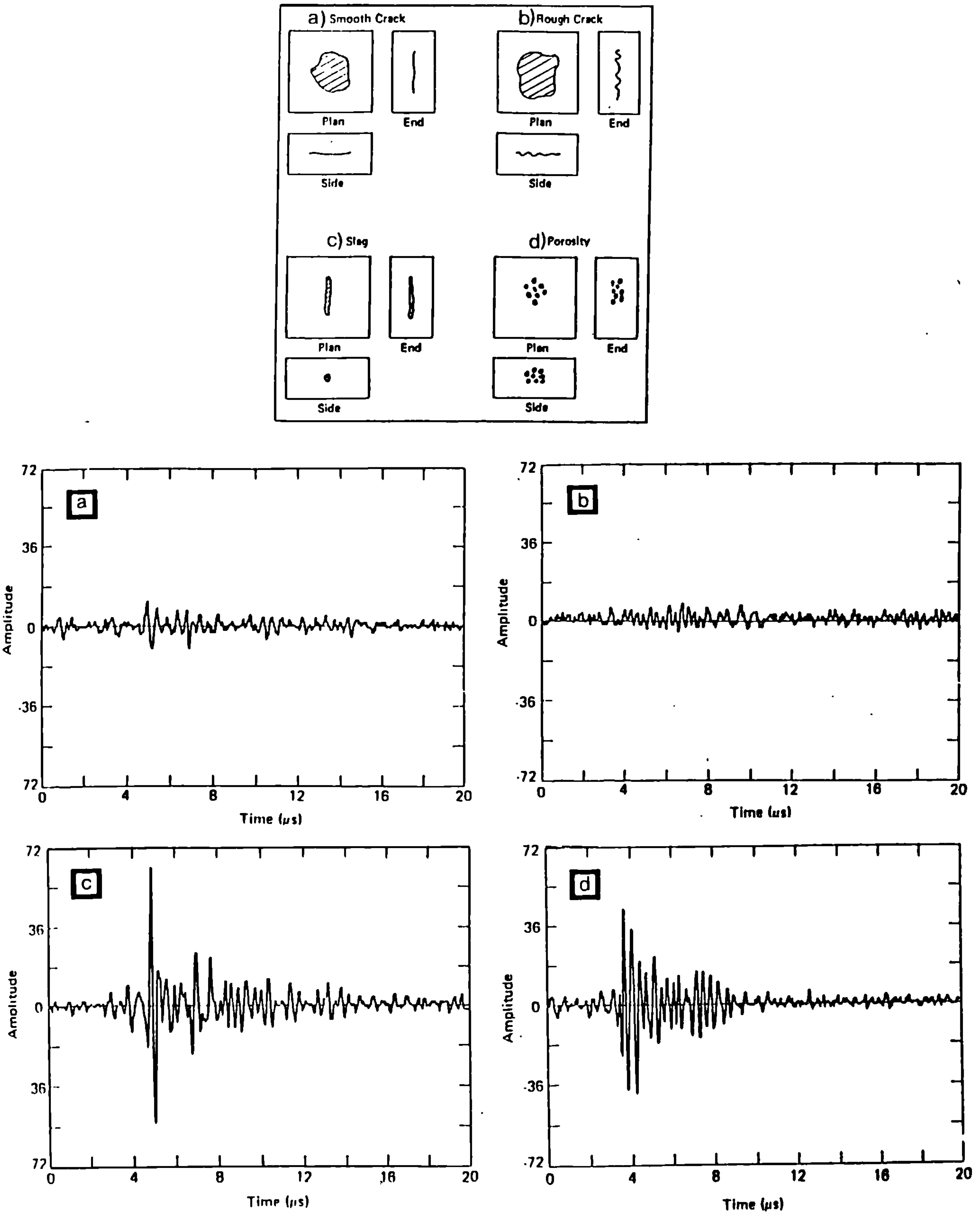


FIGURE 26. WELD DEFECT TYPES AND CHARACTERISTIC CURVES.

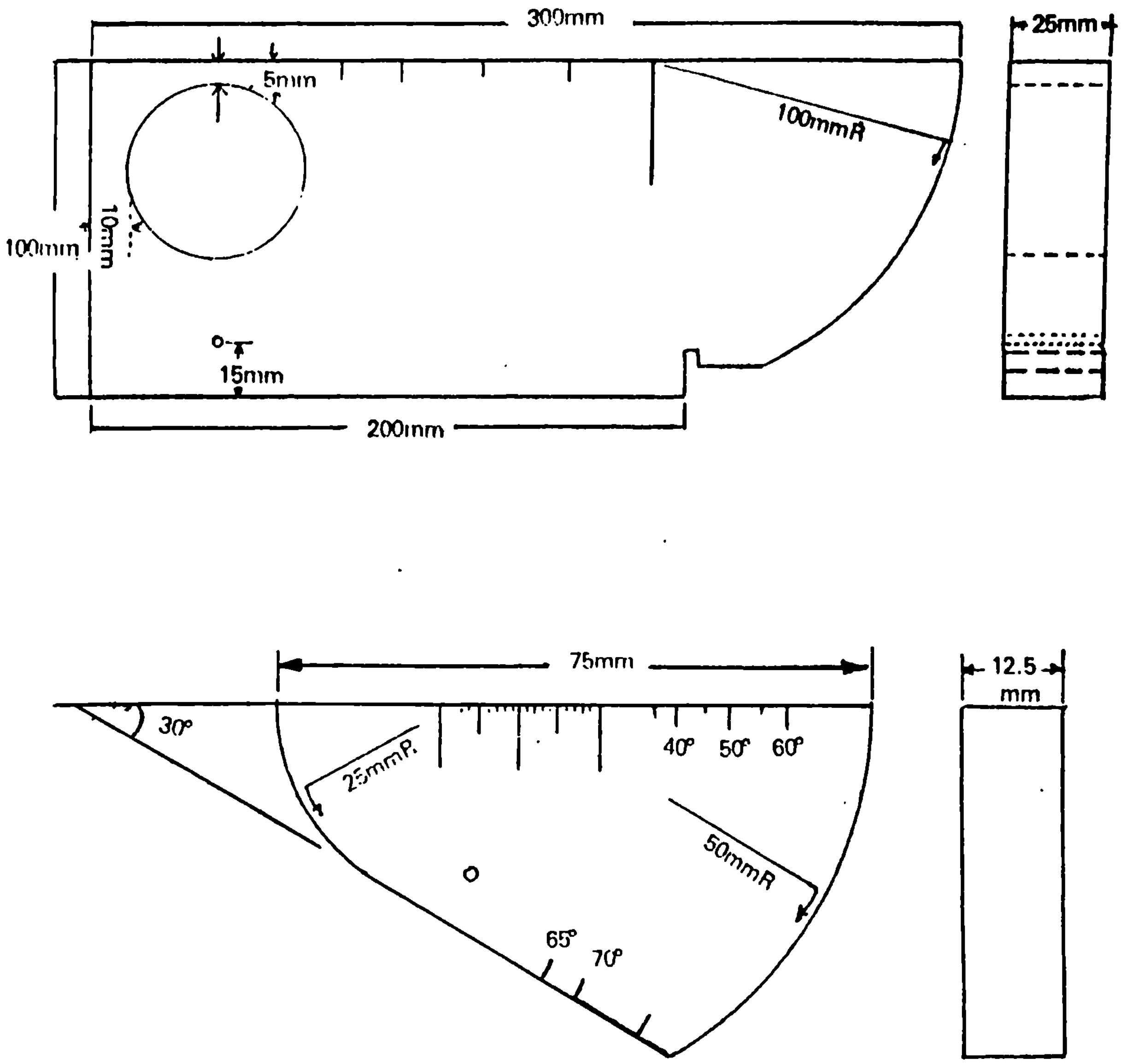


FIGURE 27. STANDARD ULTRASONIC BEAM CALIBRATION BLOCKS.

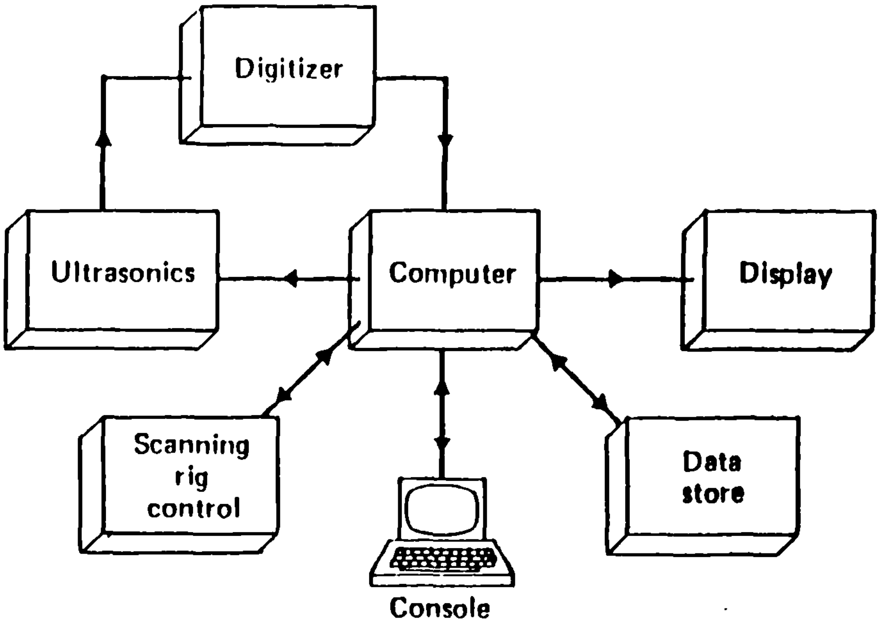


FIGURE 28. COMPUTER AIDED ULTRASONIC INSPECTION SYSTEM.

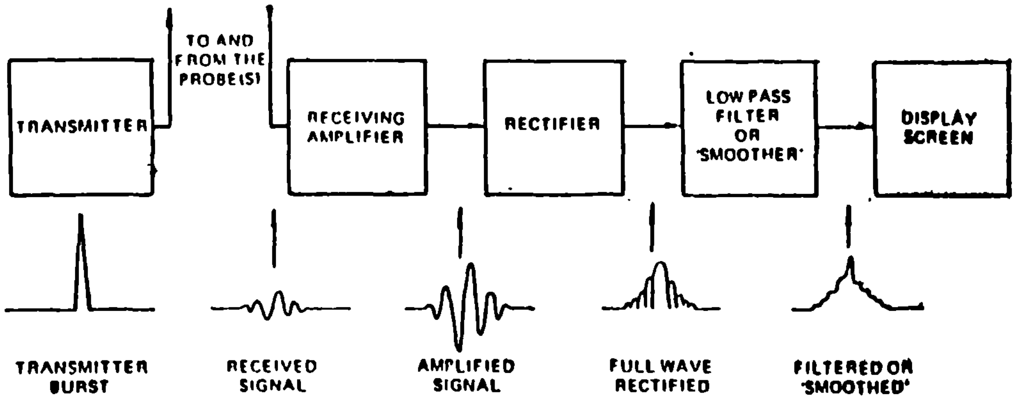


FIGURE 29. ULTRASONIC SIGNALS PROCESSING STEPS.

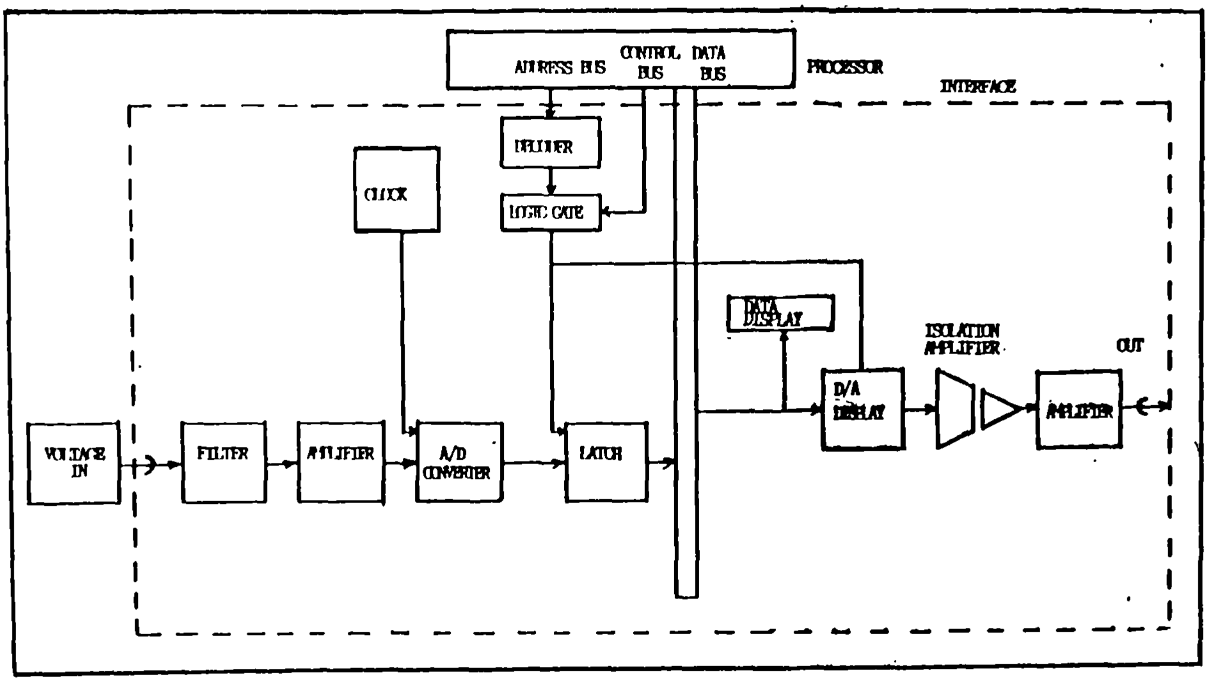


FIGURE 30. ANALOGUE TO DIGITAL (A/D) CONVERTER.

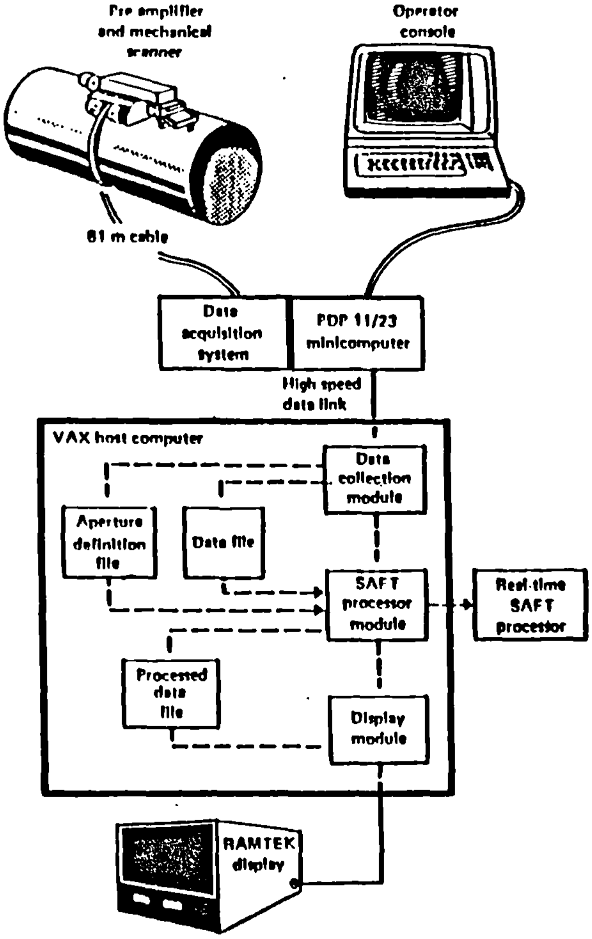


FIGURE 31. DIGITAL SIGNAL AND IMAGE PROCESSING

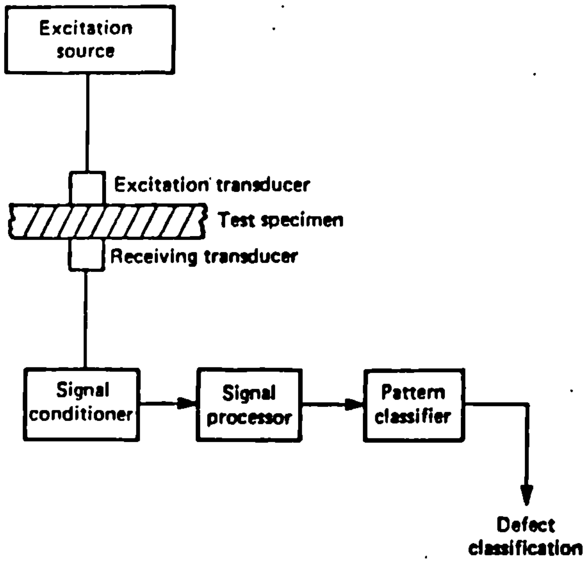


FIGURE 32. DIRECT CHARACTERISATION SCHEME.

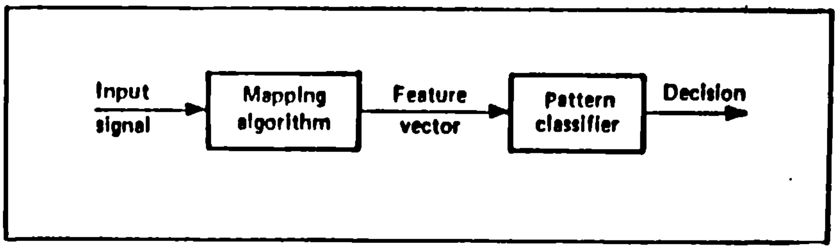


FIGURE 33. PATTERN CLASSIFICATION SYSTEM.

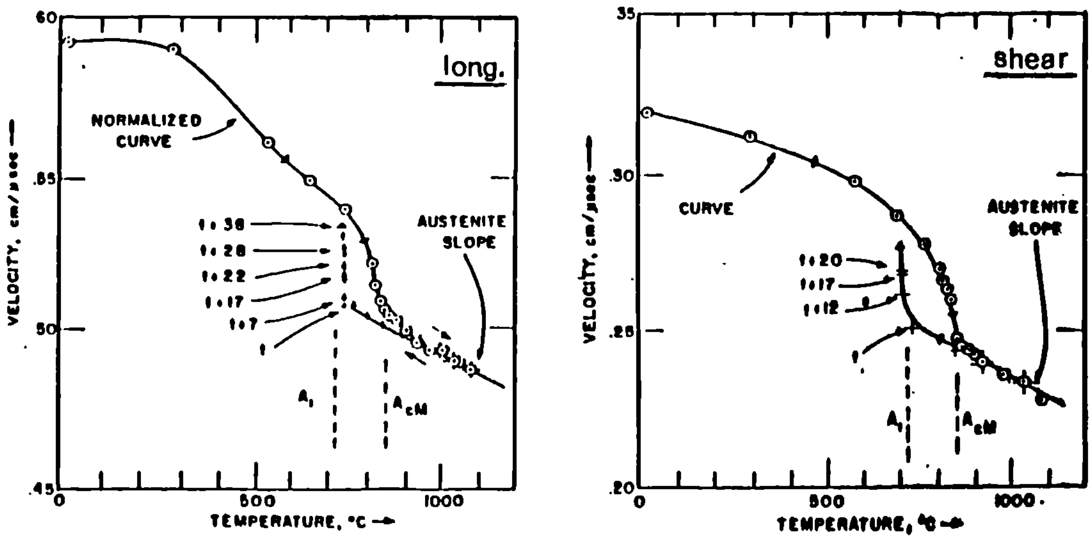
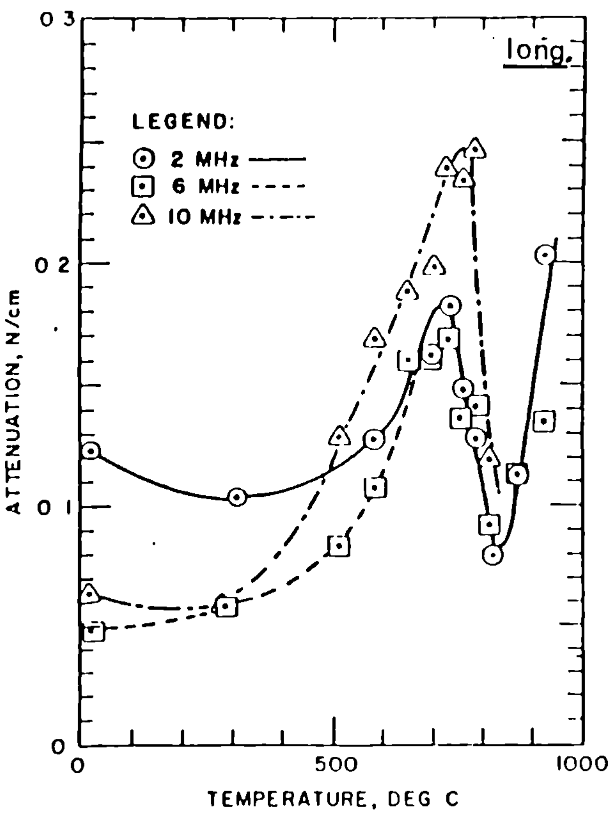


FIGURE 34. EFFECT OF TEMPERATURE ON ULTRASOUND VELOCITY.



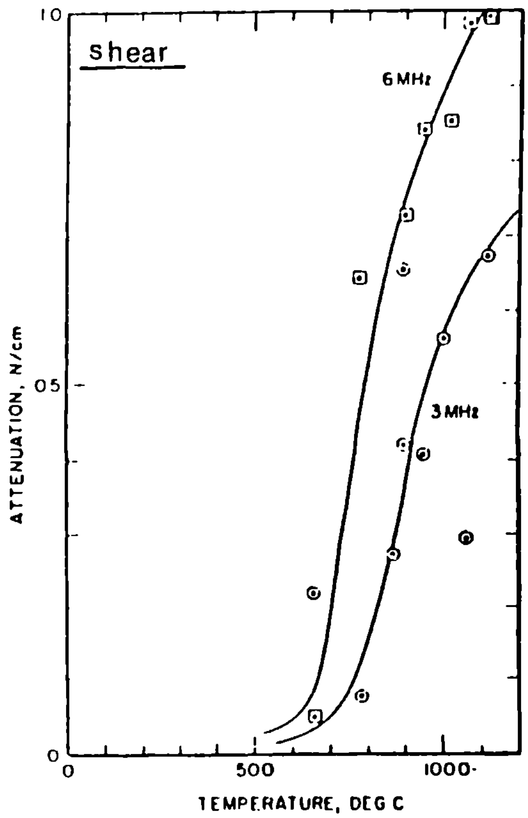


FIGURE 35. EFFECT OF TEMPERATURE ON ULTRASOUND ATTENUATION.

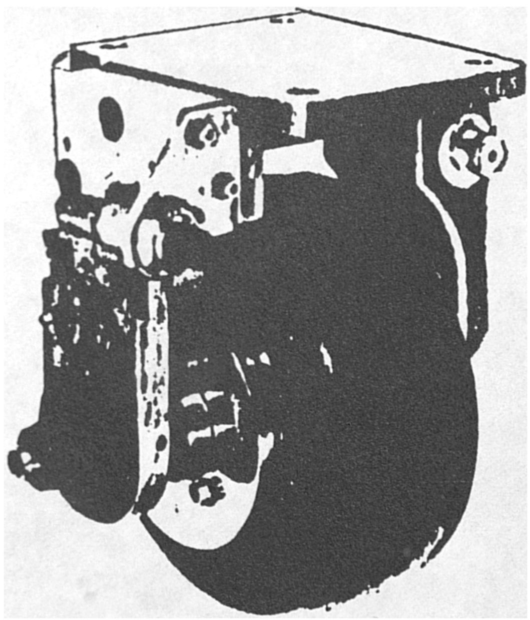


FIGURE 36. SPERRY WHEEL/ULTRASONIC TRANSDUCER.

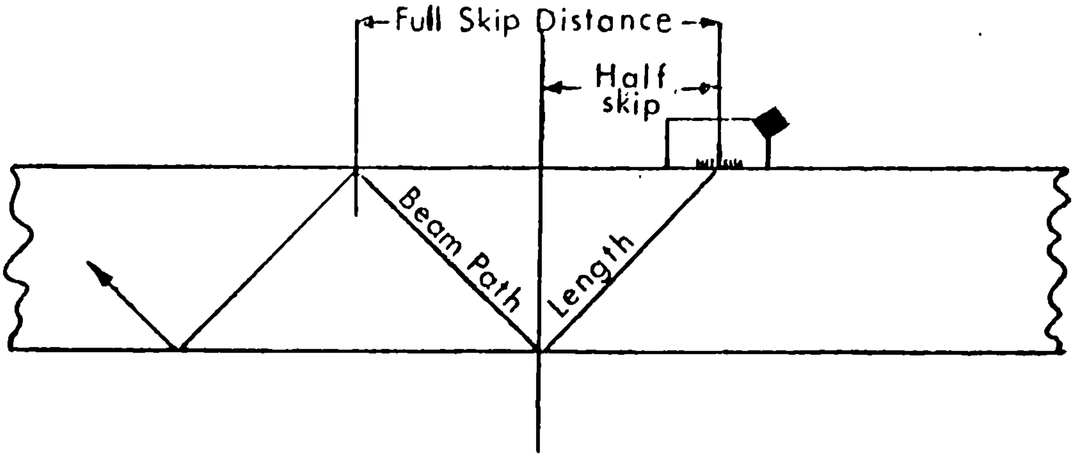


FIGURE 37. BEAM PATH LENGTH AND SKIP DISTANCE CORRELATION.

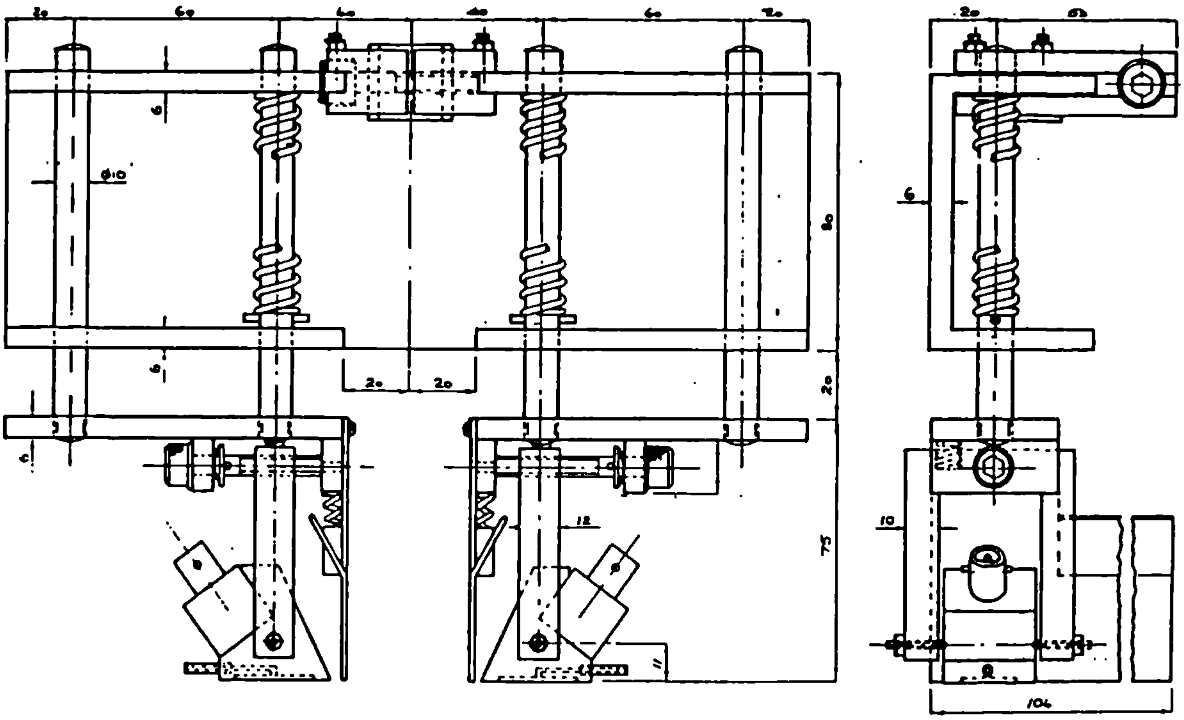


FIGURE 38. ULTRASONIC PROBE HOLDER DEVICE.

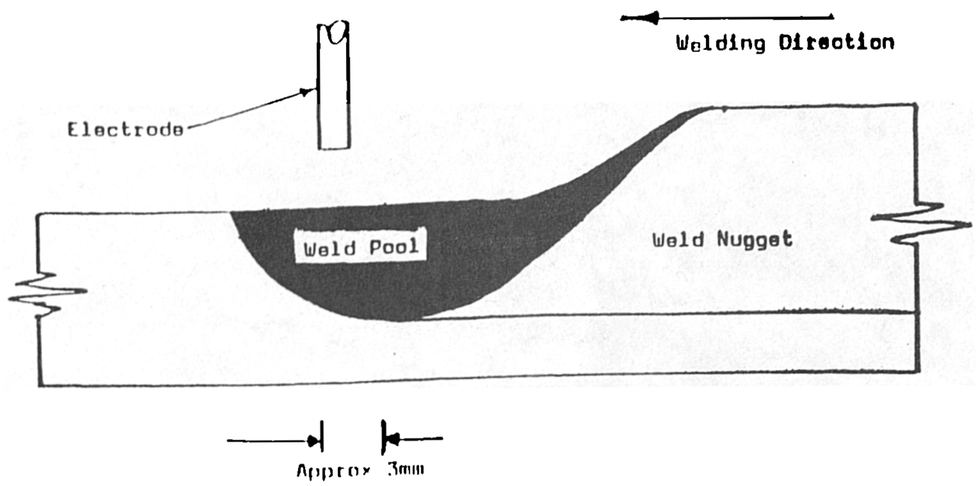


FIGURE 39. MAXIMUM WELD PENETRATION POINT.

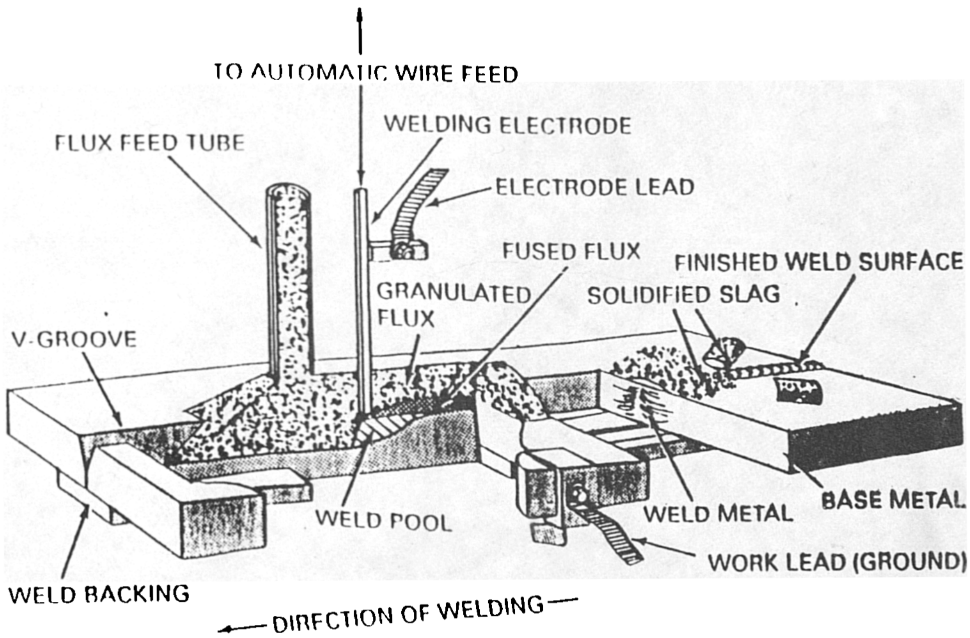


FIGURE 40. SUBMERGED ARC WELDING PROCESS.

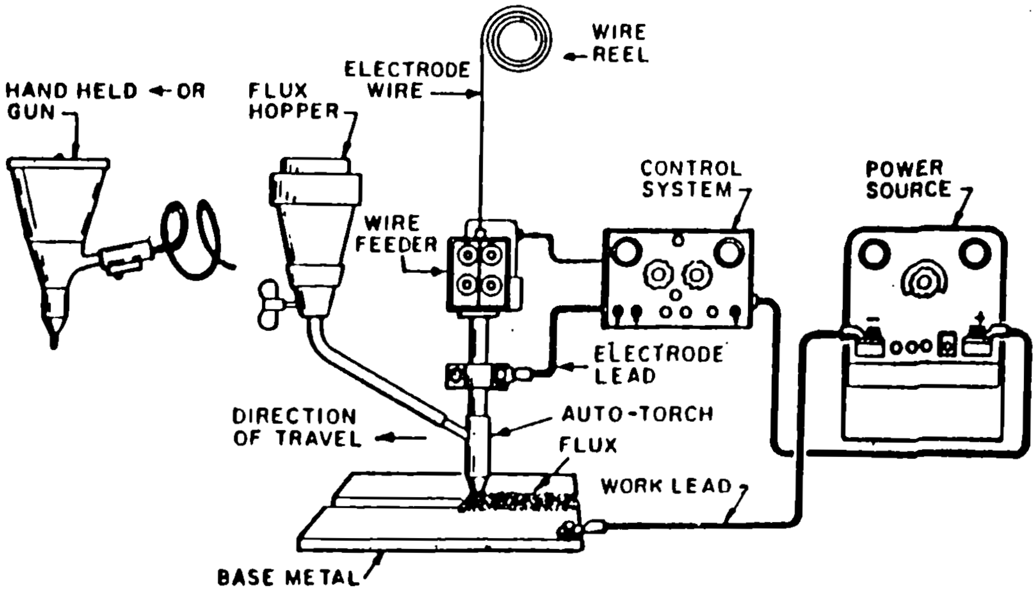


FIGURE 41. SUBMERGED ARC WELDING EQUIPMENT AND CONSUMABLES.

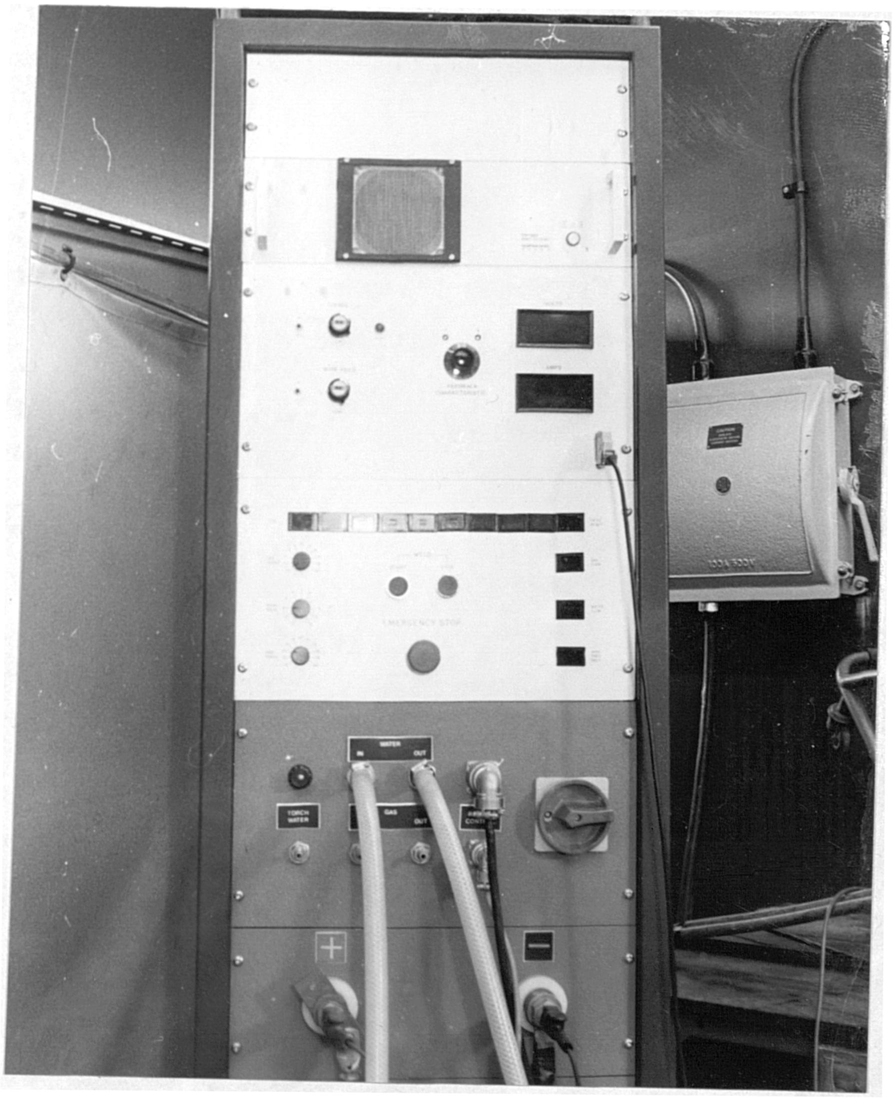


FIGURE 42. POWER SOURCE FOR S.A.W.

FIGURE 43. WIRE FEED UNIT.

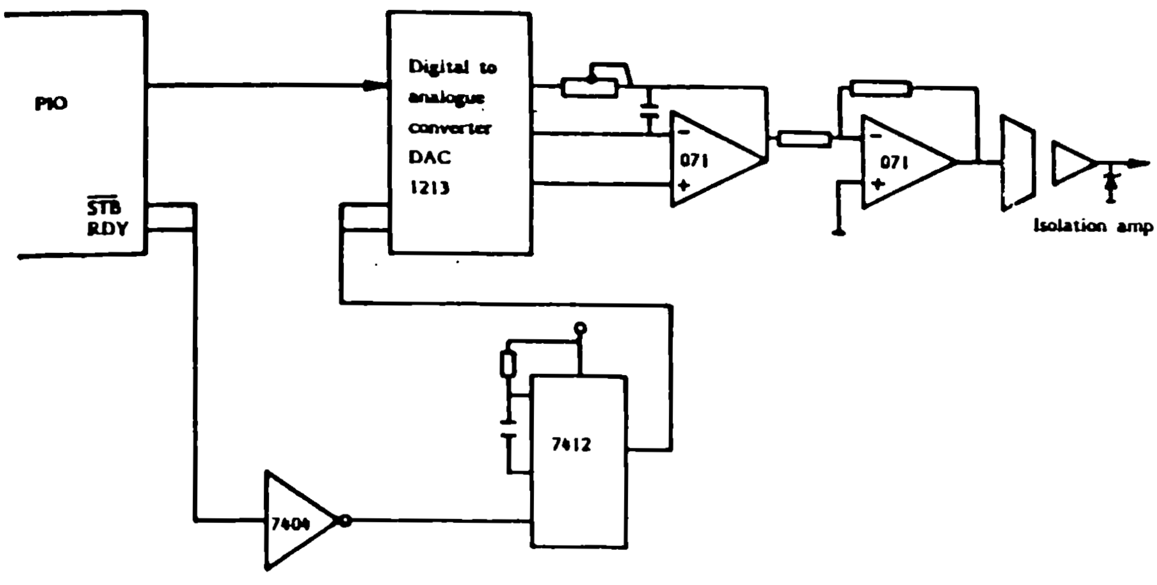


FIGURE 44. D/A CONVERTER (0-10V - 0-1000A).

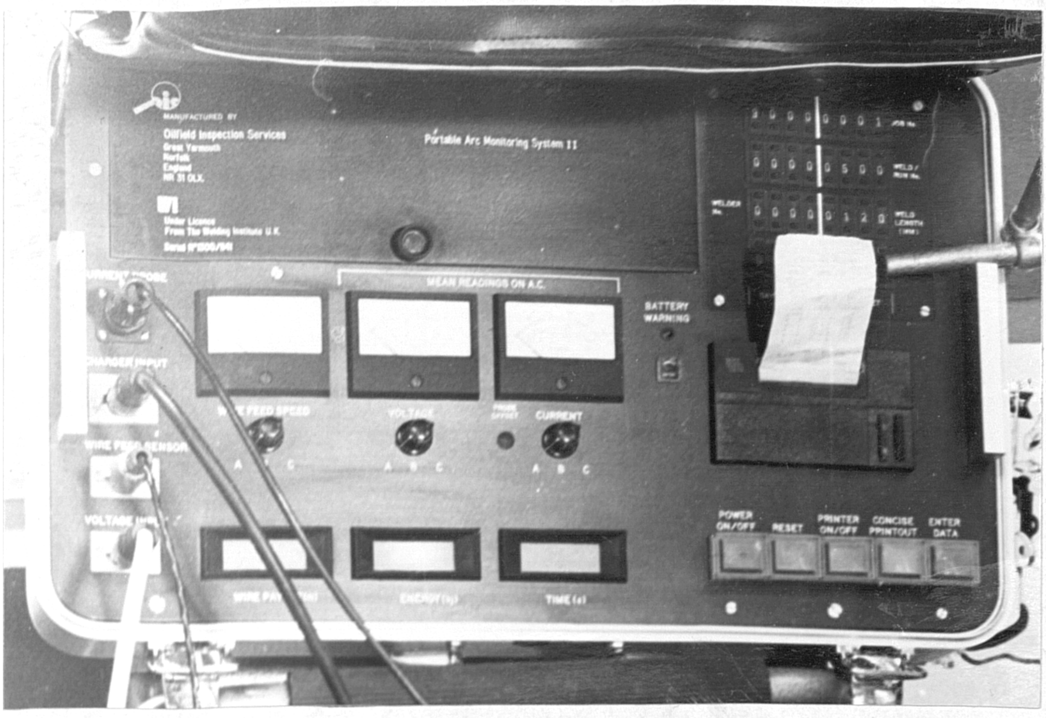


FIGURE 45. WELDING PARAMETERS MONITORING SYSTEM (MONARC).

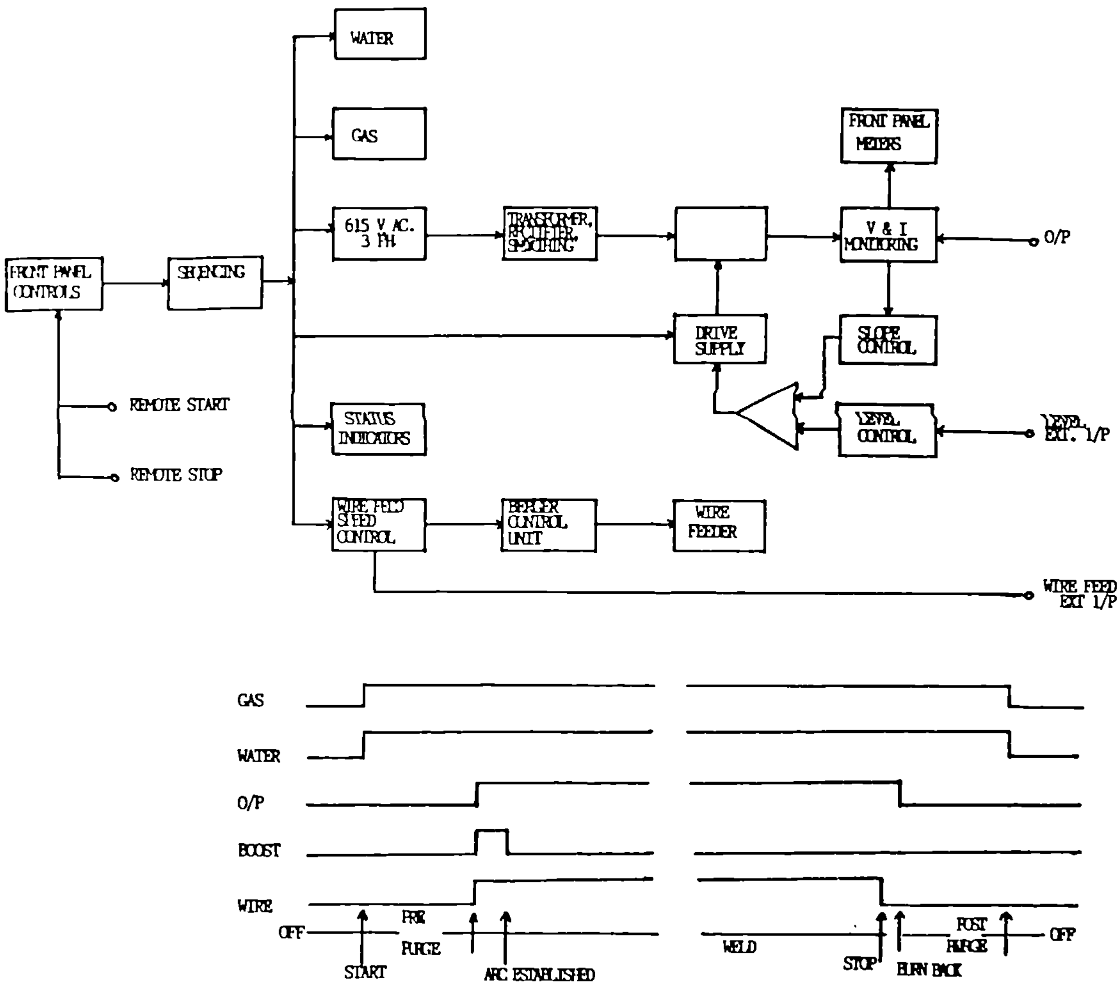


FIGURE 46. POWER SOURCE CONTROL SEQUENCE.

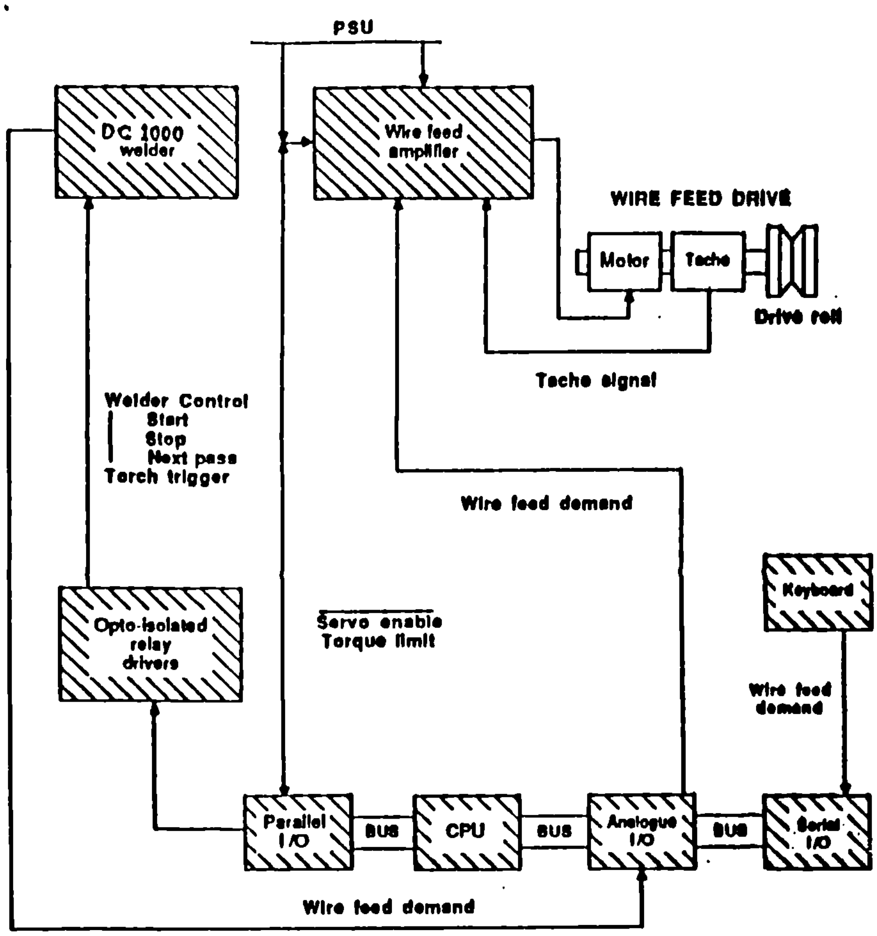


FIGURE 47. WIRE FEED SPREED CONTROL PROCEDURE.

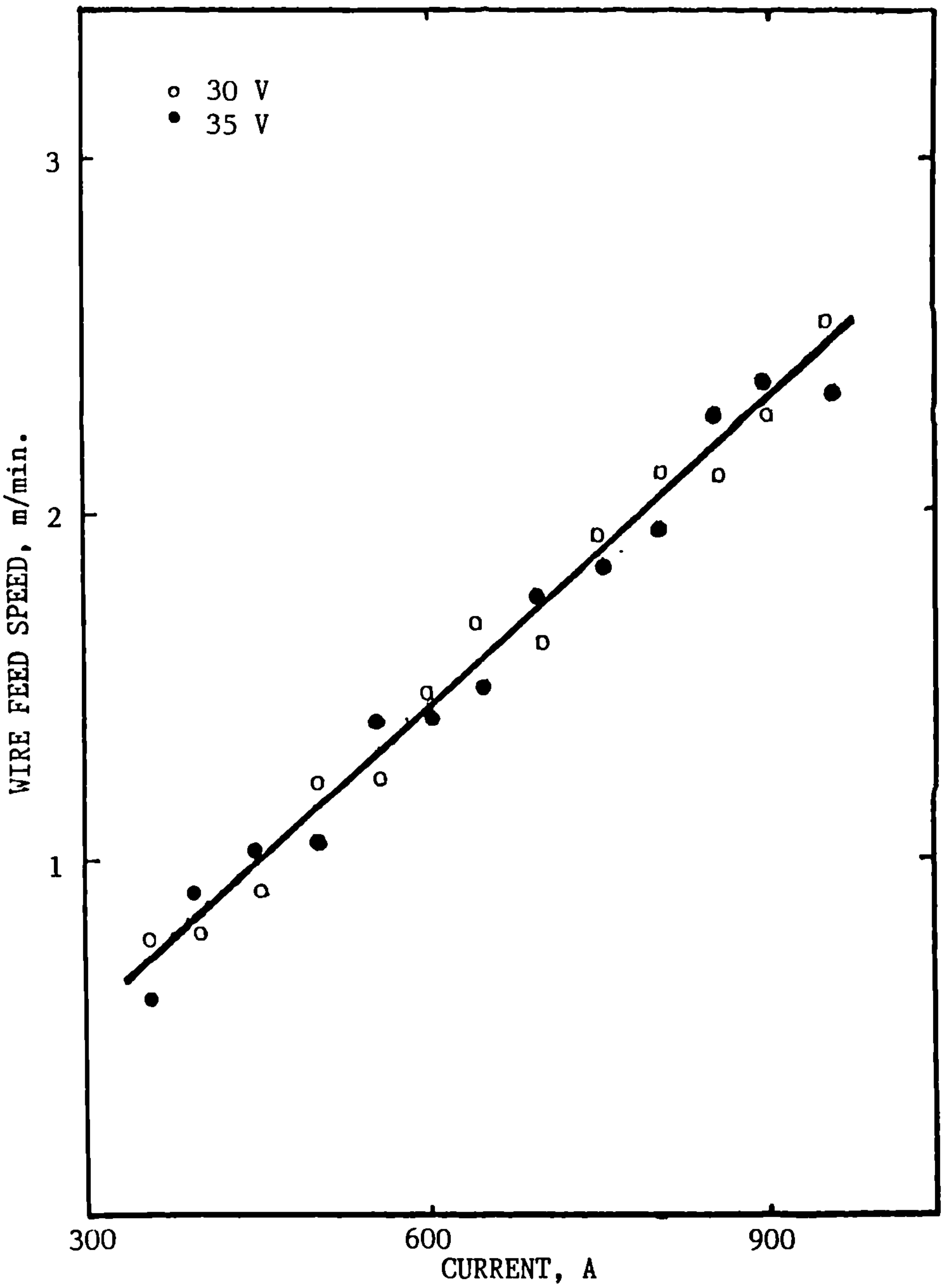


FIGURE 48. WELDING CURRENT / WIRE FEED SPEED RELATIONSHIP.

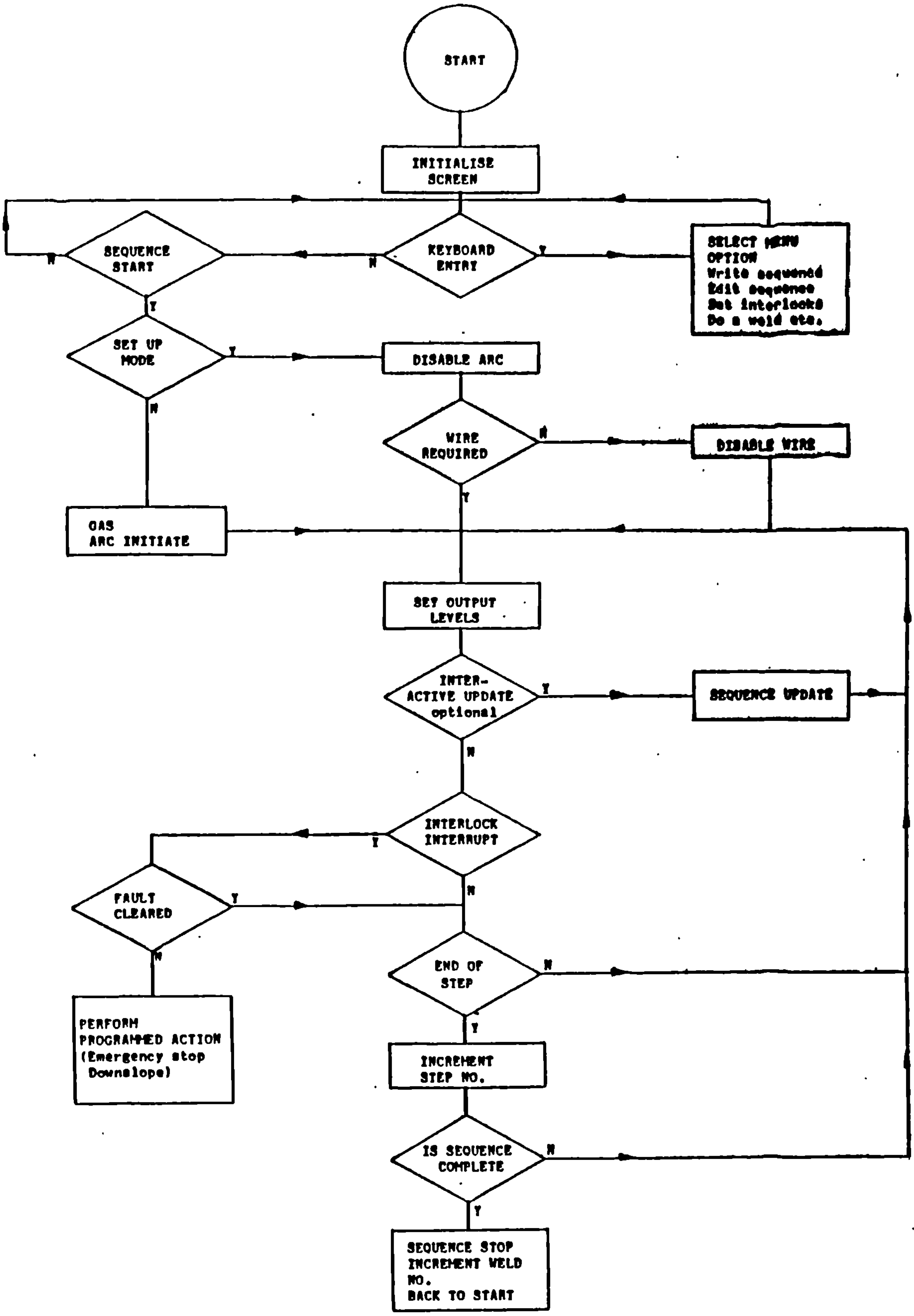


FIGURE 49. ROUTINE TO CONTROL POWER SOURCE.

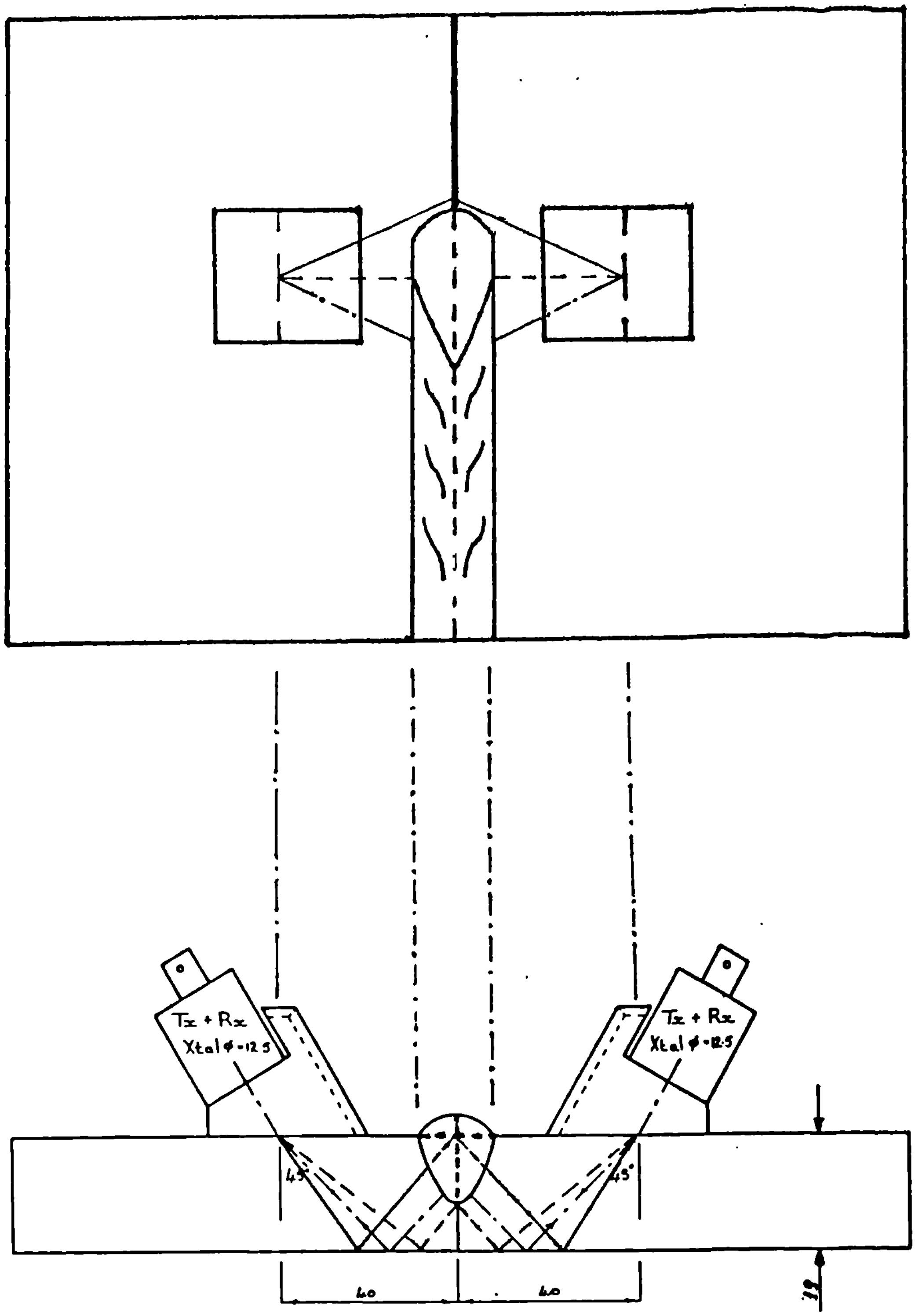


FIGURE 50. ULTRASONIC SENSOR ARRANGEMENT:

A) TOP VIEW.

B) THROUGH SECTION VIEW.

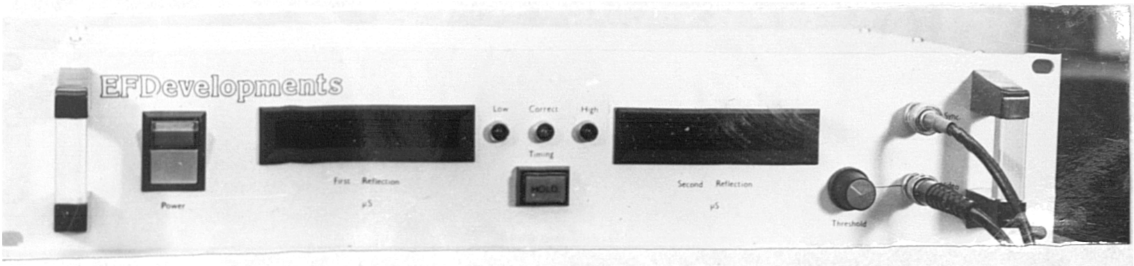


FIGURE 51. TIME-OF-FLIGHT MEASURING DEVICE.

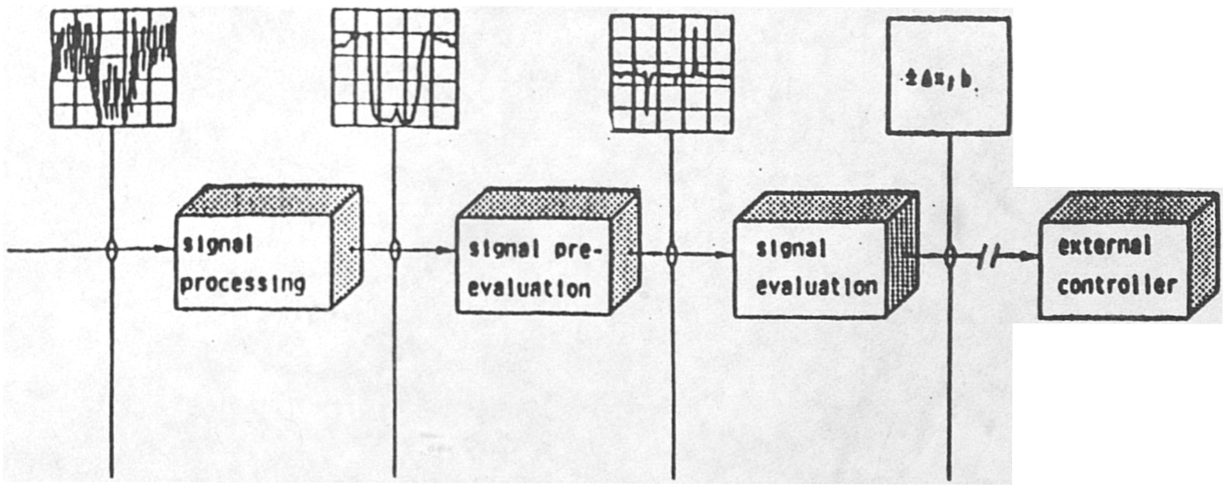


FIGURE 52. ACTIVE ELECTRIC NETWORK FOR ULTRASONIC SIGNALS DECONVOLUTION.

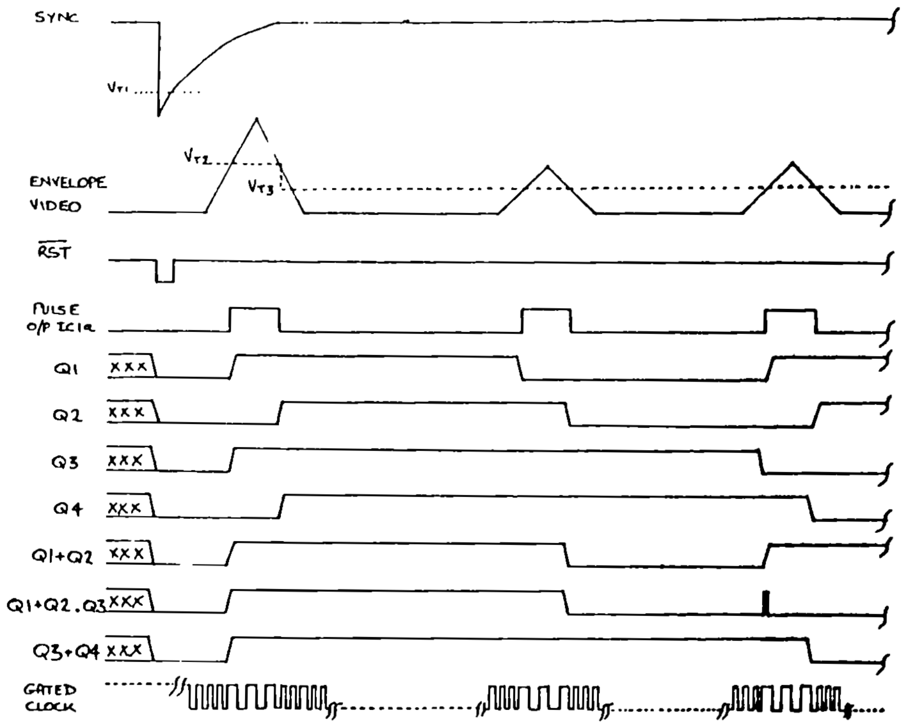


FIGURE 53. THRESHOLD OPERATION SCHEME - MIDPOINT TECHNIQUE

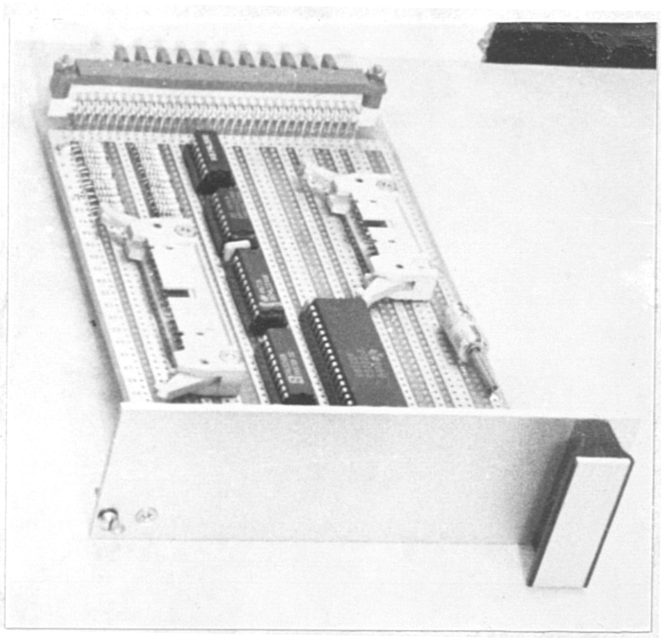


FIGURE 54. ULTRASONIC TIME DIGITIZER.

FIGURE 55. SENSORS HOLDER ASSEMBLY.

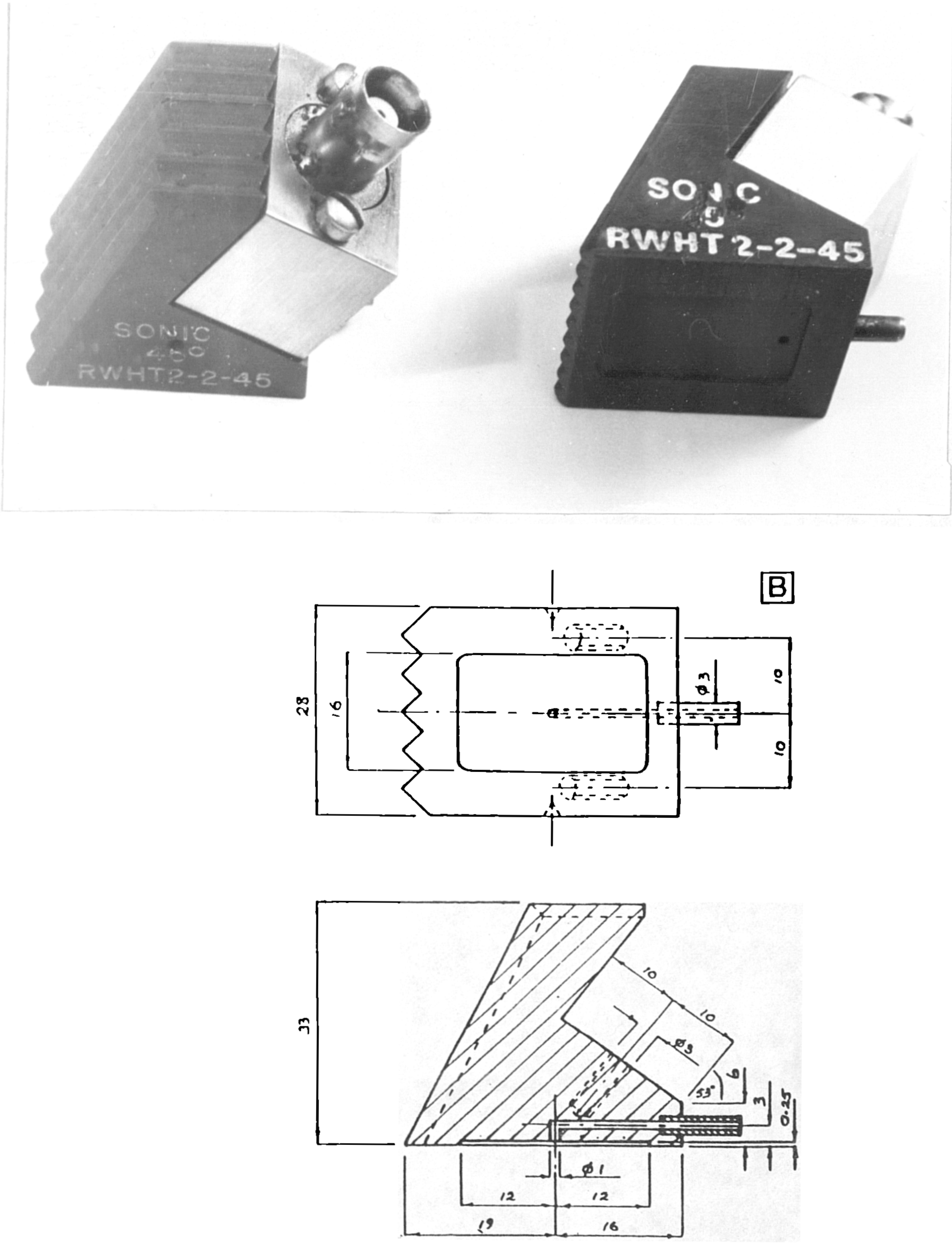


FIGURE 56. ULTRASONIC SENSORS WITH HIGH TEMPERATURE SHOES:

A) UNIT.

B) DIMENSIONS.

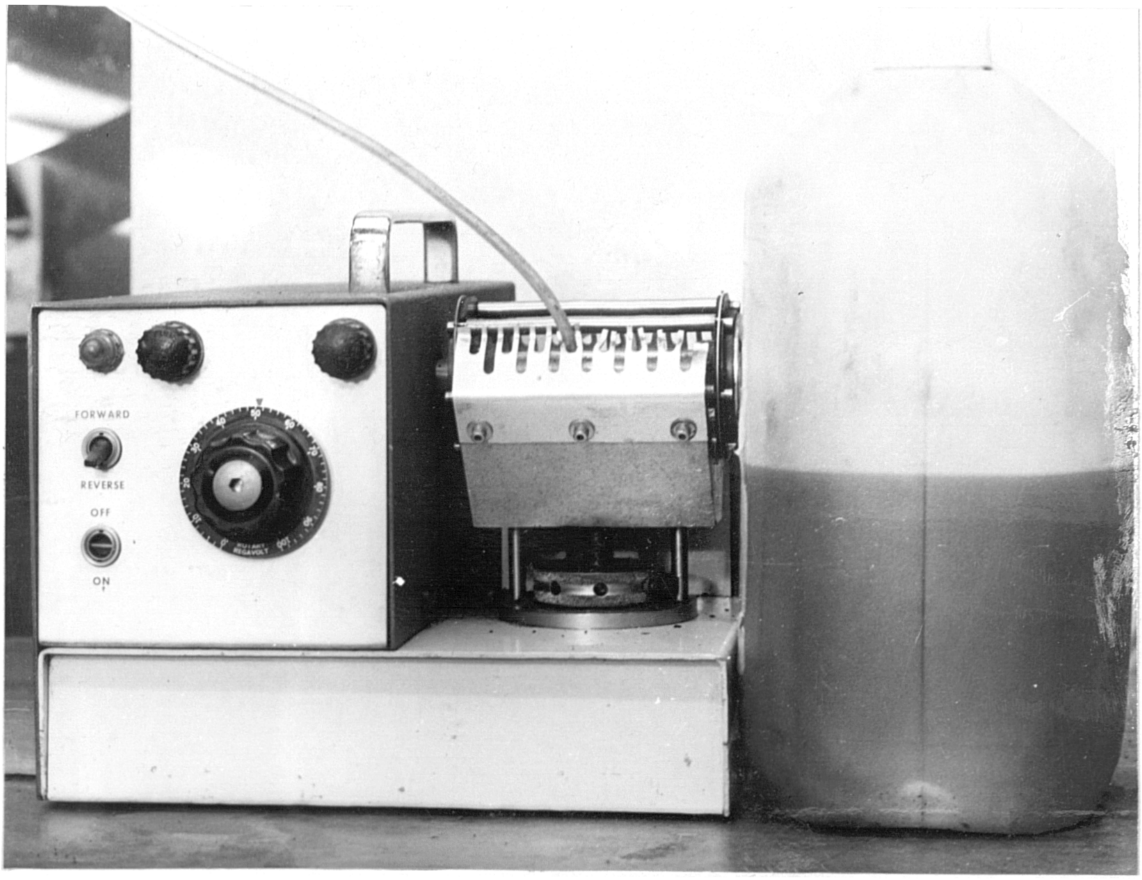


FIGURE 57. PERISTALTIC OIL PUMP.

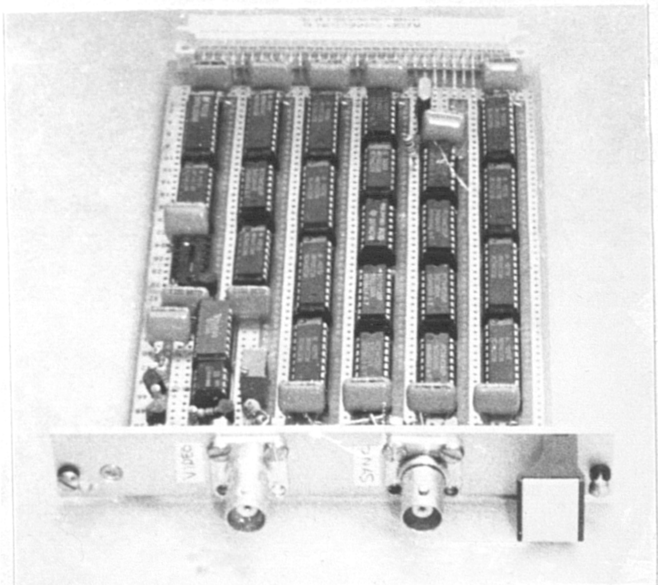


FIGURE 58. ULTRASONIC SIGNAL AMPLIFICATION UNIT.

FIGURE 59. ULTRASONASCOPE MAINFRAME AND PERIPHERALS.

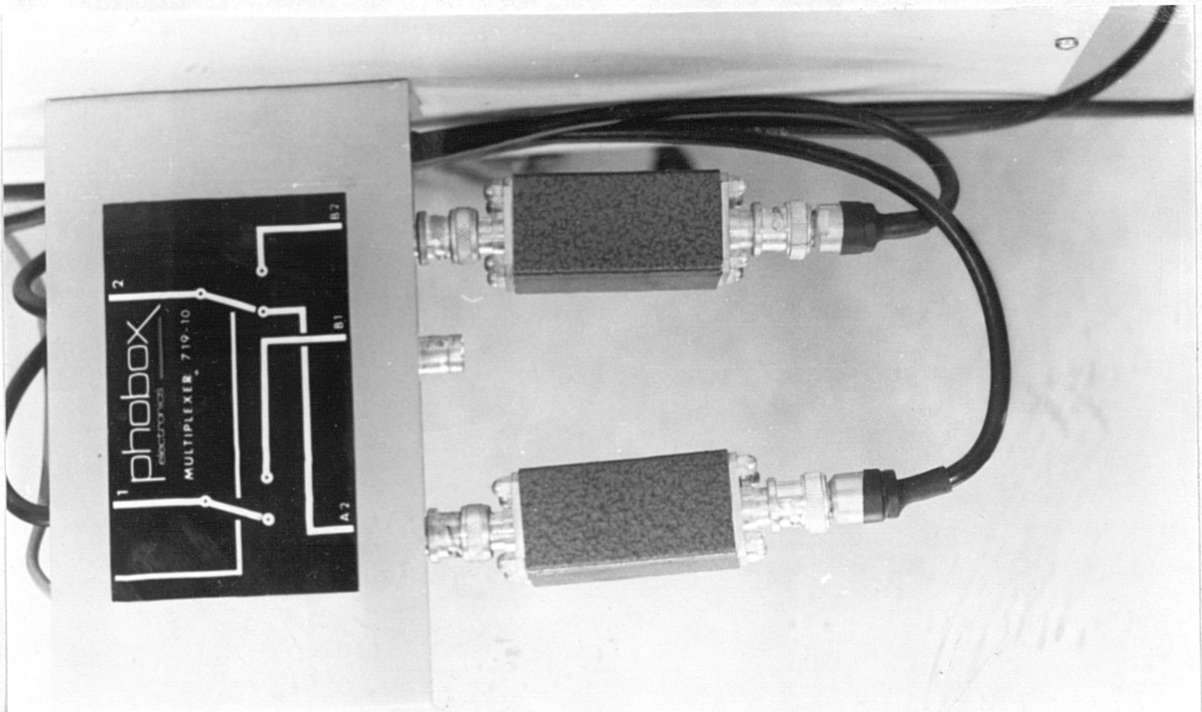


FIGURE 60. ULTRASONIC SENSORS MULTIPLEXOR.

FIGURE 61. VIDEO MONITORING CAMERA AND ACCESSORIES.

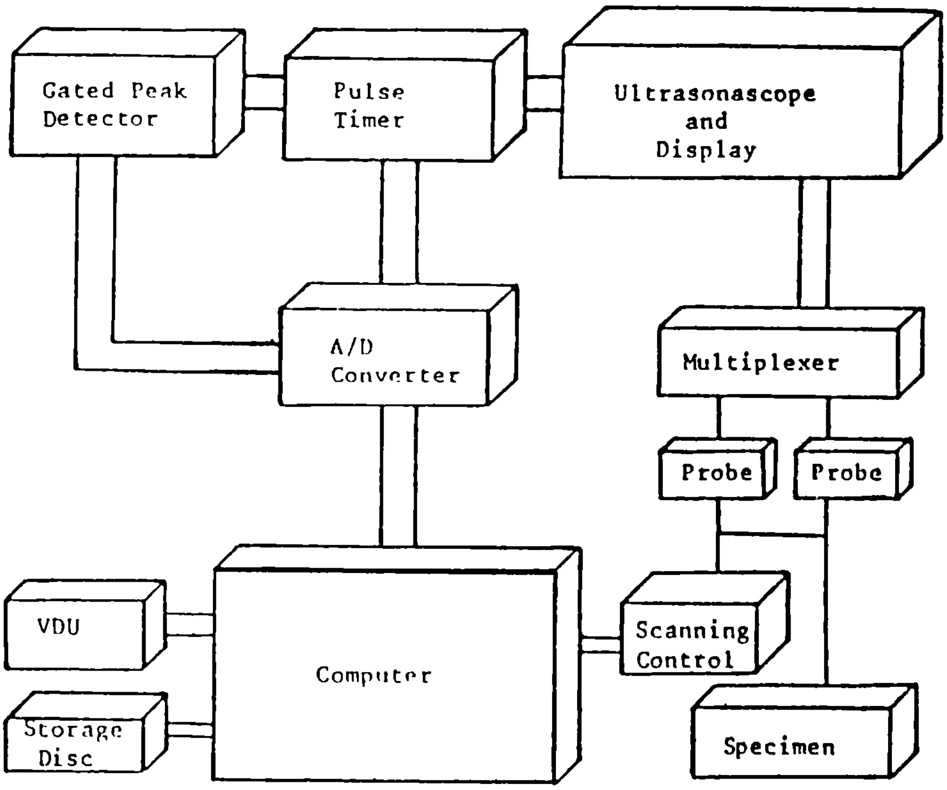


FIGURE 62. ULTRASONIC EDGE CHARACTERISATION COMPONENTS.

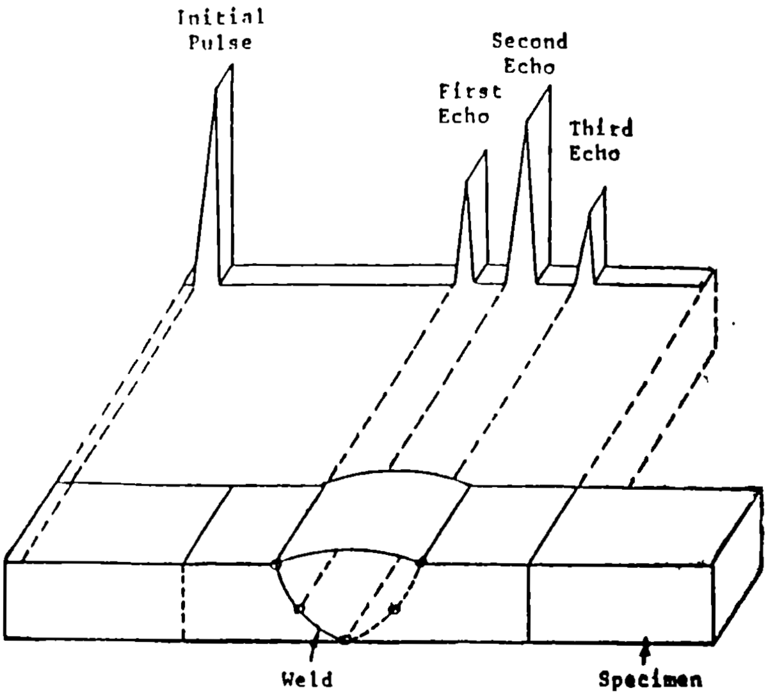


FIGURE 63. ULTRASONIC SENSORY SYSTEM'S OUTPUT:

INITIAL SIGNAL - EXCITATION PULSE.
1ST ECHO - QUALITY INDICATION.
2ND ECHO - PENETRATION INDENTIFICATION.
3RD ECHO - SEAM CHARACTERISATION.

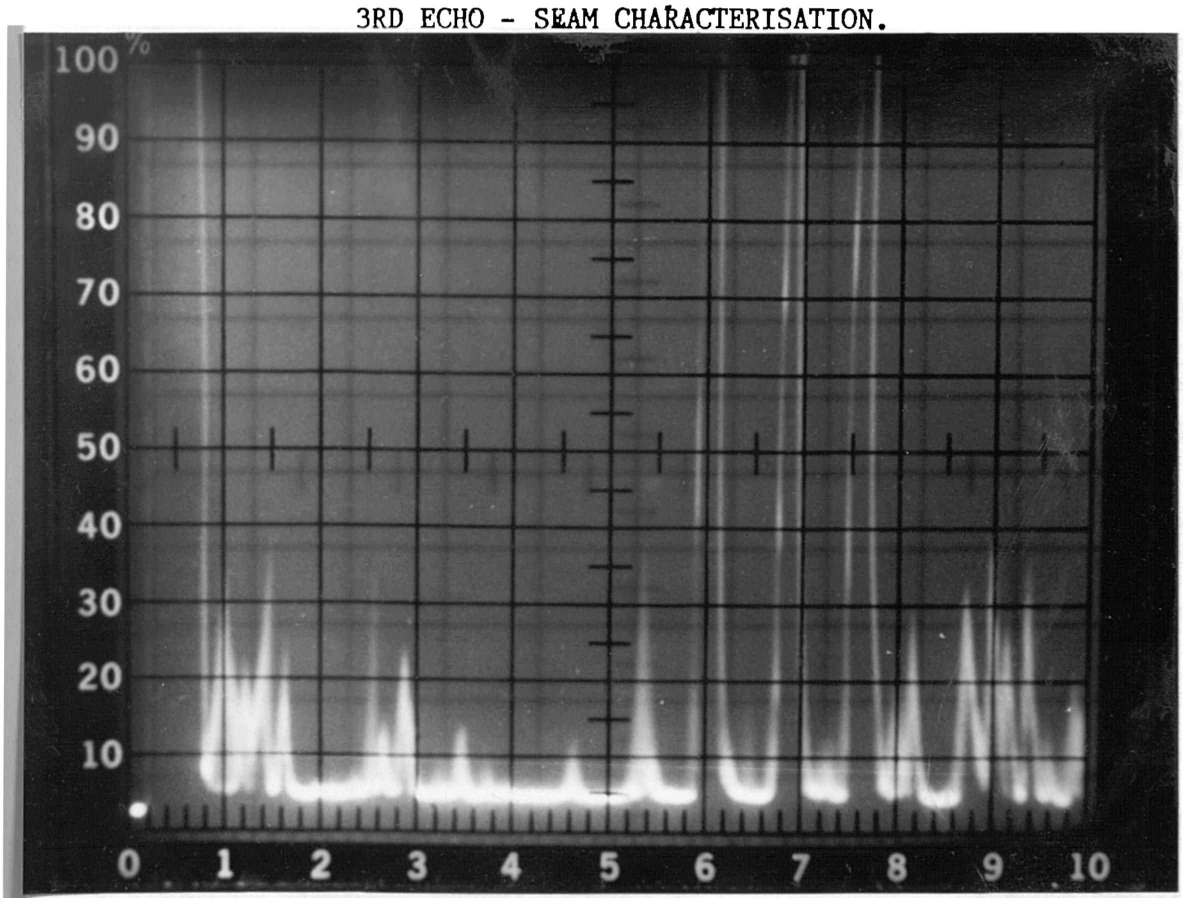


FIGURE 64. SIGNALS DISPLAY DURING SCANNING.

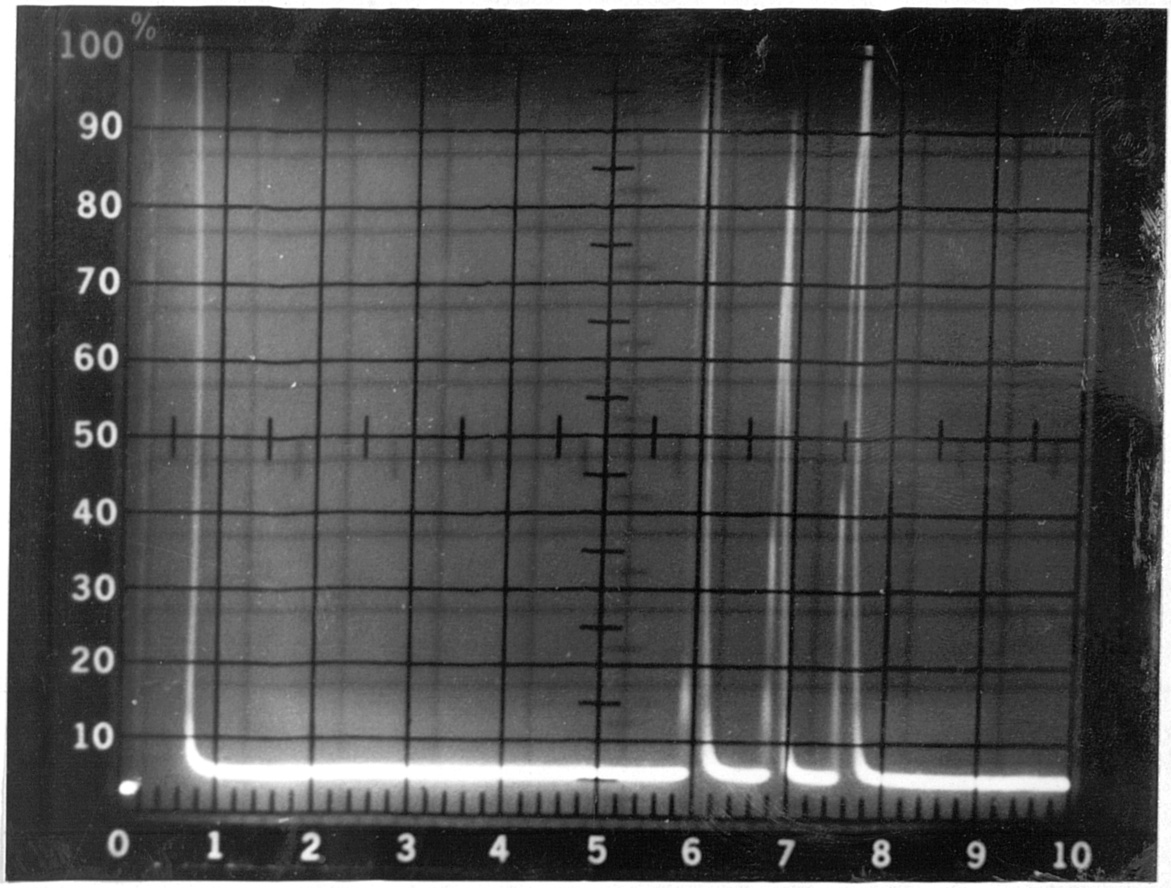


FIGURE 65. REFERENCE SIGNALS.

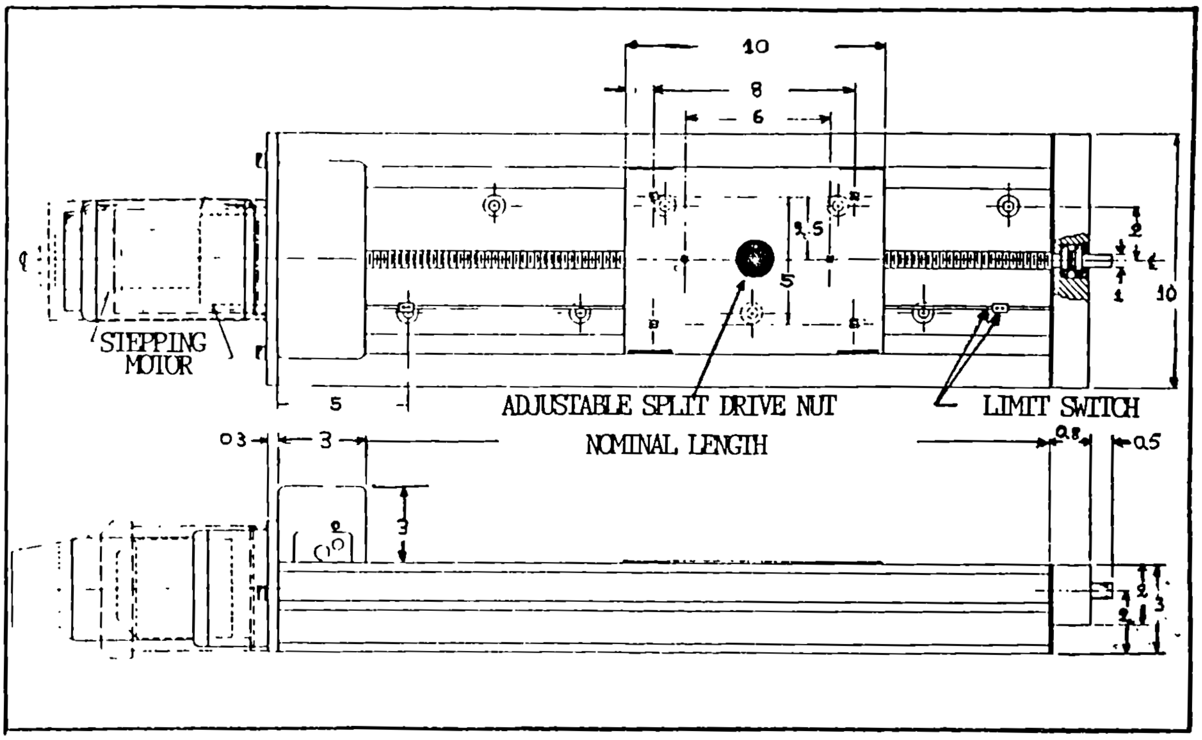


FIGURE 66. ULTRANSONIC SCANNER UNIT.

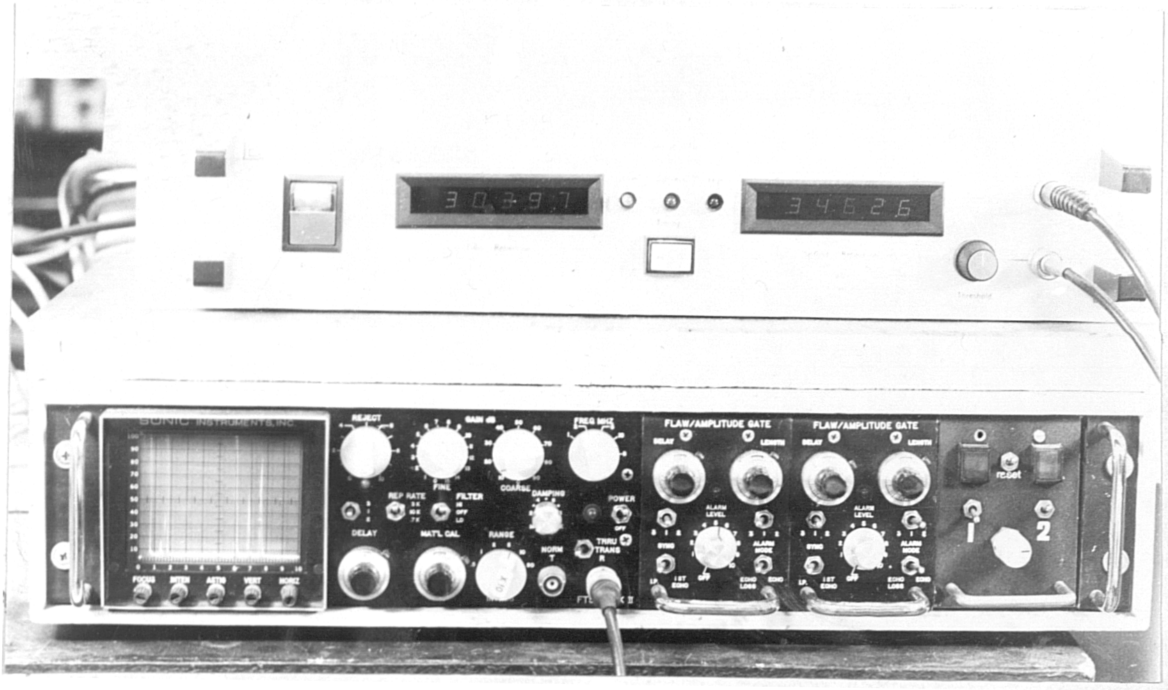


FIGURE 67. PROCESSED ULTRASONIC SIGNALS.

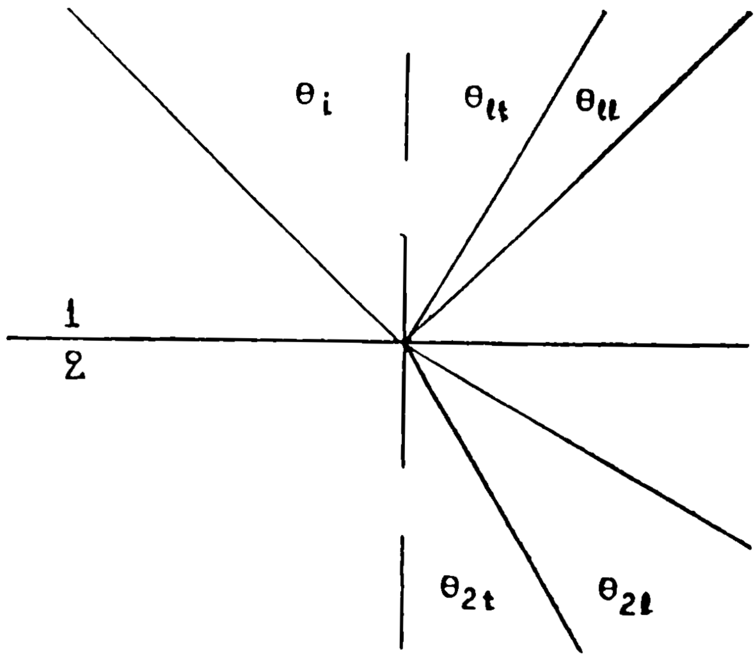


FIGURE 68. INCIDENT ULTRASOUND BEAM IN TWO MEDIA.

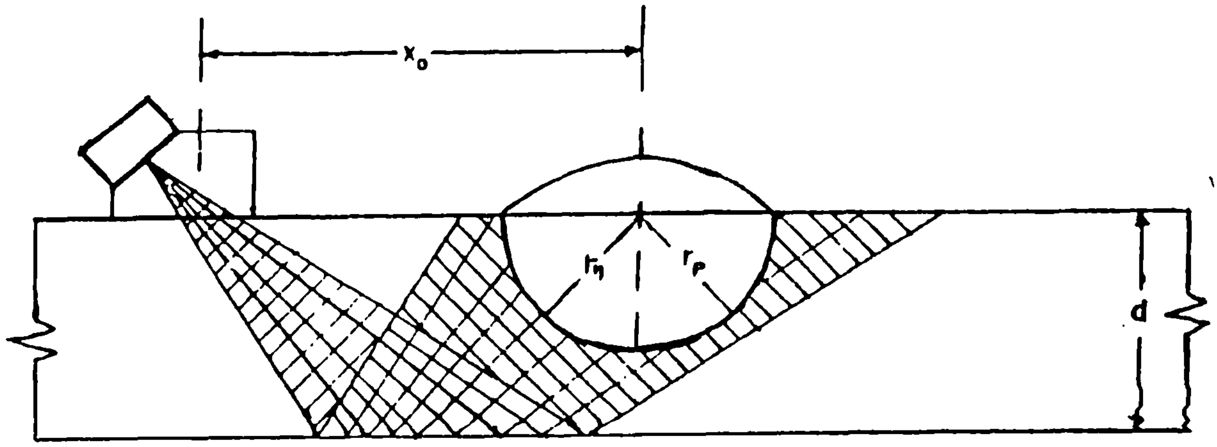


FIGURE 69. TEST PIECE, WELD BEAD AND SENSOR CONFIGURATION.

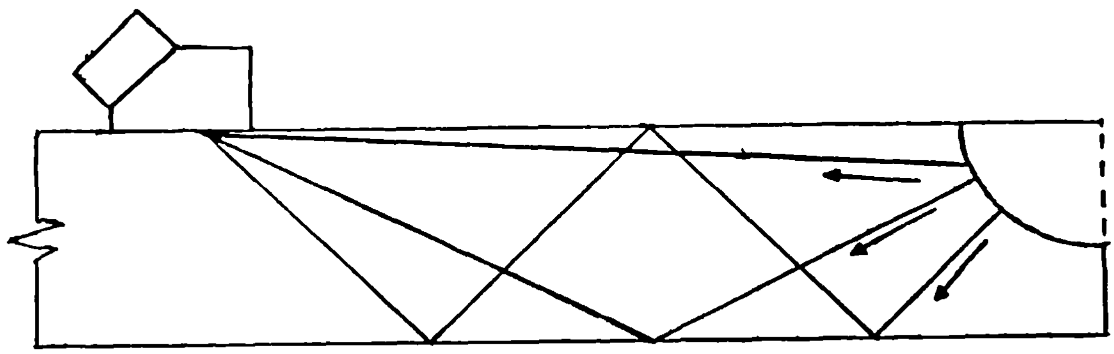


FIGURE 70. POSSIBLE ULTRASOUND RAY PATHS.

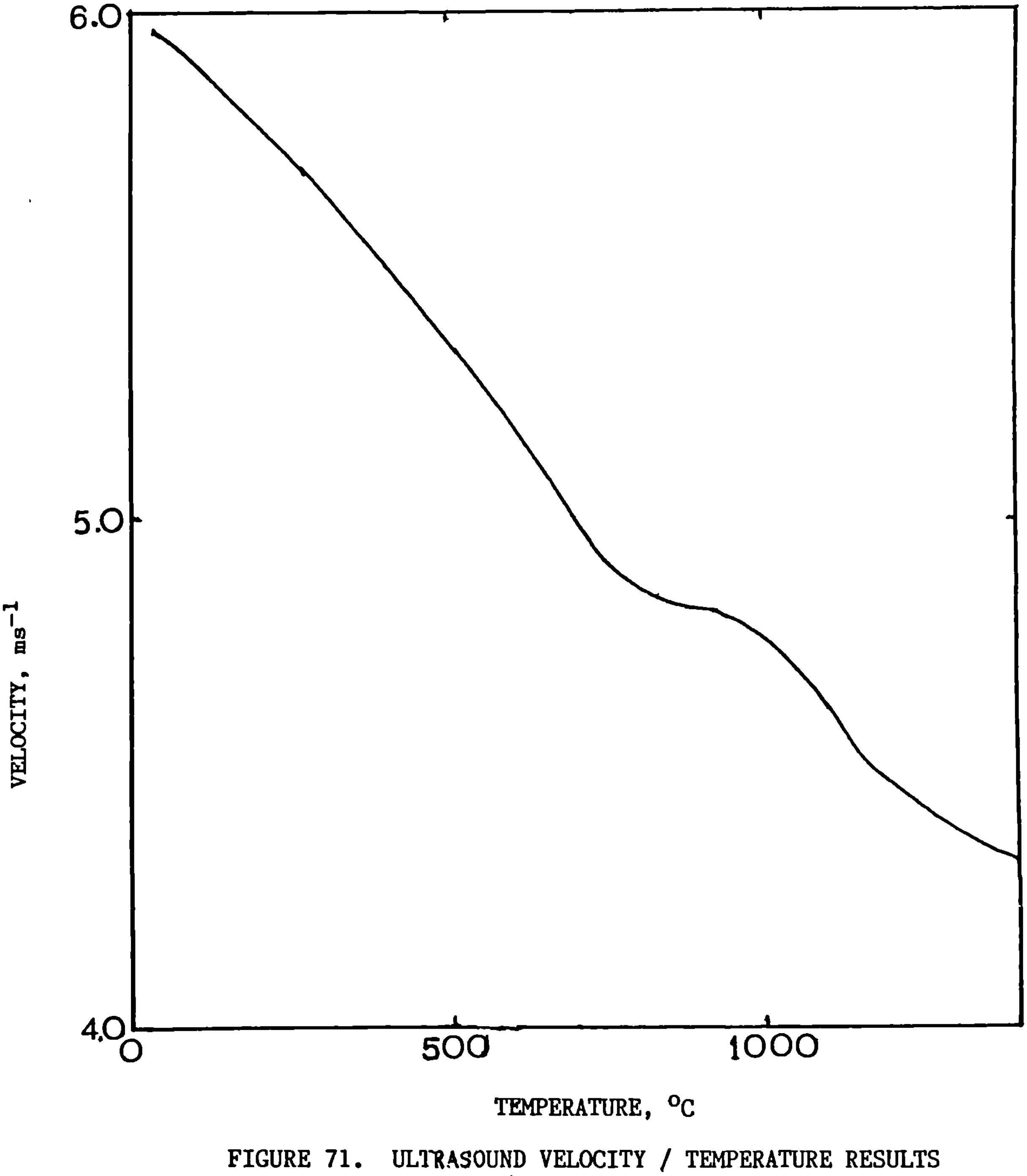


FIGURE 71. ULTRASOUND VELOCITY / TEMPERATURE RESULTS

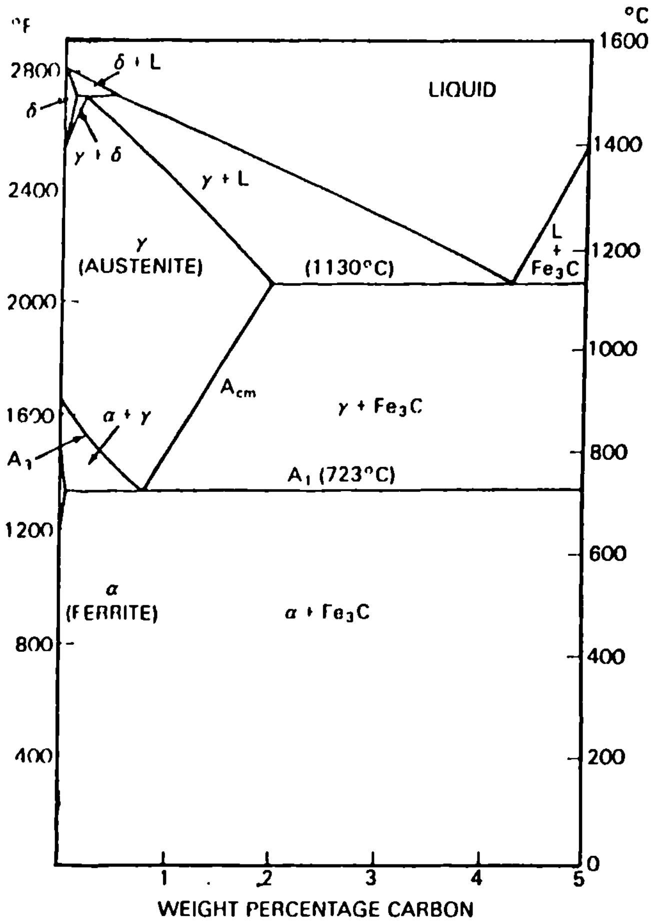


FIGURE 72. THE-IRON-CARBON PHASE DIAGRAM.

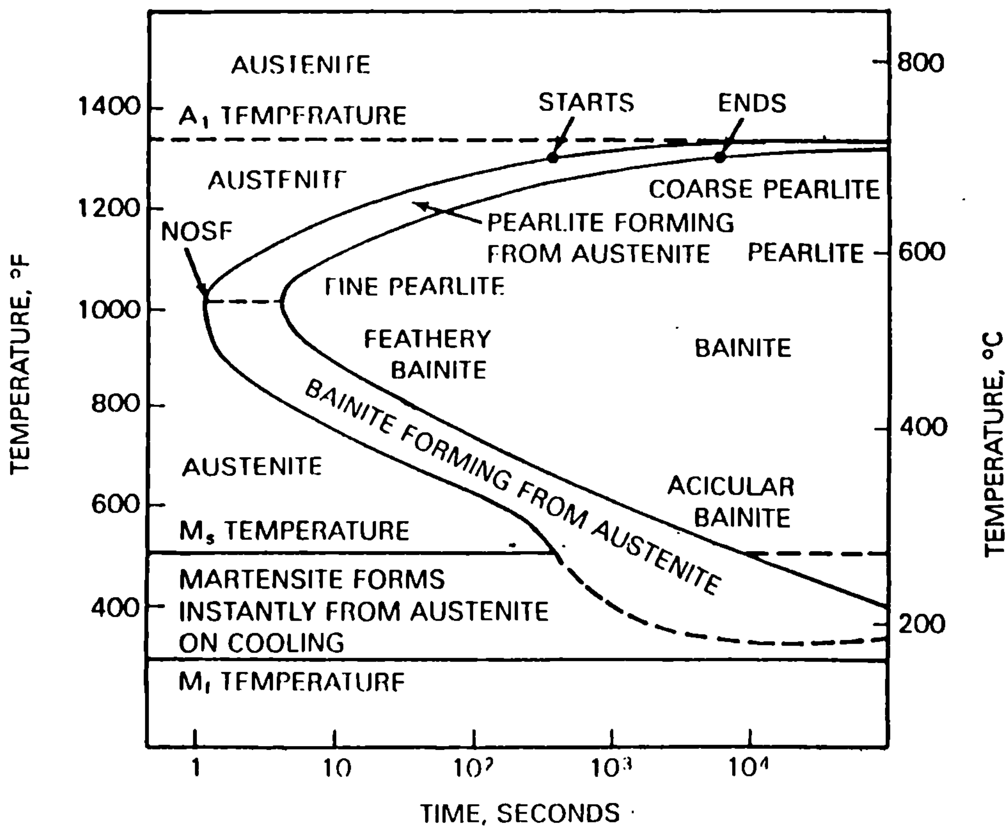


FIGURE 73. T.T.T. DIAGRAM OF EUTECTOID PLAIN CARBON STEEL.

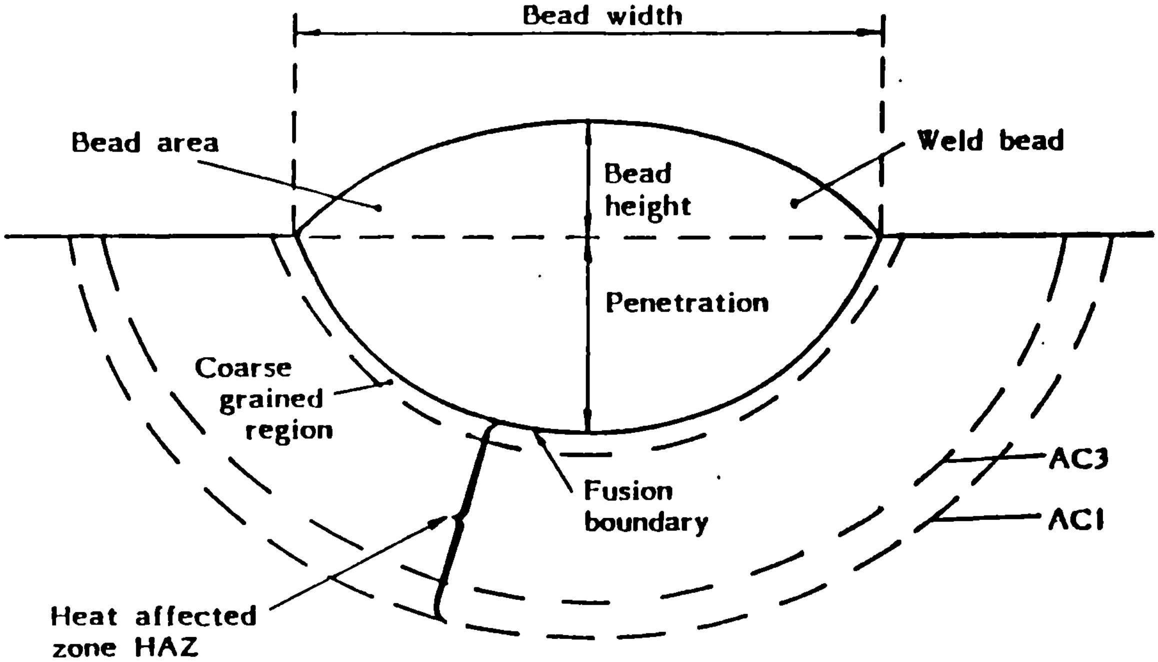


FIGURE 74. ISOTHERMS ACCORDING TO TEMEPRATURE GRADIENTS AROUND A WELD POOL.

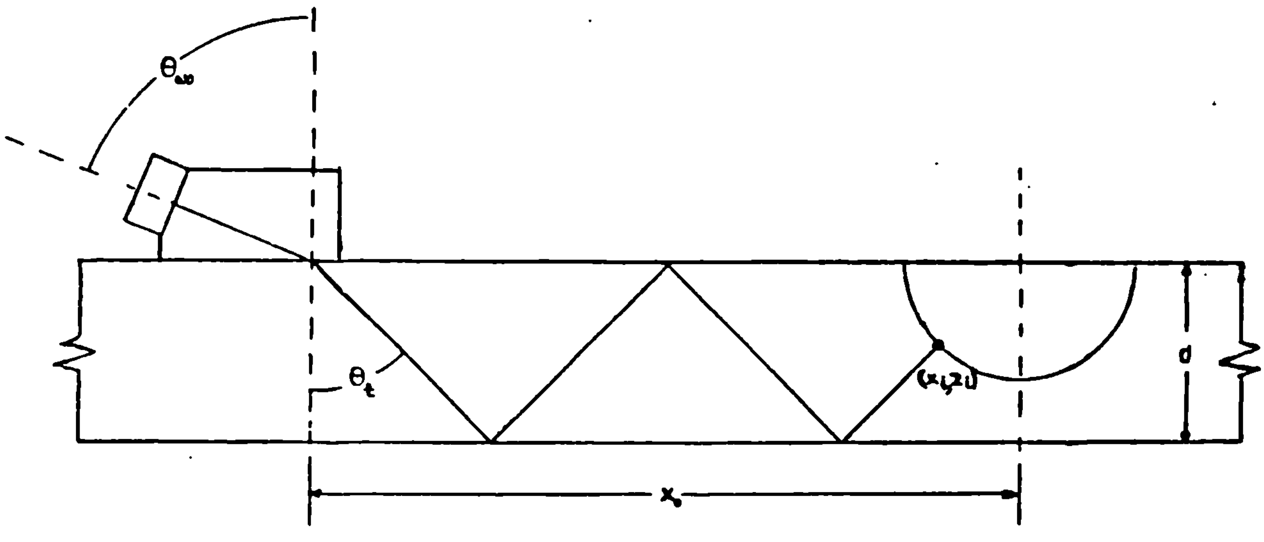


FIGURE 75. TRANSIT TIME OF "DEFECT" ESTIMATION.

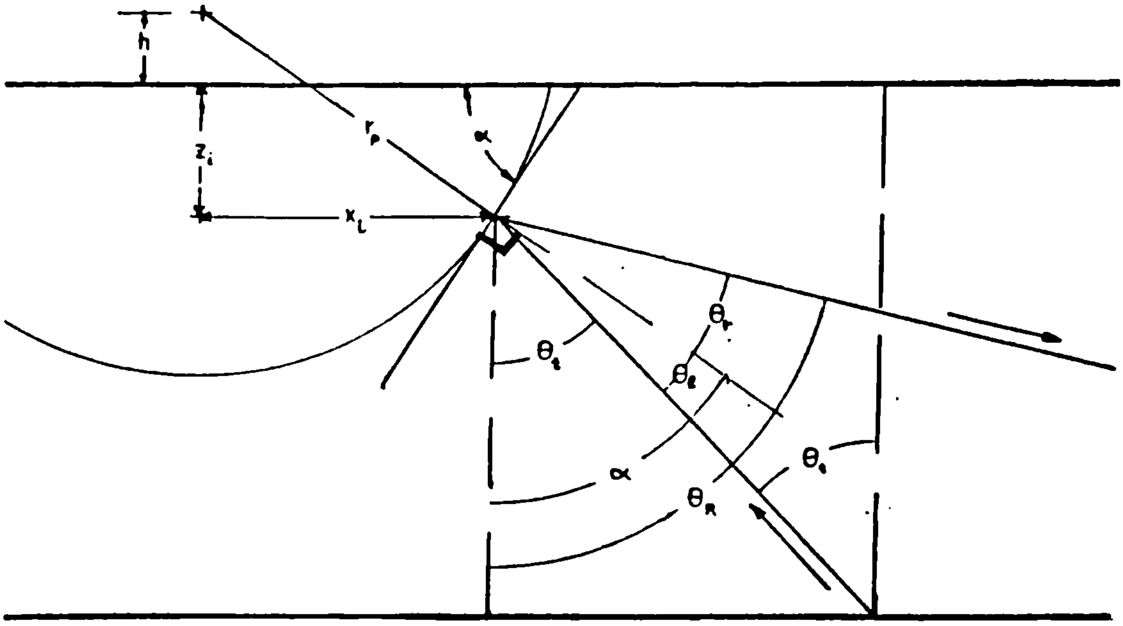


FIGURE 76. WELD POOL SURFACE DEFINITION.

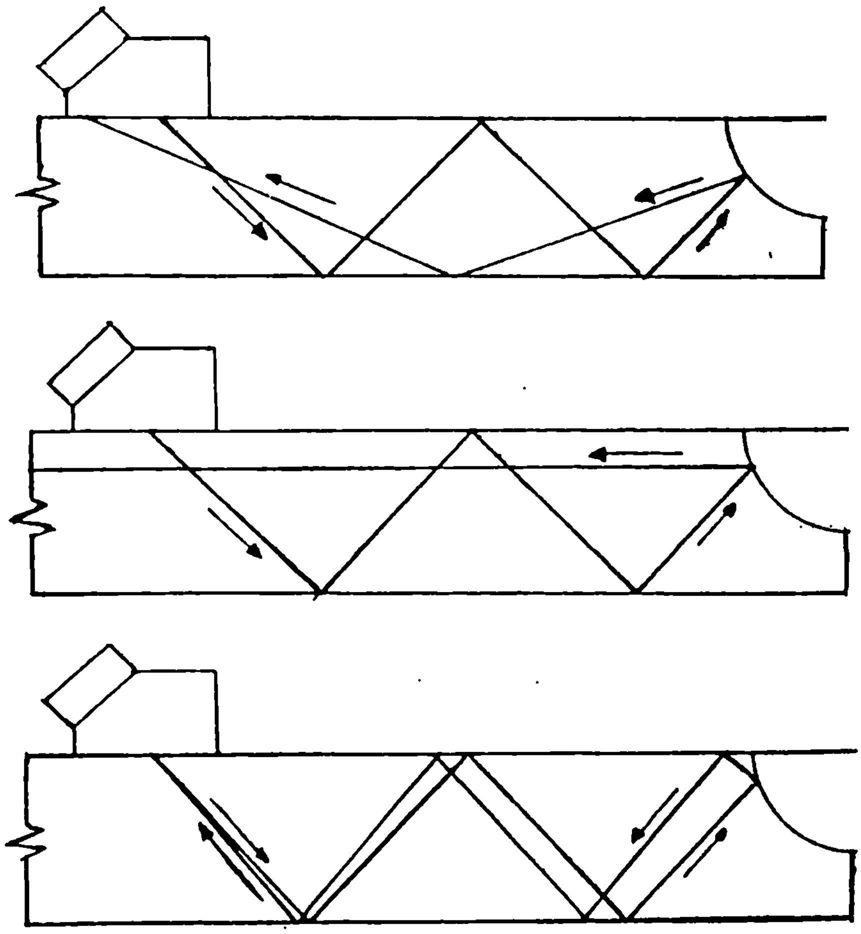
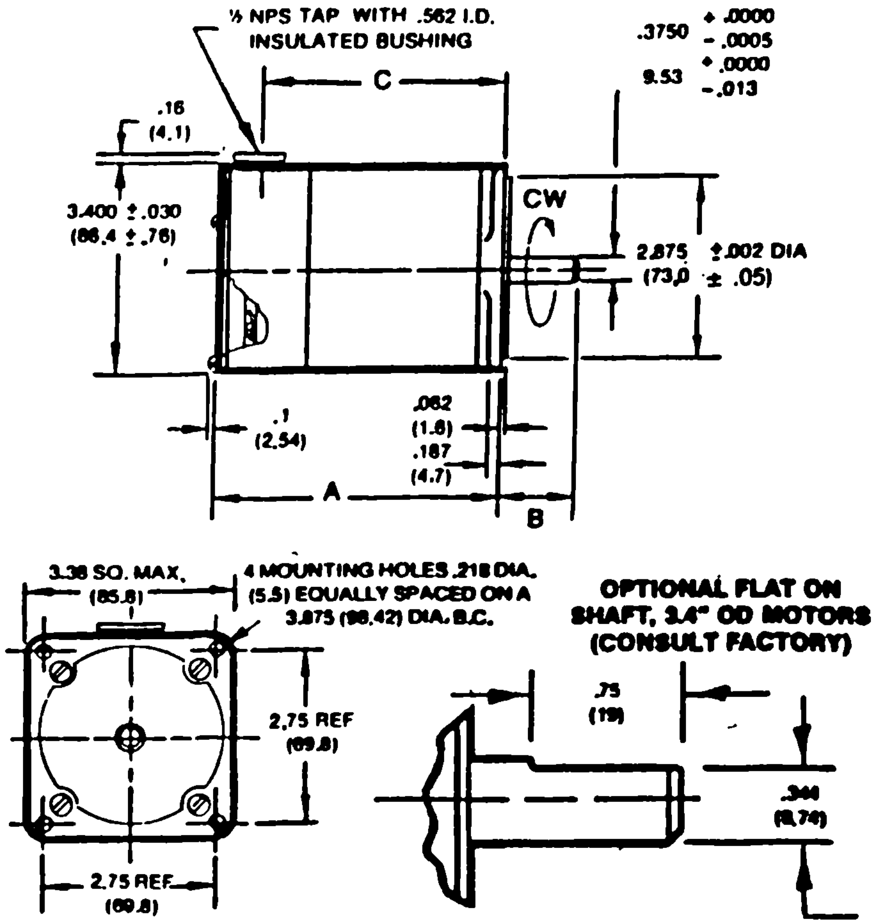


FIGURE 77. REFLECTED RAY PATHS:

A) $\theta_R < 0$
B) $\theta_R = 0$
C) $\theta_R > 0$



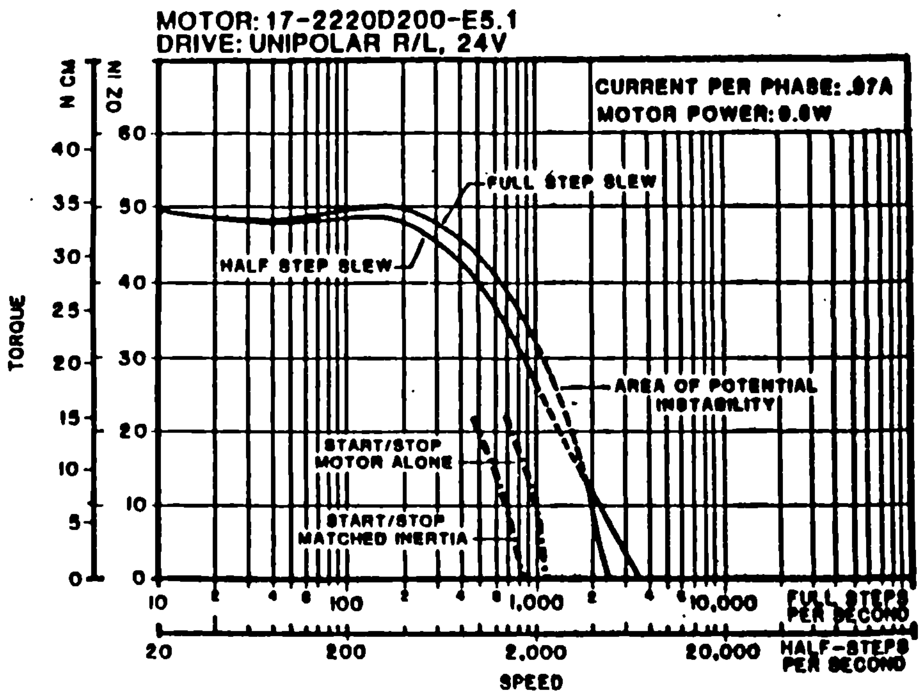


FIGURE 78. STEPPING MOTORS:

A) DIMENSIONS AND MECHANICAL DATA.

B) PERFORMANCE EVALUTION.

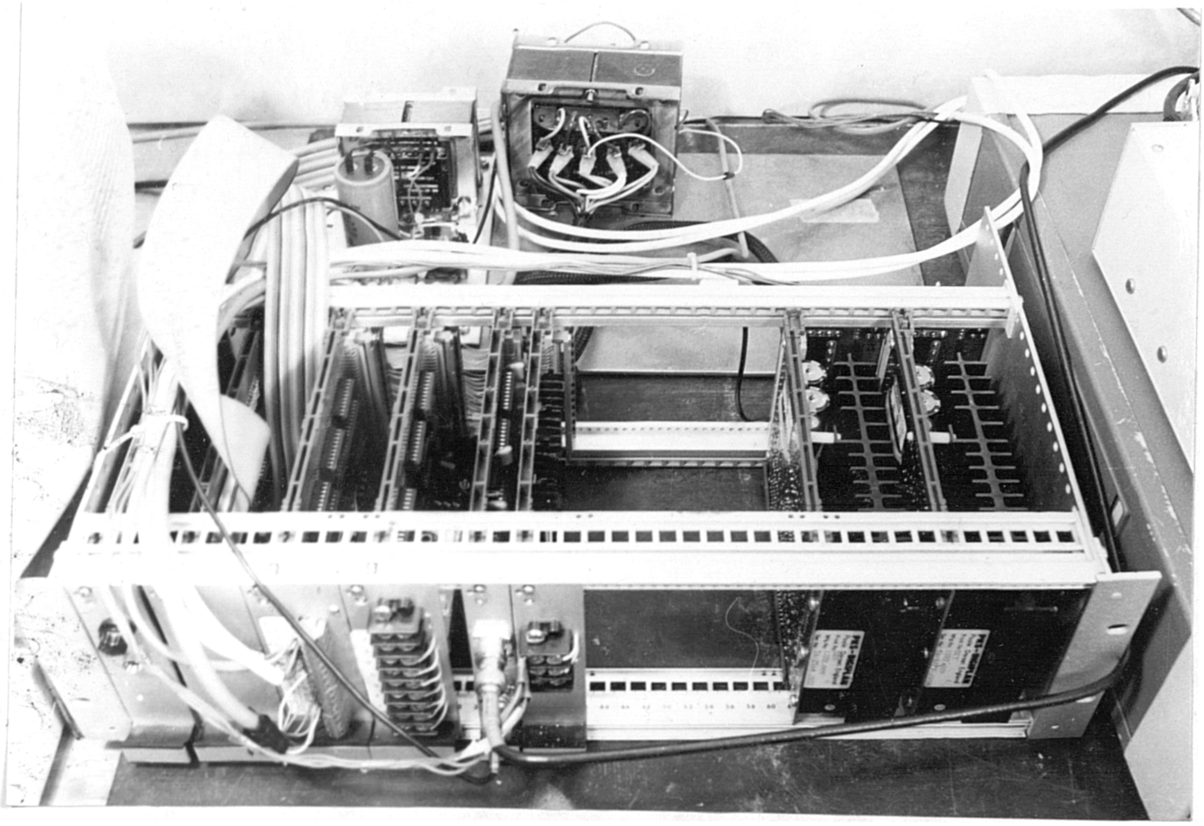


FIGURE 79. STEPPING MOTOR DRIVES AND POWER SUPPLIES.

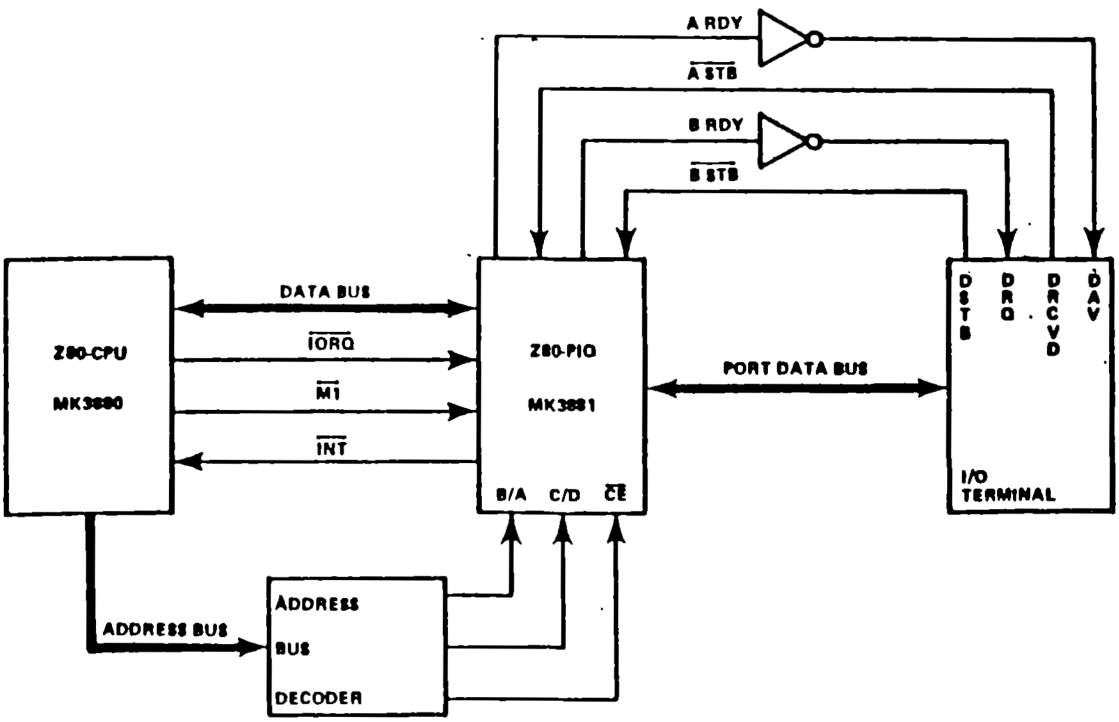


FIGURE 80. I.E.E.E. INTERFACE CAPABILITIES AND STRUCTURE.

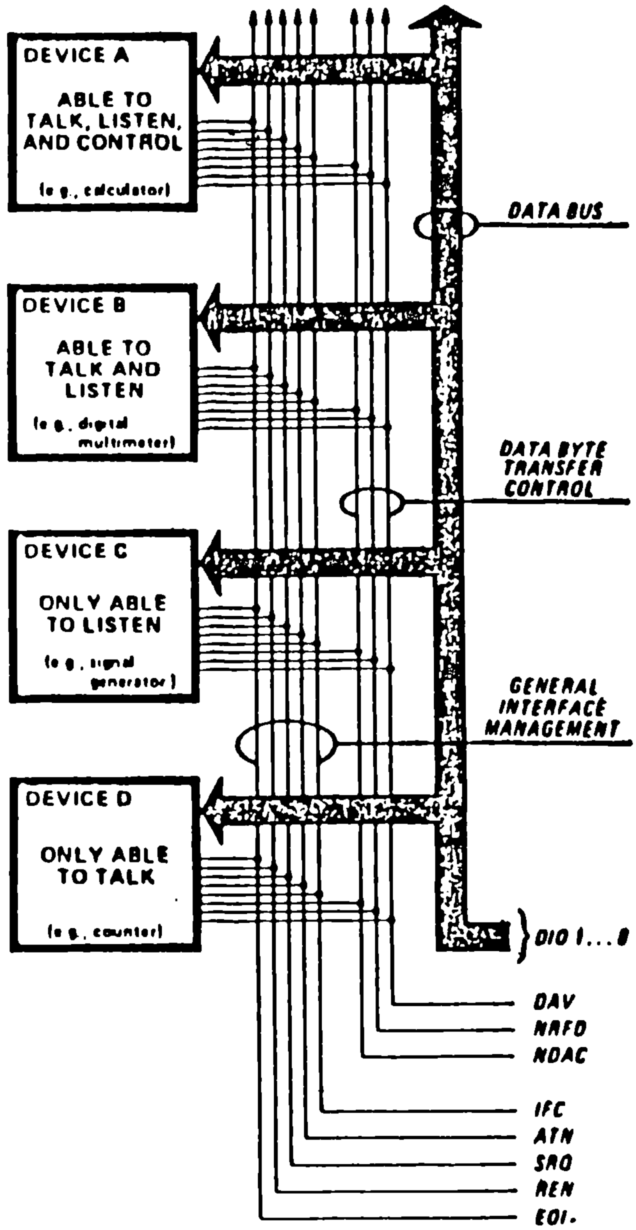


FIGURE 81. I.E.E.E. INTERFACE CONTROL FUNCTIONS.

W , H , P

A Desired values 16.9 , 1.79 , 4.25 mm.
Measured values 14.4 , 3.3 , 1.6 mm.

W , H , P

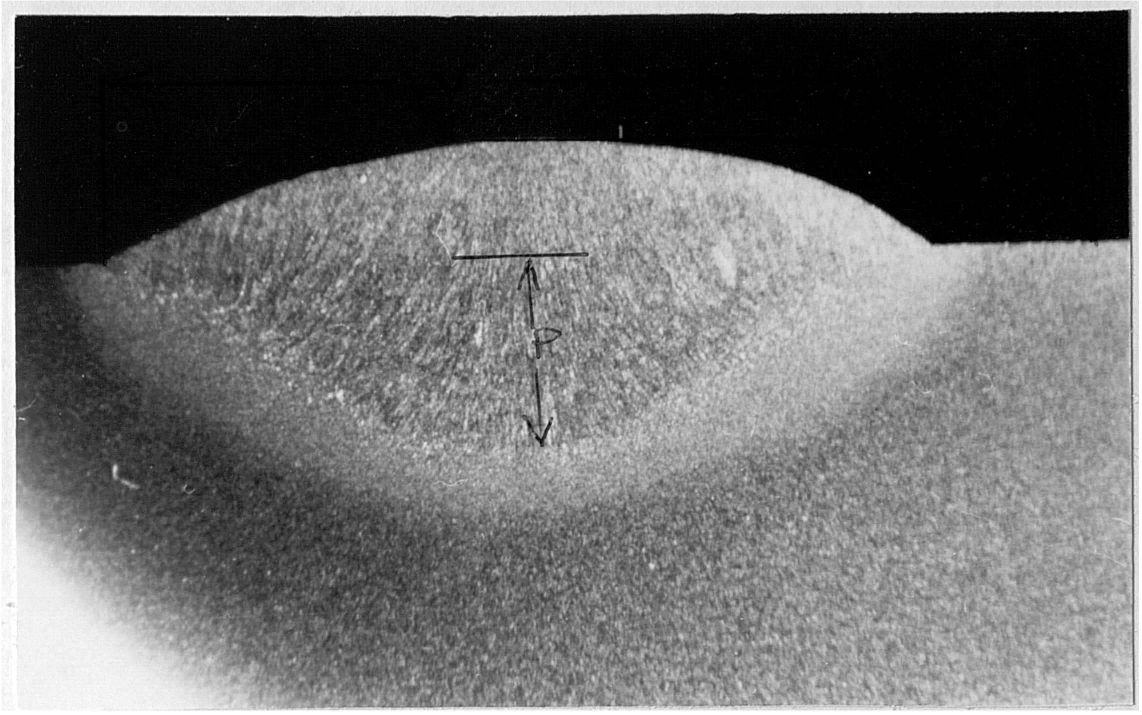
B Desired values 16.0 , 2.15 , 5.72 mm.
Measured values 14.5 , 4.53 , 2.0 mm.

C
O A DETERMINED BEAM PATH
O B ACTUAL BEAM PATH
(OA-OB IS DUE TO ULTRASOUND VELOCITY REDUCTION IN HAZ).

D
SYMETRICAL ULTRASOUND MEASURING OF WELD POOL
OA and O'B' MEASURED VALUES
OB ARE CORRECTED VALUES.

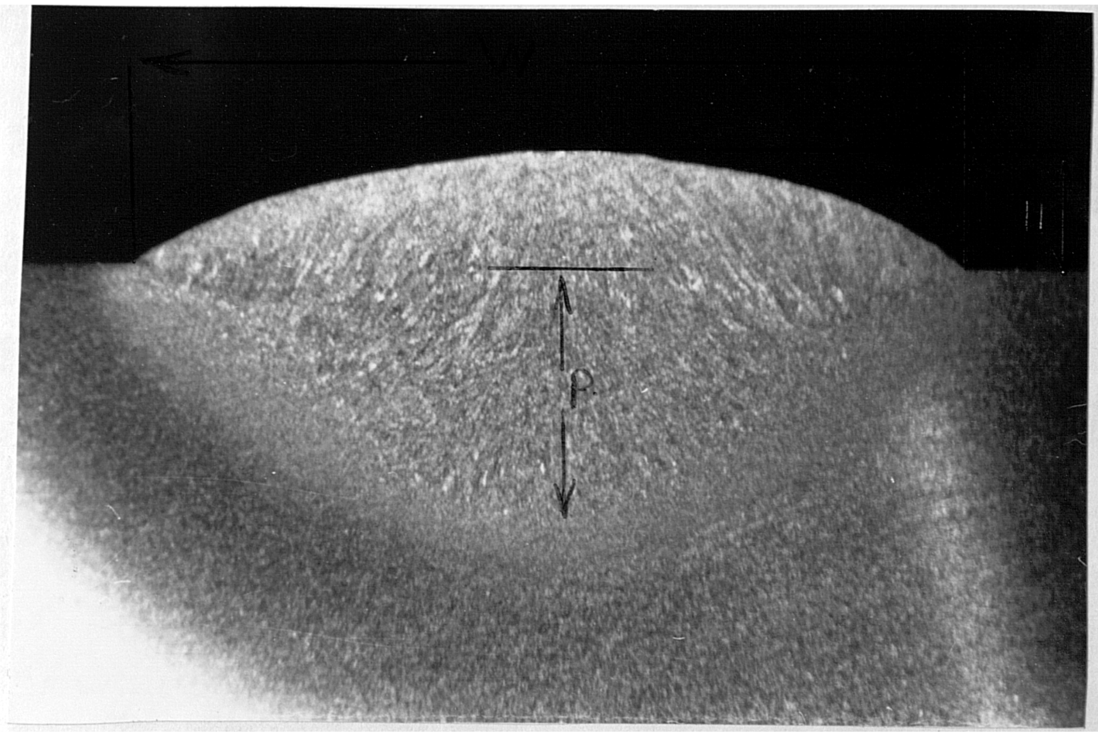
FIQURE 82. Macrosections illustrating weldpool determinants and established values (A,B) and ultrasound beam path lengths (C,D).

X7.5
app.

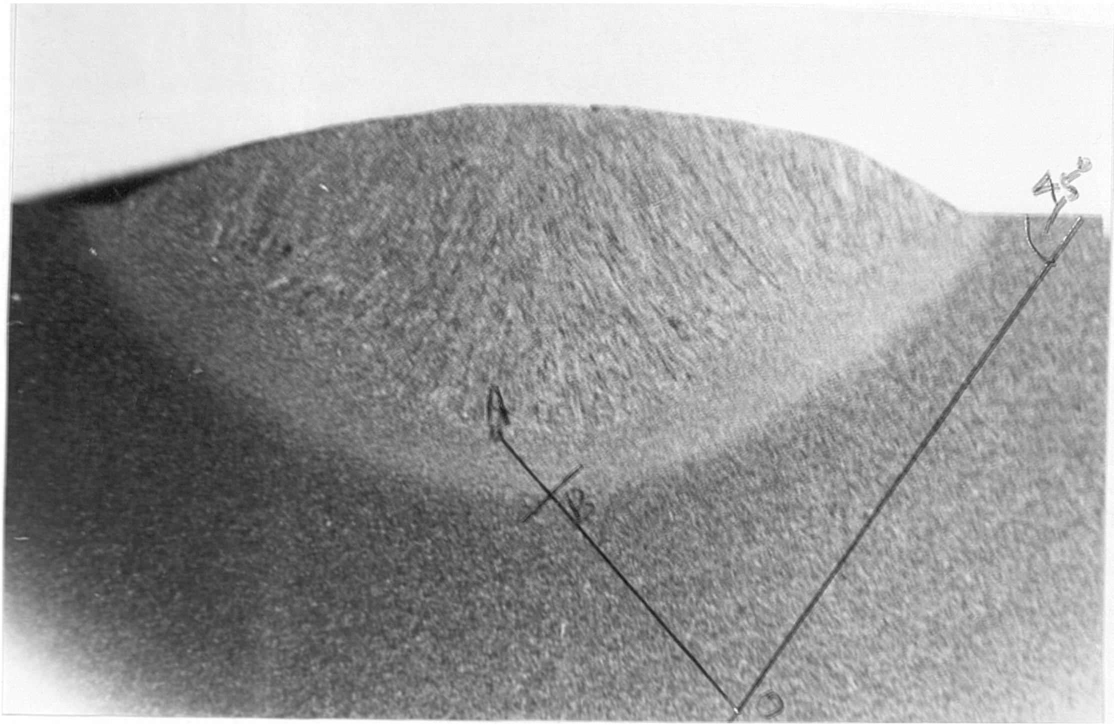


(A)

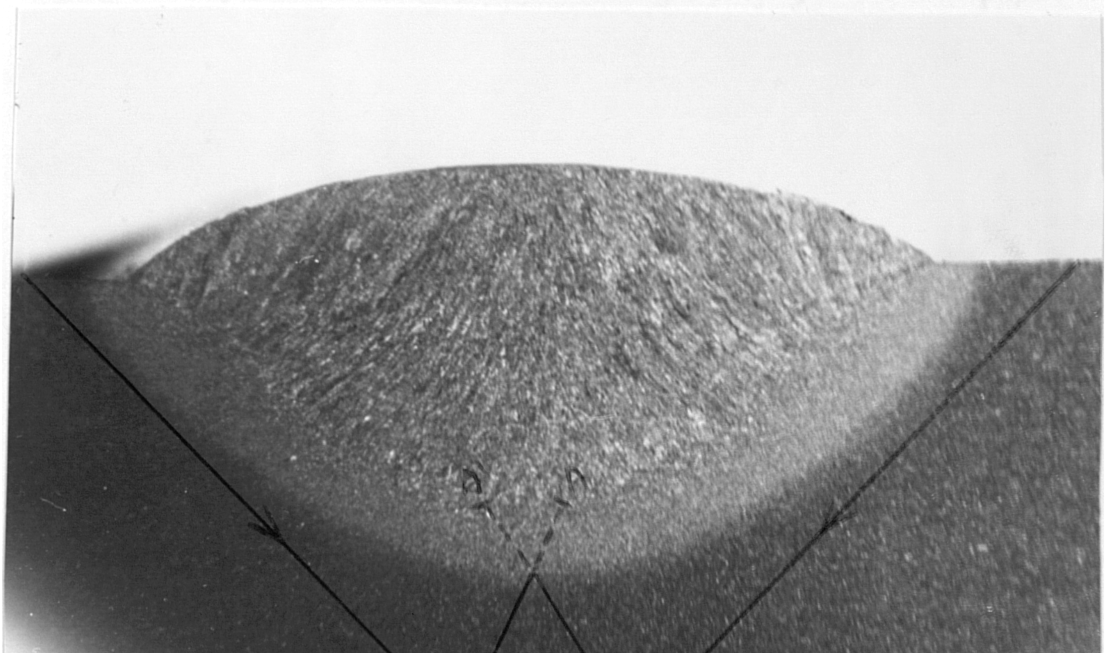
X7.5
app.



(B)



(C)



(D)

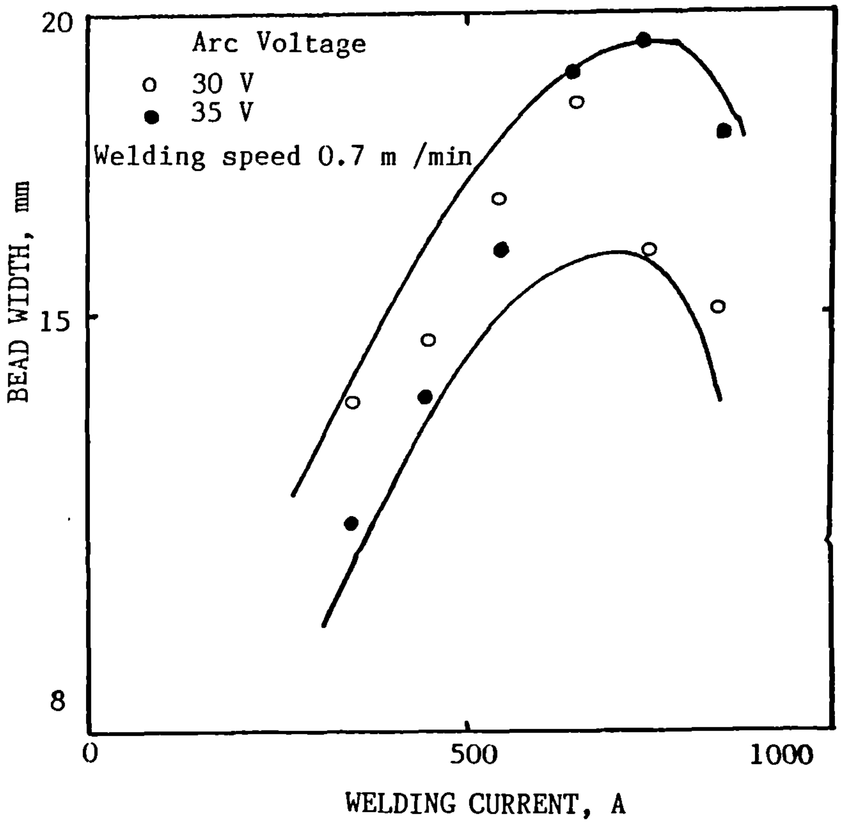


FIGURE 84. EFFECT OF WELDING CURRENT ON BEAD WIDTH.

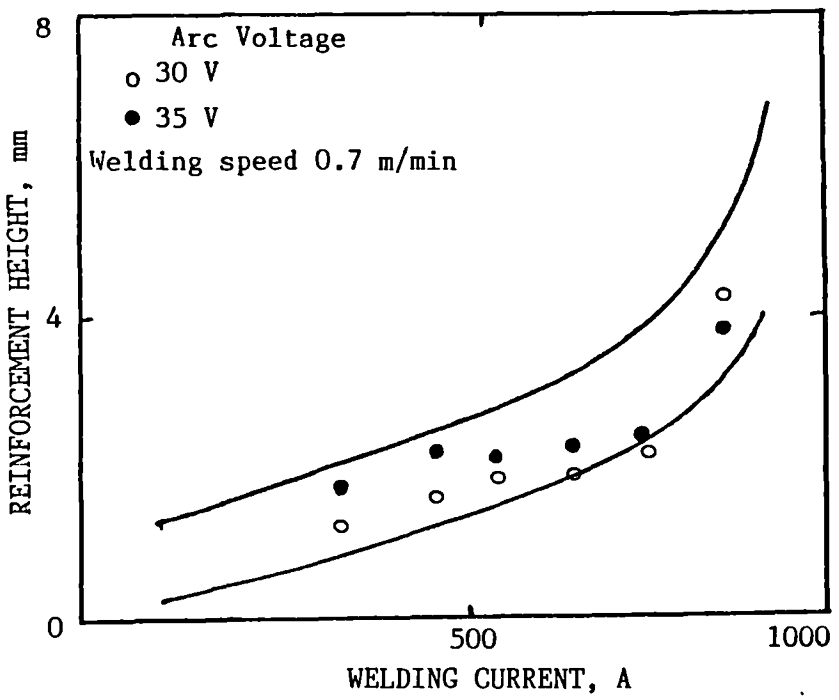


FIGURE 85. EFFECT OF WELDING CURRENT ON REINFORCEMENT HEIGHT.

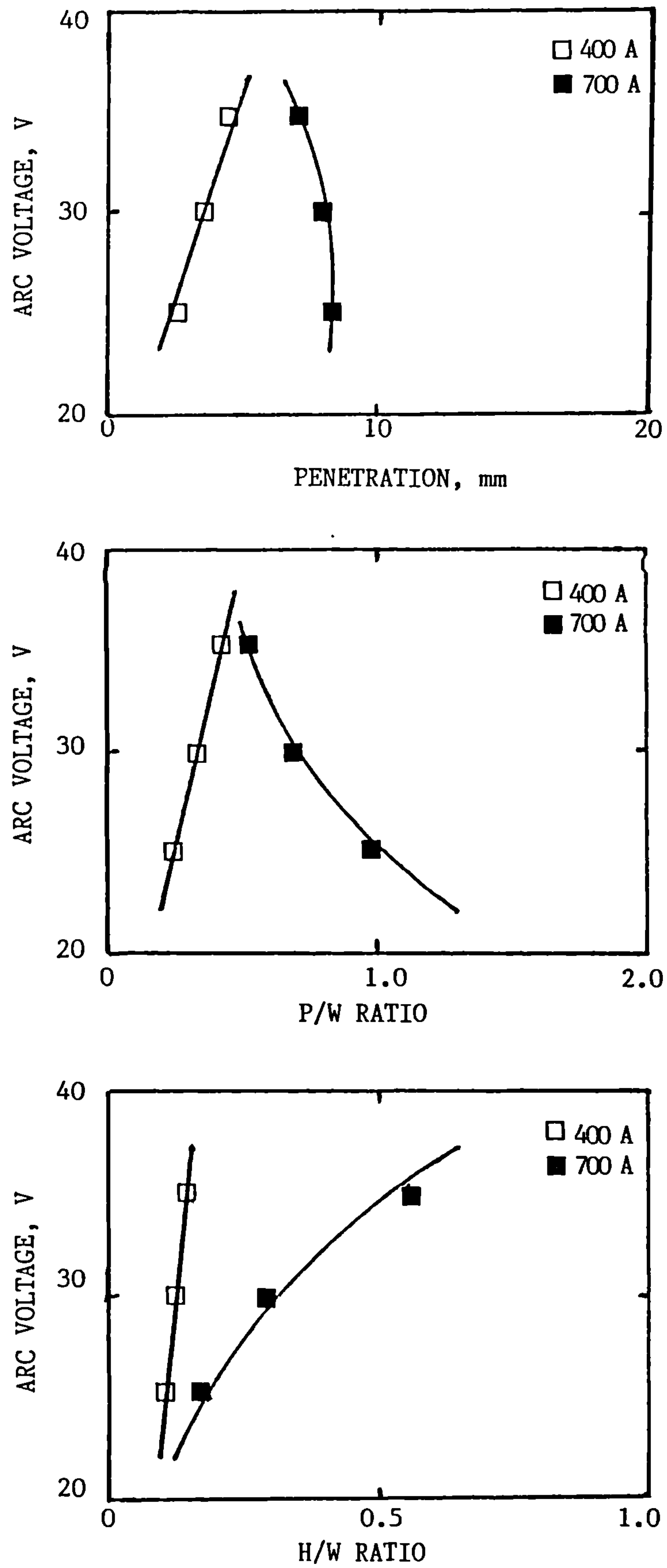


FIGURE 86. EFFECT OF ARC VOLTAGE ON:

A) WELD PENETRATION.
B) P/W RATIO.
C) H/W RATIO.

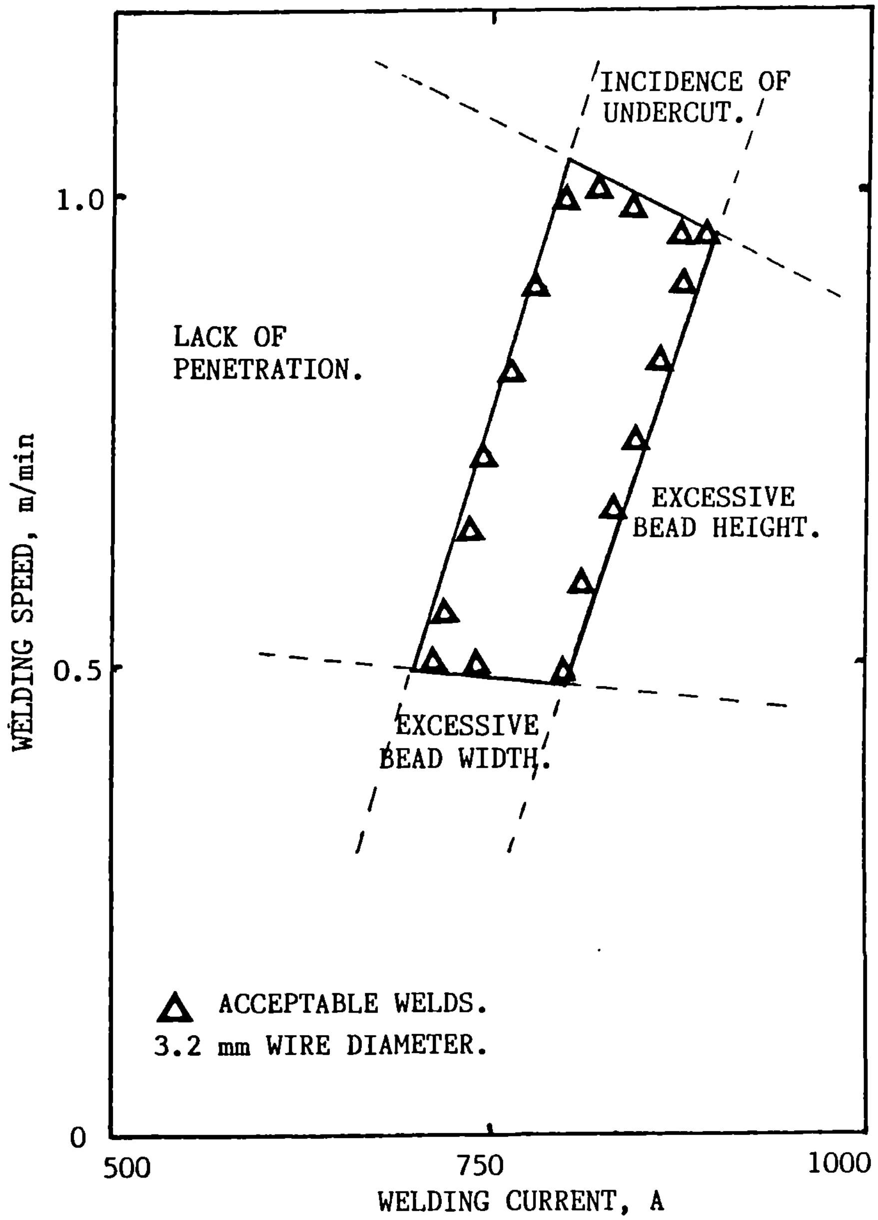


FIGURE 87. EFFECT OF WELDING SPEED ON:

A) WELD PENETRATION.

B) BEAD WIDTH.

C) REINFORCEMENT HEIGHT.

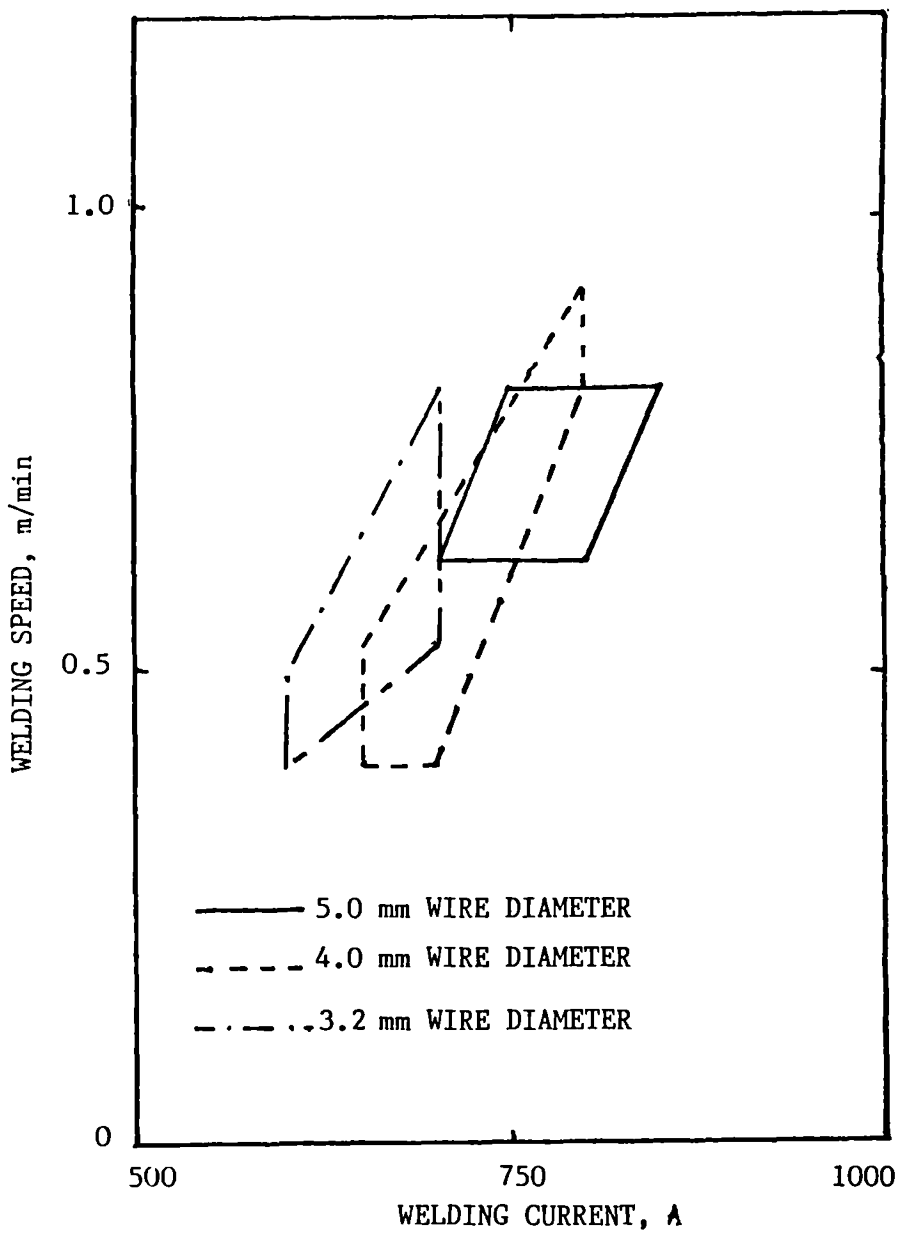


FIGURE 88. EFFECT OF WIRE DIAMETER ON:

A) WELD PENETRATION.
B) BEAD WIDTH.
C) REINFORCEMENT HEIGHT.

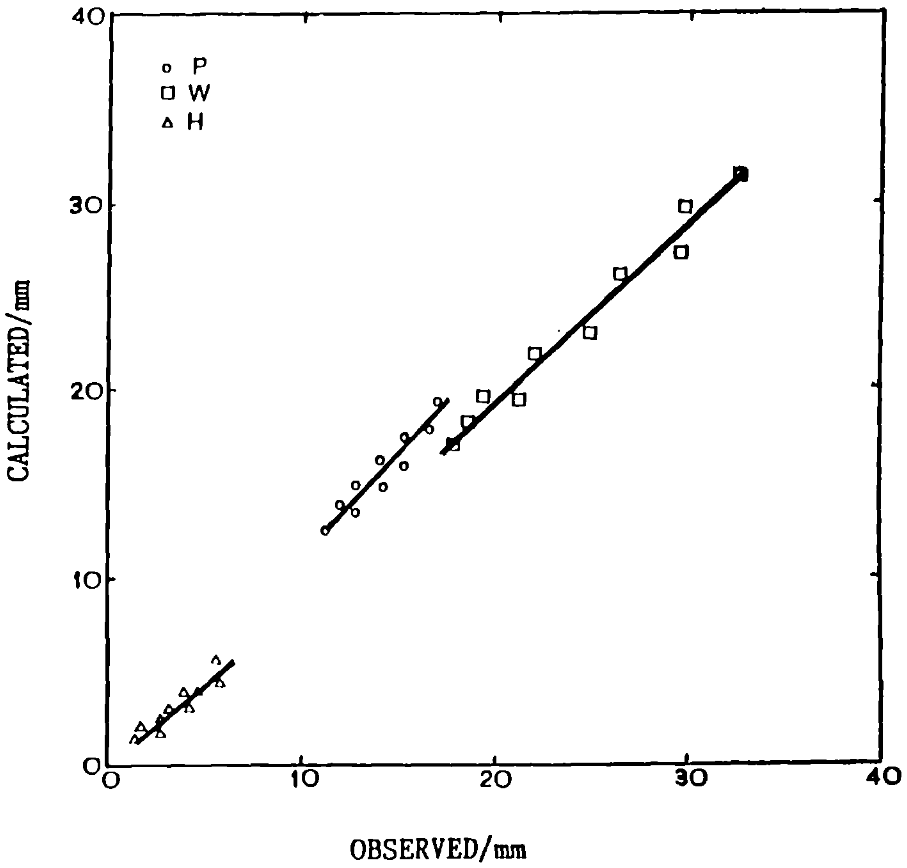


FIGURE 89. PREDICTED AND OBSERVED WELD BEAD DIMENSIONS.

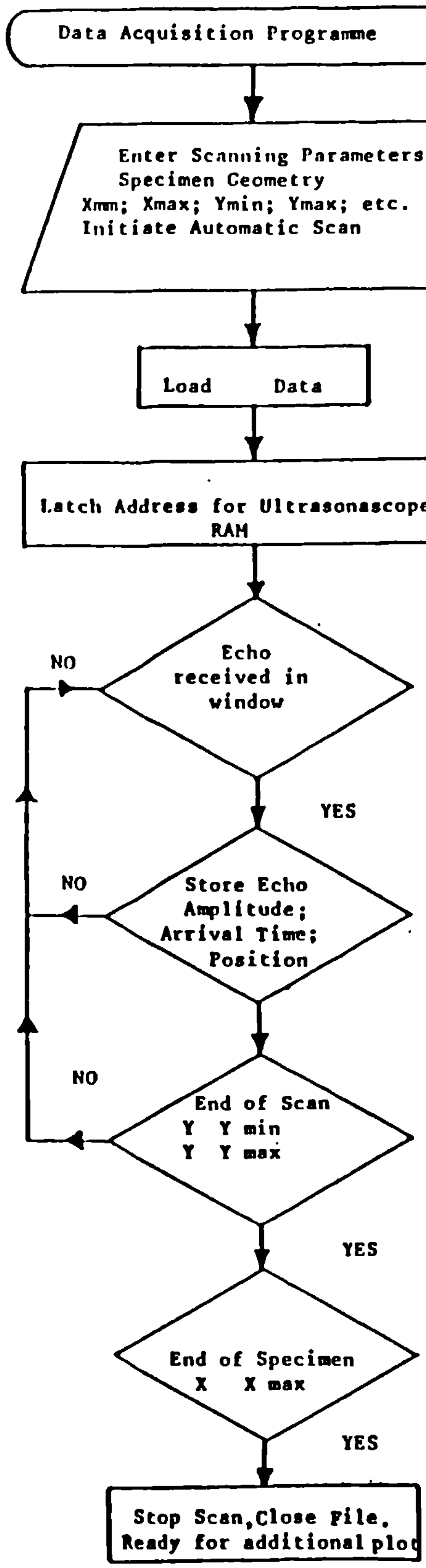


FIGURE 90. AUTOMATED ULTRASONIC DATA CONTROL ROUTINE.

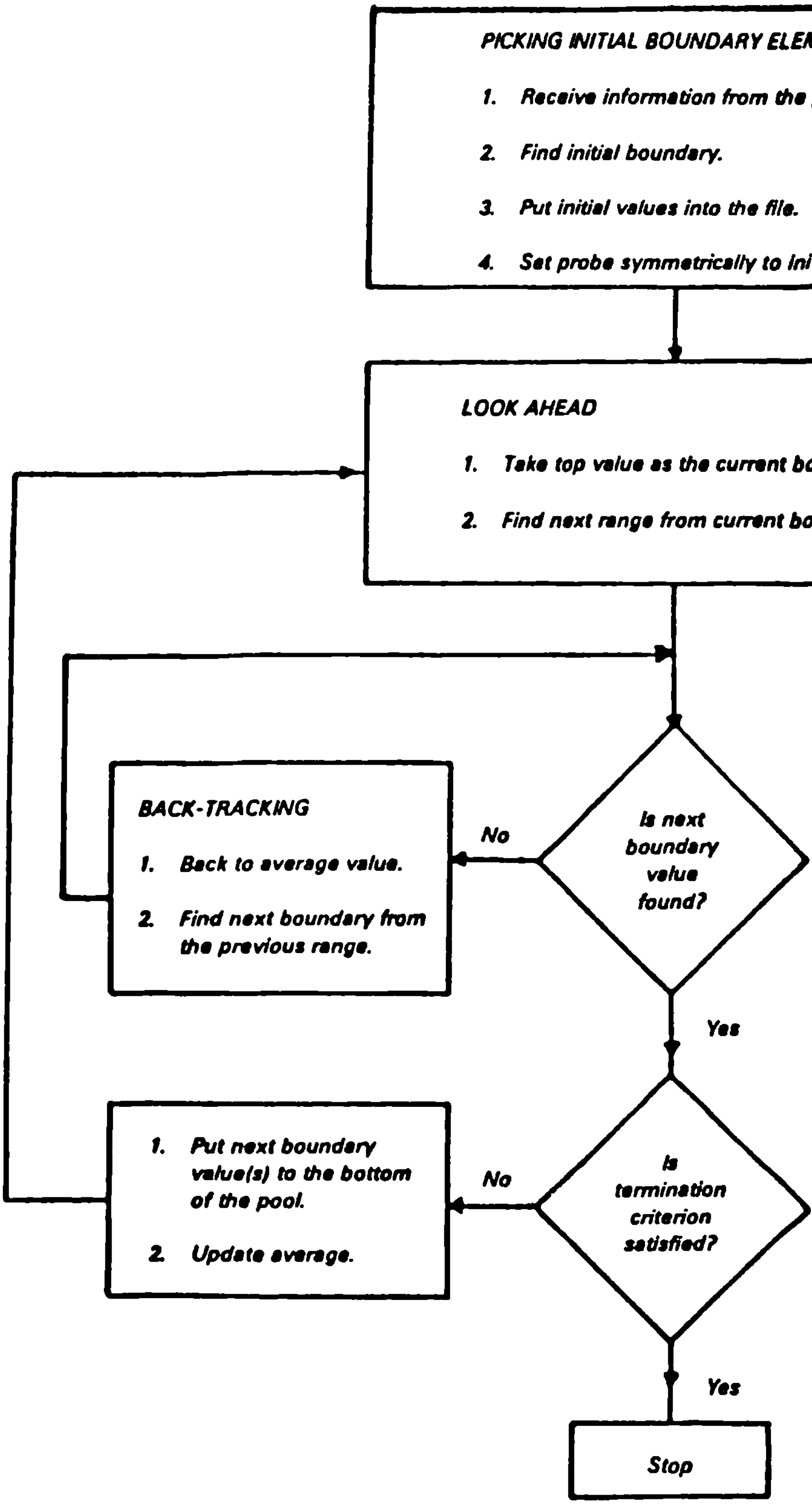


FIGURE 91. SEAM TRACKING DETECTION ALGORITHM.

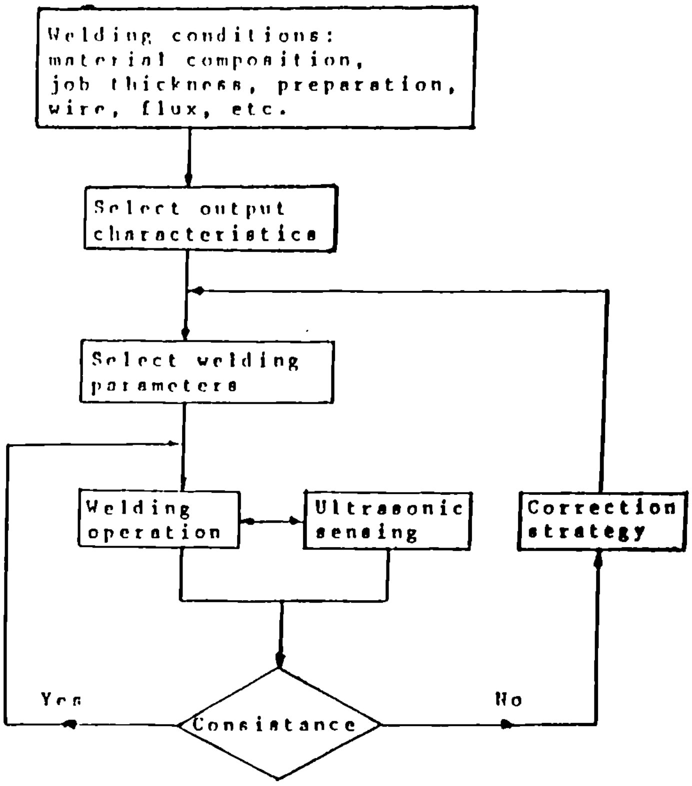


FIGURE 92. PENETRATION DETECTION ALGORITHM.

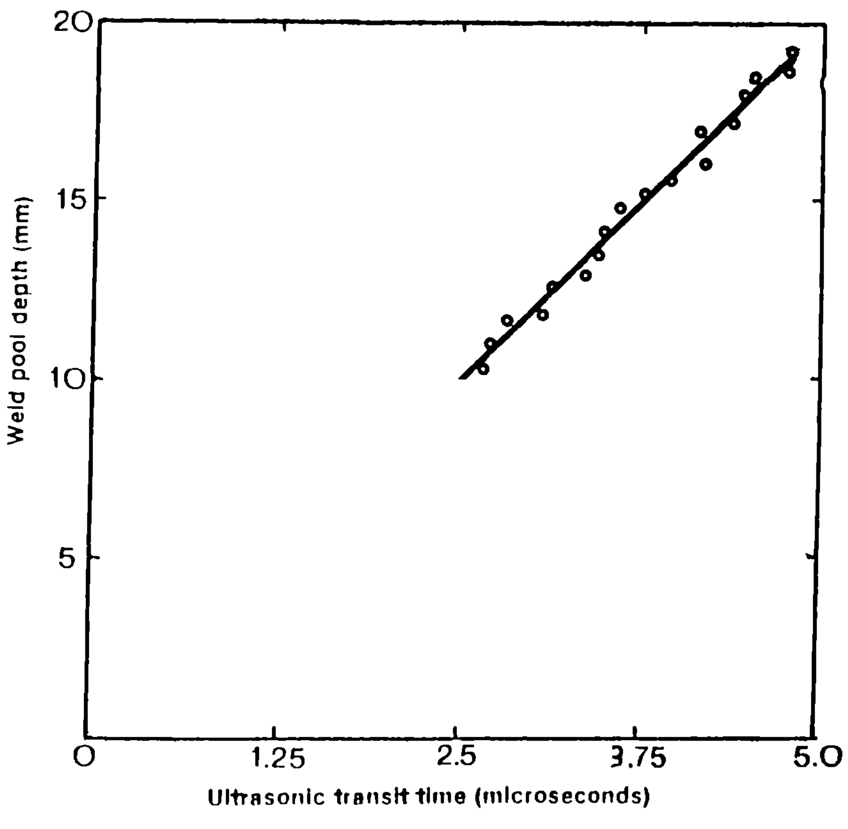


FIGURE 93. TIME-OF-FLIGHT / WELD POOL DEPTH RELATIONSHIP.

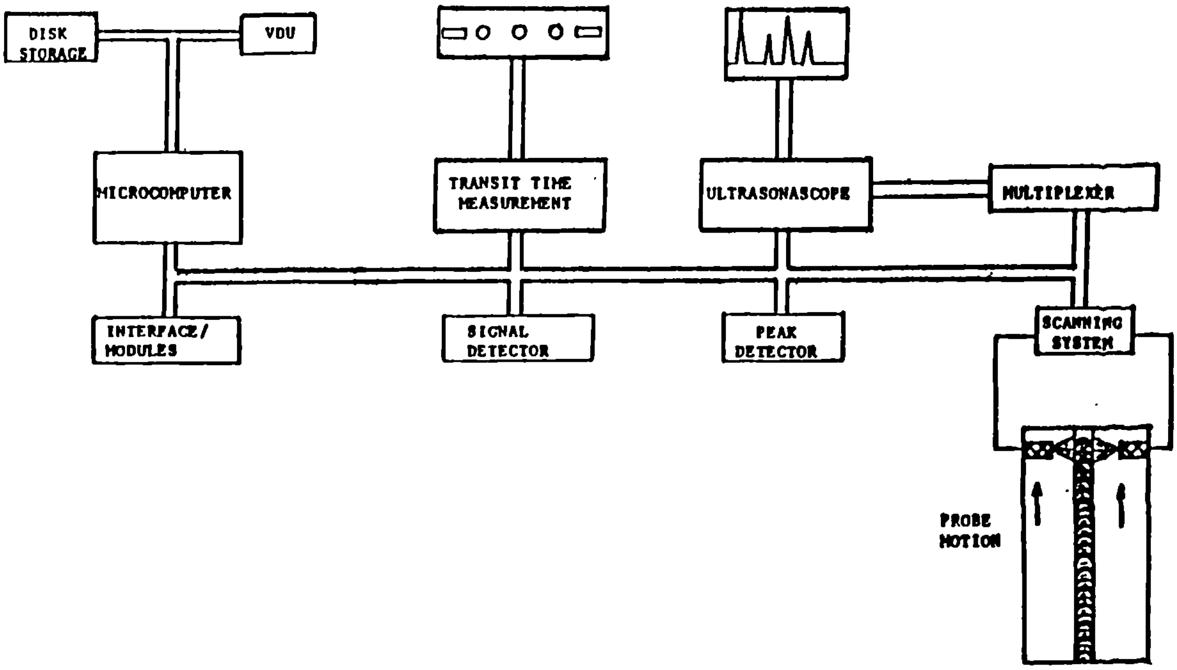


FIGURE 94. ROUTE FOR DATA COLLECTION AND MANIPULATION.

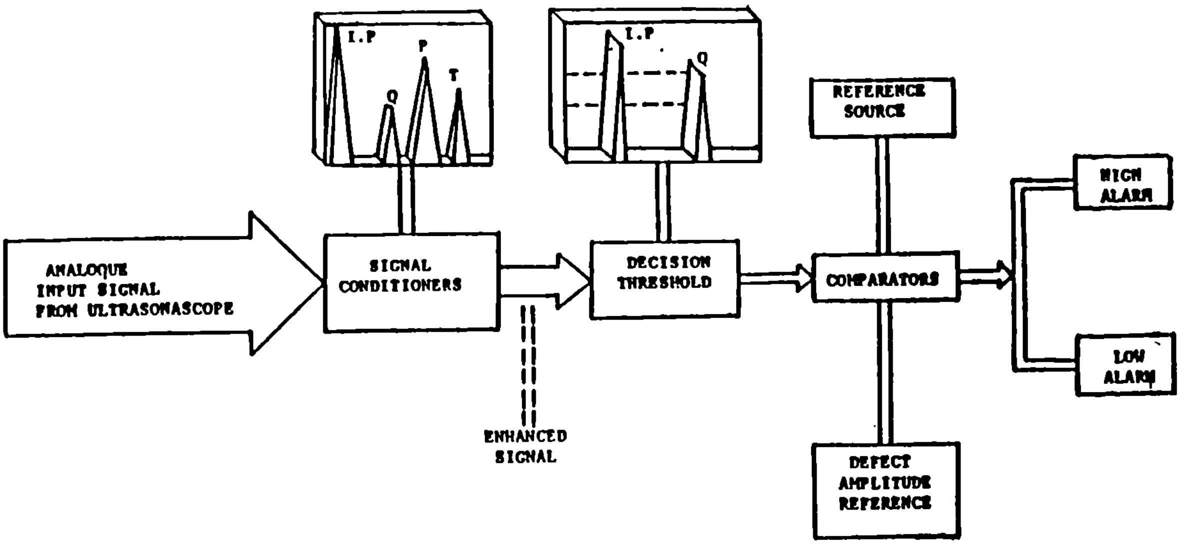


FIGURE 95. SIGNAL AMPLITUDE DISCRIMINATION SEQUENCE.

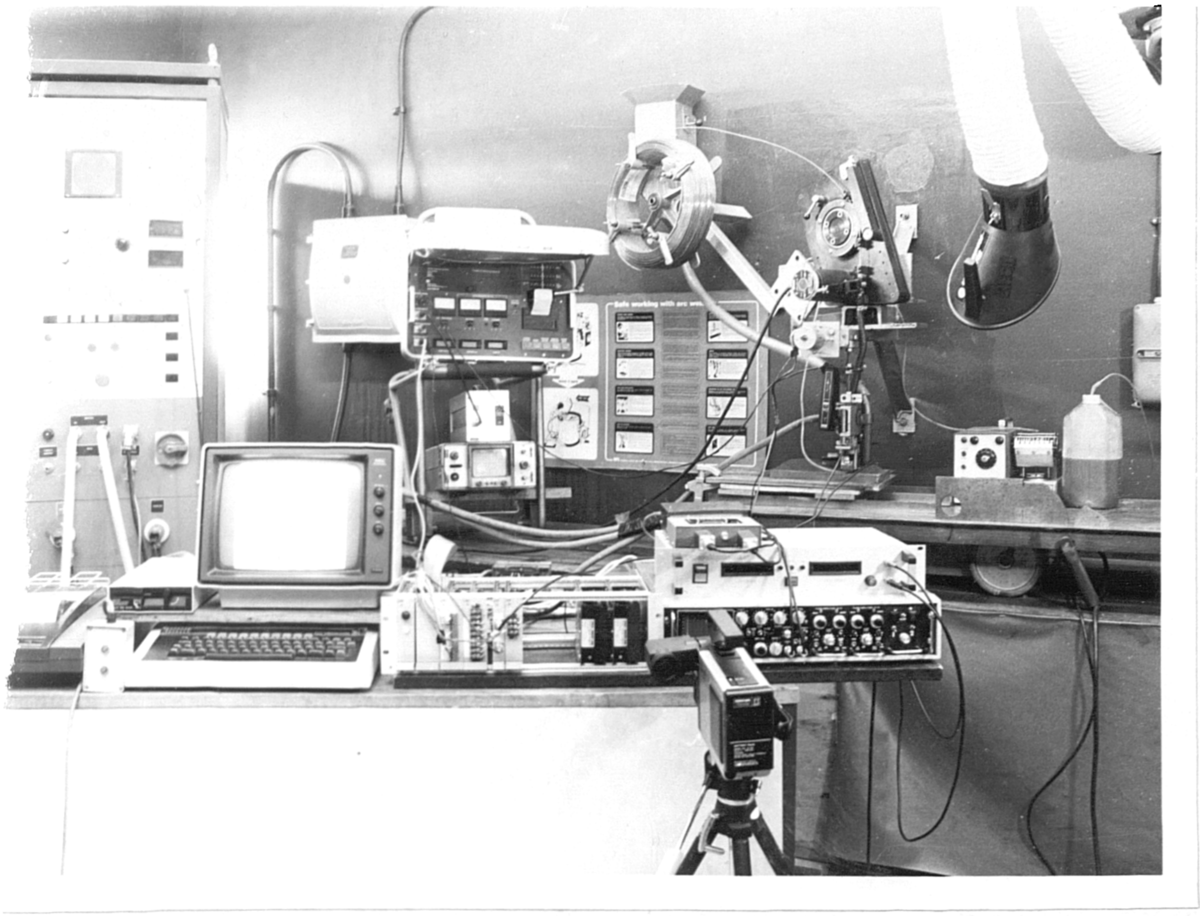


FIGURE 96. APPARATUS FOR ULTRASONIC CONTROLLED WELDING.

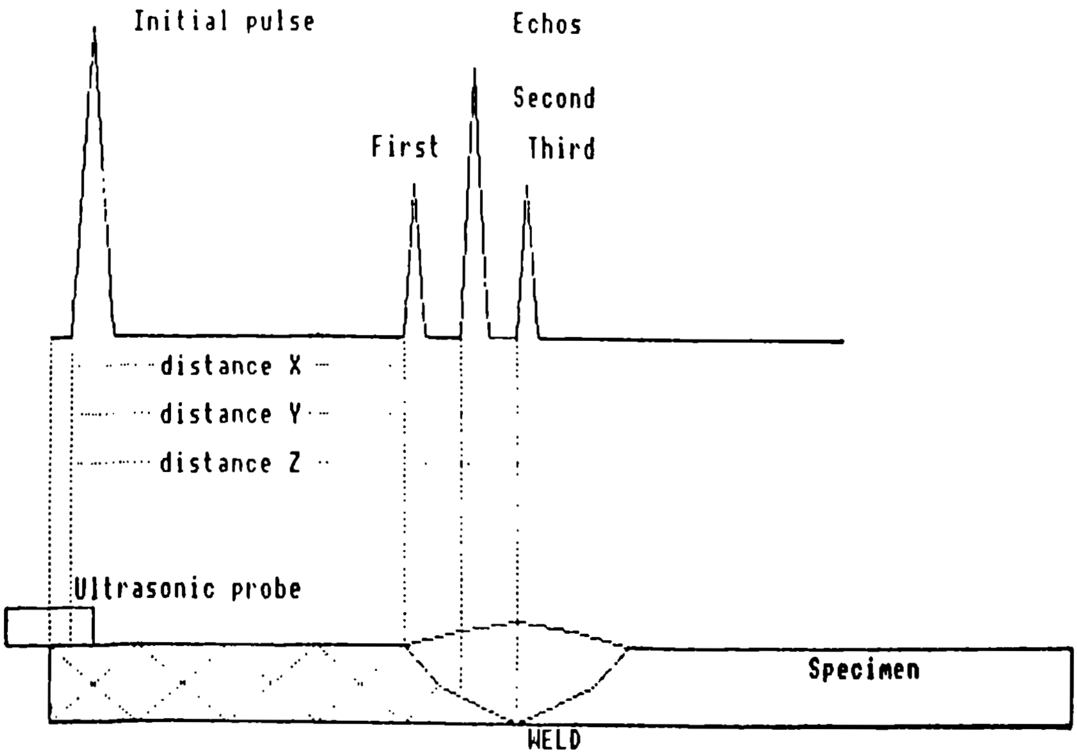


FIGURE 97. MICROPROCESSOR WELD POOL IMAGE.

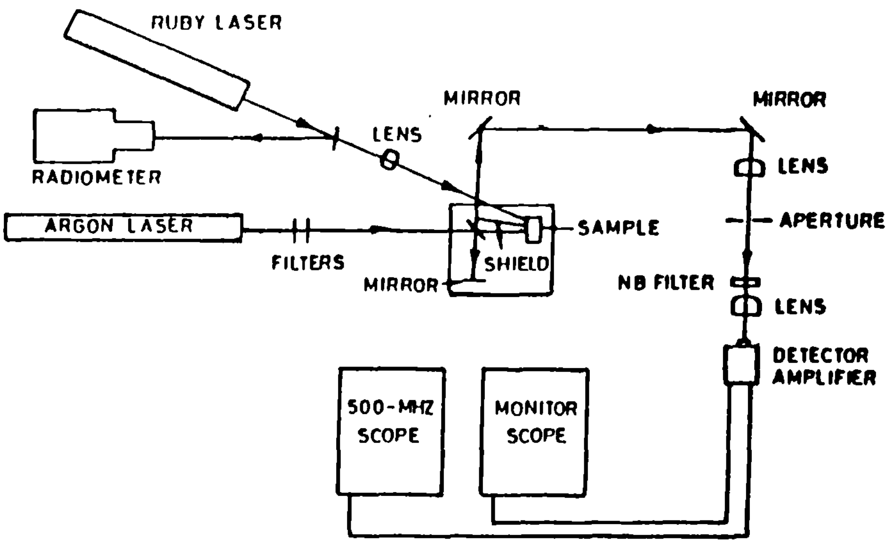


FIGURE 98. LASER INDUCED ULTRASOUND SYSTEM.

APPENDIX 1

SOFTWARE

1. LISTING OF PROGRAM "MANUAL"
2. LISTING OF PROGRAM "SETUP"
3. LISTING OF PROGRAM "BUDGE"
4. LISTING OF PROGRAM "OPTIM"
5. LISTING OF PROGRAM "STEER"
6. LISTING OF PROGRAM "AUTO"
7. LISTING OF PROGRAM "AUTO 1"
8. LISTING OF PROGRAM "AUTO 2"
9. LISTING OF PROGRAM "MENU"
10. LISTING OF PROGRAM "TEMP"
11. LISTING OF PROGRAM "UTILS"

LISTING OF PROGRAM "MANUAL"

```
0*DRIVE 0
5ON ERROR IF ERR=17THEN RUN ELSEREPORT:PRINT" at line ";ERL:END
6*KEY10 CH."MENU1"|M
7 DIMA$(5)
10 REM SUBMENU - MANUAL CONTROL PROGRAMS
20 A$(0)="Steering":A$(1)="Main Menu"
40MODE4
50VDU19,0,4;0;0;
60PROCinit
65PROCinit2
70CALLshade
72 PROCwindow(1,3,20,1)
73 PRINTTAB(0,1);"   Manual Control";
90PROCwindow(22,5,37,1)
100PROCtitle(16,A$(0))
120PROCwindow(22,11,37,7)
130PROCtitle(16,A$(1))
210VDU24,21*32;1023-30*32;29*32;1023;
220PROCmouse(25,2,22,11,26,1)
225G%=(Y%-1)DIV6
240*FX15,0
260CALLshade:PROCwindow(10,19,30,12):PROCtitle(21,"Loading :-")
270PRINT'A$(G%);
280IF G%=0 THEN CHAIN"STEER"
290IF G%=1 THEN CHAIN"MENU1"
360END
3595DEF PROCchrprint(chr%)
3600VDUchr%,chr%+2,8,8,10,chr%+1,chr%+3
3605ENDPROC
4990 DEFPROCinit2
5000VDU23,244,0,0,0,0,190,193,129,129
5010VDU23,245,0,64,64,64,95,96,64,64
5020VDU23,246,0,0,0,0,31,160,160,160
5030VDU23,247,0,32,32,32,47,176,160,160
5040VDU23,248,129,193,190,128,128,128,128,191
5050VDU23,249,64,64,64,0,0,0,0,255
5060VDU23,250,160,160,159,0,0,0,0,255
5070VDU23,251,160,176,47,0,0,0,0,255
5080VDU23,252,0,0,0,0,143,80,80,80
5090VDU23,253,0,0,0,0,144,72,69,66
5100VDU23,254,0,0,0,0,64,128,0,0
5120VDU23,255,80,80,143,0,0,0,0,255
5130VDU23,240,69,72,144,0,0,0,0,255
5140VDU23,241,0,128,64,32,16,8,4,242
5900 ENDPROC
30000REM Desk Enviroment
30005REM PCW Dec.85,p233
30010:
30020DEFPROCtitle2(width%,title$)
30021LOCALw%,len%
30022w%=width%:len%=LENtitle$:IF        width%MOD2=1          width%=width%+1:IF
len%=width%ORlen%=width%-1        PROCt3       ELSEIFlen%<width%-8        PROCt1
ELSEIFlen%>=width%-8 PROCt2
30023PRINTTAB(0,1)title$;
30024ENDPROC
```

```
30030:
30060DEFPROCscreen
30065*FX19
30070X%=0:%=0:VDU23,1,0;0;0;0;19,7,0;0;:CALLshade:PROCwindow(1,2,38,2):VDU31,1,0,224:PROCwindow(1,28,38,5):VDU19,7,7;0;
30075ENDPROC
30080:
30085DEFPROCtitle(width%,title$)
30090LOCALw%,len%
30095w%=width%:len%=LENtitle$:IF width%MOD2=1 width%=width%+1:IF len%=width%ORlen%=width%-1 PROCt3 ELSEIFlen%<width%-8 PROCt1 ELSEIFlen%>=width%-8 PROCt2
30100PRINTTAB(0,1)title$TAB(0,2)STRING$(w%,"_")
30105ENDPROC
30110:
30115DEFPROCt1
30120title$=CHR$225+CHR$226+CHR$227+STRING$((width%-6-len%)DIV2,CHR$228)+title$+STRING$((width%-len%)DIV2+len%MOD2,CHR$228)
30125ENDPROC
30130:
30135DEFPROCt2
30140title$=STRING$((width%-len%)DIV2,CHR$228)+title$+STRING$((width%-len%)DIV2+len%MOD2,CHR$228)
30145ENDPROC
30150:
30155DEFPROCt3
30160ENDPROC
30165:
30170DEFPROCinput(x%,y%,len%,ch$)
30175LOCALcount%,key$
30180ret$="":count%=0
30185REPEAT
30190REPEAT
30195key$=GET$
30200UNTILkey$=CHR$13ORkey$=CHR$127ORINSTR(ch$,key$)
30205IFINSTR(ch$,key$)ANDcount%<len% PROCchr ELSEIFkey$=CHR$127ANDcount%>0 PROCdel
30210PRINTTAB(x%,y%)ret$;
30215UNTILkey$=CHR$13
30220ENDPROC
30225:
30230DEFPROCchr
30235ret$=ret$+key$:count%=count%+1
30240ENDPROC
30245:
30250DEFPROCdel
30255VDU31,x%-1+LENret$,y%,32:ret$=LEFT$(ret$,LENret$-1):count%=count%-1
30260ENDPROC
30265:
30270DEFPROCdbl(x%,y%,a$)
30275LOCALa%,c%
30280FORa%=1 TOLENa$:c%=&C000+(ASC(MID$(a$,a%,1))-32)*8
30285VDU23,229,?c%,?c%,?(c%+1),?(c%+1),?(c%+2),?(c%+2),?(c%+3),?(c%+3),23,230,?(c%+4),?(c%+4),?(c%+5),?(c%+5),?(c%+6),?(c%+6),?(c%+7),?(c%+7),31,x%,y%,229,31,x%,y%+1,230:x%=x%+1:NEXT
30290ENDPROC
30295:
30300DEFPROCtime(a%,b%,c%,d%)
```

```
30305LOCALh$,m$,h%,m%
30310h$="":m$="":VDU28,1,2,38,2:h%=(TI.DIV360000)MOD12:m%=TI.DIV6000)MOD60
30315IFh%=0 h$="12" ELSE h$=RIGHT$(" "+STR$h%,2)
30320IFm%=0 m$="00" ELSE m$=RIGHT$("0"+STR$m%,2)
30325PRINTTAB(26,0;"Time: ";h$+":"+m$;:VDU28,a%,b%,c%,d%
30330ENDPROC
30335:
30340DEFPROCwindow(a%,b%,c%,d%)
30345VDU18,0,128,24,a%*32-4;1023-(b%+1)*32;(c%+1)*32;1023-d%*32+4;16,24,a%*32+8
;1023-(b%+1)*32-8;(c%+1)*32+8;1023-d%*32-8;16,17,135,17,0,24,a%*32;1023-(b%+1)*3
2;(c%+1)*32;1023-d%*32;28,a%,b%,c%,d%,12
30350ENDPROC
30355:
30360DEFPROCtime_set
30365LOCALh%,m%,s%
30370CLS:PROCtitle(38," Time Set  "):PRINTTAB(1,6)"Enter hours   (1-12)":    [
]":REP.P.TAB(26,6)"
":PROCinput(26,6,2,"0123456789"):U.VALret$>0A.VALret$<=12:h%=VALret$
30375PRINTTAB(1,9)"Enter  minutes  (0-59):      [    ]":REPEATPRINTTAB(26,9)"
":PROCinput(26,9,2,"0123456789"):UNTILVALret$<=59:m%=VALret$
30380PRINTTAB(1,12)"Enter  seconds (0-59):      [    ]":REPEATPRINTTAB(26,12)"
":PROCinput(26,12,2,"0123456789"):UNTILVALret$<=59:s%=VALret$
30385TIME=100*s%+6000*m%+36000*h%:PROCtime(1,28,38,5):CLS
30390ENDPROC
30395:
30400DEFPROCmove(size,source,dest)
30405X%=0:Y%=0:!SIZE=size:!SOURCE=source:!DEST=dest:CALLmove
30410ENDPROC
30415:
30420DEFFNschr(x%,y%)
30425VDU31,x%,y%:A%=135
30430=(USR(&FFF4)AND&FFFF)DIV&100
30435:
30440DEFPROCmouse(x%,y%,a%,b%,c%,d%)
30445X%=0:Y%=0:GCOL0,0:VDU5:*FX11,1
30450*FX12,1
30455REPEAT
30460PROCmove(8,FNsta(x%,y%),22000):PROCmove(8,FNsta(x%,y%+1),22008):*FX15,0
30465PROCprint:REPEATUNTILADVAL(-1)<>0
30470PROCmove(8,22000,FNsta(x%,y%)):PROCmove(8,22008,FNsta(x%,y%+1))
30475IF INKEY-122 IFx%<c% x%=x%+1 ELSE IF INKEY-26 IFx%>a% x%=x%-1
30480IF INKEY-42 IFy%<b% y%=y%+1 ELSE IF INKEY-58 IFy%>d% y%=y%-1
30485UNTILINKEY-74
30490VDU4:*FX12,0
30495X%=x%:Y%=y%:*FX15,0
30500ENDPROC
30505:
30510DEFPROCprint
30515MOVEFNpos(x%),1023-FNpos(y%):VDU231:MOVEFNpos(x%),1023-FNpos(y%+1):VDU232
30520ENDPROC
30525:
30530DEFFNpos(p%)=p%*8*4
30535DEFFNsta(x%,y%)=22528+y%*320+x%*8
30540:
30545DEFPROCinit
30550PROCass:VDU23,224,24,60,60,126,0,126,60,0,23,225,252,0,252,0,252,0,252,0,2
3,226,255,129,129,129,129,129,255,0,23,227,63,0,63,0,63,0,63,0,23,228,255,0,255,
0,255,0,255,0,23,231,0,128,192,224,240,248,252,254
```

```
 30555VDU23,232,255,252,248,216,140,12,6,6:TIME=100*0+6000*0+360000*6
 30560ENDPROC
 30565:
 30570DEFPROCass
 30575DIM  space% 35:FORpass%=0  TO2  STEP2:P%=space%:[OPTpass%:.shade:LDA£22528
MOD256:STA&70:LDA£22528                                    DIV256:STA&71:LDX£10241
DIV256:LDY£0:.loop:LDA£170:STA(&70),Y:EOR£255:INY:STA(&70),Y:INY:BNEloop:INC&71:
DEX:BNEloop:RTS:]NEXT
 30580SIZE=&70:SOURCE=&72:DEST=&74:DIM                                         move
40:FORi%=0TO2STEP2:P%=move:[OPTi%:LDY£0:LDXSIZE+1:BEQli:.l:LDA(SOURCE),Y:STA(DES
T),Y:INY:BNEl:INCSOURCE+1:INCDEST+1:DEX:BNEl:.li:LDXSIZE:BEQdo:.ll:LDA(SOURCE),Y
:STA(DEST),Y:INY:DEX:BNEll:.do:RTS
 30585]NEXT
 30590ENDPROC
```

listing of program "setup"

```
  10 REM SETUP AND CONNECTION CHECK
  20 MODE7
  30 PROCsetup
  40 IF E%<>0 THEN PROCerror:END
  50 CHAIN"MENU1"
1000 END
1999
2000 DEFPROCsetup
2010 E%=0
2011
2015 REM VIA 0
2020 ?&FDB3=0
2030 ?&FDB2=&07
2040 ?&FDB0=&01
2050 A%=?&FDB0
2060 IF NOT(A%=249) THEN E%=1
2070 ?&FDB0=&02
2080 A%=?&FDB0
2090 IF NOT(A%=250) THEN E%=1
2096 ?&FDB0=0
2097
2100 REM VIA 1
2110 ?&FD93=&FF
2120 ?&FD91=0
2130 ?&FD92=&83
2140 ?&FD90=0
2150 ?&FD91=&55
2160 A%=?&FD91
2170 ?&FD91=0
2180 IF A%<>&55 THEN E%=E%+2
2190 ?&FD9C=&0A
2200 ?&FD9B=&C0
2210 T%=50000
2220 ?&FD94=T%MOD256
2230 ?&FD95=T%DIV256
2235
2240 REM VIA 2
2250 ?&FDA2=&83
2260 ?&FDA0=0
2270 ?&FDAB=&80
2280 P%=1000
2290 HP%=P%DIV256
2300 ?&FDA4=P%MOD256
2310 ?&FDA5=HP%
2320 A%=?&FDA7
2330 IFA%<>HP%THEN E%=E%+4
2335
2340 REM VIA3
2350 ?&FDB3=&FF
2360 ?&FDB1=0
2370 ?&FDB2=&FF
2380 ?&FDB0=&3C
2390 A%=?&FDB0
2400 ?&FDB0=0
2410 IF A%<>&3C THEN E%=E%+8
```

```
2490 ENDPROC
2491
2500 DEFPROCerror
2520 PRINT "CONNECTION FAULT"
2530 PRINT
2540 PRINT "FAULT CODE",E%
2550 PRINT
2560 IF E%=15 THEN PRINT"Rack switched off or not connected"
2570 IF E%MOD2=1 THEN PRINT"VIA on card 1 not responding"
2580 E%=INT(E%/2)
2590 IF E%MOD2=1 THEN PRINT"VIA 1 on card 2 not responding"
2600 E%=INT(E%/2)
2610 IF E%MOD2=1 THEN PRINT"VIA 2 on card 2 not responding"
2620 E%=INT(E%/2)
2630 IF E%MOD2=1 THEN PRINT"VIA on card 3 not responding"
3000 ENDPROC
```

Listing of program "budge"

```
10REM Budge
20REM by Brian Lienard
30REM For BBC and Electron
40REM (C) Acorn User April 1985
50:
60*FX144,0,1
70IF ?&FFFE=164 THEN E%=0 ELSE E%=96
80MODE4:VDU19,0,4;0;
90DIMvdu$(14),val%(14,8),mode$(3)
100mode$(1)="ERASE":mode$(2)="DRAW "
110mode$(3)="MOVE "
120PROCsetchars
130PROCtitle
140PROCquestions
150PROCdisplay(H%,W%)
160L%=0:R%=W%*8-1:T%=0:D%=H%*8-1
170M%=3:X%=0:Y%=0
180PROCcomlist
190*FX4,1
200:
210REPEAT
220PRINTTAB(X%,Y%);:Z%=GET AND &DF
230IF Z%=139 AND Y%>T% THEN PROCup
240IF Z%=138 AND Y%<D% THEN PROCdn
250IF Z%=136 AND X%>L% THEN PROClt
260IF Z%=137 AND X%<R% THEN PROCrt
270IF Z%=68 THEN M%=2:PROCmode
280IF Z%=69 THEN M%=1:PROCmode
290IF Z%=77 THEN M%=3:PROCmode
300IF Z%=86 THEN PROCsave:G%=0:PROCprocess:PROCcomlist:PROCrestore
310IF Z%=76 THEN PROCload
320UNTIL Z%=81 OR Z%=113
330:
340G%=1:PROCprocess
350CLS:PRINT''"Do you want to save ";
360PRINT"VDU23 statements in a file";
370PRINT" or print them on the";
380PRINT" screen?"''
390PRINT"Press : F for file"
400PRINTSPC(8);"S for screen";
410REPEAT Z%=GET AND &DF
420UNTIL Z%=70 OR Z%=83
430IF Z%=70 THEN PROCfile : END
440CLS:FORC%=0TO14:PRINTvdu$(C%):NEXT
450PRINT"Now LOAD your program and COPY over'"
460PRINT"the statements to merge them with it."
470*FX4,0
480END
490:
500DEF PROCfile
510PRINT''"Please enter File name :";
520REPEAT:INPUT F$:UNTIL F$<>""
530F$=LEFT$(F$,7):CHAN=OPENOUT(F$)
540FOR C%=0 TO W%*H%-1
550FOR I%=1 TO LEN(vdu$(C%))
```

```
560BPUT£CHAN,ASC(MID$(vdu$(C%),I%,1))
570NEXT
580BPUT£CHAN,13:NEXT:CLOSE£CHAN
590PRINT''"Now LOAD your program ";
600PRINT"and *EXEC ";F$;" to"
610PRINT" merge the VDU23 statements with it"
620*FX4,0
630ENDPROC
640:
650DEFPROCprocess
660PROCcls
670PRINT TAB(15,27);"Processing";
680FOR C%=0 TO W%*H%-1
690P%=(C% MOD W%)*8-1
700Q%=(C% DIV W%)*8-1
710IF G%=1 THEN vdu$(C%)=STR$(LI+C%*10)+"VDU23,"+STR$(U%+C%)
720FORI%=1 TO 8:V%=128:S%=0
730FORJ%=1 TO 8
740PRINTTAB(P%+J%,Q%+I%);
750A%=135
  760IF(USR(&FFF4)AND&FFFF)DIV  &100=233-E% THEN  S%=S%+V%:IF  G%=1  THEN
PRINT"£";
770V%=V%/2
780NEXT J%
790IF G%=1 THEN vdu$(C%)=vdu$(C%)+","+STR$(S%) ELSE val%(C%,I%)=S%
800NEXT I%
810IF G%=1 THEN PRINTTAB(P%+1,Q%+1);STR$(U%+C%);
820NEXT C%
830IF G%=0 THEN PROCview
840PRINTTAB(8,27);"Press any key to continue";:Z%=GET
850ENDPROC
860:
870DEFPROCmode
880PRINTTAB(25,30);mode$(M%);
890PROCupdate:ENDPROC
900:
910DEFPROCcls
920 FORY%=24 TO 31
930PRINTTAB(0,Y%);SPC(39);
940NEXT:ENDPROC
950:
960DEFPROCsave
970K%=X%:O%=Y%:ENDPROC
980:
990DEFPROCrestore
1000X%=K%:Y%=O%
1010PRINTTAB(X%,Y%);
1020ENDPROC
1030:
1040DEFPROCsetchars
1050VDU23,224,255,128,128,128,128,128,128,129
1060VDU23,225,255,1,1,1,1,1,1,129
1070VDU23,226,129,128,128,128,128,128,128,255
1080VDU23,227,129,1,1,1,1,1,1,255
1090VDU23,228,129,0,0,0,0,0,0,255
1100VDU23,229,255,0,0,0,0,0,0,129
1110VDU23,230,129,128,128,128,128,128,128,129
1120VDU23,231,129,1,1,1,1,1,1,129
```

```
1130VDU23,232,129,0,0,0,0,0,0,129
1140VDU23,233,255,255,255,255,255,255,255,255
1150VDU23,234,60,66,153,161,161,153,66,60
1160ENDPROC
1170:
1180DEF PROCdisplay(H%,W%)
1190CLS:FOR B%=0 TO H%-1
1200FOR A%=0 TO W%-1
1210X%=A%*8:Y%=B%*8:PROCtile(X%,Y%)
1220NEXT:NEXT:ENDPROC
1230:
1240DEFPROCtile(X%,Y%)
1250PRINTTAB(X%,Y%);CHR$(224);
1260FOR I%=1 TO 6:PRINTCHR$(229);:NEXT
1270PRINTCHR$(225)
1280FOR J%=Y%+1 TO Y%+6
1290PRINTTAB(X%,J%);CHR$(230);
1300FOR I%=1 TO 6:PRINTCHR$(232);:NEXT
1310PRINTCHR$(231);
1320NEXT
1330PRINTTAB(X%,Y%+7);CHR$(226);
1340FOR I%=1 TO 6:PRINTCHR$(228);:NEXT
1350PRINTCHR$(227);
1360ENDPROC
1370:
1380DEFPROCcomlist
1390PRINTTAB(0,24);"Mode: Press D=draw, E=erase, M=move."
1400PRINT"Move: Cursor keys = up,down,left,right."
1410PRINT"View: Press V to view at normal size."
1420PRINT"Load: Press L to load VDU23 statement."
1430PRINT"Quit: Press Q to quit definition."
1440PRINTTAB(8,30);"Current mode is: ";:COLOUR1:PRINTmode$(M%):COLOUR3
1450ENDPROC
1460:
1470DEFPROCup
1480Y%=Y%-1:PROCupdate:ENDPROC
1490:
1500DEFPROCdn
1510Y%=Y%+1:PROCupdate:ENDPROC
1520:
1530DEFPROClt
1540X%=X%-1:PROCupdate:ENDPROC
1550:
1560DEFPROCrt
1570X%=X%+1:PROCupdate:ENDPROC
1580:
1590DEFPROCupdate
1600PRINTTAB(X%,Y%);
1610ON M% GOTO 1620,1630,1640
1620PROCerase:GOTO 1640
1630PRINTCHR$(233);
1640ENDPROC
1650:
1660DEFPROCerase
1670PRINTTAB(X%,Y%);
1680A%=X% MOD 8:B%=Y% MOD 8:F%=0
1690IF A%=0 AND B%=0 THEN PRINTCHR$(224);:F%=1
1700IF A%=0 AND B%=7 THEN PRINTCHR$(226);:F%=1
```

```
1710IF A%=7 AND B%=0 THEN PRINTCHR$(225);:F%=1
1720IF A%=7 AND B%=7 THEN PRINTCHR$(227);:F%=1
1730IF A%=0 AND B%>0 AND B%<7 THEN PRINTCHR$(230);:F%=1
1740IF A%=7 AND B%>0 AND B%<7 THEN PRINTCHR$(231);:F%=1
1750IF A%>0 AND A%<7 AND B%=0 THEN PRINTCHR$(229);:F%=1
1760IF A%>0 AND A%<7 ANDB%=7 THEN PRINTCHR$(228);:F%=1
1770IF F%=0 THEN PRINTCHR$(232);
1780ENDPROC
1790:
1800DEFPROCquestions
1810PRINTTAB(0,15);"No.of chars.across(1-5,default=2)";
1820REPEAT INPUT W%
1830UNTIL W%=0 OR W%<5
1840IF W%=0 THEN W%=2
1850PRINT''"No.of chars. down (1-3,default=2)";
1860INPUT H%:IF H%=0 THEN H%=2
1870IF H%>3 THEN PRINT CHR$(7);:GOTO 1860
1880PRINT''"ASCII codes for chars.to start at"
1890PRINTSPC(12);"(224-";256-H%*W%;",default=224)";
1900INPUT U%:IF U%=0 THEN U%=224
1910IF U%>256-H%*W% THEN PRINTCHR$(7);:GOTO1900
1920PRINT''"1st line no.for VDU23 statements"
1930PRINTSPC(11);"(1-32000,default=1010)";
1940INPUT LI:IF LI=0 THEN LI=1010
1950IF LI<=0 OR LI>32000 THEN PRINTCHR$(7);:GOTO1940
1960ENDPROC
1970:
1980DEFPROCtitle
1990CLS
2000PRINTTAB(5,2);"* BUDGE ";CHR$(234);" by Brian Lienard."
2010PRINTTAB(5,4);"B BBC   (& Electron)"
2020PRINTTAB(5,5);"U  User-"
2030PRINTTAB(5,6);"D   Defined"
2040PRINTTAB(5,7);"G    Graphics"
2050PRINTTAB(5,8);"E     Editor."
2060ENDPROC
2070:
2080DEFPROCview
2090PRINTTAB(8,31);"Latest  view is:------->";
2100FOR C%=0 TO H%*W%-1

2110VDU23,235,val%(C%,1),val%(C%,2),val%(C%,3),val%(C%,4),val%(C%,5),val%(C%
,6),val%(C%,7),val%(C%,8)
2120PRINTTAB(C% MOD W%+33,C% DIV W%+32-H%);CHR$(235);
2130NEXT
2140M%-3
2150ENDPROC
2160:
2170DEFPROCload
2180PROCsave:PROCcls
2190PRINTTAB(0,25);"LOAD: Which tile across(1-";W%;"/1)";
2200INPUT P%:IF P%=0 THEN P%=1:GOTO 2220
2210IF P%<1 OR P%>W% THEN PRINTTAB(31,25);CHR$(7);SPC(4);:GOTO2190
2220PRINTTAB(0,26);SPC(5);"Which tile  down (1-";H%;"/1)";
2230INPUT Q%:IF Q%=0 THEN Q%=1:GOTO2250
2240IF Q%>H% THEN PRINTTAB(31,26);CHR$(7);SPC(4);:GOTO2220
2250PROCtile((P%-1)*8,(Q%-1)*8)
2260PRINTTAB(0,28);"Type in values from VDU23 statement:"
```

```
2270FOR I%=1 TO 8
2280PRINTTAB(0,29);"Dot value for row ";
2290COLOUR1:PRINT;I%;:COLOUR3
2300PRINT" (0-255/0)";:INPUTN%
2310IF N%<0 OR N%>255 THEN PRINTTAB(30,29);CHR$(7);SPC(5);:GOTO2280
2320V%=128
2330FOR J%=1 TO 8
2340IF N% DIV V%=1 THEN
PRINTTAB((P%-1)*8+J%-1,(Q%-1)*8+I%-1);CHR$(233);:N%=N%-V%
2350V%=V%/2:NEXTJ%
2360PRINTTAB(30,29);SPC(5):NEXT I%
2370PROCcls: M%=3: PROCcomlist: PROCrestore
2380ENDPROC
```

Listing of program "OPTIM"

```
20    T$="D.D,3(7D),3(6D)"
30    PRINT " D        S      I        V      P      H      W"
40    DATA 12.7,55,80,78,1100,1,10,1,5,20,4,0.70,0.30
50    READ W,P1,P2,Smax,Imax,Ds,Di,Dv,D,W2,H2,Pw,Hw
60    P1=P1*W/100.0
70    P2=P2*W/100.0
130   FOR S=MIN(66,Smax) TO 24 STEP -6
140     FOR I=MIN(800,Imax) TO 400 STEP -25
150       FOR V=25 TO 35 STEP 5
170         Up=FNPent(I+Di,V+Dv,S-Ds,D)
180   IF FNPent(I-Di,V-Dv,S+Ds,D)<P1 OR Up>P2 THEN P2
185         Uh=FNHigh(I+Di,V-Dv,S-Ds,D)
186   IF Uh>H2 THEN GOTO P2
210   IF FNWidt(I-Di,V+Dv,S-Ds,D)>W2 THEN P2
216         Lw=FNWidt(I+Di,V-Dv,S+Ds,D)
250   IF Up/Lw>Pw OR Uh/Lw>Hw THEN P2
260   IF NOT (FNUcut(I-Di,V-Dv,S-Ds,D)) THEN P2
270       PRINT USING T$;D,S,I,V,FNPent(I,V,S,D),FNHigh(I,V,S,D),FNWidt(I,V,S,D)
280 P2:       NEXT V
290          NEXT I
300 P1:  NEXT S
310   END
320   !
330   !!!!!!!!!
340   !
350   DEF FNPent(I,V,S,D)
360     RETURN I^1.55586*V^.213918/S^.26663/D^.53186/EXP(7.1482)
370   FNEND
380   !
390   !!!!!!!!!
400   !
410   DEF FNWidt(I,V,S,D)
420     RETURN V^1.04577*D^.436533/I^.020553/S^.48228*EXP(.382095)
430   FNEND
440   !
450   !!!!!!!!!
460   !
470   DEF FNHigh(I,V,S,D)
480     RETURN I^1.41961/V^.91861/S^.49421/D^.47391/EXP(2.5854)
490   FNEND
500   !
510   !!!!!!!!!!
520   !
530   DEF FNUcut(I,V,S,D)
540     U=I^.166833*V^.320259*S^.08388228*D^.0528165/EXP(2.6131)
550     IF U>=1 THEN
560       RETURN 1
570     ELSE
580       RETURN 0
590     END IF
600   FNEND
```

listing of program "steer"

```
5 *FX15,1
6 REM "STEER"
10 REM MANUAL CONTROL PROGRAM - STEER
20 REM DRIVE MOTOR1 AT CONSTANT SPEED
30 REM READ ULTRASONOSCOPE AND DISPLAY
40 REM DRIVE CURRENT AT PRESET LEVEL
50 REM LEFT/RIGHT CONTROL OF STEERING
55 PROCsetup
60 *KEY10 CH."MANUAL"|M
65 WIND$=CHR$(157)+CHR$(132)+"        "+CHR$(156)+CHR$(135)
70 MODE7
72 Y%=6500
75 G%=0:D%=0:L%=0:F%=0
80 A=0:C%=0:P%=1:S=0:S%=20
85 CLO=0:CHI=4:PLO%=1:PHI%=25:SLO%=20:SHI%=100
90 PROCscreen1
100 IF A$=" " THEN CHAIN"MANUAL"
110 PROCscreen2
120 GOTO 90
999 END
1000 DEFPROCinit1
1010 CLS
1020 PRINT TAB(0,1);"Manual steering        set up screen";
1030 PRINT TAB(0,4);"C = set current level (0-4 Amps)"
1040 PRINT WIND$;
1050 PRINT TAB(0,7);"P = set steering pulses per keypress"
1060 PRINT WIND$;
1070 PRINT TAB(0,10);"S = set travel speed (2-10 mm/sec)"
1080 PRINT WIND$;
1090 PRINT TAB(0,13);"G = go to control screen";
1100 PRINT TAB(0,23);"press SPACE to return to menu";
1110 PRINT TAB(2,5);A;"   ";
1120 PRINT TAB(2,8);P%;"   ";
1130 PRINT TAB(2,11);S%/10;"    ";
1140 ENDPROC
1500 DEFPROCinit2
1505 CLS
1510 PRINT TAB(0,1);"Manual steering        control screen";
1520 PRINT TAB(0,3);"Controls :-"
1530 PRINT "G = go               S = stop"
1540 PRINT "C = current ON       O = current OFF"
1550 PRINT "F = forward          B = back"
1560 PRINT "L = left             R = right"
1565 PRINT TAB(0,9);"Travel speed - ";S%/10;" mm/sec."
1570 PRINT "Steering pulses per keypress - ";P%
1580 PRINT "Current value - ";A;" Amps";TAB(26,11);WIND$
1590 PRINT TAB(28,11);
1600 IF F%=0 THEN PRINT "  OFF"; ELSE PRINT "  ON ";
1610 PRINT TAB(0,13);WIND$;TAB(20,13);WIND$;
1620 PRINT TAB(2,13);:IF G%=0 THEN PRINT " STOP"; ELSE PRINT "  GO ";
1630 PRINT TAB(22,13);:IF D%=0 THEN PRINT "FORWARD"; ELSE PRINT " BACK  ";
1640 PRINT TAB(0,15);"Ultrasonoscope readings"
1650 PRINT "First reflection    Second reflection"
1660 PRINT TAB(0,17);WIND$;TAB(20,17);WIND$;
1670 PROCreadtimer
1680 PRINT TAB(0,23);"(press SPACE to return to setup screen)";
```

```
1690 ENDPROC
2000 DEFPROCscreen1
2010 PROCinit1
2020 REPEAT
2030 REPEAT
2040 A%=INKEY(10)
2050 UNTIL NOT A%
2060 A$=CHR$(A%)
2070 IF A$="C" THEN PROCcurrent
2080 IF A$="P" THEN PROCpulses
2090 IF A$="S" THEN PROCspeed
2100 UNTIL A$=" " OR A$="G"
2110 ENDPROC
2200 DEFPROCcurrent
2210 PRINT TAB(0,5);WIND$
2220 PRINT TAB(2,5);:INPUT A
2230 IF A<CLO THEN A=CLO ELSE IF A>CHI THEN A=CHI
2240 A=(INT(A*100))/100
2250 PRINT TAB(0,5);WIND$;TAB(2,5);A;
2260 C%=INT(A*63.75)
2280 ENDPROC
2300 DEFPROCpulses
2310 PRINT TAB(0,8);WIND$
2320 PRINT TAB(2,8);:INPUT P%
2330 IF P%<PLO% THEN P%=PLO% ELSE IF P%>PHI% THEN P%=PHI%
2340 PRINT TAB(0,8);WIND$
2350 PRINT TAB(2,8);P%;
2360 ENDPROC
2400 DEFPROCspeed
2410 PRINT TAB(0,11);WIND$
2420 PRINT TAB(2,11);:INPUT S
2430 S%=INT(S*10)
2440 IF S%<SLO% THEN S%=SLO% ELSE IF S%>SHI% THEN S%=SHI%
2450 PRINT TAB(0,11);WIND$;
2460 PRINT TAB(2,11);S%/10;
2470 ENDPROC
3000 DEFPROCscreen2
3010 PROCinit2
3020 REPEAT
3030 REPEAT
3040 A%=INKEY(50)
3050 PROCreadtimer
3060 UNTIL NOT A%
3070 A$=CHR$(A%)
3080 IF A$="S" THEN PROCstop
3090 IF A$="G" THEN PROCgo
3100 IF A$="C" THEN PROCon
3110 IF A$="O" THEN PROCoff
3120 IF A$="L" THEN PROCleft
3130 IF A$="R" THEN PROCright
3140 IF A$="F" THEN PROCfore
3150 IF A$="B" THEN PROCback
3160 UNTIL A$=" "
3170 ?&FD80=0:?&FD90=0:?&FD91=0:?&FDA0=0
3180 G%=0:D%=0:L%=0:F%=0
3190 ENDPROC
3500 DEFPROCstop
3510 G%=0:F%=0
```

```
3520 ?&FD90=0:?&FD91=0:?&FDA0=0
3530 PRINT TAB(2,13);" STOP";TAB(28,11);"  OFF";
3540 ENDPROC
3600 DEFPROCgo
3605 G%=1
3610 T%=INT(K%/S%)*10
3620 ?&FD36=T%MOD256
3630 ?&FD37=T%DIV256
3640 ?&FD90=2*D%+G%
3645 ?&FDA0=2*L%+G%
3650 PRINT TAB(2,13);"  GO ";
3660 ENDPROC
3700 DEFPROCon
3710 F%=1
3720 ?&FD31=C%
3730 PRINT TAB(28,11);"  ON ";
3740 ENDPROC
3800 DEFPROCoff
3810 F%=0
3820 ?&FD31=0
3830 PRINT TAB(28,11);"  OFF";
3840 ENDPROC
3900 DEFPROCfore
3910 D%=0
3920 ?&FD90=2*D%+G%
3930 PRINT TAB(22,13);"FORWARD";
3940 ENDPROC
4000 DEFPROCback
4010 D%=1
4020 ?&FD90=2*D%+G%
4030 PRINT TAB(22,13);" BACK  ";
4040 ENDPROC
4100 DEFPROCleft
4110 L%=0
4120 PROCsend
4130 ENDPROC
4200 DEFPROCright
4210 L%=1
4220 PROCsend
4230 ENDPROC
4300 DEFPROCsend
4310 ?&FDA0=2*L%+G%
4320 FOR I%=1 TO P%
4330 ?&FDA5=3
4340 MARK=TIME
4350 REPEAT:UNTIL TIME=MARK+1
4360 NEXT I%
4370 ENDPROC
5000 DEFPROCreadtimer
5010 ?&FDB0=4
5015 M=TIME:REPEAT:UNTIL TIME=M+2
5020 E%=?&FDB0 AND 8
5030 L2%=?&FD81
5040 ?&FDB0=5
5050 H2%=?&FD81
5060 ?&FDB0=6
5070 L1%=?&FD81
5080 ?&FDB0=7
```

```
5090 H1%=?&FD81
5100 ?&FD80=0
5120 R1%=H1%*256+L1%
5130 R2%=H2%*256+L2%
5140 PRINT TAB(2,17);R1%/10;TAB(22,17);R2%/10;
5150 IF E% THEN PRINT TAB(22,17);" Error ";
5160 ENDPROC
6000 DEFPROCsetup
6010 ?&FD83=0
6020 ?&FD82=&07
6030 ?&FD80=0
6040 ?&FD93=&FF
6050 ?&FD91=0
6060 ?&FD92=&83
6070 ?&FD90=0
6080 ?&FD9C=&0A
6090 ?&FD9B=&C0
6100 T%=50000
6110 ?&FD94=T%MOD256
6120 ?&FD95=T%DIV256
6130 ?&FDA2=&83
6140 ?&FDA0=0
6150 ?&FDAB=&90
6160 P%=1000
6170 ?&FDA4=P%MOD256
6180 ?&FDA5=P%DIV256
6190 ENDPROC
```

LISTING OF PROGRAM "AUTO"

```
0*DRIVE 0
 5ON ERROR IF ERR=17THEN RUN ELSEREPORT:PRINT" at line ";ERL:END
 6*KEY10 CH."MENU1"|M
 7 DIMA$(5)
10 REM SUBMENU - AUTO CONTROL PROGRAMS
20 A$(0)="Steering":A$(1)="Steer & Depth":A$(2)="Main Menu"
40MODE4
50VDU19,0,4;0;0;
60PROCinit
65PROCinit2
70CALLshade
72 PROCwindow(1,3,20,1)
73 PRINTTAB(0,1);"   Auto Control";
90PROCwindow(22,5,37,1)
100PROCtitle(16,A$(0))
120PROCwindow(22,11,37,7)
130PROCtitle(16,A$(1))
140 PROCwindow(22,17,37,13)
150 PROCtitle(16,A$(2))
210VDU24,21*32;1023-30*32;29*32;1023;
220PROCmouse(25,2,22,17,26,1)
225G%=(Y%-1)DIV6
240*FX15,0
260CALLshade:PROCwindow(10,19,30,12):PROCtitle(21,"Loading :-")
270PRINT'A$(G%);
280IF G%=0 THEN CHAIN"AUTO1"
290IF G%=1 THEN CHAIN"AUTO2"
300IF G%=2 THEN CHAIN"MENU1"
360END
3595DEF PROCchrprint(chr%)
3600VDUchr%,chr%+2,8,8,10,chr%+1,chr%+3
3605ENDPROC
4990 DEFPROCinit2
5000VDU23,244,0,0,0,0,190,193,129,129
5010VDU23,245,0,64,64,64,95,96,64,64
5020VDU23,246,0,0,0,0,31,160,160,160
5030VDU23,247,0,32,32,32,47,176,160,160
5040VDU23,248,129,193,190,128,128,128,128,191
5050VDU23,249,64,64,64,0,0,0,0,255
5060VDU23,250,160,160,159,0,0,0,0,255
5070VDU23,251,160,176,47,0,0,0,0,255
5080VDU23,252,0,0,0,0,143,80,80,80
5090VDU23,253,0,0,0,0,144,72,69,66
5100VDU23,254,0,0,0,0,64,128,0,0
5120VDU23,255,80,80,143,0,0,0,0,255
5130VDU23,240,69,72,144,0,0,0,0,255
5140VDU23,241,0,128,64,32,16,8,4,242
5900 ENDPROC
30000REM Desk Enviroment
30005REM PCW Dec.85,p233
30010:
30020DEFPROCtitle2(width%,title$)
30021LOCALw%,len%
30022w%=width%:len%=LENtitle$:IF     width%MOD2=1     width%=width%+1:IF
len%=width%ORlen%=width%-1     PROCt3     ELSEIFlen%<width%-8     PROCt1
```

```
ELSEIFlen%>=width%-8 PROCt2
30023PRINTTAB(0,1)title$;
30024ENDPROC
30030:
30060DEFPROCscreen
30065*FX19
30070X%=0:%=0:VDU23,1,0;0;0;0;19,7,0;0;:CALLshade:PROCwindow(1,2,38,2):VDU3
1,1,0,224:PROCwindow(1,28,38,5):VDU19,7,7;0;
30075ENDPROC
30080:
30085DEFPROCtitle(width%,title$)
30090LOCALw%,len%
30095w%=width%:len%=LENtitle$:IF      width%MOD2=1       width%=width%+1:IF
len%=width%ORlen%=width%-1      PROCt3       ELSEIFlen%<width%-8      PROCt1
ELSEIFlen%>=width%-8 PROCt2
30100PRINTTAB(0,1)title$TAB(0,2)STRING$(w%,"_")
30105ENDPROC
30110:
30115DEFPROCt1
30120title$=CHR$225+CHR$226+CHR$227+STRING$((width%-6-len%)DIV2,CHR$228)+ti
tle$+STRING$((width%-len%)DIV2+len%MOD2,CHR$228)
30125ENDPROC
30130:
30135DEFPROCt2
30140title$=STRING$((width%-len%)DIV2,CHR$228)+title$+STRING$((width%-len%)
DIV2+len%MOD2,CHR$228)
30145ENDPROC
30150:
30155DEFPROCt3
30160ENDPROC
30165:
30170DEFPROCinput(x%,y%,len%,ch$)
30175LOCALcount%,key$
30180ret$="":count%=0
30185REPEAT
30190REPEAT
30195key$=GET$
30200UNTILkey$=CHR$13ORkey$=CHR$127ORINSTR(ch$,key$)
30205IFINSTR(ch$,key$)ANDcount%<len% PROCchr  ELSEIFkey$=CHR$127ANDcount%>0
PROCdel
30210PRINTTAB(x%,y%)ret$;
30215UNTILkey$=CHR$13
30220ENDPROC
30225:
30230DEFPROCchr
30235ret$=ret$+key$:count%=count%+1
30240ENDPROC
30245:
30250DEFPROCdel
30255VDU31,x%-1+LENret$,y%,32:ret$=LEFT$(ret$,LENret$-1):count%=count%-1
30260ENDPROC
30265:
30270DEFPROCdbl(x%,y%,a$)
30275LOCALa%,c%
30280FORa%=1 TOLENa$:c%=&C000+(ASC(MID$(a$,a%,1))-32)*8
30285VDU23,229,?c%,?c%,?(c%+1),?(c%+1),?(c%+2),?(c%+2),?(c%+3),?(c%+3),23,2
30,?(c%+4),?(c%+4),?(c%+5),?(c%+5),?(c%+6),?(c%+6),?(c%+7),?(c%+7),31,x%,y%,
229,31,x%,y%+1,230:x%=x%+1:NEXT
```

```
30290ENDPROC
30295:
30300DEFPROCtime(a%,b%,c%,d%)
30305LOCALh$,m$,h%,m%
30310h$="":m$="":VDU28,1,2,38,2:h%=(TI.DIV360000)MOD12:m%=TI.DIV6000)MOD60
30315IFh%=0 h$="12" ELSE h$=RIGHT$(" "+STR$h%,2)
30320IFm%=0 m$="00" ELSE m$=RIGHT$("0"+STR$m%,2)
30325PRINTTAB(26,0;"Time: ";h$+":"+m$;:VDU28,a%,b%,c%,d%
30330ENDPROC
30335:
30340DEFPROCwindow(a%,b%,c%,d%)
30345VDU18,0,128,24,a%*32-4;1023-(b%+1)*32;(c%+1)*32;1023-d%*32+4;16,24,a%*
32+8;1023-(b%+1)*32-8;(c%+1)*32+8;1023-d%*32-8;16,17,135,17,0,24,a%*32;1023-
(b%+1)*32;(c%+1)*32;1023-d%*32;28,a%,b%,c%,d%,12
30350ENDPROC
30355:
30360DEFPROCtime_set
30365LOCALh%,m%,s%
30370CLS:PROCtitle(38," Time Set "):PRINTTAB(1,6)"Enter hours    (1-12)":
[                                     ]":REP.P.TAB(26,6)"
":PROCinput(26,6,2,"0123456789"):U.VALret$>0A.VALret$<=12:h%=VALret$
30375PRINTTAB(1,9)"Enter minutes  (0-59):     [    ]":REPEATPRINTTAB(26,9)"
":PROCinput(26,9,2,"0123456789"):UNTILVALret$<=59:m%=VALret$
30380PRINTTAB(1,12)"Enter seconds (0-59):     [    ]":REPEATPRINTTAB(26,12)"
":PROCinput(26,12,2,"0123456789"):UNTILVALret$<=59:s%=VALret$
30385TIME=100*s%+6000*m%+36000*h%:PROCtime(1,28,38,5):CLS
30390ENDPROC
30395:
30400DEFPROCmove(size,source,dest)
30405X%=0:Y%=0:!SIZE=size:!SOURCE=source:!DEST=dest:CALLmove
30410ENDPROC
30415:
30420DEFFNschr(x%,y%)
30425VDU31,x%,y%:A%=135
30430=(USR(&FFF4)AND&FFFF)DIV&100
30435:
30440DEFPROCmouse(x%,y%,a%,b%,c%,d%)
30445X%=0:Y%=0:GCOL0,0:VDU5:*FX11,1
30450*FX12,1
30455REPEAT
30460PROCmove(8,FNsta(x%,y%),22000):PROCmove(8,FNsta(x%,y%+1),22008):*FX15,
0
30465PROCprint:REPEATUNTILADVAL(-1)<>0
30470PROCmove(8,22000,FNsta(x%,y%)):PROCmove(8,22008,FNsta(x%,y%+1))
30475IF INKEY-122 IFx%<c% x%=x%+1 ELSE IF INKEY-26 IFx%>a% x%=x%-1
30480IF INKEY-42 IFy%<b% y%=y%+1 ELSE IF INKEY-58 IFy%>d% y%=y%-1
30485UNTILINKEY-74
30490VDU4:*FX12,0
30495X%=x%:Y%=y%:*FX15,0
30500ENDPROC
30505:
30510DEFPROCprint
30515MOVEFNpos(x%),1023-FNpos(y%):VDU231:MOVEFNpos(x%),1023-FNpos(y%+1):VDU
232
30520ENDPROC
30525:
30530DEFFNpos(p%)=p%*8*4
30535DEFFNsta(x%,y%)=22528+y%*320+x%*8
```

```
30540:
30545DEFPROCinit
30550PROCass:VDU23,221,24,60,60,126,0,126,60,0,23,225,252,0,252,0,252,0,252
,0,23,226,255,129,129,129,129,129,255,0,23,227,63,0,63,0,63,0,63,0,23,228,25
5,0,255,0,255,0,255,0,23,231,0,128,192,224,240,248,252,254
30555VDU23,232,255,252,218,216,140,12,6,6:TIME=100*0+6000*0+360000*6
30560ENDPROC
30565:
30570DEFPROCass
30575DIM              space%              35:FORpass%=0             TO2
STEP2:P%=space%:[OPTpass%:.shade:LDA£22528             MOD256:STA&70:LDA£22528
DIV256:STA&71:LDX£10241
DIV256:LDY£0:.loop:LDA£170:STA(&70),Y:EOR£255:INY:STA(&70),Y:INY:BNEloop:INC
&71:DEX:BNEloop:RTS:]NEXT
30580SIZE=&70:SOURCE=&72:DEST=&74:DIM                                  move
40:FORi%=0TO2STEP2:P%=move:[OPTi%:LDY£0:LDXSIZE+1:BEQli:.l:LDA(SOURCE),Y:STA
(DEST),Y:INY:BNEl:INCSOURCE+1:INCDEST+1:DEX:BNEl:.li:LDXSIZE:BEQdo:.ll:LDA(S
OURCE),Y:STA(DEST),Y:INY:DEX:BNEll:.do:RTS
30585]NEXT
30590ENDPROC
```

LISTING OF PROGRAM "AUTO1"

```
   5 *FX15,1
  10 REM AUTOMATIC CONTROL PROGRAM 1
  20 REM DRIVE MOTOR1 AT CONSTANT SPEED
  30 REM READ ULTRASONOSCOPE AND STEER MOTOR 2 ON RESULT
  40 REM DRIVE CURRENT AT PRESET LEVEL
  60 *KEY10 CH."AUTO"|M
  65 WIND$=CHR$(157)+CHR$(132)+"        "+CHR$(156)+CHR$(135)
  70 MODE7
  72 K%=6500
  75 G%=0:D%=0:L%=0:F%=0
  80 A=0:C%=0:P=1:S=0:S%=20
  85 CLO=0:CHI=4:PLO=1:PHI=10:SLO%=20:SHI%=100
  90 PROCscreen1
 100 IF A$=" " THEN CHAIN"AUTO"
 110 PROCscreen2
 120 GOTO 90
 999 END
1000 DEFPROCinit1
1010 CLS
1020 PRINT TAB(0,1);"Automatic steering      set up screen";
1030 PRINT TAB(0,4);"C = set current level (0-4 Amps)"
1040 PRINT WIND$;
1050 PRINT TAB(0,7);"P = set steering gain (1-10)"
1060 PRINT WIND$;
1070 PRINT TAB(0,10);"S = set travel speed (2-10 mm/sec)"
1080 PRINT WIND$;
1090 PRINT TAB(0,13);"G = go to control screen";
1100 PRINT TAB(0,23);"press SPACE to return to menu";
1110 PRINT TAB(2,5);A;"   ";
1120 PRINT TAB(2,8);P;"   ";
1130 PRINT TAB(2,11);S%/10;"    ";
1140 ENDPROC
1500 DEFPROCinit2
1505 CLS
1510 PRINT TAB(0,1);"Automatic steering     control screen";
1520 PRINT TAB(0,3);"Controls :-"
1530 PRINT "G = go               S = stop"
1540 PRINT "C = current ON       O = current OFF"
1550 PRINT "F = forward          B = back"
1565 PRINT TAB(0,9);"Travel speed - ";S%/10;" mm/sec."
1570 PRINT "Steering gain - ";P
1580 PRINT "Current value - ";A;" Amps";TAB(26,11);WIND$
1590 PRINT TAB(28,11);
1600 IF F%=0 THEN PRINT "  OFF"; ELSE PRINT "  ON ";
1610 PRINT TAB(0,13);WIND$;TAB(20,13);WIND$;
1620 PRINT TAB(2,13);:IF G%=0 THEN PRINT " STOP"; ELSE PRINT "  GO ";
1630 PRINT TAB(22,13);:IF D%=0 THEN PRINT "FORWARD"; ELSE PRINT " BACK  ";
1640 PRINT TAB(0,15);"Ultrasonoscope readings"
1650 PRINT "First reflection    Second reflection"
1660 PRINT TAB(0,17);WIND$;TAB(20,17);WIND$;
1670 PROCreadtimer
1675 V%=R1%
1680 PRINT TAB(0,23);"(press SPACE to return to setup screen)";
1690 ENDPROC
2000 DEFPROCscreen1
```

```
2010 PROCinit1
2020 REPEAT
2030 REPEAT
2040 A%=INKEY(10)
2050 UNTIL NOT A%
2060 A$=CHR$(A%)
2070 IF A$="C" THEN PROCcurrent
2080 IF A$="P" THEN PROCgain
2090 IF A$="S" THEN PROCspeed
2100 UNTIL A$=" " OR A$="G"
2110 ENDPROC
2200 DEFPROCcurrent
2210 PRINT TAB(0,5);WIND$
2220 PRINT TAB(2,5);:INPUT A
2230 IF A<CLO THEN A=CLO ELSE IF A>CHI THEN A=CHI
2240 A=(INT(A*100))/100
2250 PRINT TAB(0,5);WIND$;TAB(2,5);A;
2260 C%=INT(A*63.75)
2280 ENDPROC
2300 DEFPROCgain
2310 PRINT TAB(0,8);WIND$
2320 PRINT TAB(2,8);:INPUT P
2330 IF P<PLO THEN P=PLO ELSE IF P>PHI THEN P=PHI
2335 P=(INT(P*100))/100
2340 PRINT TAB(0,8);WIND$
2350 PRINT TAB(2,8);P;
2360 ENDPROC
2400 DEFPROCspeed
2410 PRINT TAB(0,11);WIND$
2420 PRINT TAB(2,11);:INPUT S
2430 S%=INT(S*10)
2440 IF S%<SLO% THEN S%=SLO% ELSE IF S%>SHI% THEN S%=SHI%
2450 PRINT TAB(0,11);WIND$;
2460 PRINT TAB(2,11);S%/10;
2470 ENDPROC
3000 DEFPROCscreen2
3010 PROCinit2
3020 REPEAT
3030 REPEAT
3040 A%=INKEY(50)
3050 PROCreadtimer
3060 UNTIL NOT A%
3070 A$=CHR$(A%)
3080 IF A$="S" THEN PROCstop
3090 IF A$="G" THEN PROCgo
3100 IF A$="C" THEN PROCon
3110 IF A$="O" THEN PROCoff
3140 IF A$="F" THEN PROCfore
3150 IF A$="B" THEN PROCback
3160 UNTIL A$=" "
3170 ?&FD80=0:?&FD90=0:?&FD91=0:?&FDA0=0
3180 G%=0:D%=0:L%=0:F%=0
3190 ENDPROC
3500 DEFPROCstop
3510 G%=0:F%=0
3520 ?&FD90=0:?&FD91=0:?&FDA0=0
3530 PRINT TAB(2,13);" STOP    ";TAB(28,11);"  OFF";
3540 ENDPROC
```

```
30495X%=x%:Y%=y%:*FX15,0
30500ENDPROC
30505:
30510DEFPROCprint
30515MOVEFNpos(x%),1023-FNpos(y%):VDU231:MOVEFNpos(x%),1023-FNpos(y%+1):VDU232
30520ENDPROC
30525:
30530DEFFNpos(p%)=p%*8*4
30535DEFFNsta(x%,y%)=22528+y%*320+x%*8
30540:
30545DEFPROCinit
30550PROCass:VDU23,224,24,60,60,126,0,126,60,0,23,225,252,0,252,0,252,0,252,0,2
3,226,255,129,129,129,129,129,255,0,23,227,63,0,63,0,63,0,63,0,23,228,255,0,255,
0,255,0,255,0,23,231,0,128,192,224,240,248,252,254
30555VDU23,232,255,252,248,216,140,12,6,6:TIME=100*0+6000*0+360000*6
30560ENDPROC
30565:
30570DEFPROCass
30575DIM  space% 35:FORpass%=0  TO2  STEP2:P%=space%:[OPTpass%:.shade:LDA£22528
MOD256:STA&70:LDA£22528                                DIV256:STA&71:LDX£10241
DIV256:LDY£0:.loop:LDA£170:STA(&70),Y:EOR£255:INY:STA(&70),Y:INY:BNEloop:INC&71:
DEX:BNEloop:RTS:]NEXT
30580SIZE=&70:SOURCE=&72:DEST=&74:DIM                                       move
40:FORi%=0TO2STEP2:P%=move:[OPTi%:LDY£0:LDXSIZE+1:BEQli:.l:LDA(SOURCE),Y:STA(DES
T),Y:INY:BNEl:INCSOURCE+1:INCDEST+1:DEX:BNEl:.li:LDXSIZE:BEQdo:.ll:LDA(SOURCE),Y
:STA(DEST),Y:INY:DEX:BNEll:.do:RTS
30585]NEXT
30590ENDPROC
```

```
3550 DEFPROCgo
3560 IF E%=0 THEN PROCgood ELSE PRINT TAB(2,13);"No timer";
3570 ENDPROC
3600 DEFPROCgood
3605 V%=R1%:G%=1
3610 T%=INT((K%/S%)*10)
3620 ?&FD96=T%MOD256
3630 ?&FD97=T%DIV256
3640 ?&FD90=2*D%+G%
3645 ?&FDA0=2*L%+G%
3650 PRINT TAB(2,13);"  GO    ";
3660 ENDPROC
3700 DEFPROCon
3710 F%=1
3720 ?&FD91=C%
3730 PRINT TAB(28,11);"  ON ";
3740 ENDPROC
3800 DEFPROCoff
3810 F%=0
3820 ?&FD91=0
3830 PRINT TAB(28,11);"  OFF";
3840 ENDPROC
3900 DEFPROCfore
3910 D%=0
3920 ?&FD90=2*D%+G%
3930 PRINT TAB(22,13);"FORWARD";
3940 ENDPROC
4000 DEFPROCback
4010 D%=1
4020 ?&FD90=2*D%+G%
4030 PRINT TAB(22,13);" BACK  ";
4040 ENDPROC
4300 DEFPROCsend
4310 ?&FDA0=2*L%+G%
4320 FOR I%=1 TO P%
4330 ?&FDA5=3
4340 MARK=TIME
4350 REPEAT:UNTIL TIME=MARK+1
4360 NEXT I%
4370 ENDPROC
5000 DEFPROCreadtimer
5010 ?&FD80=4
5015 M=TIME:REPEAT:UNTIL TIME>M+1
5020 E%=?&FD80 AND 8
5030 L2%=?&FD81
5040 ?&FD80=5
5050 H2%=?&FD81
5060 ?&FD80=6
5070 L1%=?&FD81
5080 ?&FD80=7
5090 H1%=?&FD81
5100 ?&FD80=0
5120 R1%=H1%*256+L1%
5130 R2%=H2%*256+L2%
5140 PRINT TAB(2,17);R1%/10;TAB(22,17);R2%/10;
5150 IF E% THEN PRINT TAB(22,17);" Error "; ELSE IF G%=1 THEN PROCcalc
5160 ENDPROC
6000 DEFPROCcalc
```

```
6010 P%=V%-R1%
6020 L%=1*SGN(P%)
6030 P%=INT(P*ABS(P%))
6040 IF P%=0 THEN ENDPROC
6050 ?&FDA0=2*L%+G%
6060 FOR I%=1 TO P%
6070 ?&FDA5=3
6080 MARK=TIME
6090 REPEAT:UNTIL TIME>MARK+1
6100 NEXT I%
6110 ENDPROC
```

LISTING OF "AUTO2"

```
5 *FX15,1
10 REM AUTOMATIC CONTROL PROGRAM 2
20 REM DRIVE MOTOR1 AT CONSTANT SPEED
30 PEM READ ULTRASONOSCOPE AND STEER MOTOR 2 TO KEEP REFLECTION 1 CONSTANT
40 REM DRIVE CURRENT TO KEEP WELD DEPTH CONSTANT
50 REM DEPTH IS PROPORTIONAL TO DIFFERENCE IN TIMER REFLECTIONS
55
60 *KEY10 CH."AUTO"|M
65 WIND$=CHR$(157)+CHR$(132)+"        "+CHR$(156)+CHR$(135)
70 MODE7
72 K%=6500:DK=1:DG=0.1:DJ=10
75 G%=0:D%=0:L%=0:F%=0
80 D=1:A=0:C%=0:P=1:S=0:S%=20
85 CLO=0:CHI=4:PLO=1:PHI=10:SLO%=20:SHI%=100
86 DLO=0:DHI=10
90 PROCscreen1
100 IF A$=" " THEN CHAIN"AUTO"
110 PROCscreen2
120 GOTO 90
130 END
999
1000 DEFPROCinit1
1010 CLS
1020 PRINT TAB(0,1);"Auto steering & depth    set up screen";
1030 PRINT TAB(0,4);"D = set target depth (mm)"
1040 PRINT WIND$;
1050 PRINT TAB(0,7);"P = set steering gain (1-10)"
1060 PRINT WIND$;
1070 PRINT TAB(0,10);"S = set travel speed (2-10 mm/sec)"
1080 PRINT WIND$;
1090 PRINT TAB(0,13);"G = go to control screen";
1100 PRINT TAB(0,23);"press SPACE to return to menu";
1110 PRINT TAB(2,5);D;"   ";
1120 PRINT TAB(2,8);P;"   ";
1130 PRINT TAB(2,11);S%/10;"    ";
1140 PRINT TAB(0,15);"Ultrasonoscope readings"
1150 PRINT "First        Second       Difference"
1160 PRINT TAB(0,17);WIND$;TAB(13,17);WIND$;TAB(26,17);WIND$;
1170 PROCreadtimer
1400 ENDPROC
1490
1500 DEFPROCinit2
1505 CLS
1510 PRINT TAB(0,1);"Auto steering & depth    set up screen";
1520 PRINT TAB(0,3);"Controls :-"
1530 PRINT "G = go                S = stop"
1540 PRINT "C = current ON        O = current OFF"
1550 PRINT "F = forward           B = back"
1565 PRINT TAB(0,9);"Travel speed - ";S%/10;" mm/sec."
1570 PRINT "Steering gain - ";P
1580 PRINT "Current value - ";A;" Amps";TAB(26,11);WIND$
1590 PRINT TAB(28,11);
1600 IF F%=0 THEN PRINT "  OFF"; ELSE PRINT "  ON ";
1610 PRINT TAB(0,13);WIND$;TAB(20,13);WIND$;
1620 PRINT TAB(2,13);:IF G%=0 THEN PRINT " STOP"; ELSE PRINT "  GO ";
1630 PRINT TAB(22,13);:IF D%=0 THEN PRINT "FORWARD"; ELSE PRINT " BACK  ";
```

```
1640 PRINT TAB(0,15);"Ultrasonoscope readings"
1650 PRINT "First        Second        Difference"
1660 PRINT TAB(0,17);WIND$;TAB(13,17);WIND$;TAB(26,17);WIND$;
1670 PROCreadtimer
1675 V%=R1%
1680 PRINT TAB(0,23);"(press SPACE to return to setup screen)";
1690 ENDPROC
1990
2000 DEFPROCscreen1
2010 PROCinit1
2020 REPEAT
2030 REPEAT
2040 A%=INKEY(50)
2045 PROCreadtimer
2050 UNTIL NOT A%
2060 A$=CHR$(A%)
2070 IF A$="D" THEN PROCcurrent
2080 IF A$="P" THEN PROCgain
2090 IF A$-"S" THEN PROCspeed
2100 UNTIL A$=" " OR A$="G"
2110 ENDPROC
2190
2200 DEFPROCcurrent
2210 PRINT TAB(0,5);WIND$
2220 PRINT TAB(2,5);:INPUT D
2230 IF D<DLO THEN D=DLO ELSE IF D>DHI THEN D=DHI
2240 D=(INT(D*100))/100
2250 PRINT TAB(0,5);WIND$;TAB(2,5);D;
2255 A=DK*D:REM FIRST GUESS TO START
2260 C%=INT(A*63.75)
2270 D%=INT(DJ*D)
2280 ENDPROC
2290
2300 DEFPROCgain
2310 PRINT TAB(0,8);WIND$
2320 PRINT TAB(2,8);:INPUT P
2330 IF P<PLO THEN P=PLO ELSE IF P>PHI THEN P=PHI
2335 P=(INT(P*100))/100
2340 PRINT TAB(0,8);WIND$
2350 PRINT TAB(2,8);P;
2360 ENDPROC
2390
2400 DEFPROCspeed
2410 PRINT TAB(0,11);WIND$
2420 PRINT TAB(2,11);:INPUT S
2430 S%=INT(S*10)
2440 IF S%<SLO% THEN S%=SLO% ELSE IF S%>SHI% THEN S%=SHI%
2450 PRINT TAB(0,11);WIND$;
2460 PRINT TAB(2,11);S%/10;
2470 ENDPROC
2990
3000 DEFPROCscreen2
3010 PROCinit2
3020 REPEAT
3030 REPEAT
3040 A%=INKEY(50)
3050 PROCreadtimer
3060 UNTIL NOT A%
```

```
3070 A$=CHR$(A%)
3080 IF A$="S" THEN PROCstop
3090 IF A$="G" THEN PROCgo
3100 IF A$="C" THEN PROCon
3110 IF A$="O" THEN PROCoff
3140 IF A$="F" THEN PROCfore
3150 IF A$="B" THEN PROCback
3160 UNTIL A$=" "
3170 ?&FD80=0:?&FD90=0:?&FD91=0:?&FDA0=0
3180 G%=0:D%=0:L%=0:F%=0
3190 ENDPROC
3190
3500 DEFPROCstop
3510 G%=0:F%=0
3520 ?&FD90=0:?&FD91=0:?&FDA0=0
3530 PRINT TAB(2,13);" STOP   ";TAB(28,11);"  OFF";
3540 ENDPROC
3545
3550 DEFPROCgo
3560 IF E%=0 THEN PROCgood ELSE PRINT TAB(2,13);"No timer";
3570 ENDPROC
3590
3600 DEFPROCgood
3605 V%-P1%:G%-1
3610 T%=INT((K%/S%)*10)
3620 ?&FD96=T%MOD256
3630 ?&FD97=T%DIV256
3640 ?&FD90=2*D%+G%
3645 ?&FDA0=2*L%+G%
3650 PRINT TAB(2,13);"  GO    ";
3660 ENDPROC
3690
3700 DEFPROCon
3710 F%=1
3720 ?&FD91=C%
3730 PRINT TAB(28,11);"  ON ";
3740 ENDPROC
3790
3800 DEFPROCoff
3810 F%=0
3820 ?&FD91=0
3830 PRINT TAB(28,11);"  OFF";
3840 ENDPROC
3890
3900 DEFPROCfore
3910 D%=0
3920 ?&FD90=2*D%+G%
3930 PRINT TAB(22,13);"FORWARD";
3940 ENDPROC
3990
4000 DEFPROCback
4010 D%=1
4020 ?&FD90=2*D%+G%
4030 PRINT TAB(22,13);" BACK  ";
4040 ENDPROC
4290
4300 DEFPROCsend
4310 ?&FDA0=2*L%+G%
```

```
4320 FOR I%=1 TO P%
4330 ?&FDA5=3
4340 MARK=TIME
4350 REPEAT:UNTIL TIME=MARK+1
4360 NEXT I%
4370 ENDPROC
4990
5000 DEFPROCreadtimer
5010 ?&FD80=4
5015 M=TIME:REPEAT:UNTIL TIME>M+1
5020 E%=?&FD80 AND 8
5030 L2%=?&FD81
5040 ?&FD80=5
5050 H2%=?&FD81
5060 ?&FD80=6
5070 L1%-?&FD81
5080 ?&FD80=7
5090 H1%=?&FD81
5100 ?&FD80=0
5120 P1%=H1%*256+L1%
5130 P2%=H2%*256+L2%
5140 PRINT TAB(2,17);R1%/10;TAB(15,17);R2%/10;TAB(28,17);(R2%-R1%)/10
5150 IF E% THEN PRINT TAB(15,17);" Error "; ELSE IF G%=1 THEN PROCcalc
5160 ENDPROC
5990
6000 DEFPROCcalc
6010 P%=V%-P1%
6020 L%=1*SGN(P%)
6030 P%=INT(P*ABS(P%))
6040 IF P%=0 THEN ENDPROC
6050 ?&FDA0=2*L%+G%
6060 FOR I%=1 TO P%
6070 ?&FDA5=3
6080 MARK=TIME
6090 REPEAT:UNTIL TIME>MARK+1
6100 NEXT I%
6110 C%=C%+INT(DG*(R2%-R1%-D%))
6120 ?&FD91=C%
6990 ENDPROC
```

Listing of program "menu1"

```
0*DRIVE 0
5ON ERROR MODE7:END
6*KEY10 CH."MENU1"!M
10 DIM A$(5)
20 A$(0)="Test programs":A$(1)="Manual control":A$(2)="Automatic":A$(3)="Utilities":A$(4)="Quit"
40MODE4
50VDU19,0,4;0;0;
60PROCinit
65PROCinit2
66CALLshade
70 PRINTTAB(1,31);" phobox electronics   tel. 0305 853767";
71 PROCwindow(1,4,10,1)
72PRINTTAB(1,1);"          ";
73PRINTTAB(1,2);" ";CHR$(244);CHR$(245);CHR$(246);CHR$(247);CHR$(252);CHR$(253);CHR$(254);" ";
74PRINTTAB(1,3);" ";CHR$(248);CHR$(249);CHR$(250);CHR$(251);CHR$(255);CHR$(240);CHR$(241);" ";
75PRINTTAB(1,4);"          ";
76 PROCwindow(1,16,18,6)
77 PRINT TAB(0,1);" ELIAS' PROGRAMS "
78 PRINT TAB(0,3);"    Main Menu     "
80 PRINT TAB(2,6);"Choose submenu"
85 PRINT TAB(2,8);"Use arrow keys"
86 PRINT "  and RETURN  ";
90PROCwindow(22,5,37,1)
100PROCtitle(16,A$(0))
120PROCwindow(22,11,37,7)
130PROCtitle(16,A$(1))
150PROCwindow(22,17,37,13)
160PROCtitle(16,A$(2))
180PROCwindow(22,23,37,19)
190PROCtitle(16,A$(3))
195PROCwindow(22,29,37,25)
200PROCtitle(16,A$(4))
210VDU24,21*32;1023-30*32;29*32;1023;
220PROCmouse(25,2,22,28,26,1)
225G%=(Y%-1)DIV6
240*FX15,0
260CALLshade:PROCwindow(10,19,30,12):PROCtitle(21,"Loading :-")
270PRINT'A$(G%);
280 IF G%=0 THEN CHAIN"TEST"
290 IF G%=1 THEN CHAIN"MANUAL"
300 IF G%=2 THEN CHAIN"AUTO"
310 IF G%=3 THEN CHAIN"UTILS"
320 MODE7
360END
3595DEF PROCchrprint(chr%)
3600VDUchr%,chr%+2,8,8,10,chr%+1,chr%+3
3605ENDPROC
4990 DEFPROCinit2
5000VDU23,244,0,0,0,0,190,193,129,129
5010VDU23,245,0,64,64,64,95,96,64,64
5020VDU23,246,0,0,0,0,31,160,160,160
```

```
5030VDU23,247,0,32,32,32,47,176,160,160
5040VDU23,248,129,193,190,128,128,128,128,191
5050VDU23,249,64,64,64,0,0,0,0,255
5060VDU23,250,160,160,159,0,0,0,0,255
5070VDU23,251,160,176,47,0,0,0,0,255
5080VDU23,252,0,0,0,0,143,80,80,80
5090VDU23,253,0,0,0,0,144,72,69,66
5100VDU23,254,0,0,0,0,64,128,0,0
5120VDU23,255,80,80,80,143,0,0,0,0,255
5130VDU23,240,69,72,144,0,0,0,0,255
5140VDU23,241,0,128,64,32,16,8,4,242
5900 ENDPROC
30000REM Desk Enviroment
30005REM PCW Dec.85,p233
30010:
30060DEFPROCscreen
30065*FX19
30070X%-0:%-0:VDU23,1,0;0;0;0;19,7,0;0;:CALLshade:PROCwindow(1,2,38,2):VDU31,1,
0,224:PROCwindow(1,28,38,5):VDU19,7,7;0;
30075ENDPROC
30080:
30085DEFPROCtitle(width%,title$)
30090LOCALw%,len%
30095w%-width%:len%=LENtitle$:IF        width%MOD2=1         width%=width%+1:IF
len%=width%ORlen%=width%-1        PROCt3       ELSEIFlen%<width%-8        PROCt1
ELSEIFlen%>=width%-8 PROCt2
30100PRINTTAB(0,1)title$TAB(0,2)STRING$(w%,"_")
30105ENDPROC
30110:
30115DEFPROCt1
30120title$=CHR$225+CHR$226+CHR$227+STRING$((width%-6-len%)DIV2,CHR$228)+title$
+STRING$((width%-len%)DIV2+len%MOD2,CHR$228)
30125ENDPROC
30130:
30135DEFPROCt2
30140title$=STRING$((width%-len%)DIV2,CHR$228)+title$+STRING$((width%-len%)DIV2
+len%MOD2,CHR$228)
30145ENDPROC
30150:
30155DEFPROCt3
30160ENDPROC
30165:
30170DEFPROCinput(x%,y%,len%,ch$)
30175LOCALcount%,key$
30180ret$="":count%=0
30185REPEAT
30190REPEAT
30195key$=GET$
30200UNTILkey$=CHR$13ORkey$=CHR$127ORINSTR(ch$,key$)
30205IFINSTR(ch$,key$)ANDcount%<len%   PROCchr    ELSEIFkey$=CHR$127ANDcount%>0
PROCdel
30210PRINTTAB(x%,y%)ret$;
30215UNTILkey$=CHR$13
30220ENDPROC
30225:
30230DEFPROCchr
30235ret$=ret$+key$:count%=count%+1
30240ENDPROC
```

```
30245:
30250DEFPROCdel
30255VDU31,x%-1+LENret$,y%,32:ret$=LEFT$(ret$,LENret$-1):count%=count%-1
30260ENDPROC
30265:
30270DEFPROCdbl(x%,y%,a$)
30275LOCALa%,c%
30280FORa%=1 TOLENa$:c%=&C000+(ASC(MID$(a$,a%,1))-32)*8
30285VDU23,229,?c%,?c%,?(c%+1),?(c%+1),?(c%+2),?(c%+2),?(c%+3),?(c%+3),23,230,?
(c%+4),?(c%+4),?(c%+5),?(c%+5),?(c%+6),?(c%+6),?(c%+7),?(c%+7),31,x%,y%,229,31,x
%,y%+1,230:x%=x%+1:NEXT
30290ENDPROC
30295:
30300DEFPROCtime(a%,b%,c%,d%)
30305LOCALh$,m$,h%,m%
30310h$="":m$="":VDU28,1,2,38,2:h%=(TI.DIV360000)MOD12:m%=TI.DIV6000)MOD60
30315IFh%=0 h$="12" ELSE h$=RIGHT$(" "+STR$h%,2)
30320IFm%=0 m$="00" ELSE m$=RIGHT$("0"+STR$m%,2)
30325PRINTTAB(26,0;"Time: ";h$+":"+m$;:VDU28,a%,b%,c%,d%
30330ENDPROC
30335:
30340DEFPROCwindow(a%,b%,c%,d%)
30345VDU18,0,128,24,a%*32-4;1023-(b%+1)*32;(c%+1)*32;1023-d%*32+4;16,24,a%*32+8
;1023-(b%+1)*32-8;(c%+1)*32+8;1023-d%*32-8;16,17,135,17,0,24,a%*32;1023-(b%+1)*3
2;(c%+1)*32;1023-d%*32;28,a%,b%,c%,d%,12
30350ENDPROC
30355:
30360DEFPROCtime_set
30365LOCALh%,m%,s%
30370CLS:PROCtitle(38," Time Set  "):PRINTTAB(1,6)"Enter hours   (1-12)":    [
]":REP.P.TAB(26,6)"
":PROCinput(26,6,2,"0123456789"):U.VALret$>0A.VALret$<=12:h%=VALret$
30375PRINTTAB(1,9)"Enter  minutes  (0-59):       [    ]":REPEATPRINTTAB(26,9)"
":PROCinput(26,9,2,"0123456789"):UNTILVALret$<=59:m%=VALret$
30380PRINTTAB(1,12)"Enter  seconds (0-59):       [    ]":REPEATPRINTTAB(26,12)"
":PROCinput(26,12,2,"0123456789"):UNTILVALret$<=59:s%=VALret$
30385TIME=100*s%+6000*m%+36000*h%:PROCtime(1,28,38,5):CLS
30390ENDPROC
30395:
30400DEFPROCmove(size,source,dest)
30405X%=0:Y%=0:!SIZE=size:!SOURCE=source:!DEST=dest:CALLmove
30410ENDPROC
30415:
30420DEFFNschr(x%,y%)
30425VDU31,x%,y%:A%=135
30430=(USR(&FFF4)AND&FFFF)DIV&100
30435:
30440DEFPROCmouse(x%,y%,a%,b%,c%,d%)
30445X%=0:Y%=0:GCOL0,0:VDU5:*FX11,1
30450*FX12,1
30455REPEAT
30460PROCmove(8,FNsta(x%,y%),22000):PROCmove(8,FNsta(x%,y%+1),22008):*FX15,0
30465PROCprint:REPEATUNTILADVAL(-1)<>0
30470PROCmove(8,22000,FNsta(x%,y%)):PROCmove(8,22008,FNsta(x%,y%+1))
30475IF INKEY-122 IFx%<c% x%=x%+1 ELSE IF INKEY-26 IFx%>a% x%=x%-1
30480IF INKEY-42 IFy%<b% y%=y%+1 ELSE IF INKEY-58 IFy%>d% y%=y%-1
30485UNTILINKEY-74
30490VDU4:*FX12,0
```

listing of program "temp"

```
5*KEY10 CH."TEST"|M
10 REM TEST PROGRAM - READ TIMER
15 PROCsetup
20 MODE7
30 PRINT TAB(0,1);"Test program        Read ultrasonoscope";
40 PRINT TAB(0,4);"First reflection    Second reflection";
45 PRINT TAB(0,23);"(press SPACE to return to menu)";
50 REPEAT
60 A$=INKEY$(50)
70 PROCreadtimer
80 IF E% THEN PROCerror
100 UNTIL A$=" "
105 PROCsetup
110 CHAIN"TEST"
1999 END
2000 DEFPROCreadtimer
2010 ?&FD80=4
2020 MARK=TIME
2030 REPEAT
2040 E%=?&FD80 AND 8
2050 UNTIL TIME=MARK+10 OR NOT E%
2060 PROCgetref
2070 PROCcalcref
2080 PROCprintref
2090 ENDPROC
3000 DEFPROCgetref
3010 L2%=?&FD81
3020 ?&FD80=5
3030 H2%=?&FD81
3040 ?&FD80=6
3050 L1%=?&FD81
3055 ?&FD80=7
3060 H1%=?&FD81
3070 ?&FD80=0
3080 ENDPROC
3100 DEFPROCcalcref
3110 R1%=H1%*256+L1%
3120 R2%=H2%*256+L2%
3130 ENDPROC
3200 DEFPROCprintref
3210 PRINT TAB(0,6);R1%/10;TAB(20,6);R2%/10;
3230 ENDPROC
3300 DEFPROCerror
3310 PRINT TAB(0,7);"(no response from ultrasonoscope)";
3320 ENDPROC
4000 DEFPROCsetup
4010 ?&FD83=0
4020 ?&FD82=&07
4030 ?&FD80=0
4040 ENDPROC
```

listing of program "utils"

```
0*DRIVE 0
5ON ERROR IF ERR=17THEN RUN ELSEREPORT:PRINT" at line ";ERL:END
6*KEY10 CH."MENU1"|M
7 DIMA$(5)
10 REM SUBMENU - UTILITIES
20 A$(0)="Disc catalogue":A$(1)="Main Menu"
40MODE4
50VDU19,0,4;0;0;
60PROCinit
65PROCinit2
70CALLshade
72 PROCwindow(1,3,20,1)
73 PRINTTAB(0,1);"      Utilities";
90PROCwindow(22,5,37,1)
100PROCtitle(16,A$(0))
110 PROCwindow(22,11,37,7)
120 PROCtitle(16,A$(1))
210VDU24,21*32;1023-30*32;29*32;1023;
220PROCmouse(25,2,22,11,26,1)
225G%=(Y%-1)DIV6
240*FX15,0
260CALLshade:PROCwindow(10,19,30,12):PROCtitle(21,"Loading :-")
270PRINT'A$(G%);
280 IF G%=0 THEN PROCcat:RUN
290 IF G%=1 THEN CHAIN"MENU1"
360END
1000 DEFPROCcat
1010 PROCwindow(1,30,38,1)
1020 *CAT
1025 PRINT
1030 PRINT"Press SPACE to continue";
1035 *FX15,0
1040 A=GET
1050 ENDPROC
3595DEF PROCchrprint(chr%)
3600VDUchr%,chr%+2,8,8,10,chr%+1,chr%+3
3605ENDPROC
4990 DEFPROCinit2
5000VDU23,244,0,0,0,0,190,193,129,129
5010VDU23,245,0,64,64,64,95,96,64,64
5020VDU23,246,0,0,0,0,31,160,160,160
5030VDU23,247,0,32,32,32,47,176,160,160
5040VDU23,248,129,193,190,128,128,128,128,191
5050VDU23,249,64,64,64,0,0,0,0,255
5060VDU23,250,160,160,159,0,0,0,0,255
5070VDU23,251,160,176,47,0,0,0,0,255
5080VDU23,252,0,0,0,0,143,80,80,80
5090VDU23,253,0,0,0,0,144,72,69,66
5100VDU23,254,0,0,0,0,64,128,0,0
5120VDU23,255,80,80,143,0,0,0,0,255
5130VDU23,240,69,72,144,0,0,0,0,255
5140VDU23,241,0,128,64,32,16,8,4,242
5900 ENDPROC
30000REM Desk Enviroment
30005REM PCW Dec.85,p233
```

```
30019:
30020DEFPROCtitle2(width%,title$)
30021LOCALw%,len%
30022w%=width%:len%=LENtitle$:IF        width%MOD2=1        width%=width%+1:IF
len%=width%ORlen%=width%-1        PROCt3        ELSEIFlen%<width%-8        PROCt1
ELSEIFlen%>=width%-8 PROCt2
30023PRINTTAB(0,1)title$;
30024ENDPROC
30030:
30060DEFPROCscreen
30065*FX19
30070X%=0:Y%=0:VDU23,1,0;0;0;0;19,7,0;0;:CALLshade:PROCwindow(1,2,38,2):VDU31,1,
0,224:PROCwindow(1,28,38,5):VDU19,7,7;0;
30075ENDPROC
30080:
30085DEFPROCtitle(width%,title$)
30090LOCALw%,len%
30095w%=width%:len%=LENtitle$:IF        width%MOD2=1        width%=width%+1:IF
len%=width%ORlen%=width%-1        PROCt3        ELSEIFlen%<width%-8        PROCt1
ELSEIFlen%>=width%-8 PROCt2
30100PRINTTAB(0,1)title$TAB(0,2)STRING$(w%,"_")
30105ENDPROC
30110:
30115DEFPROCt1
30120title$=CHR$225+CHR$226+CHR$227+STRING$((width%-6-len%)DIV2,CHR$228)+title$
+STRING$((width%-len%)DIV2+len%MOD2,CHR$228)
30125ENDPROC
30130:
30135DEFPROCt2
30140title$=STRING$((width%-len%)DIV2,CHR$228)+title$+STRING$((width%-len%)DIV2
+len%MOD2,CHR$228)
30145ENDPROC
30150:
30155DEFPROCt3
30160ENDPROC
30165:
30170DEFPROCinput(x%,y%,len%,ch$)
30175LOCALcount%,key$
30180ret$="":count%=0
30185REPEAT
30190REPEAT
30195key$=GET$
30200UNTILkey$=CHR$13ORkey$=CHR$127ORINSTR(ch$,key$)
30205IFINSTR(ch$,key$)ANDcount%<len%   PROCchr     ELSEIFkey$=CHR$127ANDcount%>0
PROCdel
30210PRINTTAB(x%,y%)ret$;
30215UNTILkey$=CHR$13
30220ENDPROC
30225:
30230DEFPROCchr
30235ret$=ret$+key$:count%=count%+1
30240ENDPROC
30245:
30250DEFPROCdel
30255VDU31,x%-1+LENret$,y%,32:ret$=LEFT$(ret$,LENret$-1):count%=count%-1
30260ENDPROC
30265:
30270DEFPROCdbl(x%,y%,a$)
```

```
30275LOCALa%,c%
30280FORa%=1 TOLENa$:c%=&C000+(ASC(MID$(a$,a%,1))-32)*8
30285VDU23,229,?c%,?c%,?(c%+1),?(c%+1),?(c%+2),?(c%+2),?(c%+3),?(c%+3),23,230,?
(c%+4),?(c%+4),?(c%+5),?(c%+5),?(c%+6),?(c%+6),?(c%+7),?(c%+7),31,x%,y%,229,31,x
%,y%+1,230:x%=x%+1:NEXT
30290ENDPROC
30295:
30300DEFPROCtime(a%,b%,c%,d%)
30305LOCALh$,m$,h%,m%
30310h$="":m$="":VDU28,1,2,38,2:h%=(TI.DIV360000)MOD12:m%=TI.DIV6000)MOD60
30315IFh%=0 h$="12" ELSE h$=RIGHT$(" "+STR$h%,2)
30320IFm%=0 m$="00" ELSE m$=RIGHT$("0"+STR$m%,2)
30325PRINTTAB(26,0;"Time: ";h$+":"+m$;:VDU28,a%,b%,c%,d%
30330ENDPROC
30335:
30340DEFPROCwindow(a%,b%,c%,d%)
30345VDU18,0,128,24,a%*32-4;1023-(b%+1)*32;(c%+1)*32;1023-d%*32+4;16,24,a%*32+8
;1023-(b%+1)*32-8;(c%+1)*32+8;1023-d%*32-8;16,17,135,17,0,24,a%*32;1023-(b%+1)*3
2;(c%+1)*32;1023-d%*32;28,a%,b%,c%,d%,12
30350ENDPROC
30355:
30360DEFPROCtime_set
30365LOCALh%,m%,s%
30370CLS:PROCtitle(38," Time Set  "):PRINTTAB(1,6)"Enter hours   (1-12)":    [
]":REP.P.TAB(26,6)"
":PROCinput(26,6,2,"0123456789"):U.VALret$>0A.VALret$<=12:h%=VALret$
30375PRINTTAB(1,9)"Enter  minutes  (0-59):       [    ]":REPEATPRINTTAB(26,9)"
":PROCinput(26,9,2,"0123456789"):UNTILVALret$<=59:m%=VALret$
30380PRINTTAB(1,12)"Enter  seconds (0-59):       [    ]":REPEATPRINTTAB(26,12)"
":PROCinput(26,12,2,"0123456789"):UNTILVALret$<=59:s%=VALret$
30385TIME=100*s%+6000*m%+36000*h%:PROCtime(1,28,38,5):CLS
30390ENDPROC
30395:
30400DEFPROCmove(size,source,dest)
30405X%=0:Y%=0:!SIZE=size:!SOURCE=source:!DEST=dest:CALLmove
30410ENDPROC
30415:
30420DEFFNschr(x%,y%)
30425VDU31,x%,y%:A%=135
30430=(USR(&FFF4)AND&FFFF)DIV&100
30435:
30440DEFPROCmouse(x%,y%,a%,b%,c%,d%)
30445X%=0:Y%=0:GCOL0,0:VDU5:*FX11,1
30450*FX12,1
30455REPEAT
30460PROCmove(8,FNsta(x%,y%),22000):PROCmove(8,FNsta(x%,y%+1),22008):*FX15,0
30465PROCprint:REPEATUNTILADVAL(-1)<>0
30470PROCmove(8,22000,FNsta(x%,y%)):PROCmove(8,22008,FNsta(x%,y%+1))
30475IF INKEY-122 IFx%<c% x%=x%+1 ELSE IF INKEY-26 IFx%>a% x%=x%-1
30480IF INKEY-42 IFy%<b% y%=y%+1 ELSE IF INKEY-58 IFy%>d% y%=y%-1
30485UNTILINKEY-74
30490VDU4:*FX12,0
30495X%=x%:Y%=y%:*FX15,0
30500ENDPROC
30505:
30510DEFPROCprint
30515MOVEFNpos(x%),1023-FNpos(y%):VDU231:MOVEFNpos(x%),1023-FNpos(y%+1):VDU232
30520ENDPROC
```

```
30525:
30530DEFFNpos(p%)=p%*8*4
30535DEFFNsta(x%,y%)=22528+y%*320+x%*8
30540:
30545DEFPROCinit
30550PROCass:VDU23,224,24,60,60,126,0,126,60,0,23,225,252,0,252,0,252,0,252,0,2
3,226,255,129,129,129,129,129,255,0,23,227,63,0,63,0,63,0,63,0,23,228,255,0,255,
0,255,0,255,0,23,231,0,128,192,224,240,248,252,254
30555VDU23,232,255,252,248,216,140,12,6,6:TIME=100*0+6000*0+360000*6
30560ENDPROC
30565:
30570DEFPROCass
30575DIM space% 35:FORpass%=0 TO2 STEP2:P%=space%:[OPTpass%:.shade:LDA£22528
MOD256:STA&70:LDA£22528                              DIV256:STA&71:LDX£10241
DIV256:LDY£0:.loop:LDA£170:STA(&70),Y:EOR£255:INY:STA(&70),Y:INY:BNEloop:INC&71:
DEX:BNEloop:RTS:]NEXT
30580SIZE=&70:SOURCE=&72:DEST=&74:DIM                                        move
40:FORi%=0TO2STEP2:P%=move:[OPTi%:LDY£0:LDXSIZE+1:BEQli:.l:LDA(SOURCE),Y:STA(DES
T),Y:INY:BNEl:INCSOURCE+1:INCDEST+1:DEX:BNEl:.li:LDXSIZE:BEQdo:.ll:LDA(SOURCE),Y
:STA(DEST),Y:INY:DEX:BNEll:.do:RTS
30585]NEXT
30590ENDPROC
```

APPENDIX 2

PUBLICATIONS

1. EGHAREVBA, F.E., FENN, R., SIORES, E., 1986, "Computer controlled Motion Devices for Automatic and Automated Welding", Proc. of the Computer Technology in Welding conf., London, U.K.

2. SIORES, E., EGHAREVBA, F.E., FENN, R., 1987, "Adaptive Control in Arc Welding Utilising Ultrasonic Sensors", Proc. of the Developments in Automated and Robotic Welding conf., London, U.K.

3. EGHAREVBA, F.E., SIORES, E., FENN, R., 1988, "Computer Imaging of Weld Pool Shapes", Proc. of the Computer Technology in Welding conf. Cambridge, U.K.

4. SIORES, E., FENN, R., EGHAREVBA, F.E., 1988, "In-process welding inspection and monitoring usihng ultrasound", Weldtech 88, Proc. of the International Convention for Welding Technologists, London, U.K.

COMPUTER CONTROLLED MOTION DEVICES FOR AUTOMATIC AND AUTOMATED WELDING

ABSTRACT

The present research work addresses an aspect of automation in welding: that of speed and position control of welding/ultrasonic transducer(s) arrangement (a seam sensing device).

Penetration can be visualised as being dependent upon torch velocity variation and position whilst seem tracking is in turn dependent on accurate tracking device.

The application here is in X-Y directon driving positional linear tables carrying welding torch/ultrasonic probe(s) laterally across a seâm (linear and non-linear).

The speed and directions of the stepping motor is controlled by suitable electronic devices integrated with a microprocessor equipped with an IEEE 488 bus facility. The stepping motor uses two drive modules to supply power to the motors. This power is in the form of carefully controlled currents which are switched in sequence and thereby causes the motor to rotate i.e. accelerate, decelerate, wait as well as the ability to store an entire multiple axis control. Move instructions takes the form of simple statements giving information such as speed, distance and direction.

Signals obtained from the sensing ultrasonic probes (transducers) are fed back to the microprocessor through a suitable event timing device. This in turn moves the torch/transducers arrangement along the seam. Any deviation from the true path is readily monitored and hence fed back to the system. This is a complete and total close loop package.

INTRODUCTION

Automation

Automation is no longer a new concept. In recent years, it has been witnessed the introduction of more and more mechanisation and control into the Nation's traditional industries. But although each industry has its own characteristic technology, some of the automation techniques which are used may very well be applicable to a wide variety of industries such as welding.

'Automation' is a word which is used to describe a wide variety of automatic control applications from simple analogue loops to complex digital computer control schemes. In all cases, however, the concept is the same, namely to measure one or more parameters of a process and to derive control action or actions which will cause the process to proceed in a chosen manner.

It is a popular misconception that 'automation' means all computers and no men. This is far from the truth; in fact, one of the most important aspects of the design of an an 'automation' scheme is the proper use of the man. The machine should be used for those tasks for which it is best suited, i.e. storage of large amounts of data, rapid and accurate calculation, frequent checking of the large number of test-points, etc, whilst the man should be used for interpretation of the numerous other factors which it would be uneconomical. In its purest form, automation implies a feed-back loop, with some mechanism automatically reacting to a predetermined signal. Companies are continually urged to increase efficiency, output and standards of quality by introducing automated manufacturing technology.

The intention of automation in welding is to extend beyond the capabilities of the human welder in terms of speed, accuracy, consistency and resistance to fatigue. In considering the functions of the welding machine operator in addition to those of the welding machinery, Okada (1) has classified these functions into three categories namely:-

Sense - information (data) detection
Experience and knowledge of operator - Data processing
Welding technique - Welding torch manipulation and peripheral equipment.

All these are within the capability of a human welder and as a result are not trivial for automation. The functions of automation can be related to the functions of human welder in each of the three areas defined above. These include:-

(i) Methods and equipment for detecting characteristics of the welding process and weld bead geometry (heat-input, penetration, bead width, torch tracking accuracy).

(ii) Understanding the physics of the arc, weld metal melting and solidification, metallurgical phenomena and thermal distortion, residual stress development in the weld and base metal.

(iii) Development and implementation of welding methods and equipment.

Automated Welding

Automated welding and automatic welding have much in common, they are similar but there is a major difference. Automatic welding involves elaborate dedicated fixturing with tooling, work holding devices, accurate part location and orientation. It also involves elaborate welding arc movement devices. Automatic welding is being used in industry where the cost of equipment is justified by the large number of pieces to be made.

Automatic welding reduces manpower requirement consistently produces high quality welds, maintains production schedules, and reduces the cost of welded parts. Some major disadvantages are the high initial cost of the welding machine involved, the need to keep automatic equipment occupied all the time and the need to provide numerous dedicated fixtures for various parts even though they are not in use continuously (2).

Automated welding eliminates, the elaborate experience fixtures and the automatic timer or limit switch input necessary to control the arc with respect to the workpiece. Automated welding provides the same time saving and precision, yet can be applied to small-lot production - even to the fabrication of a single part. It can accommodate changes in the product without necessity of redesigning and reworking the expensive fixture. These are the basic economic advantages of automated welding.

Automated welding utilises a programme coupled to a welding arc travel device of extreme capabilities instead of elaborate fixtures. The arc motion device can be capable of movement in three directions longitudinal (X), transverse (Y), and vertical (Z). Other motions such as rotation and tilt, can also be incorporated. This is automation with flexibility; the weldment is located and held at the correct location with respect to the torch. This thus provides welding accuracy and speed with repeatable quality and cost.

Sensors

The computer technique has greatly advanced the use of automated welding applications. When parts become larger or when distortion is involved or if the piece parts are not accurately prepared, there is the possibility that the weld may not be made in precisely the correct location. To allow for this, sensors of different types are employed for irregularities, and to make sure that the weld is made in the correct location even though the location may not be precisely where it is expected to be.

Sensors provide information to the microcomputer by resolving the weld joint central line and providing control signals to maintain the correct proximity. Other sensors can determine the root opening variations and mismatch of the parts being welded.

The control over-ride function provided by the sensors will change torch movement or torch lateral position with respect to the weld centreline.

THE ELEMENTS OF COMPUTER CONTROL DEVICES

A broad illustration of a computer controlled motion device is as illustrated in Figure 1.

It is a schematic illustration of the elements involved in an automated system.

From the sensory devices, signals are monitored from the workpiece by the transmission of ultrasound through the material. The signals are displayed on an oscilloscope and measurements obtained with suitable timing device are collected and sent through an interface to the computer/microprocessor for analysis and hence provide adjustment for automatic control of the linear table stepper drive system to actuate the torch about a given path.

Instrumentation

One of the major influences of the existence of the microprocessor is to make adaptive control (weld automation) increasingly attractive (3).

The latest microprocessor based instruments are superior to earlier designs. They provide a wider range of measurement facilities, higher accuracy and increased reliability. They are more versatile, easier to use and install and have the great virtue of connecting directly into interfaces. The most immediate benefit, however, is the ease of interfacing to external motion device and equipment making for ready incorporation into automatic control and monitoring system.

Interfacing

Linking together the computer with the automatic monitoring and linear tracking device system requires data paths. At the moment, the IEEE 488 programmable instrument interface, a general purpose digital interface, is suitable for this purpose and it is receiving growing recognition.

It provides a method of inter-connecting up to 16 programmable devices and provides each device with the possibility of controlling the bus, of putting data on the bus or reading data from it at the rate of 1 Mbyte(s).

It uses the talker-listener-controller concept. Each has a separate read and write address and the controlling device sets up the connection between a talker and a listener and releases the bus for transfer of data which is in the form of ASC11 characters.

The connecting cable has eight data lines for parallel transmission in bytes, three handshake lines for talker and listener to greet each other and five control lines for the controller to set it up between the potential 32 addresses that can be served. For more distant linking of equipment a bit-serial interface is needed and here the RS232C interface has achieved wide acceptance as a standard by microprocessor manufacturers. Currently without extra amplifiers, distance is limited to about 50 metres.

THE TRACKING SYSTEM

The purpose is to carry welding torch and probes to respond to U.S.S. signals. The objective here is to employ a 380Z computer to interpolate on the multi-axis system (see Fig.2). Programming in the linear interpolation mode, gives the ability to control two axes simultaneously by generating a major axis clock and deriving a minor axis clock from it.

In this mode and at all times the speeds of the two axes will be in proportion to their respective index lengths including during acceleration and deceleration. Thus, it is possible to generate a vector at any angle with an X-Y system having an accuracy within one motor step.

Axis Drives

The objective of the X-Y stepping motors and its drives is to provide simultaneously movement along either of two cartesian co-ordinate axes in order to position a desired welding head (torch/probe) along a seam. In this case the stepping motors are directly coupled to lead screws with positional error of 0.05mm (0.002inch). In order to achieve the necessary high stiffness the diameter of the screw is greater than that of a conventional lead screw.

It is important to reduce this frictional resistance to movement as small as possible so as to reduce errors in position measurement and the forces that may have to be exerted to move the linear table(s). The greater these forces are the greater the size and cost of the motor and control system. Hydraulic rams can be used to move the linear tables over small distances but it is prohibitively expensive to achieve the necessary stiffness in a long run.

In minimising positional error in following the weld seam, it is also important that backlash and pitch errors in the leadscrews are reduced as it tends to cause instability of the motor drive.

As it is necessary to sychronise the movements of the X and Y axis, it follows that this would require continuous measurement and control of motor rotation. The way in which this is to be achieved under stepping motor/linear tables control is as follows: (see Fig.3)

Initialisation

When power is applied to the interface, it automatically go through an initialisation routine. Calculations are performed as part of the sequence and the result is used to give movement data.

1) An electrical signal (ultrasound is introduced into the specimen, measuring

beam path length from the seam and weld liquid/solid interface and reflecting back. The received signal is compared with a reference signal obtained from the seam before weld-start using a purpose built ultrasonic reflective pulse timer. The conditioned signal is fed back to the stepping motor via microprocessor and controls

2) Electrical signals corresponding to the linear table movements required, i.e. increase the X-coordinate by millimetric distance and decrease Y-coordinate by X-amount, are fed from the control programme to two stepping motors controlling respectively the 'X' and 'Y' movements.

3) On each axis, there is some form of measuring transducer which provides an electrical signal indicating the distance through which the linear table has moved since a new position was commanded.

4) The stepping motor on the X-axis, say is now receiving two signals - one telling it that it should move 'X-distance' and the other telling it that it has not moved, i.e. that there is a positional error of 'X-distance'. The stepping motor operates to reduce this error to zero by moving the linear table along the x-axis (weld axis) at a speed until the signal from the measuring transducer indicates that it has moved through X-distance.

Pulse Timer and Linear Accuracy

Although it was readily possible to identify the output from the time/ analogue gate, we thought that the signal cannot be readily digitised for integration with a computer. This is as a result of cost of add-on equipment in order to achieve the same result.

A suitable timing device was thus necessary and a prototype has been developed with a digital readout (see Fig.4). The electronic system comprises of two counters one enabled between the initial (transmit) pulse and the first reflection, the other enabled differentiation between the initial pulse and the second reflection. Mid points of the pulses are taken for accuracy of timing. The resolution so far obtained from the ultrasonic reflective timer is 0.3mm for transverse wave velocity and 0.15mm for surface (Rayleigh) wave respectively. This resolution depends on the velocity of the wave in the medium. Depending on the welding speed and probable changes in the welding direction the system resolution is 0.02mm.

Measurement

The control computer maintains a record of all of the measurements. Periodically this record is up-dated and referenced. The electrical signal is converted to numerical equivalent by an analogue-to-digital converter for processing.

Display of signal is achieved through the cathode ray tube of an oscilloscope while hard copies are available using the printer; also the data are stored-in a hard disk.

CONCLUSIONS

1) It is expected that automated welding such as described will eliminate the need for complex dedicated fixtures and find increasing acceptance.

2) The ultrasonic sensor devices is real-time computer control.

3) The complete package is cost effective and adaptable.

4) Positional accuracy can be achieved using the dedicated pulse-timer device.

REFERENCES

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2) Carry H B: Modern Welding Technology Publ. Prentice-Hall International. Inc., London U.K.

3) Symposium, Institute of Measurement and Control (1980). Application of Microprocessor in devices for instrumentation and automatic control.

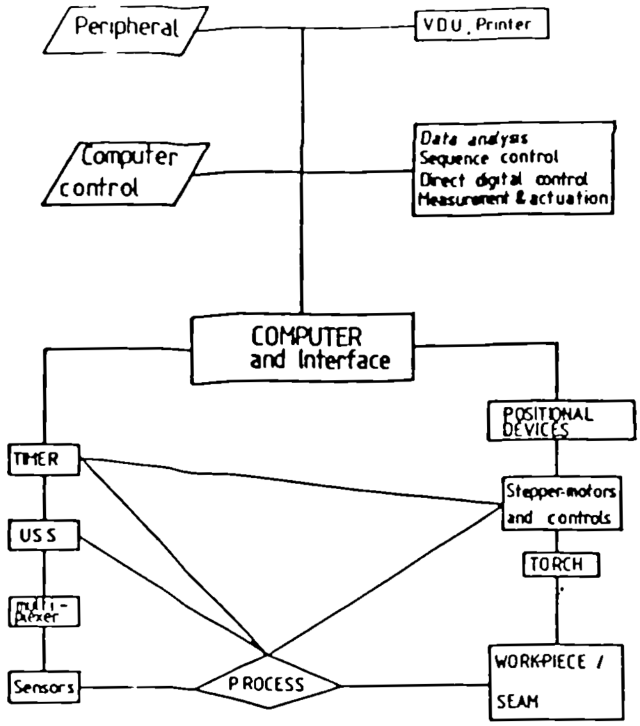

Fig. 1. Schematic Diagram of a Computer Control System.

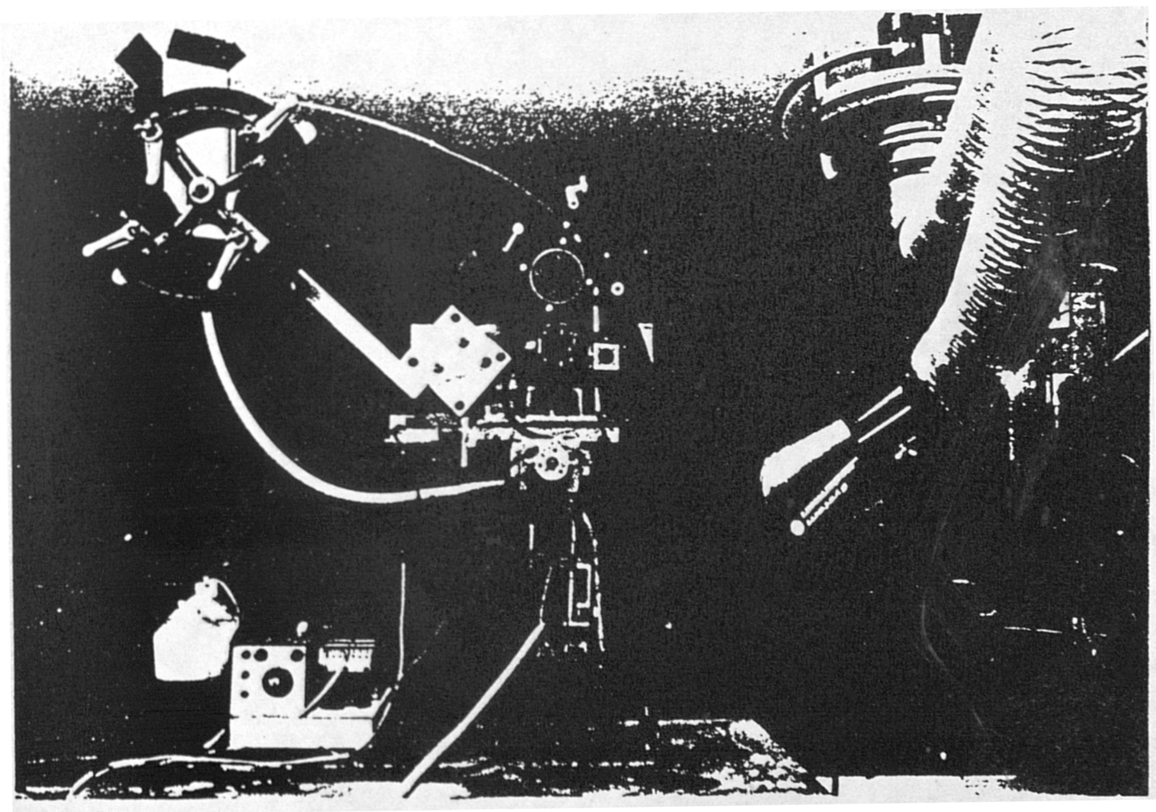

Fig. 2. Depicts the seam tracking system.

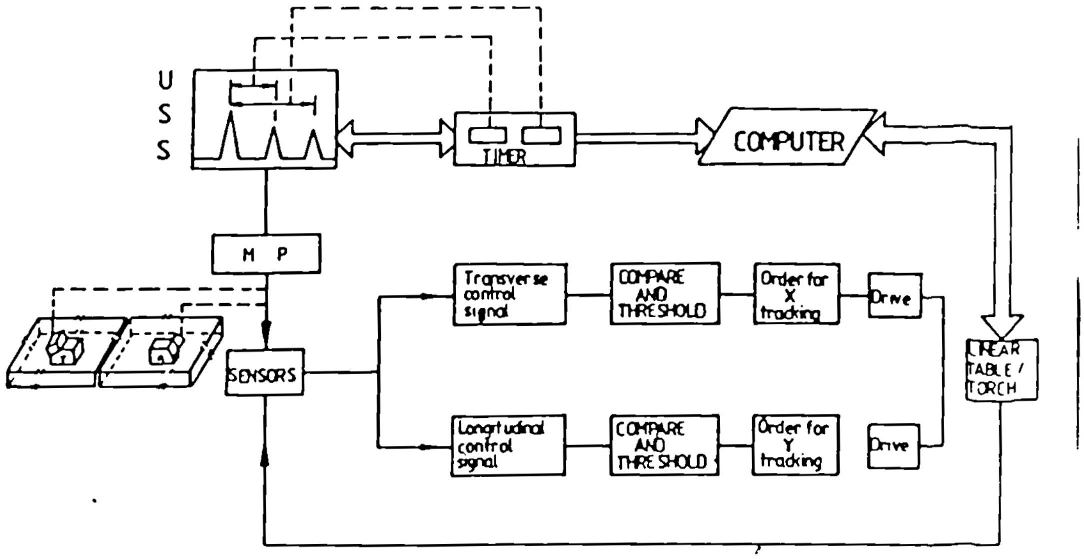

Fig. 3. Seam Tracking System.

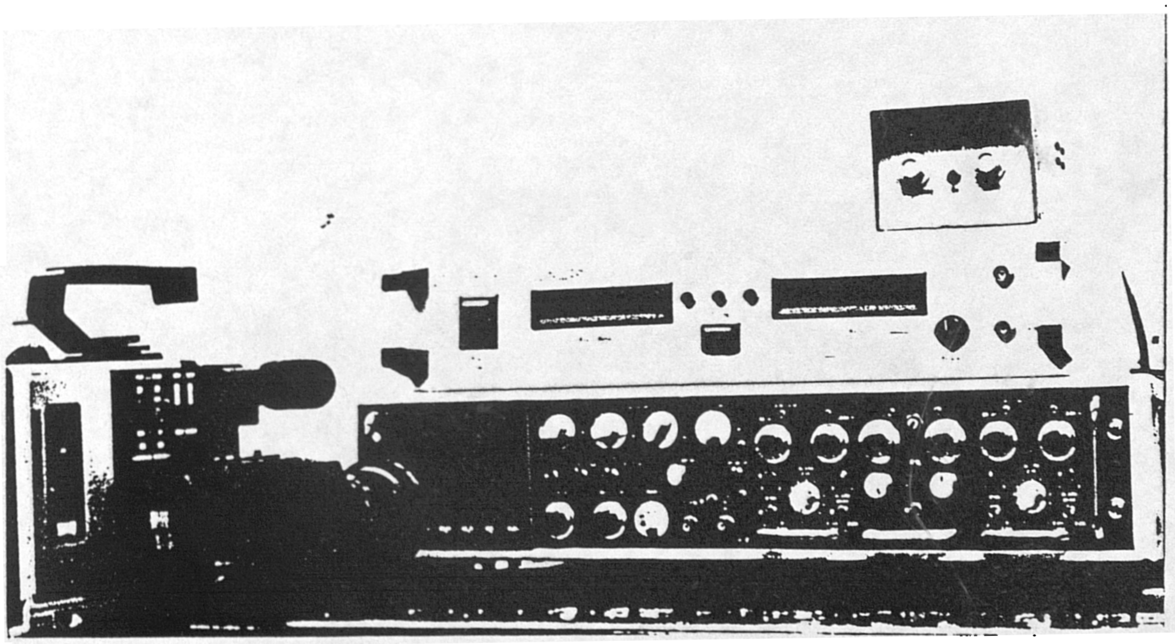

Fig. 4. Shows the Ultrasonoscope and reflective pulse timer.

ADAPTIVE CONTROL IN ARC WELDING UTILISING ULTRASONIC SENSORS

SUMMARY

During the course of automated welding, thermally induced distortions could move the seam to be welded out of the alignment with the welding torch path. These occurrances have prompted the development of a variety of seam following sensors, some are simple mechanical devices whilst many are more complex electronically based. The devices described in this paper use contacting ultrasonic probes moving parallel to the welding torch direction but centred a few millimetres behind the centre line of the welding electrode.

Were these probes solely to control the torch movement orthogonally to the seam (i.e. seam track) then the device would not be unusual. Some years ago Mannesmann (1) patented a seam tracking system based on contact U.S. probes placed a little in advance of the welding torch. The sensor system described herein is also capable of i) controlling weld penetration depth and ii) operating in real time and at real welding speeds.

Work will be described which shows how the system tracks seams and moves in two directions to do this. Lateral displacement sensing results are fed back to control both welding torch sense and probe parallelism (to the seam edges). Control strategies for various acceptable and defective joint attitudes are described as are the final stages of pre-commercial development.

INTRODUCTION

Automated, especially robotic, arc welding is always reliant upon the accuracy of pre-set seam co-ordinates. If distortion occurs and one part moves relative to the other (in any of the 3 principle planes) then welding problems are likely to arise. Heavy fixturing will prevent distortion, but at the expense of increased stresses in the weld zone. Sensors have been used to track the seam and adjust the welding torch position by reacting to an error signal by means of a closed loop control signal. As such, these systems are termed "adaptive" in that they adjust the processing unit in such a way as to account for unplanned variations. Seam tracking is probably the most studied area because the weldment edge is a clear boundary and as such readily produces the sudden changes ideal for sensing applications. There have been many seam tracking sensors, based on an extremely wide variety of techniques, employed over the last few years.

Penetration control, especially in thicker gauge material or for high quality fabrications, is also an area where adaptive control is being applied. Many penetration monitors utilise emitted radiation of some kind whilst others measure weld pool shape (including top surface smoothness) or size. Unlike the case in seam-tracking, penetration monitoring is almost uniquely control of one dependent variable by measuring an independent variable i.e. control is usually through monitoring indirect signals. As such, penetration controllers are not universally accurate, frequently requiring detailed calibration and materials of consistant surface finish to enable them to perform with sufficient accuracy. For such an important area as penetration control, the adaptation of control should enhance reproducibility and standards of performance, being dominated by uncontrolled factors. As direct measurements are used for seam tracking, the application of similar techniques to penetration control ought to result in much more positive and direct information on true penetration. There are, of course, problems. By its very nature, weld penetration infers a technique of monitoring through a solid body (i.e. measurement of the weld pool depth within the solid material). Visual or other techniques based on emitted radiation cannot fulfil this requirement and are thus imperfect. Two "through thickness" examination techniques answer the criterion: Real time Radiography and Ultrasonic inspection.

Weld penetration monitoring and control by ultrasonic sensing has been shown to be both realistic and accurate. Utilising beam spread to seam track simultaneously has, for plates over 10mm thickness, been theoretically possible; this is now being performed routinely. Plates of less than 10mm thickness are more frequently welded in automated/robotic units than those of over 10mm, recognizing this caused modifications to the basic concept. It is now possible to monitor penetration and seam track simultaneously in plates of all thicknesses and to control both factors independently but simultaneously. The accomplishment of this ability is documented beginning with work on thick plates (over 10mm) and then describing the approaches taken on thin materials.

Acoustic sensing

It is surprising that more attention has not been paid to acoustic sensing in the expanding effort to obtain more effective feedback of data to control automation systems. There are obvious difficulties with sonic and ultrasonic signals, especially if they are transmitted in air - they are affected by air movements, temperature and noise in the most literal sense. On the other hand the frequency range is very wide, and the relative slow velocity of sound waves can be put to good use as well as being a handicap in some situations. Acoustic signals carry a vast amount of information about the objects emitting or reflecting the sounds (2). This work explores a way in which this information can be analysed and used for adaptive control of the welding process.

Ultrasound in control applications

Ultrasonic is a technology which has established applications in all branches of engineering (3). It has shown an exceptional ability to live up to the claims of its technical advocates.

Basically, there is little mystery about ultrasonics which is the technology of high frequency mechanical vibrations whether these be used to change material (in cleaning, welding, or metal forming) or to carry information about the properties of the medium through which they are travelling (in sonar, flaw detection, medical diagnosis) (4).

Ultrasonic has a major part to play in serving major manufacturing, welding and assembly proceses, as well as in underwater applications and medical diagnosis.

DESCRIPTION OF CONTROL SYSTEM

Two-degrees-of-freedom manipulator

The proposed method was practically applied to a tracking control for a two-degrees-of-freedom manipulator. The heart of the system is the RML380Z microprocessor, which is based on the Z80. The system includes a Keyboard input device, a CRT display, a disc memory and its driver, and a printer which have been used for program development and for storing and displaying the measured values. In addition to the computer board, the table control processor includes the IEEE 488 card, input/output boards, pulse timer board which connect it to the sensors and actuators to provide communications with the interface and drive modules.

The outputs of the pulse-timer two 16-bit counters are multiplexed into four 8-bit groups to enable transfer to the host computer. Hardware details are shown in Fig. 1. A control program whose flow chart is given in Fig. 2, was written for the Z80 microprocessor system.

The ultrasonic sensors measures the positions to the edge of the specimen. Positioning of the torch is achieved by means of stepper motors which drive a pair of crossed lead screws. The motor can be driven in a random manner at speeds up to 200 steps/sec. without missing a step, and thus provides an ideal incremental shaft positioning device compatible with solid state digital methods. Pulses at the input produce 1.8° movement of the motor shaft or 200 steps per revolution.

Motors were controlled by digital commands translated into pulses through IEEE 488 control interface and motor drives. The absolute velocity value determined motor speed and thus welding head resolution along the appropriate axis. Motors along and across the weld centre line drove the platform supporting the welding head by a lead screw mechanism.

Digital signals were applied to both motors and the distance through which the head moved was recorded in a form of steps. A relationship between number of motor steps and ultrasonic time of flight was established and additional calibrations were performed.

Experience in using the above configuration to follow the seam showed that the calibration was quite adequate and that tracking accuracy was as high as ± 0.3mm across the weld centre line.

The equipment used for control of the welding head involved a closed loop control system. Two high temperature probes were used to "view" the area of the weld seam immediately in front of the welding head. Signals from sensors were fed and displayed onto an ultrasonascope screen and in turn captured in a digital format by a time of flight digitizer. The modified signals were finally fed to a microcromputer, processed and relevant location information were obtained. Interrogating both sides of the weld seam, the area of interest in the digitised signal was identified by using the target locator to work within an electronic signal autocalibration "envelope". Within this envelope, the unit could report to the microcomputer two alternating items of information being the two sides of the joint. Position on the axis normal to workpiece was achieved by the spring loaded jig carrying the ultrasonic sensors. This solved the problems inherent in ultrasonics which is in constant contact with the workpiece. However, oil was pumped under the high temperature shoe to alleviate any further acoustic coupling difficulties.

<u>Fusion system</u>

In order to provide data for fusion control, weld liquid/solid interface was interrogated, using shear wave (thick material > 10mm) and surface wave (thin material < 10mm) probes respectively. These data were transformed into commands suitable for the purpose built microprocessor current controller. The circuit of this device consists of an 8-bit digital to analogue converter (DAC), a constant current generator, power supply regulator and a voltage inverter. The DAC connects to the controlling computer via eight data and a control line. The 'slope' control increases the arc current from the minimum level of the power source to the selected value at the start of the weld and, at a suitably chosen program position, decreases the arc current back to the minimum level.

The parameters of interest were weld-width and penetration; these were correlated with current in terms of its effect on net heat input, such that dynamic changes in beam path length (BPL) and/or time of travel result in an increased or decreased depth of penetration. This function is being performed using further software specially tailored to relate current and beam path length fluctuations.

ADAPTIVE CONTROL DURING WELDING

Control during welding was implemented in real-time by two closed loops, ultrasonic time of flight being the governing factor. In case of joint-tracking, relative positions of the electrode and weld seam were monitored and subsequently controlled by the leading signal. If the torch deviates from the seam, corrections are made instantly before the next sampling period. Sampling periods dictated the systems accuracy, and time intervals between sampling points were always the same length.

The microprocessor torch positioning system received instructions from part of the computerised system which controls the welding process. The torch position controller is then a subsystem of the overall system. There are eight instruction codes which are reserved for the torch control, these are interpreted as:

0, Move to absolute X co-ordinate
1, Move to absolute Y co-ordinate
2, Set the X axis origin
3, Set the Y axis origin
4, Move relative to the current position along X axis
5, Move relative to the current position along Y axis
6, Reset torch position system.

The first two position instructions read new absolute co-ordinates from the computer and position the torch accordingly. The next four read a displacement from the current position, positive or negative, and use this to position the torch; instructions 2 and 3 simultaneously redefining the new position as the zero point on their respective co-ordinate axis. The 'reset' instruction drives the torch to the centre of its range; this position is determined by the pulse timer which monitors the sensor position on the specimen.

The centre position is important because the control software sees it as a reference point to check that every requested position of the torch is within the range. It is of utmost importance that the axes of measurement are adjusted to be mutually orthogonal.

To drive and control in the plane parallel to the workpiece surface it was necessary to know the angle θ made by the seam and the longitudinal axis X. In the (X-Y) plane, and the width of the gap between the plates. Experimental procedures showed that the angle θ depends on the beam spread of each individual crystal. Angles θ greater than the beam spread caused signal loss, thus, experiments were restricted to angular changes less than the angle of "sight" of individual crystals.

Information about the dynamic changes in shape and dimensions is of extreme interest; if a real-time control is to be achieved during welding. To detect the edge of the seam, we apply a two-dimensional edge detection algorithm. The algorithm is a sequential search such as:

Pick an initial boundary.

It is essential to begin the search for a boundary at a location where the likelihood of making an error is the smallest. We move the probe(s) to a location to give the algorithm a location which appears to be near the boundary. The algorithm then finds the initial boundary based on a symmetrical location on either side of the seam.

Look-ahead

If the algorithm is successful in finding the next boundary, the new one is stored in a file from which the look-ahead routine will take the new current boundary next time around.

If the algorithm fails to find a boundary (this can happen because of loss of coupling) the backtracking routine is called. In this way, we use a global threshold to guide local search and to detect error. Also, when a reliable echo is not received, the sensor co-ordinate is kept at its current position and to look-ahead several samples. The look-ahead procedure translates the sensor horizontally (one sampling distance) and attempts to perform a distance measurement.

Backtracking

Whenever this routine is called, the current boundary is a false one. We look-back from the previous boundary data, take present value from current boundary and calculate the value of one step before to guide local search before the look-ahead routine is recalled. If another boundary is found, then the algorithm continues following that new path, otherwise the backtracking routine is called again.

Termination

This procedure is used to determine that the algorithm has found the boundary. One way to implement this routine is using a logical function whose value is TRUE, when the current boundary point satisfies the termination criterion, and FALSE, otherwise. The algorithm terminates whenever the logical function yields the value TRUE. Figure 3 gives a flow-chart description of the algorithm.

The second leading pulse shows the relative depth of penetration. If monitored penetration fluctuation differs from preset values instant corrections are made before the next sampling position. The sampling periods are common to both loops. The instruction codes reserved for fusion control are:

0, Set P zero level
1, Move P to preset value
2, Reset P level.

The first instruction sets absolute coordinate of penetration. The move instruction energises the current controller to accomplish a preset level. Finally, the reset level subsequently controls the fluctuation in current according to changes in beam path length.

Further work on depth of penetration on thin materials is being proposed which works on frequency modulations. The work describes the property of a broadband Rayleigh wave, with a characteristic of having a range of frequencies present at various depths below the surface (5). The time taken to pass around a weld whose depth is of the order of a wavelength is frequency dependent.

The Rayleigh wave sensor works on the echo principle, instead of pulses it makes use of frequency modulation. A frequency modulated continuous wave is transmitted through the material and is reflected back. By the time it reaches the probe, the transmitted frequency has changed, so there is a difference between the frequency of the received wave and that of the transmitted. This frequency difference is proportional to the time delay experienced by the returning wave, and so to the depth of the weld, and in the instrument it will be obtained by heterodyning the two waves and taking the resultant difference frequency.

This information together with suitable hardware and the current controller could be interfaced with the microprocessor for a real-time control to be achieved. The system offers distinct advantages over conventional methods. Firstly, it provides a means for a realistic determination of weld depth and calibration standards are not required, since losses at interfaces and from attenuation in the specimen are not involved in the technique. Secondly, it is insensitive to surface pollutants, including spatter and residual stresses. Thirdly, the higher the transducer frequency the lower the thickness of material that could be measured. The feasibility of this approach for thin plate work has been demonstrated in our research laboratory. A typical frequency profile is as shown in Fig. 4 with an accompanying schematic layout depicted in Fig. 5.

DISCUSSION

Work on both identifiable section sizes (thick and thin) has shown that two of the three ultrasonic beam sectors can be utilised to monitor and control two desirable features (seam position and fusion depth). Weld quality should also be able to be monitored by the trailing edge signal. Work is in hand to do this. Accuracies resulting from the established equipment and system are in the order of 0.3mm which, by conventional wisdom, would be suitable for all M.I.G. (G.M.A.W.) and T.I.G. (G.T.A.W.) systems. System response time of about 1μs means that potentially both the penetration and seam track dimensions are inspected and corrected every 0.002 to 0.005mm. Much of the benefit of this system rests with the ability of the power source to respond rapidly to the changing output variations required of it. A suitable system will control both seam tracking and penetration depth adaptively to accuracies of the level expected in robotic systems. This sensing system would, therefore, be an ideal "add-on" pack to even the highest level of automation.

Plans are afoot to utilise the whole of the ultrasound information to control the process and also to produce a "blow-by-blow" 3D computer graphics head-up-display (H.U.D.) system. It is envisaged that a control console, complete with operator interference control, will be the final product. A graphic display of the weld as it is being formed would be shown with indications of, say, gas porosity regions within the solid weld bead. Whether this sensing system were fitted to high level automatic welding, or in a robotic cell would be irrelevant. What would be relevant is that the sensor adapts the welding equipment in such a manner as to maximize both quality and accuracy in operation.

CONCLUSIONS

i) Adaptive ultrasonic sensing is quite capable of bettering the accuracies demanded of high level automation in welding.

ii) Materials from 0.1 to over 100mm thickness can be welded with simultaneous penetration and seam tracking control using one or other of the two existing systems.

iii) Further quality increases are available from these control sensor systems.

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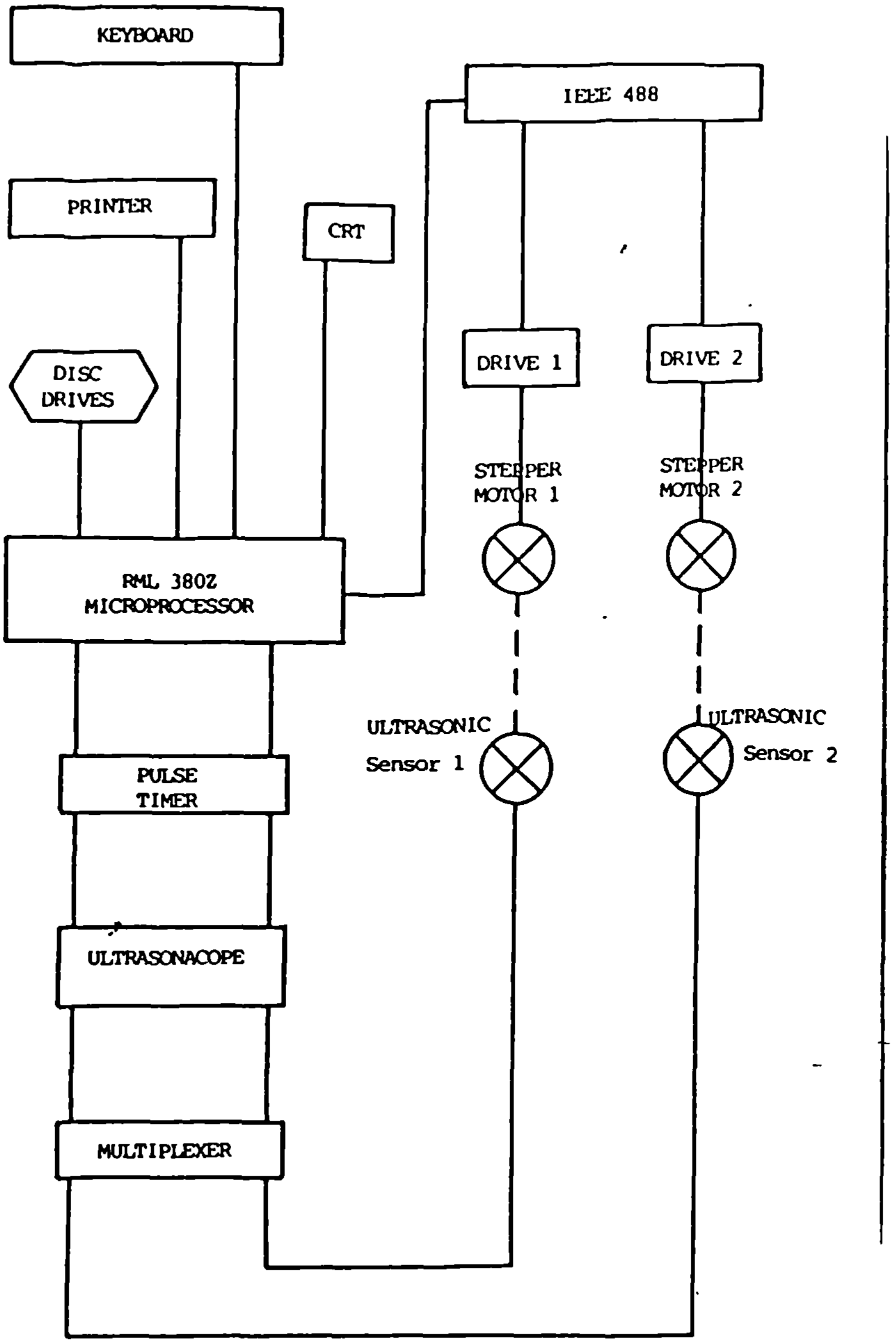

Fig. 1 Hardware details of computer control system

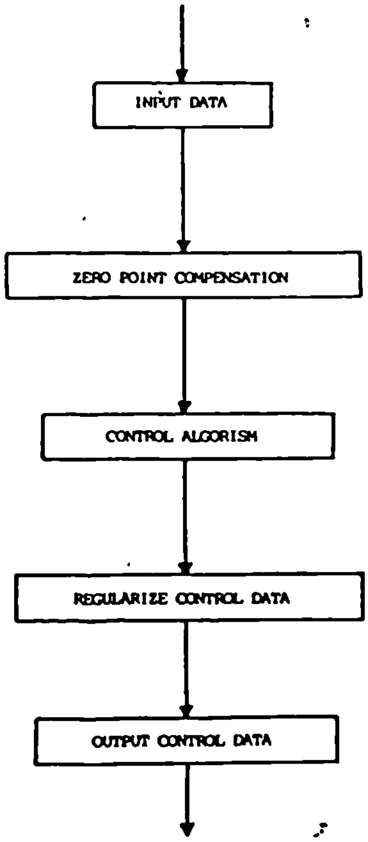

Fig. 2 Depict flow chart description of control program.

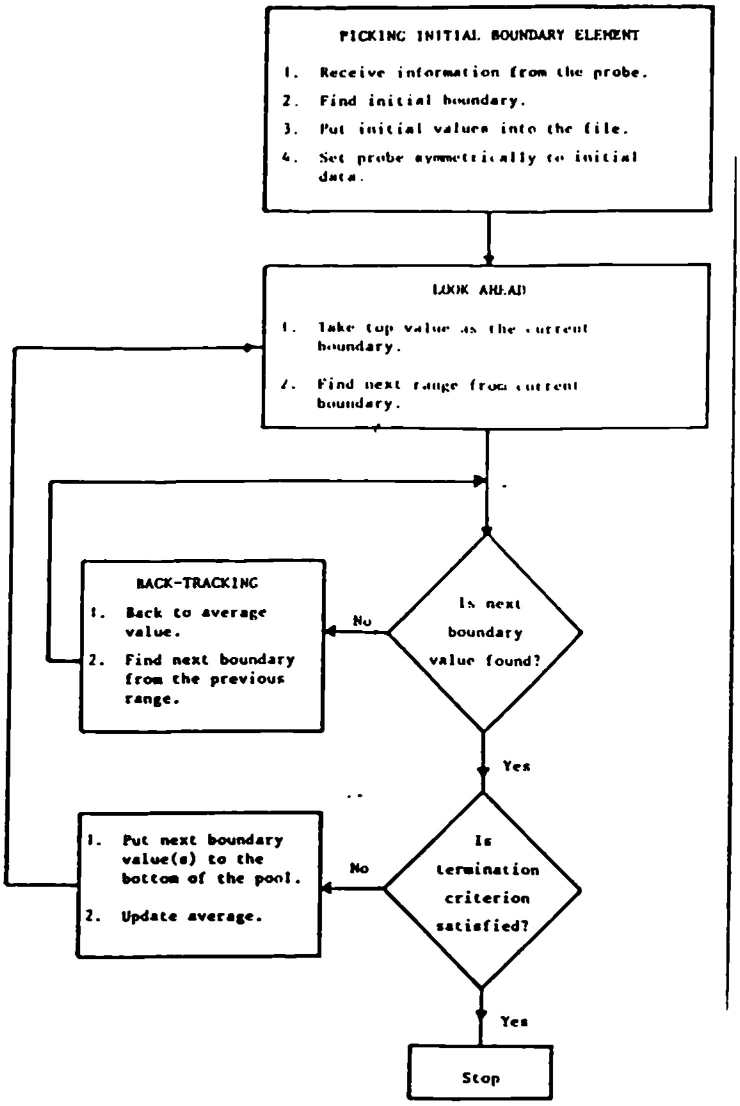

Fig. 3 Flow-chart description of the algorithm

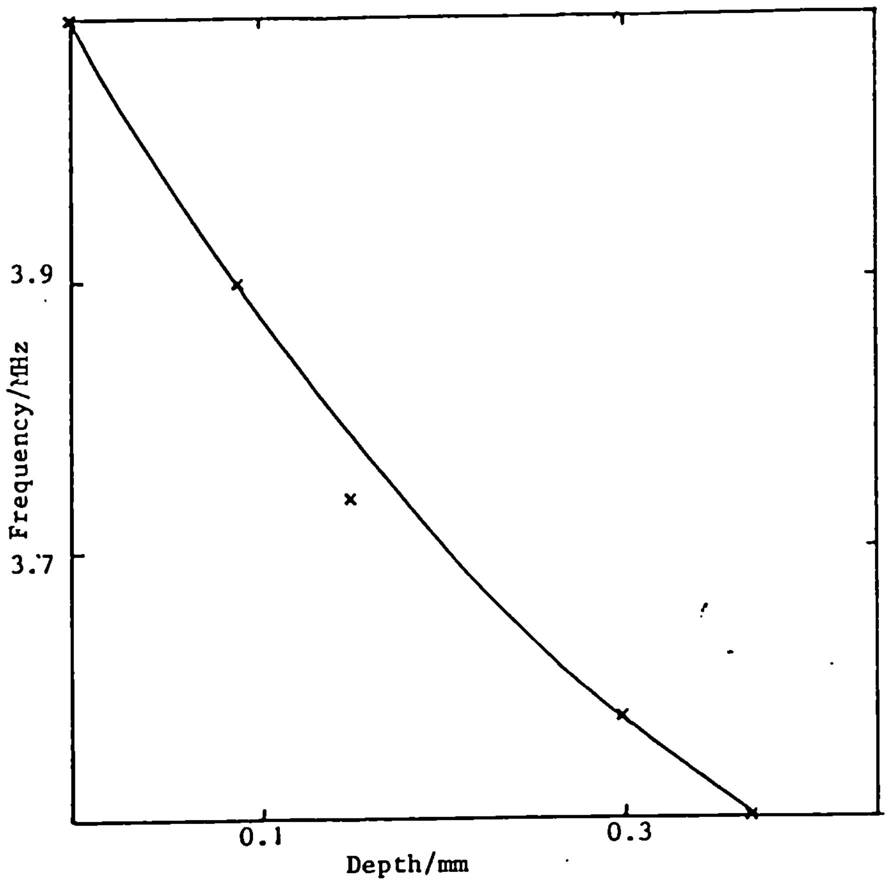

Fig. 4 Illustration of the frequency/depth variations

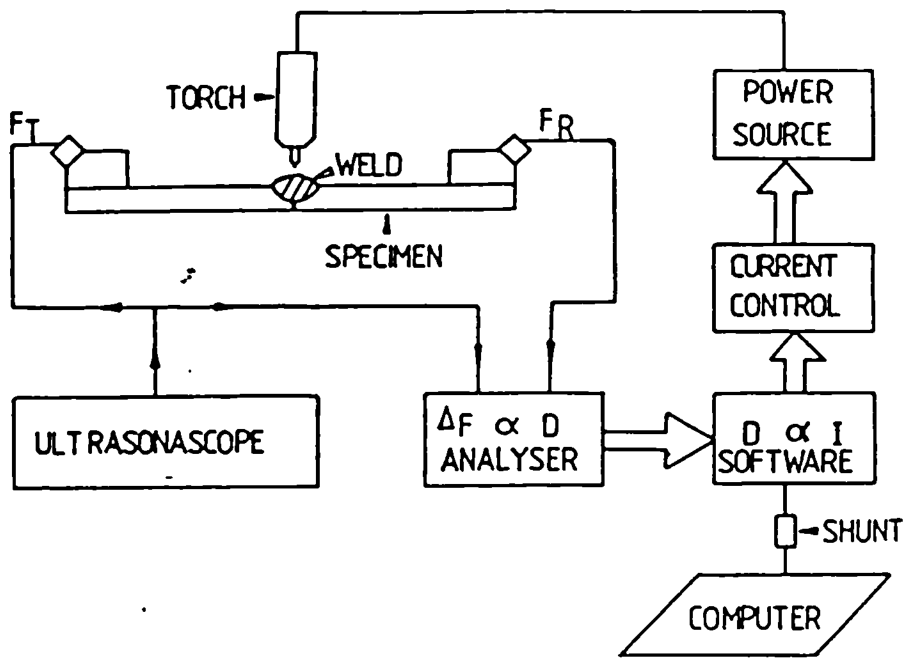

Fig. 5 Penetration control system

COMPUTER IMAGING OF WELD POOL SHAPES

SUMMARY

A great deal of effort is employed in determining whether there are faults present in manufactured parts both during production and during their useful life. As the complexity and strength-to-weight ratio of structural materials is increased, the need for evaluation of defects becomes still more severe. In the past, the main thrust of ultrasonic measurement techniques has been to evaluate the position and size of a weld. It is only recently that this technique is beginning to be applied to measure more subtle characteristics such as the size and shape of a weld. Thus accurate methods are required which can determine the location, size, depth of penetration and shape of a weld. In this paper, we address the method of ultrasonic imaging which uses ultrasound to probe the weld sample and hence produce an image. Présently, only relative demonstrations of real time imaging have been carried out in the laboratory but the technique employed appears to hold great promise for future applications.

APPROACH TO AUTOMATION

The standard techniques employed for inspection of solid parts have involved X-ray and radiographic methods, eddy current testing in metals, the use of dye penetrants, and acoustic methods (1). They require bulky apparatus particularly for thick metal parts. Furthermore, when large metal parts are being examined, very high energy beams must be employed which can involve clearing the area where the inspection is being carried out. This is a major disadvantage.

Acoustic techniques have the major advantage that they measure the elastic properties of the material. With interest in mechanical properties in mind, the acoustic measurement provides data most closely related to a determination of the viability and useful life of a material sample.

The main thrust of acoustic measurement techniques has been to evaluate the position and size of fairly major defects. Recently, acoustic techniques are beginning to be applied to measure more subtle characteristics such as the size and shape of weldment.

Automatic production of high quality welded joints requires advanced techniques for positioning the welding torch and regulating welding parameters. During the last decade, automated welding has witnessed many developments, ranging from innovations in power sources, manipulators etc. right through to subsequent automated inspection techniques. Thus, the final product quality is highly dependent on the process manipulation and the welding conditions. Additionally, extensive efforts are made to provide careful weldment inspection to ensure that they satisfy standards and customer requirements. The urge to decrease welding repair work together with the desire to increase productivity has driven welding engineers to move towards robotic manufacturing.

Investigations were performed to assess an intelligent sensory system for use in welding process adaptive control and real-time weld pool analysis. The technique used feedback signals from the welding pool to compensate for random schematically in Fig. 2. As seen, the scanning motion of the transducer is under complete computer control. A detected A-scan output of the ultrasonic receiver is obtained from the pulse echo wave form of the transducer.

The ultrasonic A-scan interface digitizes the time-of-flight delays and amplitudes of up to three consecutive echoes appearing on a single trace. Digitized data are passed to the host computer along with position coordinates of the transducer through an interface. Preprogramming of the RAM and the preamplifier echo signal at regular intervals is accomplished by the host computer through the internal timing and interface module. Control lines establish the code for passing data from the host computer to the ultrasonascope and modules, set the internal logic for an external sync and execute command. The system configuration allows fast, real time programming just prior to reception of the sync pulse of the external timer.

A digital scan converter was used to translate analogue echo representations into a digital format suitable for further analysis. Data recorded were subsequently processed by a *microprocessor* using relatively simple computational algorithms. The stages followed for each ultrasonic indication recorded were based on time of flight calculations. Initially, the transducer's position was determined according to reference points on both sides of the seam prior to welding. The calculations take into account material thickness, ultrasound and velocities within the media, transducer frequency and angle of incidence and finally stand-off distances from the seam. Due to beam spread phenomena, seam sidewalls are interrogated and additionally when welding commences, the weld pool geometry. Displays are generated after signal processing and conditioning which assist visualisation of the weld pool in real-time. An additional problem that adds to the complexity of signal processing is identification of the source of returned echoes. Equipment is being developed to improve signal deconvolution.

SCANNING PROCEDURE

The scanning procedure follows the pre-positioning of the specimen and transducer(s), on a calculated distance from the plate edge. Parameters for the ultrasonic set are adequately selected such as the gain, frequency, reject level, gate delay and gate range. The transducer is moved to the scan's starting position and then starts the scan program in the computer.

The program immediately enters its dialog section, prompting for parameter settings, and the computer displays all of the responses which could be changed if so wished. Operation parameters are scan increment sizes, position limits, amplitude threshold level, data sampling to be averaged at each position. Instruction is sent to the computer to begin the scanning. From this point on, the system is under the complete control of its microcomputer. The computer stores all of the operator's dialog responses on the floppy disk, and then it begins the inspection loop. Basic steps which occur within the loop are:

a) computer reads the specified number of peak amplitude values from the ultrasonic search unit, and averages them.

b) If the average is greater than the specified threshold level, then the average, the reflection depth, and the transducer position are recorded on the floppy disk.

c) If the scan is complete, the loop is exited. If the scan is incomplete, the computer moves the transducer to the next data sampling position, and the inspection program returns to step (a), above.

After leaving the inspection mode, a program on the minicomputer then reads the process variations during welding. Although joint tracking and weld pool data are collected, then manipulated at high speed in real-time, it is this latter task which provides control of the entire welding operation.

An ideal system would be one that can compensate for both tests simultaneously employing a feedback technique to monitor and control the entire welding process in real-time. Such a system has been developed which simply correlates output values with desired reference levels aiming at absolute weld quality which in turn is being in-process monitored using ultrasonic sensors. This microprocessor controlled system monitors the difference between measured variables and corresponding reference values and adjusts the inputs so that an equilibrium is maintained as quickly and smoothly as possible.

The sensory system extracted all necessary information from various parts of the weld pool to recognise the specific joint characteristics. A database was established for data interpolation which was analysed and compared with the initial preprogrammed welding process requirements and design data. Routines were produced allowing for the database expansion during welding. This system incorporated elements of artificial intelligence so that the system was controlled in a closed-loop fashion.

After significant features were extracted, the "object" was further discriminated by filtering the necessary information. This involved a recognition scheme based on decision making within the microprocessor's software, which was defined in a hierarchical manner so that the seam was recognised first, followed by penetration depth and then weld pool spatial location. Overall data selection ran concurrently with data interpretation which meant that the total cycle time for area recognition plus weld process handling could not be reduced. This created software limitations which do not allow for real-time weld pool geometrical shape formation in 3-dimensions at the present. Post-welding silhouettes representing weld pool boundaries along the seam can, therefore, be plotted in a 3-dimensional fashion. Proposals are currently afoot to construct these images into real representations in a "Head-up Display" mode whilst the weld pool is being formed.

COMPUTER IMAGING

Ultrasonic testing has been used effectively as a non-destructive evaluation technique for locating subsurface defects of a wide range of materials. It is a well established technique for locating cracks, lack of fusion, porosity etc. in welding.

Computer imaging methods currently used fall under the general category of pulse-echo ranging techniques (2). Within this category is a plethora of subcategories. The traditional classification starts with a three-fold breakdown into A-scan, B-scan and C-scan (1). We shall, however, be concerned with the A-scan as many ultrasonic flaw detectors testing are based on A-scan concepts.

A-scan does not actually produce an image in the usual sense of the word. However, a brief discussion of the principle should serve as a convenient springboard to explain the advanced methods. The basic ideal, illustrated in Fig. 1, is "time-of-flight". By transmitting a short pulse of sound into an object and then recording the echoes as a function of time, one can determine both range and size information. On the screen, the horizontal axis will yield range as the vertical echo amplitude. Because the echo amplitude is proportional to the emitting object, one can infer the object location. Also, as the A-scan trace gives only one dimensional spatial information, it is not traditionally thought of as an image. However, by combining the A-scan concept with careful synchronized scanning of a transducer, one can generate two-dimensional spatial information, and obtain a trace that is suitably termed an ultrasonic image.

A typical application of the pulse-echo method is the measurement of thickness of a steel plate. Data such as probe position, time of flight of the echo while the probe automaticaly and sequentially scan the surface transmitting acoustic pulses through the thickness, are recorded. Although A-scan may not usually be considered to provide an image, a map of thickness of a steel plate certainly qualifies as a two-dimensional map of a physical quantity. In a sense such a map qualifies as a "synthetic aperture" image, because it is constructed by sequentially gathering thickness information point-by-point over a two dimensional region. Moreover, the rapid advances made in microcomputer technology tend to indicate that digital signal processing will be an extremely important part of the future in acoustic imaging (3).

A newly developed weld pool constitutes a change in phase and material properties relative to the rest of the weldment and is an ultrasound reflector (4). In order to make use of this concept to measure weld pool dimensions in real-time, the following transducer arrangement was adopted. Two identical transducers mounted equidistant alongside a welding torch holder were aligned in such a way that the transducer's field of view is centred on the weld pool. Placed "millimetrically" in front of the welding torch and positioned on opposite sides of the joint they were capable of determining if the weld was moving off centre and initiated corrective action (5). This guaranteed that the transducer will observe the weld pool action at all times. Having properties similar to that of light the ultrasound beam starts from a source and propagates in a cone fashion. This cone, filled with ultrasound, illuminates the whole weld pool area provided that transducer stand-off distances from weld centre line is appropriately selected. However, large temperature gradients exist during weld pool formation which cause signal attenuation. The effect of this characteristic was reduced when larger amplitude ultrasound pulses are applied to the medium (6). Acoustic contact between the transducer and media should be continuously maintained in order for ultrasound to travel through the material. This was accomplished by applying a spring loaded action on the transducers. Additionally, oil reservoirs were machined underneath the transducer's high temperature wedge and oil was pumped peristatically acting as an acoustic couplant. Instead of using the above mentioned technique, commercially available wheel shaped transducers filled with couplant, can be employed and the whole assembly could be rolled along the seam. This set-up will alleviate any difficulties associated with acoustic coupling.

The recognition scheme was obtained using weld bead modeling techniques, in order to standardise the welding process and at the same time correlate the expected ultrasonic reflections with the actual weld bead discussions. Although this technique proved fruitful for seam tracking, penetration control and in-process inspection, it was also adequate for real-time computer imaging of weld pool shapes.

COMPUTERISED ULTRASONIC DATA ACQUISITION SYSTEM

A computer-controlled "X and Y" linear (stepper-motor driven) two transducer holder assemblies, ultrasonascope, reflective timer, gated peak detector, A/D converter, VDU, printer, disk, were used for the acquisition of ultrasonic data.

Three data points - an amplitude and a time measurement and position were collected. The gated peak detector was used to determine the amplitude of the signal within a preset gate and a reflective pulse timer to measure the time to an ultrasonic signal.

A general purpose ultrasonic data acquisition and display system is as shown floppy disk, and transfers the data to a DATA file wherein it is subsequently analysed to produce the weld image. A flow chart of the computer code for rapid scanning of the weld is shown in Figure 3. Accumulative real time plots of the data are made during scans in order to allow the operator a preview of the data collected.

Although the technique is relatively an approach to automation, further ideas are in hand to enhance the system response. These would involve the construction of weld images into real representations allowing for a display whilst the weld pool is being formed. Advances in development work resulted in computer graphic representation of the weld silhouette as depicted in Figure 4.

CONCLUSIONS

The ultrasonic computer image results have been compared in detail with those obtained by destructive testing. In all cases, there is a consistent close dimensional correlation between the actual weld silhouette and its image.

A display of weld image is important for quality assurance purpose. The use of computerised imaging and wave form reconstruction system can allow quantitative measure of weld size.

Further advancement in this work is a proposal to reconstruct the images into real representations and displaying it while the weld pool is being formed.

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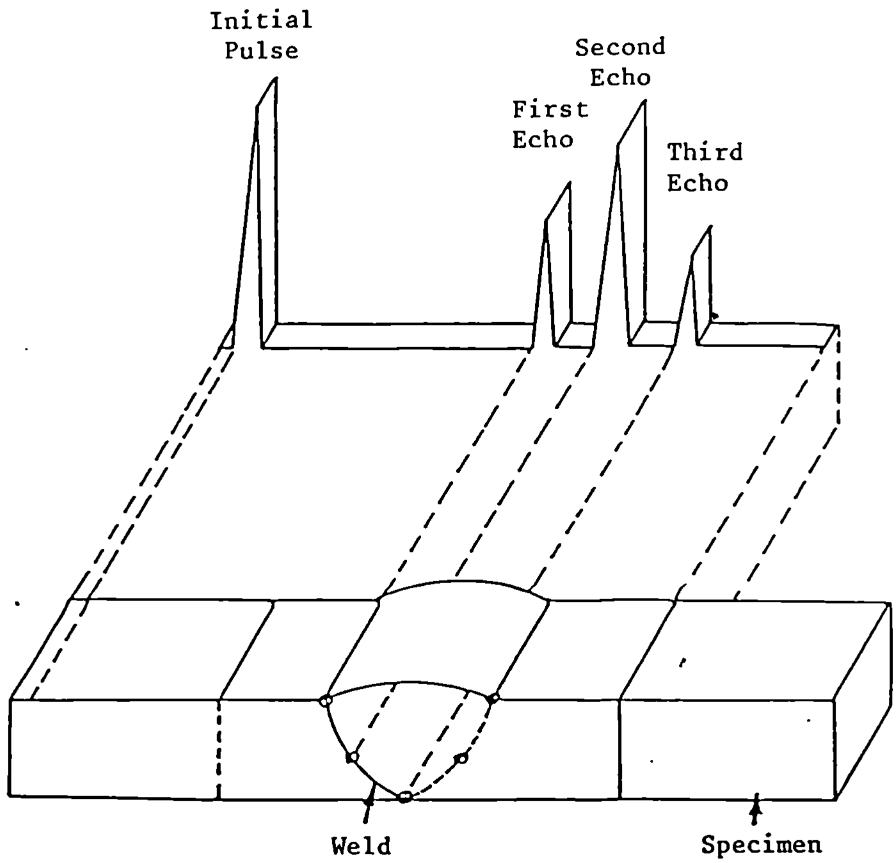
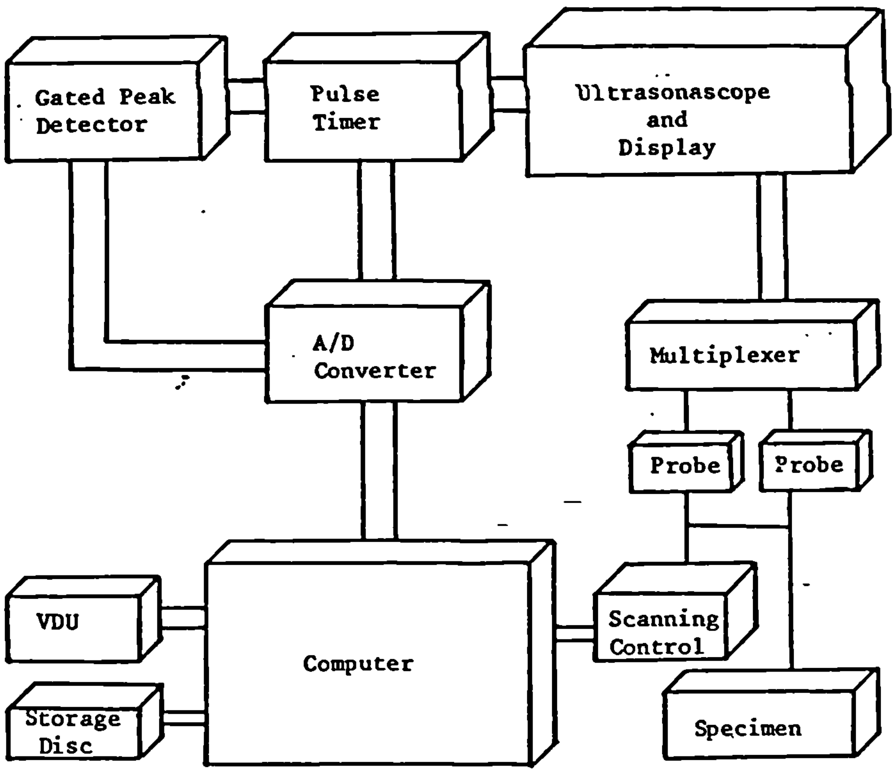
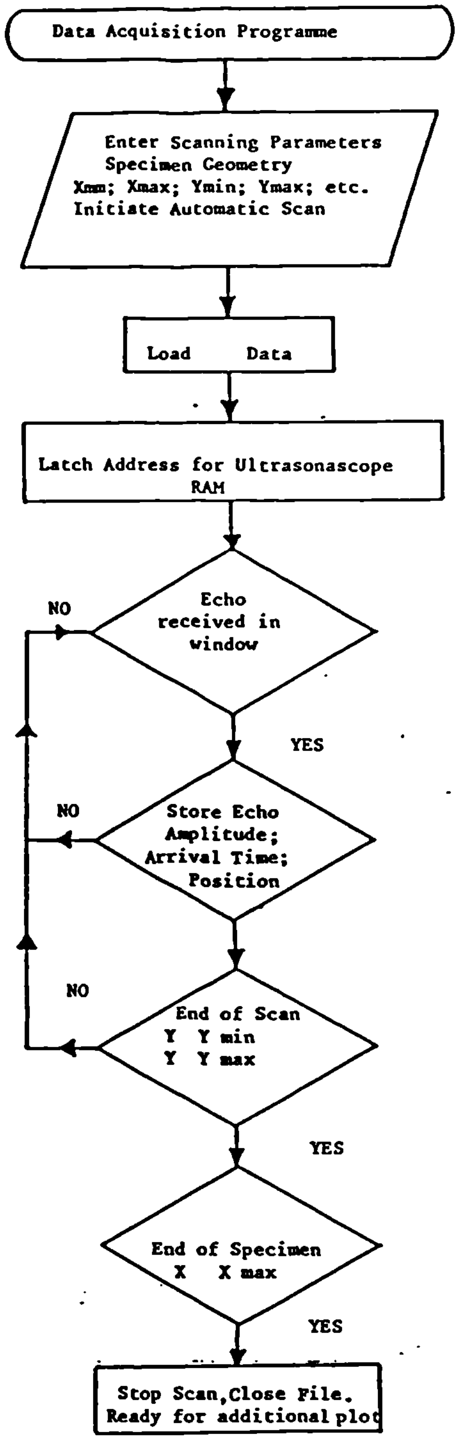


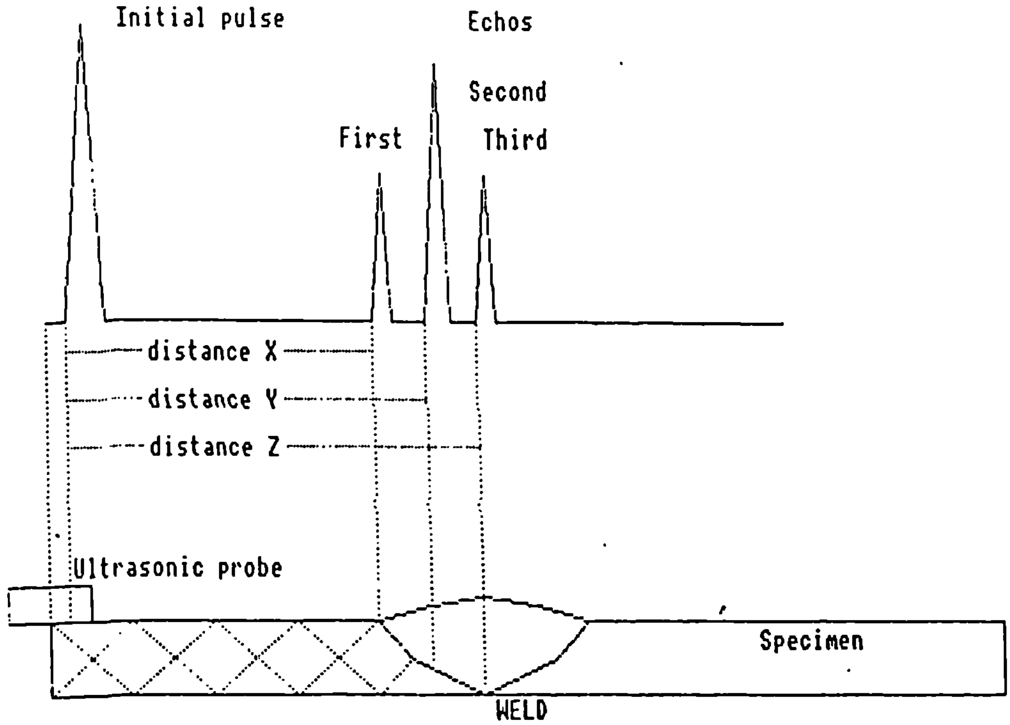
1. A Schematic projection, depicting the weld pool silhouette and time of flight



2. Block diagram of computer imaging system



3. Flow chart, depicting computer code for scanning the specimen



4. Computer graphic weld shape representation

IN-PROCESS WELDING INSPECTION AND MONITORING USING ULTRASOUND

SUMMARY

Large, complex fabrications may contain many hundreds of metres of weld, which are often required to be inspected using non-destructive testing (NDT) techniques periodically during service, as well as at the time of their manufacture.

Such inspections can be costly and time consuming, but are essential if a fabrication's continued integrity is to be assured. Success in on-line inspection depends not only on detection technique, but as much upon how it has been engineered in a system.

This paper reports on the use of ultrasound for in-process inspection and monitoring. The weldment is interrogated with ultrasound system and the resulting response signal is processed to achieve detection, delineation and identification.

The inspection system receives information signals from the molten weld pool and a whole process of signal deconvolution takes place. This signal processing concerns acquisition, enhancement and finally information retrieval, all of which is executed through a microprocessor. An information base was established with the aim of analysing and comparing with the preprogrammed design data. This allowed far more efficient data handling whilst simultaneously satisfying statutory requirements. This is achieved in real-time thus saving in post-weld inspection.

INTRODUCTION

The concept of in-process inspection and monitoring has been addressed as the act of interrogating and characterising weldments during welding cycle. When a control system measures the workpiece and uses the measurement information to compare and correct in line with design data this is termed "in-process". In-process controls rely on the sensing of variables directly at the point of welding. Very few other production processes permit such in-process control.

Automatic process control and rapid inspection techniques must be used to keep production errors from generating large numbers of faulty products. Welds must be inspected along the joint to be sure that welding defects will not weaken the final product. Ultrasonic methods are the most promising of the possible non-destructive evaluation techniques for these inspections because they can interrogate internal structures at production line speeds.

One of the most important characteristics of a fusion weld is that it should show complete and uniform penetration (1). Lack of root or side penetration can either statically or dynamically result in failure due to the formation of notchlike defects becoming the site for crack propagation. Due to the high cost of down time and destructive testing, many welded structures are not inspected as often as they should be. For an efficient application of the methods of weld quality and in-process control in welding, it is necessary to develop sensors providing accurate information of the condition of the weld, especially data on the depth of undercut, the extent of penetration, the height and shape of the underbead of the weld, the structure of weld metal, and other parameters of weld quality. Such a system of sensors combined with controlling computers ensures the formation of welded joints with the required geometrical characteristics and service properties (2).

Workpieces that have flaws in them present two major problems for industry. The first, of course, is the existence of the flaw itself, how it was created and the potential adverse effect on the finished product. The second part of the problem is detecting the flaw on a production basis and qualifying it accurately. Typically, skilled inspectors are used to check workpieces periodically, comparing them with masters that exhibit acceptable or rejectable flaws. This type of quality control is usually very expensive and inconsistent to some degree since it is dependent upon personal option. Fatigue, boredom, human error, or borderline decisions all take their toll on accuracy during the workday. In answer to these problems, the paper presented will introduce a flaw detection system which automatically performs consistent high speed, high accuracy inspection of defects through the use of ultrasonic transducers.

ULTRASONIC INSPECTION

The purpose of an inspection system is to detect defects in products to maintain established quality levels in them. Inspection of product quality for defects both in manufacturing and in-service, is an important, common and general requirement. Human inspection is, to a large and increasing extent, being replaced by automatic instrumental methods. Fully automatic methods have important advantages as outlined below:

1. Automatic methods have great potential for consistency, while the performance of the human operator is variable with respect to both recognition and judgement.

2. The speed of human operator is limited and his capability inadequate for many applications, while automatic inspection methods are potentially capable of very high speeds.

3. Many inspection tasks are highly monotonous while demanding continuous high concentration. Such tasks are prime candidates for automation.

The main tasks of ultrasonic inspection are:

a) Reliable detection of all defects with a large safety margin to relevance.

b) Location and classification, whether further analysis is necessary.

c) Sizing and characterisation of these defects.

These criteria and characterisation are valid for manual as well as mechanised ultrasonic inspections. It is a testing system that does not involve potential health hazards and work disruption. Weld inspection may be divided broadly into two classes (3):

a) Inspection for the purpose of ensuring that products comply with given specifications.

b) Inspection on a fitness-for-service basis.

The goal is effective process control for economy, for failure prevention and for operational safety of the finished product. It should be emphasised that inspection is concerned not only with test welds but also with the materials that they represent and intelligent inspection can help enormously in mundane production routine if its energy is directed more towards the fabricated components rather than languishing over post-mortems on testpieces. Certainly, if it were possible commercially to apply a single NDT conclusively to a production weld to prevent failure in service, there would be no need at all for much of the testing and certification done at present. Even so, some failures are inevitable owing to operational causes or inadequate design (4). The tragedy is that many service failures bear no relationship to the quality of welder's test, hence the latitude which should be allowed in their assessment is quite different from that accorded to actual production work.

The ideal control of weld quality is to perform such control functions whilst welding. With the present "state of the art" in measurement and control, certain combinations of the parameters create conditions which raise the question "can in-process measurement ever be applied?" Control applied to a manually controlled inspection is relatively simple. The welding operations can be stopped and the operator can use the conventional flaw detector equipment to inspect the weldment. With the particular large volume fabrication, measurement during the welding cycle can be difficult. However, the benefits which can be achieved if measurements can be made automatically during welding cycle are considerable and would be well worth any investment in equipment. The last two decades have seen enormous changes in both manufacturing and inspection technology. These developments can fulfil four-fold requirements for inspection, viz.

1) improved ease and speed of measurement
2) improved accuracy of measurement
3) reduction in the time taken to record results
4) reduction in the time taken to analyse results

The principal contributory factor in the inspection has been the development of two orthogonal linear tables carrying the probes with motorised drives. This leads to the computer assisted inspection and thence to automatic co-ordinated inspection.

Development of automation of technological processes and development of inspection methods influence and compliment each other thus becoming an integral part of automated production.

Techniques using ultrasonic waves for the detection of defects in materials are now well established in industry and have proved themselves invaluable assets in both production and laboratory. Ultrasonic flaw detection is particularly successful in the metallurgical industries where it is used for the inspection of semi-fabricated products and many finished metal components. In most cases in the past all that has been expected of ultrasonic inspection has been the detection and location of defects, but more detailed descriptions of discovered faults are increasingly demanded as engineering design advances to cope with greater speed and power. In many industries today safety factors are such that even small flaws in highly stressed components can cause catastrophic failure. Obvious examples are to be found in aircraft, atomic energy equipment and turbines, where extreme care must be taken to prevent such failure.

Designers would naturally prefer to have no defects in their materials, but in the general run of production it is difficult to produce metals completely free from defects or discontinuities. The problem of inspection therefore becomes one of deciding which defects or discontinuities will have an effect on the behaviour of the material in service. Before this can be done it is necessary to have information not only about their location but also about their size, shape, type and orientation. Defects which are large compared with the cross-section of the ultrasonic beam present little difficulty since their boundaries can be traced out to determine size and orientation. Furthermore, with the critical type of work mentioned, defects of such magnitude will usually cause rejection of the material. When it is required to obtain information other than location, it is the small defects which present problems and the principal method at present in use is one where pulse-echo technique is employed. In this technique the amplitude of the echo from the defect is compared with that from a standard known defect. The cost of locating and preparing these defects constitutes a significant portion of the total weld fabrication cost. The welding process is capital intensive, prone to quality control difficulties and unpleasant for human operator.

The current work in-process weld monitoring and adaptive control forms the basis for an intelligent welding system. An expert data base using information acquired will make intelligent decisions concerning process control without human intervention. Two major areas are addressed. Firstly, the ability to select the correct solution to a welding problem must be developed. That is, the sensors must not only be able to detect an out of limits event, the expert system must also be able to diagnose the cause and correct the situation, or determine that a human operator must be alerted. Secondly, a fitness-for-purpose criterion must be included. Thus, when a potentially defective length of weld is formed, the signficance of the defect may be assessed based on the ultimate service conditions so that an appropriate reaction (continue welding, record defect location, stop welding, etc.) occurs. Utilisation of machine intelligence (expert system) is feasible because of the ultrasonic sensors which form a computer cognition system.

THE ULTRASONIC SYSTEM

Ultrasonic systems for in-process inspection have been the subject of research and development. They include computerised "X and Y" linear (stepper-motor driven) two transducer holder assemblies, ultrasonascope, reflective pulse timer, gated peak detector, A/D converter, VDU, printer, and floppy disk and multiplexer (Pulse echo - through transmission mode). Amplitude, time and position were measurands. The gated peak detector was used to determine the amplitude of the signal within a preset gate and a pulse reflective timer to measure the time to an ultrasonic signal. A schematic layout of the system is as shown in Fig. 1. A feature of the ultrasonic hardware is the possibility of thresholding i.e. the level of signal can be varied. A block diagram of the data acquisition system is shown in Fig. 2. and a photograph of the ultrasonic hardware is shown in Fig. 2. A multiprobe system was used, the pulse-echo inspection used probes with angles of incidence of 45° and 60° and frequency of 2.5 MHz. Flaw-signal amplitude discriminator was applied to the display. Here only the flaws with signal amplitude above 60 percent of the full range are displayed.

Mechanical scanning was employed in order to speed up inspection and to ensure total coverage of the materials. The processing of this signal consisted of the following operations:

1) Defect detection - that is, the determination that the signal relates to an unacceptable departure from the target functional properties of the object. All other signals being ignored.

2) Defect delineation - following detection, the determination of the extent of the defect.

3) Defect parameter extraction and classification - the characterisation of

the defect through parameters extracted from the delineated defect signals, and the further processing of these parameters to identify the defect by name or type. It is these stages of signal processing where the most sophisticated methods are likely to be required.

DATA ACQUISITION

The role of signal acquisition is crucial in automated N.D.T. and governs the performance and accuracy of the whole system (5). Failure to deconvolute the incoming data results in loss of vital information concerning the welding and inspection process. Sampling period times must be closely controlled so that the information contained in the signal is not corrupted Coupling rate largely depends upon multiplexing frequency, increasing these frequencies allows higher sampling rates. At the same time signal to noise ratio (SNR) should be kept at a maximum level. Ultrasonic signals are often disrupted and very noisy due to artifacts inherently present in the transducer, instrumentation (6) and also scattering due to high temperatures involved during welding (7). Attempts to minimise the above effects by conditioning the signal proved to be fruitful when a filter was constructed to enhance SNR. Additionally, signal repetition suggested that averaging would adequately improve SNR.

Signal amplification also solved some of these problems associated with ultrasonic signal amplitude fluctuations. The amplification process was aided by an adjustable peak detector capable of capturing fast transient signal recordings within a predefined envelope. As the position of the probes was fixed with respect to weld centre-line, transducer position was thus uniquely defined. The peak detector deconvoluted the incoming signals by identifying their origins from a background of unwanted signals. Figure 3 depicts the layout of hardware employed.

Thus, collected data lay in an expected set envelope which eliminated the need for random signal correlation techniques to be employed. Clearly, the adapted data acquisition procedure followed produced high integrity results by restoring the ultrasonic signals.

THE DATA BASE

This was used to investigate by computer, signal processing methods for defect detection and identification. It comprised digitised scan data stored in floppy disk containing defects of one kind. Early in this work, it had been discovered that the most serious cause of corruption in establishing a data base of this type was human error. The whole scanning process was, therefore, automated. The operator positioned the plate correctly on the sample table and supplied identifying information to the computer. All remaining actions were controlled by the computer via a stepping motor, accepting scan data from the sensors, digitising and storing it. Some binary data from a basic threshold detector were also recorded for purposes of data validation. These data could either be plotted on the display unit or printed for data validation.

KNOWLEDGE BASED ANALYSIS AND RETRIEVAL

Adequate signal restoration was consequently followed by a data interrogation process of analysis and retrieval. The aim was to extract as much relevant information as possible concerning weld pool dimensions. Examining both sides of the weld, the energy transferred to the material interacts with the solid/liquid interface of the material being welded. Due to beam spread effects the whole area of fusion zone can be interrogated. The three signals present were direct responses from seam sidewalls, bottom of the weld and the weld pool itself appearing in sequencial order (8) Fig. 4. In order for all three signals to appear, accurate positioning of the probes along the seam, and with respect to electrode tip position was needed. Multiplexed variations of ultrasonic time within the predefined envelopes was easily measured using a timer device. Genuine weld pool signals, previously identified, and portraying the various parts of the weld pool were then interpreted in a suitable digital format and acknowledged by the microprocessor. Time of flight measurements were logged in memory arrayed in a form of file. Dedicated software developed to categorise this data, related time of flight to weld pool position by taking into account material thickness, ultrasonic velocity and probe separation.

Data are displayed on a VDU in real-time and also recorded on hard disk for further investigations. For reasons of clarity, ultrasonascope outputs in the analogue format and their digital signal representations can be viewed at the same time on the VDU screen.

IN-PROCESS MONITORING

An ultrasonic sensor weld quality monitor is being developed to detect, identify and correct for deviations from established welding procedures and conditions which lead to weld defects. Necessary adjustments to primary process parameters are made by automated compensation devices to eliminate weld defects in real time. When necessary specific location of discontinuities can be provided to facilitate further inspection. Secondary information about weld quality such as heat input and penetration are also computed. Data that are generated in real time can be used to stop welding, or alert an operator when an out-of-limits event occurs, and it can also be used to drive a feedback control system.

An illustration of beam spread effect on interrogating solid/solidifying weld is as shown in Fig. 2. By deconvoluting the information contained in this signal an understanding of weld quality was achieved. The initial task was accurately to identify and measure this quality signal which was relatively close to seam tracking and penetration signals respectively. During inspection and monitoring, complete scanning of the defect border provides the necessary information on the geometry of the defect, whilst another measurement made is the transit time. This is a representation of the distance between reflection points at the border of the reflector and the transducer at the respective position, e.g. it contains information concerning location and shape of the reflector. With the knowledge of the sound velocity, the corresponding path length can be calculated from the transit-time.

THE DETECTION SUBSYSTEM

The purpose of the detection is to indicate the presence of defects. without indication of severity or type. To achieve a performance compatible with a human inspector it is necessary to detect 95% of defects at low speed without wasting good material. The instrumentation is further required to replace the subjective but flexible judgement of a human inspector with the objective but inflexible judgement of a machine. Thus the specification of the requirements for detection requires some care if the quality designation of each specimen is to be compatible between man and machine. One thing that was considered here, a specimen was to be considered defective if it contains one defect indication. Thus, adequate detection does not require that the whole area of a defect trigger the detector. Provided that at least some of the defect is detected, detection may be considered successful.

The detector is presented with an analogue signal which always contains a noise (grass) component which is unwanted and is largely stochastic, and which sometimes also contains a message component indicating the presence of a defect. The detector is required to state whether the signal within each interval of observation represents noise only, or whether a message is also present. The structure of a general system for detection is shown in Fig. 2. The essential component is block 2 in which the basic decision is taken. This output is binary - at level '1' when a defect is considered to be present, and at level '0' otherwise. The decision is implemented by comparing the signal amplitude to a threshold. A defect is considered to be present when this threshold is exceeded. Two erroneous outcomes are possible: a 'missed detection' when the signal amplitude does not exceed the threshold, although a defect is present, and a 'false alarm' when the signal crosses the threshold due to noise alone The efficiency of the decision process in terms of minimising these error probabilities depends on the contrast for the message signal. Message contrast has been improved by a filter which selects message energy from the background noise.

THE DELINEATION SUBSYSTEM

Delineation of a defect is the process of locating a boundary which encloses the defect and separates it from the background surface. This boundary will be used to control the extraction of defect parameters (such as width, length, etc.) and so needs to be only as accurate as parameter extraction demands. With the scanner producing line-scan data, boundaries of detected defect signals within each scan is located. The peak of the response signal serves to locate the detected defect signal along the scan. Location plus duration give the estimated signal boundaries, as required.

THE IDENTIFICATION SUBSYSTEM

Parameter extraction goes hand-in-hand with defect delineation. Automatic inspection requires an amount of design data for the construction. Such data take the form of defect samples on the steel plate, and the collection scanning and book-keeping associated with even a modest number of samples calls for considerable effort over an extended period of time. In the pulse-echo mode technique, the dimensions of a defect are determined by comparing the amplitude of the echo given by the unknown defect with that given by a reference defect. At present it is difficult to avoid a method which uses the comparison of the amplitude of the defect echo with that of a reference echo.

An improvement in the present position is dependent on the solution of two problems:

i identification of a defect from its ultrasonic responses

ii knowledge of the reflectivity of the various defects likely to be encountered, in terms of their shape, orientation and surface condition.

DISCUSSION

Since the possibility of monitoring weld pool penetration by ultrasonic means was first proposed, the potential for controlling weld penetration was identified (9). Work has progressed steadily, utilising the 100% sound pressure signal for penetration control (10) and later the sound envelope leading edge signal for seam following (2,8,11). The existence of the (sound envelope) trailing edge signal, which interrogates the solid/solidifying weld bead, has potential as a final quality arbiter, but has not yet been developed. Work has concentrated on the development and integration of machine intelligence (an "expert system") for the rates of simultaneous seam following and weld penetration control. As these devices currently exist they represent early versions of dual ability mono-sensors. It is possible to produce, under complete machine control, a weld to given dimensions accurately down the joint, in metals of any thickness.

Currently, the "expert" system being evolved for this task is very simple, because the control functions are essentially very simple. Despite the simplicity of the expert system (but in many ways because of this simplicity) control in real time and at real rates of weld travel has been achieved. The desire to overcomplicate the intelligent system was subordinated the desire to achieve short processing times and retain real time control as a principal goal. Since the initiation of these studies, the aim of producing a useful sensor system has predominated; now an intelligent and adaptive device exsists which performs two important functions simultaneously. As an academic exercise it is reaching almost its natural conclusion but it has very clearly illustrated the potential of, and need for, such developmental approaches utilising the cheap control facilities offered by the current generation of micro-computers. In the foreseeable future, work like this will not be considered "new", "novel" or "exciting" but will be common place as cheap computational power increasingly controls welding.

CONCLUSIONS

1) The integration of manufacturing and inspection technology is a developing theme in the modern production concept. We are at long last seeing the elimination of the divided control of "We weld - you inspect". As the collaboration and understanding of each other's role in the production of components develops, then we can expect improved quality of product at an economic cost.

2) Ultrasonic scanning techniques have been described which allow the detection of flaws during welding. It thus gives early warning when defective material is being produced, thus reducing the volume of waste products, allowing changes in weld parameter to be made.

3) The system can predict the occurrence of defects. Lack of penetration/-fusion in metal weldments can also be determined and adaptive control algorithms are presently being developed for real time in-process correction of these defects.

4) Current techniques indicate the system will operate adequately for weld travel speeds of 10mm/sec.

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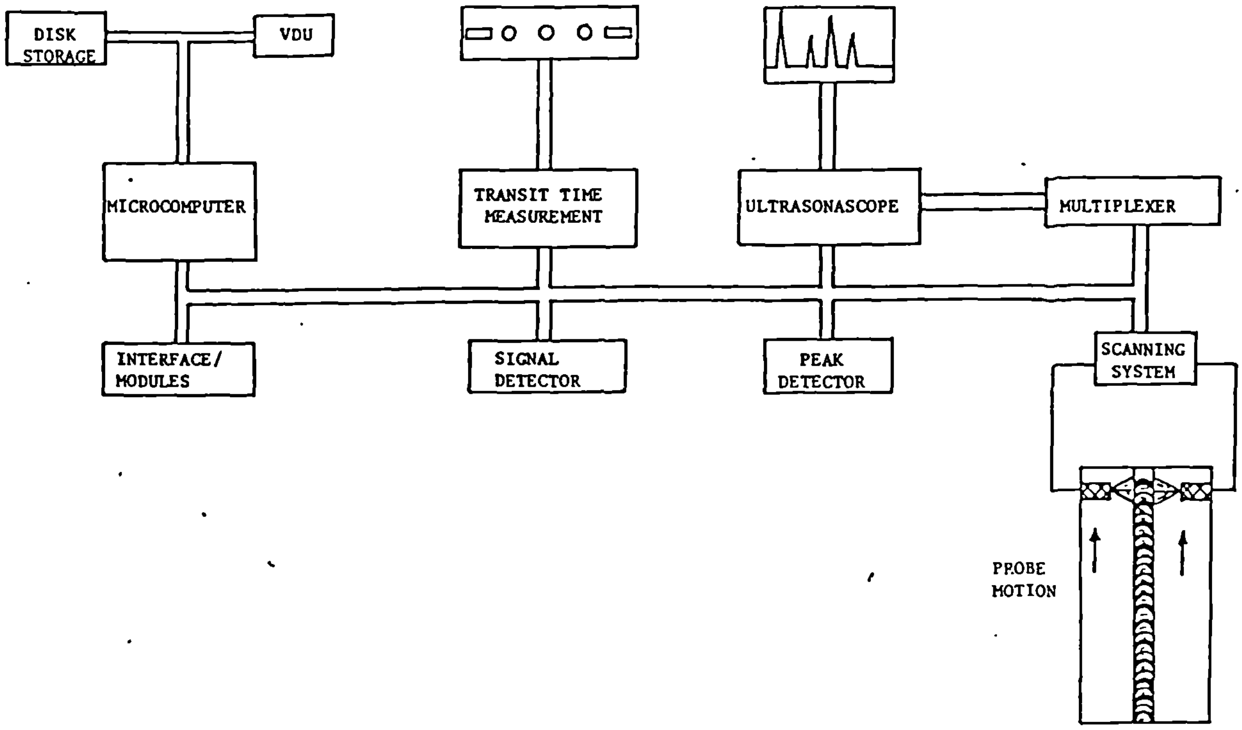

Figure 1 General system structure for inspection

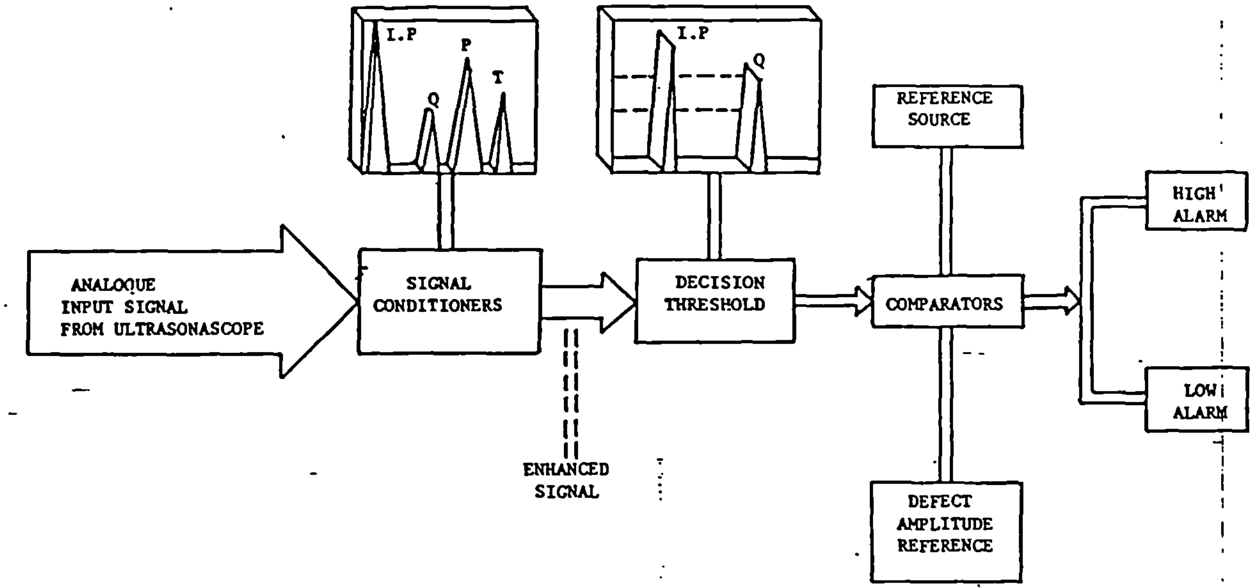

Figure 2 Schematic of process data detection system

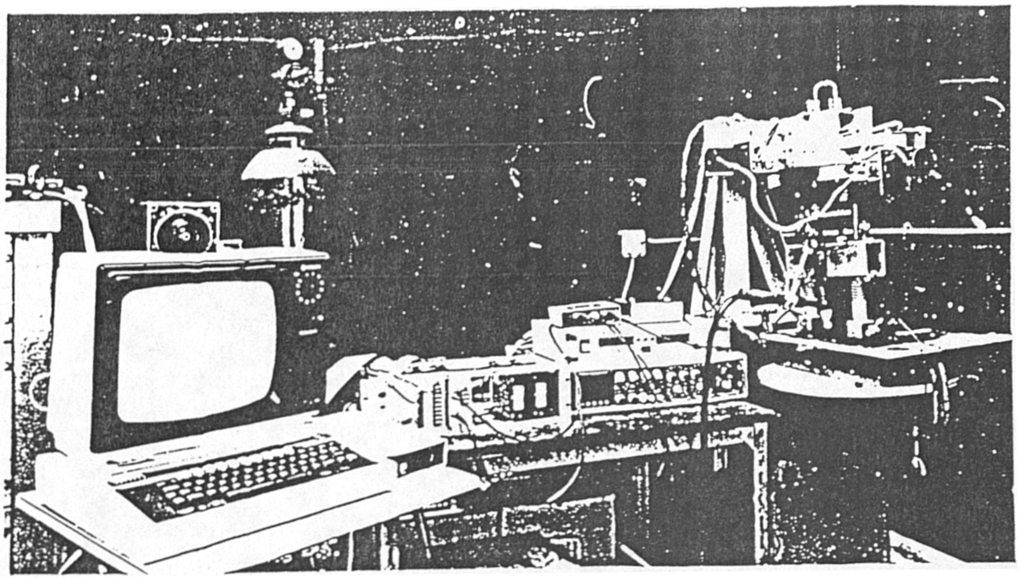

Figure 3   Layout of in process ultrasonic inspection hardware

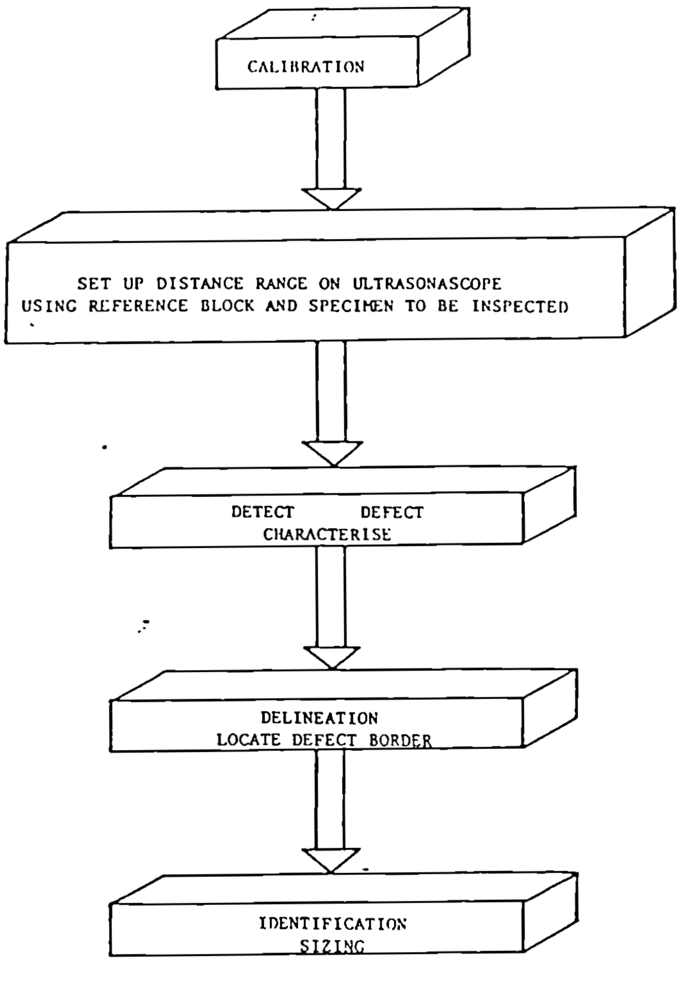

Figure 4   Procedure developed for defect characterisation