CLOSED LOOP CONTROL OF
FULL PENETRATION WELDS USING
OPTICAL SENSING OF BACKBEAD WIDTH

by

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B.S.M.E., University of Vermont (1977)

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MASSACHUSETTS INSTITUTE
OF TECHNOLOGY

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Abstract

A major concern in automated welding is to obtain
sufficient weld penetration to insure joint quality.
Previous attempts at automating the weld process were only
marginally successful, mainly because a sensor has not yet
been developed which measures weld penetration. These
control systems could regulate a bead dimension within a
loose tolerance band along with a steady state error.

The first step in improving weld penetration control
system performance is to develop a better sensor.

This research introduces an optical sensor which
directly measures the backbead width of a fully penetrated
weld. Subsequently, this sensor was used in a feedback
control system which regulated backbead width to within
±.020 inches with zero steady state error.

Thesis Supervisor: David E. Hardt
Title: Assistant Professor of Mechanical Engineering
Acknowledgements

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It is hard to imagine what I would have done without the staff of the Laboratory for Manufacturing and
Productivity which includes the technical instructors Fred (Andy) Anderson, Ralph Whittemore, John Ford and Fred Cote who were helpful with not only their manufacturing expertise but also their consultation on other aspects of this research.

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Chapter I

Introduction

Automation has become increasingly important in manufacturing because of the desire for increased productivity. Welding, being one of the major joining processes, has become automated to some extent, however, welding is a very complicated process and to date, the best welds are still produced manually. A skilled welder visually and aurally monitors the weld during the process and corrects for deficiencies by making subtle changes in torch elevation, orientation and travel speed. The welder strives to produce a weld bead centered across the joint and of sufficient depth and width.

Welding robots cannot produce quality welds comparable to that of a skilled welder because they cannot, as of yet, fully monitor the welding process. Welding robots can be thought of as preprogrammed machines because they weld along a predetermined path. These machines are termed "open loop" referring to the lack of feedback about the welding process to the machine. The machine blindly welds along its predetermined course independent of the welding process. Even if the torch tracks the seam perfectly, the weld bead can wander from the joint since the bead location is partially determined by heat transfer within the weldment, which is asymmetric. For example, if parts of different thickness are being welded, the thicker part will
conduct away more heat, which means less material in the thicker part will be melted producing an insufficient joint (Figure 1).

Weld quality is dependent on a variety of factors such as bead size, bead shape, and part cooling rate. In the case of seam tracking, closed loop control only keeps the torch centered across the joint. During the welding process, the weld bead does not necessarily remain a specific size. Thus, preprogrammed machines could be further improved to produce a consistent bead size as a step towards improving weld quality.

Accordingly, to produce a quality weld, more than one quantity must be controlled. For the present work, rather than deal with this multi-variable process, only one variable, specifically depth of penetration, was chosen as a starting point. The depth of penetration of the weld bead is closely linked to weld quality, since if the weld bead does not penetrate sufficiently, the fusion zone will be an area of stress concentration in the weldment. If the penetration is excessive, part distortion can occur and, in the extreme case, the arc burns through the part.

**Sensing Techniques**

The first step in the development of a weld penetration control system is to obtain a sensor which measures penetration. There are a number of variables of the welding
Figure 1. The Effect of Plate Thickness on Weld Quality
process which can be measured and subsequently correlated to the penetration of a weld.

Welds can be classified as being either partially or fully penetrated. A weld is termed partially penetrated when the depth of the molten region does not exceed the part thickness (Figure 2). For fully penetrated welds, the bottom surface becomes molten and there are three distinct occurrences:

1) The puddle is no longer supported by solid material, and is instead supported by surface tension.

2) As a consequence of the transition to puddle support forces via surface tension, the puddle drops to a new equilibrium position because of gravity.

3) The thermal radiation on the back surface changes from a dull red glow to a bright yellow, indicative of the higher temperature of the molten metal.

The size of the weld bead determines the strength of the joint, therefore, it is important that the sensor output correspond to a dimension of the bead since when placed under feedback control, it is the bead size which should be regulated. For partially penetrated welds, the depth of the weld bead is the primary dimension which governs the strength of the joint. Therefore, partial penetration sensors should indicate the depth of the bead. For fully penetrated welds, the width of the backbead is a good measure of joint strength, accordingly, the output of a full penetration sensor should either measure directly or
Figure 2A. A Partially Penetrated Weld

Figure 2B. A Fully Penetrated Weld
be related to backbead width.

This section presents various measurement techniques, their relation to bead size and the limitations of each method. The sensors are categorized as being either partial or full penetration measurement devices.

Partial Penetration Sensors

It is difficult to measure the degree of penetration of partially penetrated welds. Katz (1) investigated using ultrasound to measure bead geometry while in the process of welding. He showed that the ultrasonic system could detect the weld puddle, however, the relation of the data to bead geometry has yet to be established.

Vroman and Brandt (2) used a line scan camera to measure top side bead width. However, top side bead width measurement does not necessarily relate to depth of penetration. For example, for an abrupt change in material thickness, a fully penetrated weld becomes partially penetrated while the top bead width will remain the same. In addition, since the bead geometry is determined partially by the transfer of heat in the plate, even for the same thickness material, the penetration of a weld can vary. Therefore, this system only measures top side bead width and is not necessarily related to depth of penetration.

The line scan camera's operation is analogous to the operation of an ordinary video camera with the exception
that only a single line views the puddle as opposed to a square area. A linear array of 64 photodiodes is scanned electronically to form a train of voltage pulses proportional to the amount of light that illuminates each diode (Figure 3). The video signal is then thresholded to produce a binary signal that goes positive whenever a video signal pulse is above an adjustable threshold level and remains positive until a diode is sampled whose output level is below the threshold. The data signal was then processed to produce an analog voltage from 0-64 volts corresponding to the number of diodes illuminated. The camera was focused on a point some distance behind the arc intersection point, presumably because the light from the arc interfered with the light from the weld bead. This sensing technique measured top bead width accurately but caused instabilities in the control system discussed later.

Full Penetration Sensing Techniques

When fully penetrated, the puddle surface tension forces combine with the puddle mass and act like a mechanical oscillator with a natural frequency given by \( \sqrt{\frac{K}{M}} \) where \( K \) is the effective spring constant of the surface tension and \( M \) the puddle mass (Figure 4). Based upon this model of a fully penetrated weld, Zacksenhouse (3) devised a sensing technique that involved exciting the puddle with a vertical force (originating from the welding arc momentum) and then determining the natural frequency of oscillation.
Figure 3. Signal Processing of a Line Scan Camera Output (2)
Figure 4. Model of a Fully Penetrated Weld Puddle (3)
In turn, the natural frequency is related to puddle size. The determination of the natural frequency of the puddle involves the use of real-time Fast Fourier Transforms (FFT) to implement a puddle oscillation frequency control system. This sensing technique dealt only with a stationary heat input. Further research is required to determine the feasibility of implementing this sensing technique with a traveling source of heat.

When a puddle becomes fully penetrated, it drops to a new position because of gravity, thereby increasing the arc length. This increase in arc length produces a detectable increase in the arc voltage. Zackenhouse also investigated the relationship between weld puddle size and the arc voltage, however the signal is extremely noisy, making data interpretation difficult.

Nomura et al. (4) also used a photosensor for the weld process sensor. The photosensors function as a back side radiation detection system. Photosensor sensitivity to radiation is dependent on the frequency range of the light and the surface area viewed. However, a puddle can grow in length but not grow appreciably in width. Therefore, the sensor output can increase without an increase in bead width. This sensor is not a good measure of weld quality because it measures back side radiation which is not necessarily related to backbead width.
Weld Process Control Attempts

The previous section presented various sensing techniques of which only two were used for closed loop control of the welding process. Prior to discussing these control attempts, a review of the variables which determine the source of heat of the welding process is necessary.

In gas tungsten arc (GTA) welding, the heat source is referred to as the arc energy input, which is the energy introduced per unit length of weld from a traveling arc. The arc energy input is the ratio of the total power of the heat source to its travel velocity.

\[
H_{\text{net}} = \frac{P}{V} \quad (1)
\]

\(H\) - Energy input (joules/mm)

\(P\) - Total input power of heat source (watts)

\(V\) - Travel velocity of heat source (mm/sec)

The input power is the arc current multiplied by the arc voltage.

\[
P = E \cdot I \quad (2)
\]

\(I\) - Arc current

\(E\) - Arc voltage

The portion of the total heat generated by the arc which affects the material being welded is:

\[
H = f\left(\frac{EI}{V}\right) \quad (3)
\]

where \(f\) is the heat transfer efficiency, equal to the heat
actually transferred to the workpiece divided by the total heat generated (5,19).

The input to be modulated by a control system can be the arc voltage, the arc current, or the travel speed of the heat source. For a single input control system, only one of these variables should be altered while the others are maintained at a constant value.

The arc voltage is dependent on the arc gap, and if it were desired to use the arc voltage as the input to the system, the voltage would have to be altered by changes in the arc gap. Glickstein (8) showed that when increasing the arc gap, the weld penetration remained the same or decreased. He attributes this phenomenon to a widening of the heat source incident on the surface of the plate. In other words, the heat transfer efficiency is lower for larger arc gaps. Thus it appears that voltage variations are not desirable. In fact, automatic voltage control for GTAW is normally used to prevent these variations.

Arc current can be used as the control input to the system, and is in fact the most common variable. However, a sophisticated power source would be required to modify the current with the response time required by a fully automatic system.

Accordingly, travel speed is the easiest input to modify since a fully automated system will necessarily
require a servomechanism to maintain desired torch speed.

**Vroman and Brandt Control System**

The torch travel speed was chosen by Vroman and Brandt as the controlled input for maintaining top side bead width. The control algorithm was somewhat successful, however, its performance was hindered by sensor limitations.

The line scan camera, since it was focused on a point behind the arc, caused control system instability because of the pure delay introduced. This instability can be understood by examining the case where the heat source is stationary. The top surface of a stationary weld is circular. If the bead radius is less than the distance to the point where the camera is focused, the sensor will not measure the bead width (Figure 5). In addition, once the bead is measured, it does not measure the full width but some portion thereof. For the case where the welding speed is decreased instantly to an extremely low speed, there would be a time delay before the camera would register any change in bead width. On the other hand, when the welding speed is increased instantly to an extremely high speed, the camera would sweep over the entire puddle yielding puddle width growth or decay not actually present. In order to reduce the instability caused by this limitation, the camera response was slowed down. The slow response of the camera can also cause instability because of the increased phase lag at low frequencies. This requires careful
Figure 5. Limitations of the Line Scan Camera
selection of the camera response time.

By using a proportional controller, the torch speed becomes proportional to the error signal generated by the difference between a setpoint and the measured puddle width. However, the normal operation of this controller is to reduce its output in order to reduce a positive error. If the torch velocity (output of controller) is decreased to reduce a positive error (too large of a bead), the system is unstable since the puddle will increase in size. By using a negative gain, the controller will appropriately alter the torch velocity to reduce the error. From Equation 3 it can be seen that the heat input to the system is reciprocally related to the velocity. By choosing a negative gain and therefore using \(-\Delta V\) instead of \(\Delta (\dot{V})\) as the system input, Vroman and Brandt model the heat input as an approximation to the actual input. This is a good approximation for small changes in velocity (Figure 6).

Vroman and Brandt's control system regulated top side bead width within \(\pm 0.010\) with a steady state error ranging from .051 to .071 inches. In addition, the response time of the control system ranged from 10 to 20 seconds.

**Nomura Control System**

Nomura et. al. developed a weld penetration control system for submerged arc welding. In submerged arc welding, the arc and molten metal are shielded from view by an
Figure 6. Relationship of the change in Velocity to the Heat Input
envelope of molten flux and a layer of unfused granular flux particles. When the arc is struck, the tip of the continuously fed electrode is submerged in the flux and the arc is therefore not visible (6). The weld is made without the intense radiation that characterize the open arc processes. Nomura et. al. mounted four photosensors in a square pattern on a cart which allowed the photosensors to symmetrically view the bottom surface of the weld bead (Figure 7). The cart was kept centered about the weld bead by what could be considered a "bang-bang" control scheme. The cart had only two velocity modes, fast and slow. The difference between the sum of the front sensor output to the sum of the rear sensor output would determine the cart velocity mode. If the rear output exceeded the front output, the cart velocity would be in the slow mode. If the front output exceeded the rear output, the cart would be in the fast mode. This control scheme allowed the cart to follow the weld bead in an oscillatory manner. Nomura et. al. selected the arc current as the control system input (Figure 8). Using a special power source containing several transformers connected in parallel by electronic switches, the arc current was modified by inputting a D.C. voltage to the power source which determined the number of switches to be turned on or off. The circuit control signal was determined by comparing the sum of all four photosensor outputs to a reference value. The performance of this control scheme is dependent on the resolution of the
Figure 7. Nomura Photosensor Arrangement (4)
the discrete increments in arc current. If the resolution is too large, this control scheme would produce a steady state value which oscillates about a setpoint (Figure 9).

Nomura et. al.'s control system was developed for shipbuilding where backbead widths of .75 inches are common. This control system maintained backbead width within a .16 inch tolerance band. However, this system requires the operator to adjust the torch travel speed and setpoint in order to achieve a desired bead width.

Research Objectives

The previous control attempts were successful within the limitations of the sensor used. Nomura et. al. used the photosensors to measure back side radiation which is not a direct measure of backbead width. This control system therefore controls radiation not bead width. Vroman and Brandt used a sensor that measured top side bead width, however, this does not necessarily relate to the penetration of the weld. Both control systems could maintain the bead width within a particular tolerance band but in each case there was a steady state error. This requires the operator to adjust the setpoint to produce the desired bead width. It is the goal of this research to develop a better full penetration weld control system.

The first step towards a better full penetration weld control system is to develop a better sensing technique.
Figure 9. Problems with Arc Current Regulating Power Sources
With the previous attempts at weld process control in mind, the following guidelines for sensor development were chosen:

1) Since most successful attempts at penetration control used some form of a photo-optic sensor, only photo-optic sensors such as photodiodes or phototransistors, were considered.

2) By sensing the back side, the sensor can view the entire puddle or any portion thereof. This avoids errors caused by the arc light.

3) Backbead width, as a measure of the degree of full penetration, should be correlated to the sensor output.

4) Processing time of the data should be kept to a minimum.

5) The sensor should be hard-mounted to insure that the sensor always looks at the same location relative to the torch centerline.

Admittedly, the bottom side measurement cannot be easily adapted to the diverse part shapes used in production. However, this approach is used as a step towards fully understanding the weld process. As a result, a sensor was developed that measures backbead width without any processing time.

Subsequent to the sensor development, in order to complete a full penetration weld control system, a transfer function must be determined for the process. This research is concerned with controlling a single output (backbead width) by modulating only one input. Using the previous weld process control attempts as guidelines, the torch travel speed was chosen as the input to the process. The
transfer function therefore relates backbead width to torch travel velocity.

After a transfer function was determined, various controllers were implemented in an attempt to achieve the following set of specifications for system performance:

1) Zero Steady State Error - The previous control attempts could contain the bead width within a particular tolerance range, however, each system required an operator to monitor the system and adjust it to produce a desired bead width.

2) The transient response of the closed loop system must not be underdamped to avoid overshoot in bead width.

Chapter II discusses the theory and development of the backbead width sensor. Upon completion of the sensor development, various control systems were tested for steady state error and response to parameter variation. Chapter III discusses the transfer function identification of the process in addition to control system performance. Chapter IV is a discussion of areas requiring further research such as improvements in sensing techniques and the development of more sophisticated controllers.
Chapter II
SENSOR DEVELOPMENT

Introduction

Although there are many choices for thermal and visible radiation sensing, phototransistors were chosen as the sensing device primarily because of price and availability. The theory of phototransistor operation is presented to detail all of the variables involved in the sensing process and how each affects the resultant output. The study of these variables and their relation to sensor output proved useful in developing a full penetration weld sensing technique. In addition to phototransistor theory of operation, penetration sensing designs and their subsequent testing and evaluation are presented.

Radiation Theory

Prior to introducing phototransistor operation, a review of thermal radiation theory is necessary. Thermal radiation, which includes ultraviolet, visible and infrared radiation, is defined as the radiant energy emitted from a medium by virtue of its temperature. A blackbody emits (and absorbs) at any temperature the maximum possible amount of radiation at any given wavelength. The temperature of the blackbody determines the distribution of the radiant energy within the thermal radiation frequency range as indicated by Figure 10. As the temperature increases,
Figure 10. Spectral Energy Distribution of a Blackbody
the distribution of the energy shifts further into the visible range. The area under each constant temperature curve is the total rate of energy emission per unit area given by:

\[ e_b = \int_0^\infty e_{b\lambda} \, d\lambda \]  \hspace{1cm} (4)

- \( e_b \) - rate of energy emission per unit area or blackbody emissive power (ergs/sec)
- \( e_{b\lambda} \) - monochromatic blackbody emissive power (ergs/sec)
- \( \lambda \) - wavelength of the electromagnetic radiation.

The monochromatic emissive power \( e_{b\lambda} \) is a function of temperature and wavelength:

\[ e_{b\lambda} = \frac{2\pi \hbar c^2 \lambda^{-5}}{e^{(\hbar c / kT)} - 1} = \frac{(3.74041 \times 10^{-5}) \lambda^{-5}}{e^{(1.43868/\lambda T)} - 1} \] \hspace{1cm} (5)

- \( \hbar \) - Plank's Constant = \( 6.62377 \times 10^{-27} \) (erg·sec)
- \( c \) - speed of light = \( 2.997902 \times 10^{10} \) (cm·sec)
- \( \lambda \) - wavelength (cm)
- \( k \) - Boltzmann's Constant = \( 1.38026 \times 10^{-16} \) (erg/k)
- \( T \) - blackbody temperature (°k)

Thermal radiation emitted from real surfaces is related to the radiation from a blackbody by the emissivity.

\[ e_{s\lambda} = \frac{e_{s\lambda}}{e_{b\lambda}} \] \hspace{1cm} (6)
\( \varepsilon_{s\lambda} \) - monochromatic emissivity
\( \varepsilon_{s\lambda} \) - monochromatic emissive power of the real source
\( \varepsilon_{b\lambda} \) - monochromatic emissive power of a blackbody.

There are three types of radiating sources which are described by their emissivity:

1) Blackbody - by definition \( \varepsilon_b = 1 \)

2) Graybody - defined by an emissivity equal to a constant less than unity \( \varepsilon_g < 1 \)

3) Selective Radiator - defined by an emissivity which varies with wavelength.

Figure 11 is a graphical illustration of these radiating sources. A graybody has the same spectral energy distribution as a blackbody. Therefore, at the melting point of steel (2800°F) a graybody's peak monochromatic power is in the near infrared frequency range. Additionally, there is more power radiated at the red light frequency than at the yellow light frequency. However, when the puddle is viewed with the human eye, it appears predominantly yellow since the eye cannot detect infrared radiation and therefore acts like an optical filter that is more sensitive to yellow light than it is to red light.

The total radiation leaving blackbody surface \( A_1 \) and arriving at blackbody surface \( A_2 \) is:

\[
E_{b_{12}} = e_{b_1} A_1 F_{12}
\]

\( E_{b_{12}} \) - total radiation energy emitted from surface \( A_1 \) incident on surface \( A_2 \)
Figure 11. Comparison of the Emissivity of a Blackbody, A Graybody and a Selective Radiator (20)
\( A_1 \) - surface area of emitting surface

\( E_{b1} \) - rate of energy emission per unit area of blackbody

\( F_{12} \) - geometry shape factor

The geometry shape factor is a proportionality constant which indicates what fraction of the total radiation leaving one surface is intercepted by another (Figure 12).

The geometry shape factor is a function of the projected surface area of each surface as viewed from the other surface and inversely proportional to the square of the distance between the two surfaces (Figure 13).

\[
F_{12} = \frac{(A_1 \cos \phi_1)(A_2 \cos \phi_2)}{d^2}
\]

(8)

With the phototransistor as the receiving surface \( A_2 \), and the weld puddle as the emitting surface \( A_1 \), the amount of radiation received by the phototransistor is:

\[
E_G = \varepsilon_G E_{b1} A_1 F_{12}
\]

(9)

where:

\( E_G \) - radiation received by the phototransistor

\( \varepsilon_G \) - emissivity of steel

\( A_1 \) - puddle surface area

\( F_{12} \) - shape factor determined by puddle area and the square of the distance between the puddle and the phototransistor.
Figure 12. Variables which Determine the Geometry Shape Factor (16)
Figure 13. Variables which Determine the Geometry Shape Factor (16)
Phototransistor Operation (17)

A phototransistor is a combination amplifier and transducer. The incident thermal radiation produces an input signal to the phototransistor called the photocurrent. The output current of the phototransistor is an amplification of the photocurrent. This amplification process is:

\[ I_{o\lambda} = K I_{p\lambda} \]  

(10)

- \( I_{o\lambda} \) - transistor output current (amps) for incident radiation of wavelength
- \( I_{p\lambda} \) - photocurrent (amps) for incident radiation of wavelength
- \( K \) - gain.

Phototransistors are sensitive to radiation in the visible and infrared spectra. A typical spectral response curve of a phototransistor is shown in Figure 14. The photocurrent is related to the incident radiation by the phototransistor sensitivity.

\[ I_{p\lambda} = \delta_{\lambda} E_{G\lambda} \]  

(11)

From Equation 9 we know that:

\[ E_{G\lambda} = E_G e^{b_{\lambda} A^1 F^2} \]  

(12)

The net output current is the sum of all the frequency components in the spectrum or:

\[ I_o = \int_0^\infty I_{o\lambda} d\lambda \]  

(13)

substituting Equations 10 into 13 we have:
Figure 14. A Typical Spectral Response of a Phototransistor (17)
\[ I_0 = \int_0^\infty K I_\lambda \, d\lambda \]  \hspace{1cm} (14)

The photocurrent is related to the incident radiation by Equation 11 such that:

\[ I_0 = \int_0^\infty K \delta_\lambda E_{\lambda} \, d\lambda \]  \hspace{1cm} (15)

where \( E_{\lambda} \) is defined by Equation 12 so:

\[ I_0 = \int_0^\infty K \delta_\lambda \epsilon_\lambda \epsilon_{b\lambda} A_1 F_{12} \, d\lambda \]  \hspace{1cm} (16)

Bringing the frequency independent variables outside the integral:

\[ I_0 = K \epsilon_\lambda A_1 F_{12} \int_0^\infty \delta_\lambda \epsilon_{b\lambda} \, d\lambda \]  \hspace{1cm} (17)

where \( \delta_\lambda \) is defined by Figure 14 and the blackbody emissive power \( \epsilon_{b\lambda} \) is given by Equation 5. Therefore:

\[ I_0 = K \epsilon_\lambda A_1 F_{12} \int_0^\infty \left( \frac{(3.74041 \times 10^{-5}) \lambda^{-5}}{e^{(1.43868 / \lambda T)} - 1} \right) \delta_\lambda \, d\lambda \]  \hspace{1cm} (18)

The integral can be approximated by numerical integration (Appendix A). The integral is exponentially related to the temperature of the radiating source as indicated by Figure 15 or:

\[ I_\rho = \int_0^\infty \frac{(3.74041 \times 10^{-5}) \lambda^{-5}}{e^{(1.43868 / \lambda T)} - 1} \delta_\lambda \, d\lambda \]  \hspace{1cm} (19)
Figure 15. The Spectral Photocurrent for a Blackbody at 1800° K
The phototransistor output is a function of

\[ I_0 = KA_1 F_{i2} \varepsilon_g I_p \]  

(20)

where:

- **K** - phototransistor gain
- **A_1** - puddle surface area
- **F_{i2}** - shape factor which is determined by the surface area of the puddle and phototransistor and the square of the distance between them
- **\varepsilon_g** - the emissivity of steel
- **I_p** - the net photocurrent which is exponentially related to the puddle temperature.

Table 1 discusses how these variables can change during the welding process. Phototransistor output is dependent on a number of variables however, most of these do not change significantly during the welding process.

The gain of the phototransistor is a function of the power source. If the power source can be maintained at a constant value, the phototransistor gain will also be constant. With the appropriate design, the effects of the geometry shape factor can be minimized. The geometry shape factor is governed by the surface areas of the weld puddle and the phototransistor and the distance between them. The surface of the weld puddle is determined by the welding process. Therefore, the shape factor is primarily determined by the distance between the puddle and the transistor.
<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
<th>PARAMETERS WHICH CAUSE VARIATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>Phototransistor Gain</td>
<td>The gain is determined by the power supplied to the phototransistor. If this supply picks up electrical noise prior to entering the transistor or if the signal is itself time varying, the output of the transistor will vary accordingly.</td>
</tr>
<tr>
<td>$\delta\lambda$</td>
<td>Phototransistor Sensitivity</td>
<td>The sensitivity is a function of the temperature of the transistor. An increase in transistor temperature increases the sensitivity.</td>
</tr>
<tr>
<td>$\varepsilon_G$</td>
<td>Graybody Emissivity</td>
<td>This assumes that there is no interference from other radiating sources. In the weld process, the weld puddle contains slag and gives off fumes both of which will affect transistor output.</td>
</tr>
<tr>
<td>$A_t$</td>
<td>Emitting Surface Area at Constant Temperature $T$</td>
<td>The temperature distribution in a plate for a moving source is determined by the speed and the thermal conductance of the material.</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>$F_{12}$</td>
<td>Shape Factor</td>
<td>The phototransistor output is inversely proportional to the square of the distance between the projected emitting and receiving surfaces.</td>
</tr>
</tbody>
</table>

Table 1. Factors which affect phototransistor output.
If the phototransistor is placed extremely close to the puddle, the shape factor will become significant since it is inversely proportional to the square of the distance. As the puddle becomes fully penetrated it drops because of gravity. This change in the distance drastically affects the transistor output if it is close to the puddle, therefore, a large enough distance must be chosen to negate the small changes in puddle position. In addition, a large distance will keep the heating of the transistor to a minimum thereby maintaining a constant spectral sensitivity. In addition, most metals, including steel, are defined as graybodies. Assuming that these variables \((k, \varepsilon_G, F_{12})\) are essentially constant, the phototransistor output is proportional to the surface area viewed and the temperature of the source.

\[
I_0 = \mathcal{IK} \sum_{T=T_0}^{T=\text{TMAX}} A_T I_P(T) \tag{21}
\]

\(I_0\) - photosensor output

\(\mathcal{IK}\) - overall gain of sensor determined by the phototransistor gain, the emissivity of the source and the geometry shape factor

\(A_T\) - surface area at constant temperature \(T\)

\(I_P(T)\) - photocurrent generated by a blackbody at temperature \(T\)
Sensor Development Experiments

The objective of this phase of the research was to develop a better sensing device that measures the degree of full penetration in welding. The following design guidelines were cited in Chapter I:

1) Since most successful attempts at penetration control used some form of a photo-optic sensor, only photo-optic sensors such as photodiodes or phototransistors were considered.

2) By sensing the back side, the sensor can view the entire puddle or any portion thereof. This avoids errors caused by the arc light.

3) Backbead width, as a measure of the degree of penetration, should be correlated to the sensor output.

4) Processing time of the data should be kept to a minimum.

5) The sensor should be hard-mounted to insure that the sensor always looks at the same location relative to the torch centerline.

Equipment

The gas tungsten arc (GTA) welding machine generates heat from the energy liberated from an electric discharge between two electrodes (Figure 16). The workpiece is one electrode, the other is a non-consumable two percent thoriated tungsten electrode. The arc and molten region are purged by a bath of inert argon gas to isolate the molten region from impurities such as oxygen. The 440 volt welding power supply produced a three-phase, full wave, rectified current controlled output. As mentioned in the Introduction, the heat input to the workpiece is the product of the arc
Figure 16. A Typical Gas Tungsten Arc Welding Configuration (19)
current and arc voltage divided by the torch travel speed. Travel speed was chosen as the controllable input to the system (weld puddle), and a Bridgeport milling machine, with a servomechanism on the table axis, was used to modulate this speed. The servo input voltage was commanded by a Cromenco Z-2D micro-computer using FORTRAN. An integer value corresponding to a specific velocity was converted into an analog voltage using a 12 bit digital to analog converter.

A clamping device mounts the part to be welded roughly five inches above the milling machine bed (Figure 17). The torch is mounted in the normal cutter location of the milling machine. Mounted to the same fixture which holds the torch is an arm that extends underneath the workpiece enabling the phototransistor to view the bottom surface, thus the workpiece moves by the stationary torch and transistor. The phototransistor circuit that was used is shown in Figure 18. This circuit can:

1) offset any bias signals;

2) amplify the phototransistor output; and

3) provide a first order low pass filter with a break point at 5 Hz.

From the operational amplifier the output signal was input to the computer via an analog to digital converter. The analog to digital converter transforms an input voltage of ±5 volts into an integer number of ±2048. During each test
Figure 17. The Configuration of the Gas Tungsten Arc Welding Machine Mounted to the Servo
Figure 18. Phototransistor Schematic
the transistor output could be plotted on a chart recorder and/or stored digitally on the computer for data processing (Figure 19).

As detailed earlier, the phototransistor is primarily sensitive to the surface area viewed and the amount of radiant energy. The two sensor designs, discussed in the Results section, differ only in the surface area viewed. The first design allowed the phototransistor to view the entire puddle. Evaluation of this design led to a second one which limited the view to a specific segment of the weld puddle. A minor modification of the second design produced satisfactory backbead width measurement. The methods for testing each design were the same in all three cases.

**Methods**

When the arm that holds the phototransistor was designed, an appropriate distance between the puddle and the transistor was not known. The easiest way to determine the proper distance was by experimentation. For this reason, the arm was designed to allow for two different mounting positions of the transistor (Figure 20). One method allowed the transistor to look directly at the puddle, and the other method would bounce light off a front surface mirror before reaching the transistor. This would allow the distance from the weld puddle to change from five to fifteen inches. The larger distance, although
Figure 19. Block Diagram of Laboratory Equipment
Figure 20. Options for Mounting Phototransistor
it reduced the transistor output, was chosen to reduce the heating of the transistor. In order to assure repeatability of the measurements, an alignment procedure of the torch and phototransistor was incorporated. This allowed the phototransistor to view the same relative spot of the puddle regardless of travel direction. The attitude of the torch with respect to the workpiece was inspected by replacing the electrode with a long rod. Using a machinist's square, the long rod (torch axis) was adjusted to be perpendicular to the workpiece (Figure 21). The transistor was aligned with the electrode axis by adjusting the angle of the mirror (Figure 22).

Prior to each test, the electrode gap was 1/8 inch, the tip shape was checked for wear (Figure 23), the argon gas flow was 20 cfm and the arc current was set at 125 amps. Only 11 gauge hot rolled steel was used. Local heat input to the weldment was altered by table velocity. Each test consisted of selecting a torch velocity that produced a particular bead width. When the workpiece was cool enough to handle, the width of each backbead was measured in several locations using a machinist's scale and was compared to the sensor output.

Several computer programs were developed to aid in the evaluation of the sensor designs:

1) Testing programs - allow the user to run the table at constant velocities. At the user's command, the program will sample the transistor output and store the data on a disk.
Figure 21. Torch Alignment
Figure 22. Mirror Adjustment
Figure 23. Electrode Adjustment
2) Data evaluation programs - these programs read the data files generated by the testing programs to calculate average values or perform spectral analysis of the signal. The resulting data is stored on a disk.

3) Hardcopy programs - allow the user to produce hardcopy in the form of printout or plots from any of the datafiles generated.

Table 2 briefly describes each program and Figure 24 is a flow chart which indicates how the programs are interrelated.

Results

Design #1 - "Full View Method"

Figure 25 is a typical plot of transistor output versus time for full-view sensing. The correlation of two features of the output signal to backbead width were investigated:

1) average D.C. value; and

2) frequency of the signal (The frequency of the signal was postulated to be a direct function of bead width since the puddle was thought to have a vortex motion. The time to complete one cycle would indicate the circumference and consequently the width of the weld puddle.)

Figure 26 indicates no relation between D.C. voltage and the measured backbead width.

In order to determine the frequency content of the output signal, the program FFTDATA was used in conjunction with STEPDATA. The FFT program produced a data file that contained the signal frequency components and their magnitudes.
## TEST PROGRAMS

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEPDATA</td>
<td>Runs table at selected velocities and, at the user's command, stores the transistor output on a data file. The data file can store up to 1024 points.</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>Runs table at selected velocities and, at the user's command, samples the transistor output. The program then calculates the average voltage of the 1000 datapoints and prints it out on a screen.</td>
</tr>
</tbody>
</table>

## EVALUATION PROGRAMS

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCFILTER</td>
<td>Subtracts the D.C. value from the sampled data file and produces a new data file of strictly oscillatory components (A.C. data file).</td>
</tr>
<tr>
<td>FFTDATA</td>
<td>Reads the sampled data file or the A.C. data file then produces an FFT data file. Contained within this data file are the magnitudes of each frequency</td>
</tr>
</tbody>
</table>

## HARDCOPY PROGRAMS

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLOTDATA</td>
<td>Reads data from sampled data file, A.C. data file or FFT data file and produces a plot on a varian.</td>
</tr>
<tr>
<td>PRINTDAT</td>
<td>Reads data from sampled data file, A.C. data file or FFT data file and produces a printout.</td>
</tr>
</tbody>
</table>

Table 2. Sensor Test Programs
Figure 24. Test Program Flow Chart
Figure 25. A Typical Phototransistor Output for Viewing the Entire Puddle
Figure 26. The Relation of Phototransistor Output vs. Backbead Width When Viewing the Entire Puddle
Figure 27 is typical of the random nature of the frequencies in the signal.

For identical widths, the magnitude for each frequency is different. Additionally, the peak magnitude of each plot occurs at a different frequency. In spite of this, the frequency spectrum of the transistor output was always less than 1 Hz. It is speculated that these frequencies are caused by random puddle growth or decay.

During these experiments the back surface of the workpiece could be viewed by the human eye. The puddle surface area changed considerably during the process, and from Equation 21 we know the phototransistor is sensitive to not only temperature but also the surface area. Therefore, a change in the puddle surface area should produce a change in the output of the sensor. References 7-14 indicate puddle growth is determined by torch velocity, the electromagnetic stirring of the puddle, tip shape, and surface tension.

As a result of these multiple influences, backbead width measurement inaccuracies occur because the puddle can grow appreciably in length and not in width. The second design of the sensor eliminated the errors caused by the puddle growth in length by constraining the sensor to view a particular area of the puddle. By adding a bracket with a .03 inch wide slot, the sensor view was limited to a rectangular
Figure 27. The Phototransistor Output Signal Frequencies Differ in Magnitude for the Same Backbead Width
area (Figure 28). The area viewed by the phototransistor is:

\[ \text{AREA VIEWED} = \text{(SLOT WIDTH)} \times \text{(PUDDLE WIDTH)} \]

It can be seen now, that the area viewed changes linearly with the backbead width. This design shall be referred to as the "Slot Method".

**Design #2 - "Slot Method"**

Following the same experimental procedure as with Design #1, the average D.C. value of the "Slot Method" was found to be linearly related to backbead width as shown in Figure 29. Referring to Figure 15 we know the transistor output is exponentially related to temperature. In order for the average D.C. voltage to be linearly related to the puddle width, the puddle temperature must be nearly constant. It is speculated that the puddle is a constant temperature for two reasons:

1) The changing of the metal from the solid state to the liquid state is a constant temperature process.

2) the electromagnetic stirring of the puddle helps maintain a uniform temperature.

Figure 29 shows a distinct difference between the first and second series of tests. These tests were run on the same plate approximately five minutes apart, therefore, the second series of runs were made on a preheated plate. Since the plate was at a new steady state temperature, the
Figure 28. The Slot Design
Figure 29. Phototransistor Output vs. Backbead Width for the Slot Design
temperature gradient of the puddle surroundings decreased. (A simple test to determine the feasibility of using a photo-diode array as a sensor led to the understanding of the effect of the plate temperature gradients on transistor output (Appendix B).) Figure 30 is an illustration of the temperature distribution of the first and last runs. The transistor will not sense thermal radiation below a certain threshold temperature $T_{\text{Threshold}}$. For the first run, the high temperature distribution in the plate is contained within a narrow region allowing an accurate measurement of the bead width. By the last run, the plate has reached a new ambient temperature $T_L$. This broader distribution of temperature causes the sensor to incorrectly measure the bead width since the sensor detects a significant amount of radiation from the puddle surroundings.

Christensen (15) studied the temperature distribution for moving sources of heat (Figure 31) and showed that the temperature distribution in the workpiece is a function of travel speed. At higher travel velocities the temperature gradients are larger and the bead widths are smaller. Christensen also shows that the larger temperature gradients occur at the leading edge of the puddle. The puddle, because of its higher temperature, emits significant radiation in the visible range. The human eye, since it filters out all infrared radiation, detects only the visible radiation. The radiation emitted from the puddle surroundings is predominantly in the infrared range. Therefore, the only
Figure 30. A Typical Cross Section of the Temperature Gradient of a Weld
Figure 31. The Temperature Distribution in a Plate for a Moving Heat Source (15)
significant visible radiation is emitted strictly from the puddle. This is the reason why bead size can be determined visually, but is difficult to measure with an unfiltered photosensor. The sensor can be made to function more like a human eye by placing heat absorbing glass (an infrared filter) between the phototransistor and the weld puddle.

Figure 32 is a graph of percent transmission versus frequency of the heat absorbing glass. This filter will absorb or reflect most of the infrared radiation which is the majority of the radiant energy. This necessitated increasing the operational amplifier gain to improve the resolution of the sensor output. By repeating the tests, the sensor output was found to be linearly related to backbead width regardless of the temperature of the puddle surroundings (Figure 33). During the tests, backbead widths below .1 inches could not be produced. The weld was either fully penetrated with bead widths greater than .1 inches or the weld only partially penetrated the plate.

Conclusions

Phototransistor output is a function of the surface area viewed and the temperature of the radiating source. The constant temperature of the weld puddle allows phototransistor output to be linearly related to the surface area viewed. By constraining the phototransistor to view a rectangular segment of the puddle, the sensor output becomes linearly related to bead width. An infrared filter
Figure 32. Filtering Effect of Heat Absorbing Glass
Using Method of Least Squares the best fit line is:

\[ \text{integer} = (888) \text{ width} - 111 \]

Figure 33. The relationship of backbead width to phototransistor output using slot method and heat absorbing glass.
must be used to eliminate errors caused by thermal radiation from the puddle surroundings. With an effective gain of 100, the analog to digital converter measures bead width with a resolution of \( \frac{.001 \text{ inch}}{\text{Integer No.}} \). The phototransistor output is corrupted by sparks which fly from the puddle surface, fumes emanating from the puddle, slag on the bottom of the puddle and electrical noise originating from the arc.
Chapter III

Closed Loop Control of
Full Penetration Welds

Having developed a full penetration sensor which measures backbead width, the next phase of this research was to determine a transfer function which relates the backbead width to torch travel speed. Once a transfer function was identified, several controller designs were implemented in an attempt to achieve the following performance criteria:

1) Zero steady state error.

2) The transient response of the system must not be underdamped to avoid overshoot (bead width too large).

The first section of this chapter discusses the determination of the transfer function. In the second section, several controller designs and the performance of each are discussed. Observations and conclusions of the chapter are summarized in the final section.

Open Loop Transfer Function Identification

Thermal systems are typically modelled as a resistance capacitance (RC) network with temperature as the controlled variable. The welding process, as described here, differs from typical thermal systems because the control variable is a puddle dimension (backbead width) as opposed to temperature.
A heat balance for the welding process is:

$$\dot{Q}_{in} = \dot{Q}_{stored} + \dot{Q}_{cond} + \dot{Q}_{conv} + \dot{Q}_{rad}$$  \hspace{1cm} (22)

as illustrated by Figure 34 where:

$$\dot{Q}_{in} = f \left( \frac{ET}{V} \right)$$  \hspace{1cm} (3)

- the portion of heat stored in the puddle
- heat conducted away from the puddle
- heat convected away from the puddle
- heat radiated from the puddle

or:

$$\dot{Q}_{in} = \dot{Q}_{stored} + \dot{Q}_{dissipated}$$  \hspace{1cm} (23)

The sensor development phase of this research revealed that the puddle is nearly constant in temperature caused partly by a phase change, therefore the puddle stores heat by virtue of its change in volume.

$$\dot{Q}_{stored} = \rho h \frac{dV}{dt}$$  \hspace{1cm} (24)

where:

- \( \rho \) - density
- \( h \) - latent heat of fusion
- \( \frac{dV}{dt} \) - volume rate of change of the puddle.
Figure 34. A Heat Balance for the Welding Process
Rearranging Equation 23 yields:

$$\dot{Q}_{\text{stored}} = \rho h \frac{dV}{dt} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{dissipated}}$$

(25)

The rate of heat storage in the puddle is the difference between the heat flow into the puddle and the heat flow out of the puddle. The puddle size is altered by a change in the heat input rate or by a change in the rate of heat dissipated to the puddle surroundings. For example, as the welding process continues, the temperature of the plate rises. Consequently, the portion of heat that flows into the workpiece decreases, resulting in an increase in puddle size. The rate of heat flow from the puddle is difficult to predict since it is governed by many parameters such as travel speed, convection effects from the random stirring of the puddle, plate diffusivity, initial plate temperature distribution, and the geometry of the plate.

Another aspect of the welding process is the interdependence of the variables. For example, a change in velocity alters the magnitude of the heat input, but it also affects the nature of the plate temperature distribution. With a stationary point source, the temperature in the plate is uniformly distributed in a circular pattern. The temperature distribution shifts to a "tear drop" shape with a traveling source. The larger the velocity, the larger the aspect ratio of the droplet. Because of these
difficulties in predicting melting dynamics, a transfer function for the process was determined experimentally.

Transfer function identification was pursued by producing a step change in velocity (heat input) and recording the time response of the backbead width on a chart recorder. Equation 3 states the heat input to the weld puddle is inversely related to velocity. Therefore, an increase in the heat input is produced by decreasing the velocity. The open loop transfer function should therefore be:

\[
\frac{\text{Width}}{\text{Inverse Velocity}} = \frac{W(s)}{IV(s)} = G(s) \quad (26)
\]

The response of the backbead width to a step change in input, in all cases, was first order (Figure 35). A first order system can be completely defined by its steady state gain and the time constant (Figure 36).

The steady state gain is determined by plotting the steady state output (backbead width) versus the input (1/velocity). As evidenced by Figure 37, the steady state gain varies considerably.

The time constant was estimated using three techniques. The simplest method is to divide the estimated settling time by 4. A second method is to find the time to reach .632 of the steady state value. The third method is to plot \( \log (C(\infty) - C(t)) \) versus time. The time constant is the
Figure 35. A Typical Response of Backbead Width Growth for a Step Change in Heat Input
Figure 36. The Definition of a First Order System Response to a Step Change Input
Figure 37. The Experimentally Determined Steady State Gain of the Plant
value of time where \( C(\tau) = C(\infty) - 0.368(C(\infty)) \). This method is also a check as to how close of an approximation the system is to a linear system. Figure 38 illustrates a few test runs using this third method.

The time constant was found to:

1) vary for the same step input (Figure 39). It is believed that the time constant increase is related to the plate temperature increase.

2) Increase as the step size increases.

Based on these results, the weld process can be modelled as a first order system with a time constant that varies from 1 to 7 seconds. The gain of the system also changes. With \( 1/V \) as the input, the open loop block diagram is:

\[
\begin{align*}
\frac{1}{V} & \quad \rightarrow \quad fEI \quad \rightarrow \quad \text{Heat} \quad \rightarrow \quad \frac{K}{\tau S + 1} \quad \rightarrow \quad \text{Width}
\end{align*}
\]

or:

\[
\begin{align*}
\frac{1}{V} & \quad \rightarrow \quad fEI \frac{K}{\tau S + 1} \quad \rightarrow \quad \text{Width}
\end{align*}
\]

So, the steady state gain is determined partially by the heat input. The constant \( f \), is an easy way of expressing the heat input efficiency but it does not explain how or what can cause a variation in the input. As mentioned in Chapter I, the heat into the weld is a function of arc gap and tip shape. During the welding process, the electrode
Figure 38. A Plot of $\log (C(\infty) - C(t))$ vs. Time
$\tau$ varies for the same step size

$\tau$ increases with the step size

Figure 39. The Experimentally Determined Steady State Gain of the Plant
shape degrades. Also, with full penetration welds, the arc gap increases with puddle size. In fact, the efficiency factor is a predetermined value that, at best, puts us in the right ball park. However, it is believed that the variation of the steady state gain and time constant is also a function of the heat transfer characteristics of the plate. Consider the transfer function:

\[
\frac{\text{WIDTH}}{\text{HEAT INPUT}} = \frac{W(s)}{Q(s)} = \frac{K}{\tau s + 1}
\]  

(27)

Multiplying by the denominators:

\[W(s)(\tau s + 1) = KQ(s)\]  

(28)

In the time domain this equation becomes:

\[\tau \frac{dw}{dt} + w = K \dot{Q}_{in}\]  

(29)

A time constant can be an RC network, therefore:

\[RC \frac{dw}{dt} + w = K \dot{Q}_{in}\]  

(30)

Dividing by the resistance yields:

\[C \frac{dw}{dt} + \frac{1}{R} w = \frac{K}{R} \dot{Q}_{in}\]  

(31)

This is an equation which relates backbead width to the heat input based on experimental results.
In an attempt to explain the phenomena which cause the variation in the transfer function, a simple model was developed.

As mentioned earlier, a heat balance of the weld process is:

\[ \dot{Q}_{in} = \dot{Q}_{\text{stored}} + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} \quad (22) \]

Neglecting radiation and convective heat transfer we have:

\[ \dot{Q}_{in} = \dot{Q}_{\text{stored}} + \dot{Q}_{\text{cond}} \quad (32) \]

A stationary heat input produces a puddle with a circular geometry on the top and bottom surfaces of the plate. This further simplifies our model since the effect of torch travel velocity on bead shape is not considered (Figure 40). Recalling that the heat stored by the puddle is:

\[ \dot{Q}_{\text{stored}} = \rho h \frac{dV}{dt} \quad (24) \]

The puddle volume for stationary, fully penetrated welds can be approximated by a cylinder of radius \( r \) and length \( L \):

\[ V = \pi r^2 L \quad (33) \]

then:

\[ \frac{dV}{dt} = 2\pi r^2 \frac{dr}{dt} \quad (34) \]
Figure 40. A Thermal Model for a Stationary Weld
substituting this into Equation 24 yields:

\[ \dot{Q}_{\text{STORED}} = (hp2\pi2r) \frac{dr}{dt} \]  

(35)

calling the variables in parenthesis a capacitance which is a function of the puddle radius:

\[ \dot{Q}_{\text{STORED}} = C(r) \frac{dr}{dt} \]  

(36)

Assuming that the temperature of the plate at some distance \( r \) from the puddle does not change, the dissipation of heat from the puddle is then:

\[ \dot{Q}_{\text{COND}} = KA_s \frac{dT}{dr} \]  

(37)

where:

- \( K \) - material thermal conductivity
- \( A_s \) - area through which the heat flows
- \( \frac{dT}{dr} \) - temperature gradient

For a cylindrical puddle, the area \( A_s \) is:

\[ A_s = 2\pi r^2 \]  

(38)

The heat conducted from the puddle is:

\[ \dot{Q}_{\text{COND}} = (2\pi r^2 K \frac{dT}{dr}) r \]  

(39)
Or:

\[ Q_{\text{cond}} = \frac{1}{R} (r) \]  \hspace{1cm} (40)

We now have a mathematical model for the welding process that is of the same form as the experimental findings:

\[ Q_{in} = C(r) \frac{dr}{dt} + \frac{1}{R} r \]  \hspace{1cm} (41)

Taking the Laplace Transform:

\[ \frac{R(s)}{Q(s)} = \frac{R}{RCS + 1} \]  \hspace{1cm} (42)

where the time constant is determined by:

\[ \tau = RC = \left( \frac{1}{\frac{1}{k} + \frac{2 \pi \sqrt{r}}{dr}} \right) \left( \frac{h \rho 2 \pi r^2}{r} \right) \]  \hspace{1cm} (43)

or:

\[ \tau = \left( \frac{h \rho}{k} \right) \frac{r}{d^2 r/dt^2} \propto \frac{r}{d^2 r/dt^2} \]  \hspace{1cm} (44)

The steady state gain is:

\[ R = \frac{1}{k2\pi^2 d^2 r/dt^2} \propto \frac{1}{2 d^2 r/dt^2} \]  \hspace{1cm} (45)

The steady state gain represents how much heat is dissipated from the puddle. Therefore, as the plate
thickness increases, the resistance to heat flow decreases. If the plate temperature increases, the temperature gradient in the plate will decrease. A lower temperature gradient will increase the resistance to heat flow.

The time constant will also increase as the temperature gradient decreases. At first glance, this may seem incorrect since if the plate temperature rises, less heat is conducted away from the puddle, consequently you might think the puddle will reach the desired size sooner. However, what is misleading is that the plate temperature affects both the steady state gain and the time constant. In other words, as the plate temperature increases the puddle grows to a larger volume and as a result takes longer to reach this new steady state.

The time constant also increases with puddle size. For instance, if the puddle radius were to increase .1 inches, it would take less time to grow from \( r = .1 \) inches to \( r = .2 \) inches than from \( r = .3 \) inches to \( r = .4 \) inches since there is a significant difference in volume growth.

Admittedly, this model is very crude. It does not deal with all of the factors which determine the transfer function, particularly, the torch travel velocity. For a traveling source, the puddle becomes oblong, and the temperature distribution surrounding the puddle shifts to a tear drop shape. The magnetic fields created by the arc cause stirring of the puddle which can increase the heat flow by
convection. In addition, for larger puddles, the radiation heat transfer may become significant.

However crude this model is, it does present a viable reason for the variation of the transfer function.

Going back to the experimentally determined transfer function we have:

\[
\frac{\text{WIDTH}}{\text{INVERSE VELOCITY}} = \frac{\Delta K}{\Delta T s + 1} \quad \frac{\Delta K/\Delta T}{s + 1/\Delta T}
\]

where the delta (\(\Delta\)) indicates a variation of the gain and the time constant. Based on the crude plant model and the experiments, the gain variation is believed to be caused by:

1) Plate temperature rise - as the plate temperature rises, the temperature gradient decreases, therefore the steady state gain increases.

2) Heat input efficiency - for larger puddles, the heat input efficiency decreases which decreases the plant gain.

3) Plate thickness - as the plate thickness increases, the gain decreases.

The time constant (for 11 gauge steel) ranged from 1 to 7 seconds and is believed to be a function of:

1) Plate temperature rise - the time constant increases with plate temperature.

2) Bead size - the time constant increases with bead size.
The largest contributor to the plant variation is the plate temperature rise. However, for a short weld the temperature rise is not significant. If multiple welds are produced over a long period of time, the plate and its fixture will increase in temperature and cause the plant transfer function to vary. Figure 41 is a root locus plot of the plant which shows the effect of temperature rise on pole location.

Closed Loop Control of Backbead Width

In the previous section the transfer function was found to be a first order system with varying time constant and gain. An advantage of closed loop control is its ability to maintain a steady state value in the presence of parameter variations. In closed loop control of bead width it is desired to have zero steady state error. The open loop transfer function is a type 0 system which gives a steady state error proportional to \( \frac{1}{1+K} \). For zero steady state error the system must be at least a type 1 system or:

\[
G(s) = \frac{\Delta K/\Delta \tau}{s(s + \frac{1}{\Delta \tau})}
\]  

(47)

The closed loop transfer function is then:

\[
\frac{W(s)}{R(s)} = \frac{(\Delta K/\Delta \tau)}{s^2 + (1/\Delta \tau)s + (\Delta K/\Delta \tau)}
\]  

(48)
Figure 41. Root Locus Plot of the Plant and the Effect of Temperature Rise on Pole Location.
The characteristic equation of the closed loop system is dependent on the varying quantities of the open loop system. Therefore, the transient response characteristics of the closed loop system will vary. However, the steady state value will remain a constant with zero steady state error since in the steady state:

$$\frac{w(s)}{r(s)} = \frac{\Delta K/\Delta t}{s^2 + (1/\tau) s + \Delta K/\Delta t} = 1$$

(49)

A control system designed to produce a consistently overdamped transient response was not considered in this research due to lack of time, however, controller designs of this nature are discussed in Chapter IV.

Before discussing specific control designs, the disturbances that affect control system performance must be addressed. The most significant disturbance was caused by the electric arc since the operational amplifier has such a low signal to noise level. Increasing the sensor gain, in an attempt to improve the signal to noise ratio, only amplified the electrical noise. A first order low pass filter, with a break point at 5 Hz. or 30 rad/sec, reduced the magnitude of the electrical noise (Figure 42). The open loop transfer function is:
Electrical Noise in the Feedback Signal

The Feedback Signal After Low Pass Filtered at 30 rad/sec

Figure 42. Low Pass Filtering of Feedback Signal
Another disturbance was caused by sparks which at times showered the sensor. Eliminating the sparks from the sensor view was attempted by purging the bottom surface of the weld pool with argon gas. This did not work effectively, but since the occurrence of the sparks was infrequent, no other method of eliminating the sparks was attempted.

Control Algorithms

Three controller designs were tested:

A) Integral Control (I)
B) Proportional Plus Integral Control (PI)
C) Pseudo-Derivative Control (PDF) (18)

The closed loop transfer function for integral control is (Appendix C):

$$\frac{W(s)}{R(s)} = \frac{K(t)(s+q)}{S^3 + (q+\zeta)S^2 + (\frac{q}{2})S + \zeta t} \approx \frac{IK}{S^2 + 2\zeta \omega_n S + \omega_n^2}$$

Integral control does not allow the user to specify independent values of the damping ratio $\zeta$ and natural frequency $\omega_n$. 
\( W_n \). In addition, this control scheme can go unstable as indicated by the Root Locus plot in Figure 43.

By adding a zero, a proportional plus integral control scheme can be incorporated. The proportional plus integral controller allows independent selection of \( \beta \) and \( W_n \), and improves stability (Figure 44). The closed loop transfer function is:

\[
\frac{W(s)}{R(s)} = \frac{K_T(s+2)(s+\alpha)}{s^3 + (\alpha + \beta) s^2 + (\frac{\alpha}{\tau} + \beta_k) s + \frac{\beta_k}{\tau}} \approx \frac{IK(s+2)}{s^2 + 2\beta w_n s + w_n^2}
\]

The zero, however, makes the system react quicker, which with disturbances, may not be desirable. This led to the pseudo-derivative controller:

Feeding back the signal in this manner allows independent selection of \( \beta \) and \( W_n \) without a zero (Figure 45). The closed loop transfer function is:

\[
\frac{W(s)}{R(s)} = \frac{K_T K(s+\alpha)}{s^3 + (\alpha + \beta) s^2 + (\frac{\alpha}{\tau} + \beta_k) s + \frac{\beta_k}{\tau}} \approx \frac{IK}{s^2 + 2\beta w_n s + w_n^2}
\]

These control schemes were implemented on a digital computer. In each case the sampling time was of the order of
Figure 43. Root Locus Plot Using Integral Control
Figure 44. Root Locus Plot Using Proportional Plus Integral Control
Figure 45. Root Locus Plot Using Pseudo-Derivative Control
.006 seconds. The fastest pole is that of the low pass filter at 30 rad/sec, thus, the digital control system sampling time is roughly $5\frac{1}{2}$ times faster than the fastest pole.

The normal operation of a controller is to reduce its output in order to reduce a positive error. For welding, the control algorithms must be designed to produce a velocity signal for the servo. However, if the velocity (output of controller) is decreased, the error is increased because of the reciprocal relation of velocity to heat input. One way to correct for this peculiarity is to use a negative gain (Figure 46). Now, for a positive error (bead too large) the controller will increase the torch velocity and reduce the bead size.

Another controller design operates on the inverse of velocity. In this case, the controller works in the normal fashion since it decreases its output ($1/V$) to reduce a positive error. By reducing $1/V$, the velocity is increased. However, the controller output must be inverted to produce a velocity signal for the servo. The block diagram can be imagined as having a fictitious block which inverts the controller output into a velocity signal and subsequently re-inverts this signal to produce the appropriate input to the plant (Figure 47).

Both the negative gain and inverse velocity methods were tested as control variables for I and PI control.
If the error signal is positive, velocity increases (puddle too large)

If the error signal is negative, velocity decreases (puddle too small)

Figure 46. The Block Diagram for Determining Torch Travel Speed Using Negative Gain
If the error signal is positive: \( \frac{1}{V} \) decreases, \( V \) increases
(puddle too large)

If the error signal is negative: \( \frac{1}{V} \) increases, \( V \) decreases

Figure 47. The Block Diagram for Determining Torch Travel Speed Using the Inverse of Velocity
The variation in the open loop system made selection of the controller gains difficult. However, both methods could produce the desired bead width depending on the selection of their respective gains. Table 3 lists each control scheme and its digital equivalent. The actual test programs are contained in Appendix D.

**Integral Control Experiments**

Figure 48 is a sample of closed loop control using the negative gain to determine velocity. The weld bead is fairly consistent, however, the chart recorder (which plots bead width with respect to time) indicates a marginally stable response. This controller operation is analogous to a discrete spot welder. The velocity changes so fast that the torch jumps ahead of the weld bead producing a partially penetrated weld. This causes the torch to stop immediately and wait for the bead to grow to its desired width. During the time while the torch is stationary, the recorder generates a plot of the weld which is not indicative of the actual weld continuity. You will notice that the peak of each spike is essentially of the same magnitude. Various gains were selected and each produced the same response features which varied only in magnitude and its associated travel distance prior to stopping (Figure 49). This type of response is aggravated by the nonlinearities in the system. When the bead becomes partially penetrated the sensor output becomes nonlinear. Additionally, the velocity
<table>
<thead>
<tr>
<th>Type of Control Using Inverse Velocity</th>
<th>Block Diagram</th>
<th>Analog Controller</th>
<th>Digital Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td>$V = \left(\frac{K}{s}\right)E$</td>
<td>$V = V_{n-1} + (-K)E$</td>
</tr>
<tr>
<td>PI</td>
<td></td>
<td>$V = \left(\frac{-K(s+\omega)}{s}\right)E$</td>
<td>$V = (K_1)E_n + (K_2)E_{n-1}$</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>$\frac{1}{V} = \left(\frac{K}{s}\right)E$</td>
<td>$\frac{1}{V_n} = \frac{1}{V_{n-1}} + (K)E$</td>
</tr>
<tr>
<td>PI</td>
<td></td>
<td>$\frac{1}{V} = \left(\frac{-K(s+\omega)}{s}\right)E$</td>
<td>$\frac{1}{V_n} = \frac{1}{V_{n-1}} + K_1 E_n - K_2 E_{n-1}$</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td>$\frac{1}{V} = \left(\frac{K}{s}\right)E - K_2 w$</td>
<td>$\frac{1}{V_n} = \frac{1}{V_{n-1}} + K_1 E_n + K_2 (W_n - W_{n-1})$</td>
</tr>
</tbody>
</table>
Figure 48. Closed Loop Control Using a Negative Gain and Integral Control
Figure 49. Typical Welds Using a Negative Gain and Integral Control
was constrained to a minimum value of 0 in order to prevent backward motion.

The inverse of velocity as the control variable could not be made to work with integral control (Figure 50). It is believed to be due to the inherently slow response time of this particular system. The addition of a zero (PI control) speeds up the system response time and improves stability.

Proportional Plus Integral Control Experiments

Proportional plus integral control using the negative gain method produced a response similar to integral control.

Proportional plus integral control using the inverse of velocity method can maintain zero steady state error within ±.020 inch. Figure 51A, B, and C are three consecutive tests with the same bead width setpoint. Figure 51A is the first run on a cold plate. The second bead (Figure 51B) was one inch away from the first bead and was therefore on a preheated plate. For the third test (Figure 51C), the plate was hotter still. The importance of these curves is that regardless of their transient response, the steady state values are the same. The transient response changes because the open loop pole drifts toward the imaginary axis. Another phenomenon of these responses is that the steady state value has a larger variation with each subsequen.
Figure 50. A Typical Weld Using Inverse Velocity and Integral Control
Figure 51A. The First of Three Consecutive Welds Using Proportional Plus Integral Control and $1/V$
Figure 51B. The Second of Three Consecutive Welds Using Proportional Plus Integral Control and 1/V
Figure 51C. The Third of Three Consecutive Welds Using Proportional Plus Integral Control and 1/V
test. This can be attributed to the pole movement since, as a pole approaches the imaginary axis, the system becomes less stable. Inspection of the actual beads shows that the variation in width was essentially the same for each run, contrary to the chart recorder readings. It is believed that the control system measures and corrects for deviations in the molten width, which in turn, produces a more consistent cold bead width. Lastly, the puddle has an increasing tendency to wander from the joint centerline as the number of runs increases. It is assumed that this is related to the rise in plate temperature.

From this point on the negative gain method of control was no longer tested since the inverse velocity method appeared to be a better way to regulate backbead width.

**Pseudo-Derivative Control Experiments**

Pseudo-derivative control has an advantage over PI control because it lacks a zero and consequently is not as sensitive to noise and disturbances. However, of greater concern in backbead width regulation is the plant pole and gain variation. Unfortunately, PDF control cannot deal with parameter variation any better than PI control. The PDF controller, however, could maintain steady state backbead width as well as PI control (Figure 52).
Figure 52. A Typical Response Using Pseudo-Derivative Control Using Inverse Velocity
Closed Loop Transfer Function Identification

Closed loop frequency response tests were attempted with PI control. The setpoint consisted of a nominal reference bead width plus a sinusoidal component whose amplitude (width) and frequency could be specified. The tests were run one after the other, therefore the plate was not at the same initial temperature for each run. The sensor output was recorded by the computer and, using an FFT algorithm, the response frequency and its associated amplitude were determined for each run. The test plate is shown in Figure 53, a typical FFT result is shown in Figure 54, and the Bode plot is shown in Figure 55. The nominal steady state value in all runs were nearly identical. The Bode plot however, is misleading since the runs were made at different plate temperatures. This means the characteristic equation is not the same for each run. Despite this, the closed loop transfer function is a dominant second order system.

Conclusions and Observations

The open loop transfer function for full penetration welds can be approximated as:

\[
\frac{1}{V} \quad \frac{K}{\tau s + 1} \quad \omega
\]

where both the time constant and steady state gain vary.
Figure 53. The Weld Plate Used for the Bode Plot of the Proportional Plus Integral Controlled System
Figure 53. The bold state is one of the lowest of the energy levels that stimulate the field.
Figure 54. A Typical FFT Result Used for the Bode Plot of the Closed Loop System
Figure 55. A Bode Plot of the Closed Loop System Using Proportional Plus Integral Control.
Based on a crude plant model and experiments, the gain variation is believed to be caused by:

1) Plate temperature: as the plate temperature rises the steady state gain increases.

2) Heat input efficiency: for larger puddles the heat input efficiency decreases and consequently decreases the plant gain.

3) Plate thickness: the gain decreases with increasing thickness.

The time constant varies from 1 to 7 seconds and is believed to be a function of:

1) Plate temperature: the time constant increases as the plate temperature rises.

2) Bead size: based on a model of a stationary cylindrical puddle the time constant increases with bead size.

A controller which uses a negative gain to determine torch travel speed works to some degree but in a very crude fashion. This type of controller design is highly nonlinear and is not recommended.

PI and PDF control using the inverse of velocity as the controlled input to the plant can maintain steady state backbead width within ±0.020 inches. The transient response of these closed loop designs can be either overdamped or underdamped depending on the time constant and gain of the plant. It should be noted that as the plate temperature rises the plant pole approaches the imaginary axis. This pole movement will produce less overshoot in bead width when under closed loop control. In addition,
as the plate temperature rises, there is a tendency for the bead to wander back and forth across the joint.

Even with the variation of the plant parameters, closed loop control can maintain a steady state backbead width. Figures 56 and 57 are a good indication of the advantage closed loop control has over a constant velocity welding system. As you can see, closed loop control varies the torch travel speed to maintain a uniform backbead width.

There is a lot of room for improvement in the control of the weld process. Chapter IV discusses areas for further improvement such as parameter adaptive control and new sensing techniques.
Figure 56. A Simultaneous Plot of Backbead Width and Torch Travel Velocity Using Proportional Plus Integral Control
Figure 57. A Comparison of a Closed Loop Controlled Weld and a Constant Velocity Weld
Chapter IV

Recommendations for Further Study

This research developed a backbead width control system which maintains zero steady state error. A weak point of this system is that the transient response is not consistent. The transient response is affected by the parameter variation of the plant. The plant is a first order system with a time constant that increases with bead width and plate temperature. The gain of the plant also increases with plate temperature but decreases with plate thickness. The combination of these variables make it difficult to produce a repeatable closed loop transient response.

In addition to transient response problems, the bead has a tendency to wander from the joint and in some cases, porosity occurs.

These problems remain as areas for further research. This chapter suggests methods for improving this weld penetration control system. Only elementary controller designs were tested in this research, naturally more sophisticated controller designs should be investigated which can deal with the inconsistent transient response.

Problems such as the bead wandering from the joint and the occurrence of porosity can hopefully be controlled but first a sensing technique must be devised to measure
these variables. The latter part of this chapter discusses improvements in the sensing technique used in this research.

**Improvement in Control**

A large contributor to the transient response variation is the plate temperature rise. As the plate temperature rises the plant pole approaches the imaginary axis. This pole movement increases the closed loop system damping and therefore reduces overshoot. If controller gains can be selected to produce an overdamped response on a cold plate, the plate temperature rise will never cause overshoot. However, gain selection can be very tricky since the pole movement can increase the system settling time and cause instability. Additionally, in a production environment, this control system would have to be fine tuned for different part shapes since each shape would have a particular time constant, gain and range of variation.

An improved control technique is model reference control. Throughout this research, the control system responded to a step change in the setpoint. This abrupt change affects the transient response of the control system. If the change in the setpoint were not as abrupt, the control system would not respond as aggressively. Model reference control is a way of smoothing the input to the closed loop system by using a prefilter (Figure 58).
The prefilter is simply a model of a desirable transient response. Essentially, the control system tries to follow this desirable response (setpoint). Model reference control only alters the setpoint to the control system, it does not regulate the dynamics of the closed loop system.

A more complicated controller design is parameter adaptive control. An adaptive control system measures the plant dynamics, compares it to a desired transfer function, and uses this difference to adjust the controller characteristics to produce the desired transient response (Figure 59). The transfer function of the plant must be measured and identified without affecting the normal operation of the system. The plant can be identified by analyzing the normal operating data or by use of test signals. Stochastic test signals can be input to the system and, by using cross-correlation techniques, the plant response characteristics can be determined. Since the parameter adaptive control is used in a feedback mode, the system is affected by time delays and can go unstable. For welding, the plant transfer function variation was caused primarily by the temperature gradient of the plate. If the temperature gradient could be determined, this information might be all that is required to use parameter adaptive control.

There are other areas for research besides inconsistent transient response. The weld process is a multiple
input - multiple output system. This research chose to investigate a single input (velocity), single output (backbead width) system. In the future, in addition to bead width regulation, it would be desirable to produce a bead centered across the joint and void of porosity. Although there is no data available, it is speculated that the transformation of the bead from an oblong to a circular shape may cause porosity. A multiple input - multiple output scheme for welding could use the arc current to regulate bead width, modify the torch travel speed to maintain a desired bead aspect ratio and alter the torch orientation to keep the bead centered across the joint. This type of control system may be difficult to design since the variables in the weld process are interrelated. However, before multiple input - multiple output systems can be employed, sensors must be developed which can monitor the important aspects of the weld process. The numerous tests performed throughout this research has provided a solid base for understanding the phototransistor and its application for sensing the weld process. The following section discusses the versatility of the phototransistor for sensing the weld process.

**Sensor Applications**

Full penetration control cannot, as of yet, control the bead location relative to the joint. With a slight modification, the sensing technique developed in this
research could be used to sense bead location. Two phototransistors can be aligned such that each sees only one half of the joint. The output of each transistor can then be summed to indicate bead width and their outputs can be compared to indicate bead location relative to the joint (Figure 60). By using four phototransistors in this manner, the sensor can measure the aspect ratio of the puddle, the location of the bead relative to the joint and the width of the puddle.

Back side puddle measurements have a disadvantage since only a limited number of part shapes can be welded. The phototransistor could be used for top side measurement of bead width. As mentioned earlier, the top bead width is not necessarily an indication of penetration. However, the arc length increases when a weld becomes fully penetrated. Perhaps a phototransistor could be used to measure arc length as an indication of weld penetration. The sensing technique would work a little differently than bead width sensing since there is a temperature gradient associated with the arc (Figure 61). As long as the range of the temperature between the electrode and the puddle remains the same, the phototransistor will measure arc length. Recall that the phototransistor is sensitive to temperature and area. Therefore, if the temperature range does not change, the transistor will measure area. By using a thin slot to constrain the sensor to view only the arc itself, the length of the arc will be measured. An advantage of
Figure 60. A Diagram for a Combination Bead Width and Location Sensor
arc length measurement is that the sensor could also be used for welding aluminum.

In summary, this research regulates backbead width only. However, improvements in both controller designs and sensing techniques can hopefully produce welds comparable to that of a skilled welder, if not better.
References


10. Andrews, J.G., Craine, R.E., "Fluid Flow in A Hemisphere Induced by a Distributed Source of Current"


Bibliography


The integral:

$$I_p = \int_0^\infty \frac{(3.74041 \times 10^{-5}) \lambda^{-5}}{e^{(1.43868/\lambda T)} - 1} \delta_\lambda \, d\lambda$$

can be approximated numerically as:

$$I_p \approx \sum_{\lambda=400 \text{Nm}}^{\lambda=1200 \text{Nm}} \frac{K_i \lambda^{-5}}{e^{k_2/\lambda T} - 1} \delta_\lambda \Delta \lambda$$

where:

- $\lambda = 400, 600, 800 \ldots 1200 \text{ Nm}$
- $\delta_\lambda$ = Approximated as shown in Figure 62
- $\Delta \lambda = 200 \text{ Nm}$

The following program approximates this integral.
Figure 62. Phototransistor Spectral Sensitivity for Computer Simulation
PROGRAM PHOTOCAL
BYTE LINE(112)
DIMENSION WAVELN(37),TEMP(11),VOLTS(10),EMISS(10,36)
DIMENSION TRAN(37),AMPS(10,36),IPOINT(8,90),ELAMDA(37)
COMMON IPOINT
WRITE(5,150)
150 FORMAT(' INPUT SURFACE AREA VIEWED '/)
READ(5,160) AREA
160 FORMAT(F10.7)
WAVELN(1)= .000038
TEMP(1)=1200.
DO 5 J=2,11
  TEMP(J)=TEMP(J-1)+100.
DO 5 I=2,37
  WAVELN(I)=WAVELN(I-1)+.000002
  DENOM1=EXP(1.43868/(WAVELN(I)*TEMP(J))-1.
  DENOM2=(26735.64)*(WAVELN(I)**5.)
  N=J-1
  K=I-1
  EMISS(N,K)=1./((DENOM1*DENOM2)
550 C BUILD TRANSISTOR SENSITIVITY ARRAY
DO 10 I=2,21
  WAVELN(I)=WAVELN(I-1)+.000002
  K=I-1
10 TRANS(K)=545.*WAVELN(I)-.0136
DO 20 K=21,27
20 TRANS(K)=.03
DO 30 I=28,37
30 TRANS(I)=1333.*WAVELN(I)-.1567
555 C BUILD SPECTRAL EMISSIVITY ARRAY
DO 25 I=2,37
25 ELAMDA(K)=-1052.6*WAVELN(I)+.4317
555 C CALCULATE TRANSISTOR OUTPUT
  UNITS=.0000001*1.000002*AREA
  RESIST=2200.
  DO 40 J=1,10
  VOLTS(J)=0.
  DO 40 I=1,36
  AMPS(J,I)=ELAMDA(I)*EMISS(J,I)*UNITS*TRAN(I)
  VOLTS(J)=VOLTS(J)+AMPS(J,I)*RESIST
40  DO 410 I=1,10
410  J=I+1
555 C WRITE(S,70) TEMP(J), VOLTS(I)
555 C PRINT DATA
WRITE(5,181)
FORMAT(' TYPE 1 TO PRINT DATA,<CR> OTHERWISE',/
READ(5,182)IPRINT
182 FORMAT(I2)
   IF(IPRINT.NE.1)GO TO 183
   DO 50 L=1,110
   50 LINE(L)=',
   LINE(11)=13
   LINE(112)=10
   DO 60 N=1,10
   J=N+1
   ENCODE(LINE,70)TEMP(J),VOLTS(N)
   FORMAT(' TEMPERATURE=',F9.3,', VOLTS=',F6.3)
   CALL STLNE(11,LINE)
   DO 60 K=1,36
   I=K+1
   ENCODE(LINE,30)WAVLEN(I),EMISS(N,K),AMPS(N,K)
60 FORMAT(3X,'LAMBDA=',E12.5,', EMISS=',E12.5,', AMPS=',E12.5)
   CALL STLNE(11,LINE)
C
C PLOT DATA
C
WRITE(5,184)
184 FORMAT(' TYPE 1 TO PLOT DATA,<CR> TO QUIT',/
READ(5,182)IPLLOT
   IF(IPLLOT.NE.1)GO TO 185
   DO 120 J=1,10
   VALMAX=0,
   VALMIN=100000.
   DO 110 I=1,36
   IF(AMPS(J,I).LT.VALMIN)VALMIN=AMPS(J,I)
   IF(AMPS(J,I).GT.VALMAX)VALMAX=AMPS(J,I)
   DELTA=VALMAX-VALMIN
   NCOUNT=0
   ICOUNT=1
   DO 130 K=1,90
   DO 120 L=1,8
   NCOUNT=NCOUNT+1
   IF(NCOUNT.EQ.20)ICOUNT=ICOUNT+1
   IF(NCOUNT.EQ.20)NCOUNT=0
   120 CONTINUE
   130 CONTINUE
 135 WRITE(5,136)
136 FORMAT(' TYPE 1 TO INPUT NEW AREA',/
READ(5,182)NEW
   IF(NEW.NE.1)GO TO 1
   WRITE(5,201)
201 FORMAT(' TYPE 1 FOR SPECTRAL ENERGY,<CR> OTHERWISE',/
READ(5,182)ENERGY
   IF(ENERGY.NE.1)GO TO 205
   WRITE(5,202)
202 FORMAT(' TYPE INTEGER EQUIV. OF FREQ. DESIRED',/
READ(5,182)LAMBDA
   DO 203 J=1,10
   VOLTS(J)=AMPS(J,LAMBDA)*RESIST
   K=J+1
203 WRITE(5,70)TEMP(K),VOLTS(J)
   GO TO 125
205 END
Appendix B

A preliminary effort to determine viable sensing techniques investigated using either a photodiode array or a single phototransistor which viewed a small area of the bead. In order to determine the feasibility of either of these ideas a crude linear scanning device was built by attaching a phototransistor to a lead screw which can be rotated manually. A simple test using a stationary torch was to record the transistor output for each revolution of the lead screw. A typical output is shown in Figure 73. This experiment suggested two phenomena of the welding process which eventually led to an effective sensing technique. These phenomena are:

1) The puddle appeared to be a nearly constant temperature.

2) The phototransistor measures significant infrared radiation from the puddle surroundings.
Figure 63. The Experimental Determination of the Temperature Distribution of a Stationary Weld
Appendix C

For I and PI control, the closed loop block diagram is of the form:

\[ R \overset{+}{\longrightarrow} G_C \overset{G_P}{\longrightarrow} H \overset{-}{\longrightarrow} \mathcal{W} \]

where:

\[ G_P = \frac{K_P/\tau}{s + \sqrt{\tau}} \]

and:

\[ H = \frac{1}{s + \alpha} \]

For Integral Control:

\[ G_C = \frac{K_C}{s} \]

therefore:

\[ \frac{\mathcal{W}(s)}{R(s)} = \frac{G_C G_P}{1 + G_C G_P H} = \frac{\left( \frac{K_C}{s} \frac{K_P/\tau}{s + \sqrt{\tau}} \right)}{1 + \left( \frac{K_C}{s} \frac{K_P/\tau}{s + \sqrt{\tau}} \right) \frac{1}{s + \alpha}} \]
or:

\[
\frac{W(s)}{R(s)} = \frac{\left(\frac{KcKn}{\tau} \right) (s+\alpha)}{s^3 + \left(\alpha + \frac{\omega_n}{\tau}\right)s^2 + \left(\frac{\omega_n}{\tau}\right)s + \frac{KcKn}{\tau}}
\]

This equation can be broken down into a first and a second order system:

\[
\frac{W(s)}{R(s)} = \frac{\frac{KcKn}{\tau} (s+\alpha)}{(s+\beta)(s^2 + 2\zeta \omega_n s + \omega_n^2)}
\]

If the first order systems in the numerator and denominator are much faster than the second order system, the equation can be reduced to:

\[
\frac{W(s)}{R(s)} = \frac{\frac{KcKn\alpha}{\tau \beta}}{s^2 + 2\zeta \omega_n s + \omega_n^2}
\]

\[
= \frac{IK}{s^2 + 2\zeta \omega_n s + \omega_n^2}
\]
For PI Control:

\[ G_c = \frac{k_c (s+2)}{s} \]

Therefore:

\[ \frac{W(s)}{R(s)} = \frac{G_c G_p}{1 + G_c G_p H} = \frac{\left(\frac{k_c (s+2)}{s}\right) \left(\frac{k_p / \tau}{s + \frac{1}{\tau}}\right)}{1 + \left(\frac{k_c (s+2)}{s}\right) \left(\frac{k_p / \tau}{s + \frac{1}{\tau}}\right) \left(\frac{1}{s + a}\right)} \]

or:

\[ \frac{W(s)}{R(s)} = \frac{k_c k_p (s+2)(s+a)}{s(s+\frac{1}{\tau})(s+a) + \frac{k_c k_p (s+2)}{\tau}} \]

\[ \frac{W(s)}{R(s)} = \frac{k_c k_p (s+2)(s+a)}{s^3 + (a+\frac{1}{\tau}) s^2 + (\frac{a}{\tau} + \frac{k_c k_p}{\tau}) s + \frac{k_c k_p}{\tau}} \]
This denominator can be broken down into:

\[
\frac{W(s)}{R(s)} = \frac{\frac{K_cK_p}{\tau} (s+Z)(s+a)}{(s+b)(s^2+2\zeta\omega_n s + \omega_n^2)}
\]

With the appropriate selection of the controller gain and zero location the equation becomes:

\[
\frac{W(s)}{R(s)} = \frac{\frac{K_cK_p\alpha}{\tau b} (s+Z)}{s^2+2\zeta\omega_n s + \omega_n^2}
\]

\[
\frac{W(s)}{R(s)} = \frac{IK (s+Z)}{s^2+2\zeta\omega_n s + \omega_n^2}
\]
PDF Control

The block diagram for PDF control is a little different.

\[ E_1 = R - \left( \frac{1}{s+\Theta} \right) \omega \]  \hspace{1cm} (1)

\[ E_2 = E_1 \left( \frac{K_f}{s} \right) - \left( \frac{K_2}{s+\Theta} \right) \omega \]  \hspace{1cm} (2)

\[ \omega = E_2 \left( \frac{K_p/\tau}{s+\sqrt{\tau}} \right) \]  \hspace{1cm} (3)

Substituting Equations 1 and 2 into equation 3 yields:

\[ \omega = \left[ \left( \frac{K_f}{s} \right)(R-\frac{1}{s+\Theta})\omega - \left( \frac{K_2}{s+\Theta} \right)\omega \right] \frac{K_p/\tau}{s+\sqrt{\tau}} \]

\[ \hspace{1cm} E_2 \]
Rearranging this equation:

\[
\frac{W(s)}{R(s)} = \frac{\frac{K_i K_p}{\tau} (s+\alpha)}{s^3 + (\alpha + \frac{\alpha}{\tau}) s^2 + (\frac{\alpha^2}{\tau} + \frac{K_i K_p}{\tau}) s + \frac{K_i K_p}{\tau}}
\]

This equation can be broken down into:

\[
\frac{W(s)}{R(s)} = \frac{\frac{K_i K_p}{\tau} (s+\alpha)}{(s+\beta) (s^2 + 2\beta w_1 s + w_1^2)}
\]

If the first order systems are faster than the second order system, the equation becomes:

\[
\frac{W(s)}{R(s)} = \frac{\frac{K_i K_p \alpha}{\beta \tau}}{s^2 + 2\beta w_1 s + w_1^2}
\]

\[
= \frac{IK}{s^2 + 2\beta w_1 s + w_1^2}
\]
Appendix D

This appendix contains the computer programs which are organized according to the type of controller design (Table 4).
Table 4. Control Programs

<table>
<thead>
<tr>
<th></th>
<th>Negative Gain</th>
<th>Inverse Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CONTROLL1</td>
<td>CONTROL2</td>
</tr>
<tr>
<td>PI</td>
<td>STEPIVEL</td>
<td>PICNTRL2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BODEPLOT</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td>ZEROLESS</td>
</tr>
</tbody>
</table>
C THIS PROGRAM CONTROLS WELD PENETRATION VIA BACK:BEAD
C WIDTH MEASUREMENT.HEAT INPUT IS CONTROLLED BY TABLE
C VELOCITY.

PROGRAM CONTROL1
5 WRITE(5,10)
10 FORMAT(’ INPUT DESIRED BACK BEAD WIDTH (INCHES)’,/)
20 FORMAT(F6.4)
30 STEP=0.
40 WIDTH=931.*WIDTH-11.
50 WRITE(5,21)
60 FORMAT(’ TYPE 1 FOR STEP TEST,<CR> OTHERWISE’,/)
70 READ(5,56)ISTEP
80 IF(ISTEP.NE.1)GO TO 22
90 WRITE(5,23)
100 FORMAT(’ TYPE STEP SIZE AND DIRECTION’,/)
110 READ(5,30)STEP
120 WRITE(5,30)
130 FORMAT(’ INPUT # OF POINTS’,/)
140 READ(5,40)LOOPS
150 FORMAT(I5)
160 HALF=LOOPS/2
170 WRITE(5,80)
180 FORMAT(’ INPUT GAIN (REAL)’,/)
190 READ(5,90)GAIN
200 FORMAT(F8.4)
210 WRITE(5,55)
220 FORMAT(’ TYPE 1 TO RETURN TABLE’,/)
230 READ(5,56)IVAL
240 FORMAT(I3)
250 IF(IVAL.NE.1)GO TO 57
260 CALL OUTPUT(-300)
270 WRITE(5,53)
280 FORMAT(’ TYPE <CR> TO START TABLE MOTION’,/)
290 READ(5,40)IVER
300 CALL OUTPUT(IVER)
310 WRITE(5,50)
320 FORMAT(’ START ARC,TYPE <CR> TO BEGIN CONTROL’,/)
330 READ(5,40)IVER
340 DO 60 I=1,LOOPS
350 CALL ATOD12(9,IVOL)
360 VOLT=FLOAT(IVOL)
370 IF(I.EQ.HALF)WIDTH=WIDTH+STEP
380 ERROR=WIDTH+VOLT
390 IVEL=IVEL-IFIX(GAIN*ERROR)
400 IF(IVER.LT.0)IVER=0
410 CALL OUTPUT(IVER)
420 GO TO 5
430 END
PROGRAM CONTROL

5 WRITE(5,10)
10 FORMAT( 'INPUT DESIRED BACK BEAD WIDTH (INCHES)',/)
READ(5,20)WIDTH
20 FORMAT(F6.4)
STEP=0.
WIDTH=931.*WIDTH-111.
WRITE(5,21)
21 FORMAT( 'TYPE 1 FOR STEP TEST, <CR> OTHERWISE',/)
READ(5,26)ISTEP
IF (ISTEP.NE.1) GO TO 22
WRITE(5,23)
22 FORMAT( 'TYPE STEP SIZE AND DIRECTION',/)
READ(5,20)STEP
STEP=931.*STEP
WRITE(5,30)
30 FORMAT( 'INPUT # OF POINTS',/)
READ(5,40)LOOPS
40 FORMAT(I5)
HALF=LOOPS/2
WRITE(5,80)
80 FORMAT( 'INPUT GAIN (REAL)',/)
READ(5,90)GAIN
90 FORMAT(F8.4)
WRITE(5,55)
55 FORMAT( 'TYPE 1 TO RETURN TABLE',/)
READ(5,56)IVAL
56 FORMAT(I3)
IF (IVAL.NE.1) GO TO 57
CALL OUTPUT(-300)
57 WRITE(5,58)
58 FORMAT( 'TYPE <CR> TO START TABLE MOTION',/)
READ(5,40)J
IVEL=70
CALL OUTPUT(IVEL)
WRITE(5,50)
50 FORMAT( 'START ARC, TYPE <CR> TO BEGIN CONTROL',/)
READ(5,40)J
DO 80 I=1,LOOPS
CALL ATOD12(9,IVOLT)
VOLT=FLOAT(IVOLT)
IF (I.EQ.HALF) WIDTH=WIDTH+STEP
ERROR=WIDTH+VOLT
VALUE=VALUE+GAIN*ERROR
IVEL=IFIX(1./VALUE)
IF (IVEL.LT.0) IVEL=0
80 CALL OUTPUT(IVEL)
GO TO 5
END
C THIS PROGRAM CONTROLS WELD PENETRATION VIA BACK BEAD
C WIDTH MEASUREMENT. HEAT INPUT IS CONTROLLED BY THE
C TABLE VELOCITY. THIS IS A P-I CONTROLLER.
C THIS PROGRAM ALLOWS CLOSED LOOP STEP RESPONSE TESTS
C TO BE PERFORMED.

PROGRAM STEPVEL
WRITE(5,10)
FORMAT(’INPUT DESIRED BACK BEAD WIDTH (INCHES)’,/)
READ(5,20)WIDTH
20 FORMAT(F6.4)
WRITE(5,6)
FORMAT(’INPUT OP-AMP GAIN (1. OR 2.)’,/)
READ(5,7)AMP
7 FORMAT(F4.2)
STEP=0.
IWIDTH=IFIX(WIDTH/931.*AMP)-111.*AMP
WRITE(5,21)
 FORMAT(’TYPE 1 FOR STEP TEST, <CR> OTHERWISE’,/)
READ(5,56)ISTEP
 IF(ISTEP.NE.1)GO TO 22
 WRITE(5,23)
23 FORMAT(’TYPE STEP SIZE AND DIRECTION’,/)
READ(5,20)STEP
 ISTEP=IFIX(STEP/931.*AMP)
 WRITE(5,22)
22 FORMAT(’THE CONTROLLER IS OF THE FORM’,/)
 WRITE(5,80)
80 FORMAT(’OUTPUT K(S+A)’,)
WRITE(5,82)
82 FORMAT(’—— = ———’)WRITE(5,83)
83 FORMAT(’INPUT AS’,/)
WRITE(5,84)
84 FORMAT(’INPUT K,A (REAL)’,/)
READ(5,90)GAIN,ZERO
90 FORMAT(‘2F20.8’)GAIN=GAIN*AMP
 WRITE(5,85)
85 FORMAT(’INPUT SAMPLING TIME’)READ(5,86)TIME
86 FORMAT(F9.8)
IGAIN2=IFIX(GAIN/ZERO)
IGAIN1=IFIX((GAIN/ZERO)*(EXP(-ZERO*TIME)))WRITE(5,40)
40 FORMAT(’TYPE IN # OF LOOPS’,/)
READ(5,41)LOOPS
41 FORMAT(15)
HALF=LOOPS/2
WRITE(5,55)
55 FORMAT(’TYPE 1 TO RETURN TABLE’,/)
READ(5,56)IVAL
56 FORMAT(13)
 IF(IVAL.NE.1)GO TO 57
 CALL OUTPUT(-300)
57 WRITE(5,58)
FORMAT(' TYPE <CR> TO INITIALIZE TABLE VELOCITY',/)
READ(5,56)J
IVEL=70
CALL OUTPUT(IVEL)
WRITE(5,50)
FORMAT(' START ARC, TYPE <CR> TO BEGIN CONTROL'/)
READ(5,56)J
LAST=0
DO 60 I=1,LOOPS
CALL ATOD12(9,IVCLT)
IF(I.EQ.HALF)IUID:=+IWIDTH+ISTEP
NOW=IWIDTH+IVOLT
IVEL=IVEL-IGAIN*NOW+IGAIN1*LAST
LAST=NOW
IF(IVEL.LT.0)IVEL=0
CALL OUTPUT(IVEL)
CONTINUE
GO TO 5
END
C THIS PROGRAM CONTROLS WELD PENETRATION VIA BACK BEAD WIDTH MEASUREMENT. HEAT INPUT IS CONTROLLED BY THE INVERSE OF TABLE VELOCITY. THIS IS A P-I CONTROLLER.

PROGRAM PICNTRL2

WRITE(5,10)

10 FORMAT(’ input desired back bead width (inches)’,/)
READ(5,20)WIDTH

20 FORMAT(F6.4)
WRITE(5,30)

30 FORMAT(’ type 1 for closed loop step tests’,/)
READ(5,31)ITEST

31 FORMAT(I2)
IF(ITEST.NE.1)GO TO 32
WRITE(5,33)

33 FORMAT(’ type in final bead width (inches)’,/)
READ(5,20)WIDTH2
ISTEP=IFIX(S31.*WIDTH2)

32 IWIDTH=IFIX(S31.*WIDTH)
WRITE(5,20)

80 FORMAT(’ the controller is of the form:’,/)
WRITE(5,31)

81 FORMAT(’ output k(s+a)’,)
WRITE(5,32)

82 FORMAT(’ ______ = ______’)
WRITE(5,33)

83 FORMAT(’ input as’,/)
WRITE(5,34)

84 FORMAT(’ input k,a (real)’,/)
READ(5,90)GAIN,ZERO

90 FORMAT(2F20.8)
WRITE(5,95)

85 FORMAT(’ input sampling time’)
READ(5,86)TIME

86 FORMAT(F9.8)
GAIN2=GAIN/ZERO
GAIN1=EXP(-ZERO*TIME)
WRITE(5,40)

40 FORMAT(’ type in # of loops desired’,/)
READ(5,41)LOOPS

41 FORMAT(I5)
HALF=LOOPS/2
WRITE(5,55)

55 FORMAT(’ type 1 to return table’,/)
READ(5,56)IVAL

56 FORMAT(I3)
IF(IVAL.NE.1)GO TO 57
CALL OUTPUT(-300)

57 WRITE(5,58)

58 FORMAT(’ type <CR> to initialize table velocity’,/)
READ(5,56)J

50 FORMAT(’ start arc, type <CR> to begin control’,/)
READ(5,56)J
ERROR1=0.
DO 60 I=1,LOOPS
CALL ATOD12(G,IVOLT)
IF(I.EQ.HALF)IWIDTH=ISTEP
ERROR2=FLOAT(IWIDTH-IVOLT)
VALUE=GAIN2*ERROR2-GAIN1*ERROR1+VALUE
ERROR1=ERROR2
IVEL=IFIX(1./VALUE)
IF(IVEL.LT.0)IVEL=0
CALL OUTPUT(IVEL)

60 CONTINUE
GO TO 5
END
C THIS PROGRAM IS USED TO MEASURE THE SAMPLING TIME FOR
C PROGRAM PICCTRL2. THE USER NEEDS A STOP WATCH.
C THIS PROGRAM CAN ALSO BE USED FOR FREQUENCY RESPONSE
C TESTS

PROGRAM BODEPLOT
DIMENSION INPUT(1201), VOLT(512)
BYTE NAME(11)

5 WRITE(5, 3)
9 FORMAT(' TYPE 1 TO RETURN TABLE', /
READ(5, 246) IVAL
IF(IVAL .NE. 1) GO TO 8
CALL OUTPUT(-300)
IVAL = 0
WRITE(5, 6)
6 FORMAT(' INPUT DESIRED WIDTH(INCHES)', /
READ(5, 7) WIDTH
7 FORMAT(F6.4)
WRITE(5, 19)
19 FORMAT(' DO YOU WANT STEP TESTS OR FREQ. RESP. TESTS?', /
WRITE(5, 10)
10 FORMAT(' TYPE IN FREQUENCY(RAD/SEC) AND AMPLITUDE(INCHES)', /
READ(5, 20) OMEGA, AMP
20 FORMAT(2F8.4)
WRITE(5, 84)
84 FORMAT(' INPUT K, A (REAL)', /
READ(5, 90) GAIN, ZERO
90 FORMAT(2F10.8)
WRITE(5, 301)
301 FORMAT(' INPUT ESTIMATED SAMPLING TIME', /
READ(5, 302) TIME
302 FORMAT(F7.6)
DELTA = 0.
601 DELTA = DELTA + 1.
NMAX = IFIX(6.283185307/(OMEGA*TIME*DELTA))
IF(NMAX .GT. 1200) GO TO 601
OMEGA = 6.283185307/(FLOAT(NMAX)*TIME*DELTA)
WRITE(5, 502) OMEGA
602 FORMAT(' OMEGA=', F8.4, ' RAD/SEC')
WT = OMEGA*TIME*DELTA
DO 150 N = 0, NMAX
150 INPUT(N) = IFIX(931.* (WIDTH*AMP*(SIN(WT*FLOAT(N))))) - 111.
GAIN2 = GAIN*ZERO
GAIN1 = GAIN2*EXP(-ZERO*TIME)
WRITE(5, 245)
245 FORMAT(' TYPE IN INITIAL VELOCITY', /
READ(5, 246) IVEL
246 FORMAT(I3)
VALUE = 1./(FLOAT(IVEL)
CALL OUTPUT(IVEL)
NCOUNT = 0.
ERROR1 = 0.
IDELTA = IFIX(DELTA)
KCOUNT = 0
ICOUNT = 0
JCOUNT = 0
WRITE(5,51)
FORMAT(,' INPUT NUMBER OF LOOPS DESIRED <32000',/)
READ(5,52)LOOPS
WRITE(5,50)
FORMAT(,' START STOP WATCH, TYPE <CR> TO BEGIN LOOP',/)
READ(5,20)J
DO 60 I=1,LOOPS
   JCOUNT=JCOUNT+1
   IF(JCOUNT.EQ.IDELTA)NCOUNT=NCOUNT+1
   IF(JCOUNT.EQ.IDELTA)JCOUNT=0
   IF(NCOUNT.GT.NMAX)NCOUNT=1
   CALL ATOD12(9,IVOLT)
   IF(NCOUNT.EQ.512)GO TO 61
   KCOUNT=KCOUNT+20*ICOUNT
   IF(KCOUNT.EQ.I)ICOUNT=ICOUNT+1
   IF(KCOUNT.EQ.I)VOLT(ICOUNT)=FLOAT(IVOLT)
   ERROR2=FLOAT(NCOUNT-IVOLT)
   VALUE=GAING2ERROR2-1*ERROR1+VALUE
   ERROR1=ERROR2
   IVEL=IFIX(1./VALUE)
   IF(IVEL.LT.0)IVEL=0
   CALL OUTPUT(IVEL)
C901 WRITE(5,901)I,JCOUNT,NCOUNT,KCOUNT,ICOUNT
C901 FORMAT(,' I=',I5,' JC=',I2,' NC=',I4,' KC=',I5,' IC=',I3)
60 CONTINUE
WRITE(5,25)
25 FORMAT(,' INPUT LOOP TIME',/)
READ(5,26)TIME
26 FORMAT(F6.4)
   TIME=TIME/(FLOAT(LOOPS))
WRITE(5,27)TIME
27 FORMAT(,' SAMPLING TIME=',F10.3,/) WRITE(5,510)
510 FORMAT(,' TYPE 1 TO STORE DATA ',/)
READ(5,511)KEEP
511 FORMAT(I2)
   IF(KEEP.NE.1)GO TO 5
   DO 501 J=1,S12
   501 VOLT(J)=VOLT(J)*S12/2048.
   WRITE(5,502)
502 FORMAT(,' INPUT DATAFILE NAME XXXXXXXXDAT',/)
READ(5,503)NAME
503 FORMAT(A11)
   CALL OPEN(6,NAME,1)
   WRITE(6)(VOLT(J),J=1,S12)
ENDFILE 6
   GO TO 5
END
C THIS PROGRAM CONTROLS WELD PENETRATION VIA BACK BEAD WIDTH MEASUREMENT. HEAT INPUT IS CONTROLLED BY THE INVERSE OF TABLE VELOCITY. THIS IS A P-I CONTROLLER.
C THIS PROGRAM ALLOWS CLOSED LOOP STEP RESPONSE TESTS TO BE PERFORMED.

PROGRAM ZEROLESS
WRITE(5,10)
10 FORMAT(' input desired back bead width (inches)',/)
READ(5,20)WIDTH
20 FORMAT(F6.4)
STEP=0.
WIDTH=931.*WIDTH-111.
WRITE(5,21)
21 FORMAT(' type 1 for step test, <cr> otherwise',/)
READ(5,56)ISTEP
IF(ISTEP.NE.1)GO TO 22
WRITE(5,23)
22 FORMAT(' type step size and direction',/)
READ(5,20)STEP
STEP=STEP*931.
23 WRITE(5,84)
84 FORMAT(' input k1,k2 (real)',/)
READ(5,90)GAIN1,GAIN2
90 FORMAT(2F20.8)
WRITE(5,85)
85 FORMAT(' input sampling time')
READ(5,86)TIME
86 FORMAT(F9.8)
WRITE(5,40)
40 FORMAT(' type in # of loops',/)
READ(5,41)LOOPS
41 FORMAT(I5)
HALF=LOOPS/2
WRITE(5,55)
55 FORMAT(' type 1 to return table',/)
READ(5,56)IVAL
56 FORMAT(I3)
IF(IVAL.NE.1)GO TO 57
CALL OUTPUT(-300)
57 WRITE(5,53)
53 FORMAT(' type <cr> to initialize table velocity',/)
READ(5,56)J
IVAL=70.
VALUE=1./FLOAT(IVAL)
CALL OUTPUT(IVEL)
WRITE(5,50)
50 FORMAT(' start arc, type <cr> to begin control',/)
READ(5,56)J
OLDVOL=0.
DO 60 I=1,LOOPS
CALL ATOD12(9,IVOLT)
VOLT=FLOAT(IVOLT)
IF(I.EQ.HALF)WIDTH=WIDTH+STEP
ERROR=WIDTH+VOLT
DELTA=VOLT-OLDVOL
VALUE=GAIN1*DELTA+GAIN2*ERROR+VALUE
OLDVOL=VOLT
IVEL=IFIX(1./VALUE)
IF(IVEL.LT.0)IVEL=0
CALL OUTPUT(IVEL)
60 CONTINUE
GO TO 5
END