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Process monitoring and on-line modelling of the gas metal arc welding process

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LAWRENCE ANTHONY SANDERS

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GAS METAL ARC WELDING PROCESS

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SUPERVISOR: PROFESSOR MICHAEL WEST
DECLARATION

This is to certify that the work presented in this thesis was carried out by the author in the Department of Mechanical Engineering of the University of Wollongong and has not been submitted for a degree to any University or Institution.

Lawrence Anthony Sanders, B.Sc., M.Sc.
ABSTRACT

PROCESS MONITORING AND ON-LINE MODELING OF THE GAS METAL ARC WELDING PROCESS


Progress in development of Advanced Process and Equipment for GMAW, especially in Automated and Mechanised Welding, requires clear understanding of the physical phenomena of the Welding Process [1]. The objective of this thesis is to design and develop modern experimental facilities capable of providing instrumentation and photography to record welding phenomena, so as to allow a thorough study of the physical welding processes.

The thesis initially describes the development of an Experimental Facility for Monitoring the Gas Metal Arc Welding (GMAW) Process. The Facility described consists of:

a) Weld Testing Facilities.

b) A Physical Testbed with a Weld Table moving under a stationary GMAW Gun.

c) Electronic Monitoring of the GMAW Parameters including Weld Voltage (V), Weld Current (I), Wire Feed Rate (WFR) and Weld Travel Speed (TS).

d) Computer Control of GMAW Parameters including Weld Voltage, Wire Feed Rate and Weld Travel Speed.

e) Weld Visualisation using High Speed Photography with a Communications Link from the High Speed Camera to the Electronic Monitoring System allowing the Camera, when it commences its filming run, to trigger the Electronic Monitoring System, thereby enabling time-correlated Electronic Data and Visual Images to be obtained.

The thesis next describes in detail the Weld Testbed and Electronic Monitoring System in terms of Electronic Hardware, Software Algorithms for Weld Monitoring, Algorithms for Weld Parameter Control and two Graphical User Interface (GUI's) Packages developed for the Viewing and Analysis of Weld Data. These Software Packages are:

a) 'Shortmon': A package for Viewing and Analysing the Parameter Traces of short bursts of Welding Data (< 2 seconds).
b) 'Longmon': A package for Viewing and Analysing the behaviour and stability of Weld Parameter Settings over longer welding periods (up to 120 seconds).

Both of the above described Packages also include Computer Controlled Setting of Weld Parameters. 'Longmon' also allows in-weld alteration of Weld Parameters thus enabling the effects of Weld Parameter variation to be studied.

The verification of the MWEF as a facility for GMAW Control Strategy development was achieved through a series of experimentation in which process irregularities were induced and monitored in Real-time.

The next Stage of the thesis describes the development of a Graphical User Interface (GUI) for On-line Modeling of the Welding Process in a single weld run utilising Weld Parameter Feedback for a range of Computer Controlled Weld Parameter Settings. An important research interest is the development of Strategies and Models for the effective Real-time Control of the Welding Gun Standoff (L) (also often referred to as 'Contact-tip to Workpiece Distance'). The On-line Modeling Package has therefore been initially developed to generate Least-Squares Models of:

\[ I = f(V, WFR, L) \] and also \[ L = f(V, I, WFR) \]

which are intended for use as Real-time Estimators for Current and Standoff Control.

This work is funded by the Cooperative Research Centre (CRC) for Materials Welding and Joining as part of Project 93/12 which is a collaborative research effort in the area of Welding Automation between the University of Wollongong, The University of Sydney and the CSIRO Division of Applied Physics (Sydney).

Please Note that Welding Visualisation with High Speed Photography was developed by Dr. Wee King Soh and Mr. Hernan Ratto whilst the Welding Testbed and the Electronic Monitoring and Control of the Welding Process was developed by the Author under the supervision of Professor Michael West.
Acknowledgments

I would like to foremosty thank Professor Michael West whose professional and personal supervision over the last three years has made the completion of this project possible. Professor West has been an excellent Supervisor and I will always be grateful for what I have been able to learn from him in terms of technical knowledge, project management and leadership.

I am also grateful to Professor John Norrish for his contributions towards the end of the project as well as other members of Staff in the Department of Mechanical Engineering who have provided technical assistance over the period of study.

I would also thank to thank the Professional and Technical Officers in the Department of Mechanical Engineering who have made a significant contribution to the practical work of this project. A thank you must also be given to Mr. Hernan Ratto for his assistance with the time correlation of High Speed Photography with the Electronic Data Acquisition Systems described in this thesis.

Gratitude is also expressed to the funding organisations that have provided the finances for this project. These include

a) the Department of Employment, Education and Training (DEET) who provided an Overseas Postgraduate Research (OPRA) Scholarship and

b) The Cooperative Research Centre (CRC) for Materials Welding and Joining who provided a living allowance and funding for equipment under Project 93.12.

I am also very grateful to my Wife, Susan. Without her support, this project would also not have been possible.
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Chapter 1

An Introduction to Gas Metal Arc Welding (GMAW)

1.1) A Brief Description of the GMAW Process:

A continuous-feed electrode is fed towards the workpiece and an Arc is formed between the Electrode and workplace which melts the Electrode to form a molten Weldpool. On solidifying, the Weldpool forms the Weld Bead. Both the Electrode and the Weldpool are protected from Atmospheric Contamination by a Shielding Gas.

1.2) Gas Metal Arc Welding Equipment:

A schematic Diagram of a Gas Metal Arc Welding unit is shown below:

![GMAW Equipment Diagram]

**Fig 1.1: GMAW Equipment**

1.2.1) Power Source:

A traditional GMAW Power Source is simply a Transformer/Rectifier/Inductor Unit. The Input to the Power Source is
normally Three-Phase Alternating Current (AC) at 50Hz. The Transformer modifies the Power to the required Voltage and Current levels and the Rectifier then converts the AC signal into a Direct Current (DC) Signal. The Inductor is used to stabilise the Current levels supplied to the Electrode.

It should be noted at this point that GMAW is a Direct Current Process. The Electrode is the Anode (i.e. +ve) and the workpiece is the Cathode (i.e. -ve) and therefore the Gas Metal Arc Welding Process is often referred to as being Electrode Positive.

One of the major drawbacks of the traditional Power Supply is the AC ripple, which is the residue of the AC Signal on the rectified DC Signal. On some Welding Machines, this residue can be quite large, and hence can cause problems with respect to the Automatic Control of the Welding Process. A recent improvement upon the traditional Power Supply is the Inverter.

With the Inverter Power Supply, the Three-Phase 50Hz AC Current is passed through a Rectifier and Capacitor Filter to produce a smooth DC Signal. The DC Current produced is passed through an Inverter which converts the Current back into AC but at a much higher frequency (20 - 25 KHz). This High-Frequency AC Signal is then passed through a Transformer which produces the correct Power level. The AC Signal is then rectified again to produce DC Voltage and Current. The Inverter produces a much smoother DC Output which can readily be utilised in Automatic Control of Welding Operations.

All GMAW Power Supplies are Constant Voltage (CV) machines because they enable better Arc control. Constant Voltage means that there will be very little change in Voltage over the Current range of the Machine.

1.2.2) Wire Feed Unit:

In GMAW, the Electrode is in the form of a Copper coated Wire which is continuously fed into the Arc. The Unit which feeds the Wire into the Weld is referred to as the Wire Feed Unit.

The Wire Feed Unit consists of a Set of Wire Feed Rollers, a reel of Electrode Wire, and a Variable-Speed DC Electric Motor connected to one of the Rollers via a Gearbox. The Rollers mechanically grip the Electrode Wire and are then driven by the Motor, feeding the Electrode into the Weld at the desired Wire Feed Rate. The Wire Feed Rate can vary between 0m/min and 20m/min with common Wire Diameters ranging from 0.6mm to 1.6mm.

1.2.3) Welding Gun:

The Welding Gun is used by the Welder to position the Weld where required and guide the Weld through the correct path at the correct Welding Speed. At
the Head of the Welding Gun is a Copper Tube called the Contact Tip, through which the Welding Current is passed to the Wire. The Inside Diameter of the Contact Tip is the same as the Wire Diameter so that there is always contact between the Contact Tip and the Electrode as it is fed into the Arc, thereby ensuring continuous current flow into the Wire.

The Head of the Welding Gun also has an external Nozzle for directing the flow of the Shielding Gas to the Weld Pool Area. The Shielding Gas is fed to the Weld Pool through a Gas Diffuser which is placed just above the Contact Tip.

Another important component of the Welding Gun is the Trigger. The Trigger, when pressed, closes a relay which has the effect of closing the Welding Circuit allowing the Current to flow. The Trigger is always placed in the Hand Grip of the Welding Gun to enable easy starting and stopping of Welding. A typical GMAW Gun is illustrated in Fig 1.2 below:

1.2.4) **Lead Cable:**

The Lead Cable (also referred to as the Power Cable or Control Cable) connects the positive (+ve) terminal of the Power Supply to the Welding Gun via the Wire Feed Unit and is used to supply the Current, Electrode Wire and Shielding Gas to the Welding Gun.

The Lead Cable has a hollow insulated interior for the Gas Flow and Wire Feed. Because the Wire Electrode is fed to the Weld through the Lead Cable,
the Lead Cable is always directly connected to the Wire Feed Unit and not the Power Supply.

1.2.5) **The Return Cable:**

The Return Cable connects the workpiece to the negative (-ve) Terminal of the Power Source completing the Electric Circuit.

1.2.6) **The Shielding Gas Supply:**

The Shielding Gas is stored in a Cylinder and the Gas Flow Rate is set by monitoring the Flow Rate Meter while adjusting the Regulator until the required Gas Flow Rate has been achieved.

1.3) **GMAW Parameters and their effect on the GMAW Process and Weld Bead Profile:**

A basic illustration The Gas Metal Arc Welding Process is shown in Fig 1.3 below:

![GAS METAL ARC WELDING PROCESS](image)

**Fig 1.3: The Gas Metal Arc Welding Process**
It can be seen from Fig 1.3 that in the GMAW Process, the Heat Input to the Consumable Electrode (resulting from the Voltage and Current) causes a melting of the Electrode and transfer of the Weld Metal across the Arc to form the Weld Bead. It should be noted that Fig 1.3 illustrates welding in Spray Transfer Mode. Spray Transfer is achieved at higher Voltage and Current Settings whilst Dip Transfer, another Welding Transfer Mode commonly used in Industry, is achieved at lower Voltage and Current Settings and is characterised by perpetual Electrode Dipping into the Weld Pool and Burnback at frequencies ranging from 20 to 200 Dip/Burnback Cycles per Second. Details of the Dip and Spray Transfer Modes can be found in Section 1.5 but Table 1.1 below gives some indication at this stage of typical Dip and Spray Transfer operating ranges:

<table>
<thead>
<tr>
<th>Welding Mode</th>
<th>Welding Position</th>
<th>Voltage Range (V)</th>
<th>Current Range (A)</th>
<th>Electrode Diam (mm)</th>
<th>Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip</td>
<td>All</td>
<td>13 - 24</td>
<td>60 - 220</td>
<td>0.6 - 1.2</td>
<td>Sheet. Thin Section</td>
</tr>
<tr>
<td>Spray</td>
<td>Downhand</td>
<td>26 - 40</td>
<td>210 - 410</td>
<td>0.8 - 1.6</td>
<td>Thicker Sections</td>
</tr>
</tbody>
</table>

As stated, GMAW is a Constant Voltage (CV) Process. This means that the process has relatively flat Voltage/Current Characteristics indicating that for a large change in the Current setting, there will only be small changes in the Voltage as illustrated in Fig 1.4 below:

\[
\text{Slope} = \frac{\Delta V}{\Delta I}
\]

**Operating point**

![Fig 1.4: GMAW Voltage/Current Characteristics](image)

The Current supplied to the Electrode varies with:
i) The Wire Feed Rate (WFR) setting and

ii) the Contact-tip to Workpiece Distance (L) as illustrated in Fig 1.3, which to abbreviate the definition will hence forth be referred to as the Standoff.

The Wire Feed increases with the Current in a Curvi-linear relationship as illustrated in Fig 1.5. The Current decreases almost linearly with increasing Standoff values.

![Typical Current/WFR Characteristics for varying Wire Diameters](image)

**Fig 1.5: Typical Current/WFR Characteristics for varying Wire Diameters**

A typical GMAW Weld Bead profile is illustrated in Fig 1.6 below:

![Typical Weld Bead Profile produced by GMAW](image)

**Fig 1.6: Typical Weld Bead Profile produced by GMAW**

The Arc Voltage (V), Wire Feed Rate (WFR), Current (I) and Weld Travel Speed (TS) are Parameters that significantly affect the Welding Process and the resulting Weld Bead Profile. The Electrode Material Composition, Shielding Gas Type and Gas Flow Rate are Parameters that also determine the Weld Bead Profile and are discussed in Section 1.4.
The effect of the increases of Voltage, Current and Weld Travel Speed on the Weld Bead Profile are presented in Table 1.2 below:

<table>
<thead>
<tr>
<th>Parameter Increase</th>
<th>Bead Width</th>
<th>Bead Height</th>
<th>Penetration</th>
<th>Bead Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>I</td>
<td>D</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>Current</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>

I = Increase, D = Decrease, U = Unaffected

Please note that because the WFR directly controls the Current, the effects of WFR increase have exactly the same effect as the Current increase and has therefore not been included in Table 1.2

1.4) Gas Metal Arc Welding Consumables:

1.4.1) Solid Wire Electrodes:

Commercial Wires for the Welding of Low Carbon Steels using a Standard GMAW Machine are supplied in 15Kg Reels with Wire Diameters ranging from 0.6mm to 1.6mm.

For Low Carbon Steel, Electrode Wires typically have a Yield Stress of 400MPa, Tensile Strength of 520mpa and Impact Energy (Charpy V Notch Test) of 80J at -20 Degrees Celsius.

Table 1.3 below provides some indication of the Operating Ranges of Various Wire Diameters:

<table>
<thead>
<tr>
<th>Wire Diam (mm)</th>
<th>Current (Amps)</th>
<th>WFR (Meters/min)</th>
<th>Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>35 - 100</td>
<td>3.0 - 12.5</td>
<td>12 - 14</td>
</tr>
<tr>
<td>0.8</td>
<td>50 - 180</td>
<td>3.5 - 12.5</td>
<td>14 - 22</td>
</tr>
<tr>
<td>0.9</td>
<td>70 - 230</td>
<td>3.5 - 12.5</td>
<td>15 - 26</td>
</tr>
<tr>
<td>1.0</td>
<td>100 - 280</td>
<td>3.5 - 12.5</td>
<td>16 - 28</td>
</tr>
<tr>
<td>1.2</td>
<td>120 - 350</td>
<td>2.5 - 15.0</td>
<td>18 - 32</td>
</tr>
<tr>
<td>1.6</td>
<td>200 - 400</td>
<td>2.5 - 7.5</td>
<td>18 - 34</td>
</tr>
</tbody>
</table>

AS2171 Part 1 classifies Solid Wire Electrodes by a three-group Code. The Classifications for Low Carbon Steel Electrodes are:

ES4-GM-W503H (Mixed Gas Welding)
ES4-GC-W503H (Pure CO₂ Gas Welding)

The first 3 letters of the Classification Code refer to the Chemical Composition of the Wire. The 'ES' is an abbreviation for 'Electrode Solid' and the following digit is code for the Chemical Composition. The Composition of Solid Electrode Wires is given in Table 1.4 below:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Carbon (%)</th>
<th>Manganese (%)</th>
<th>Silicon (%)</th>
<th>Phosphorous (%)</th>
<th>Sulphur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES2</td>
<td>0.07</td>
<td>0.90-1.40</td>
<td>0.40-0.70</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>ES3</td>
<td>0.07-0.15</td>
<td>0.90-1.40</td>
<td>0.45-0.70</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>ES4</td>
<td>0.07-0.15</td>
<td>1.00-1.50</td>
<td>0.60-0.85</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>ES5</td>
<td>0.07-0.19</td>
<td>0.90-1.40</td>
<td>0.30-0.60</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>ES6</td>
<td>0.07-0.15</td>
<td>1.40-1.85</td>
<td>0.80-1.15</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>ES7</td>
<td>0.07-0.15</td>
<td>1.50-2.00</td>
<td>0.50-0.80</td>
<td>0.025</td>
<td>0.035</td>
</tr>
</tbody>
</table>

The second group of characters indicates the type of Shielding Gas with which the Electrode Wire should be used. The characters 'GM' indicate that a Mixed Shielding Gas (i.e.: Argon + Oxygen + Carbon Dioxide) should be used whilst 'GC' indicate that the Electrode should only be used with a Carbon Dioxide Shielding Gas.

The third group of characters is initialised by the letter 'W' followed by three digits. The first two digits are 1/10 of the Tensile Strength of the Electrode Material in MPa and the last digit is a code for the minimum Impact Value (Charpy V-notch test), measured in Joules at a specific temperature.

Table 1.5 below gives the minimum Impact Values of Carbon Steel Electrode Materials (Tensile Strength = 500 MPa):

<table>
<thead>
<tr>
<th>Electrode Classification</th>
<th>Minimum Impact Energy (J) (Charpy V-Notch Tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W500</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>W501</td>
<td>47J at +20°C</td>
</tr>
<tr>
<td>W502</td>
<td>47J at 0°C</td>
</tr>
<tr>
<td>W503</td>
<td>47J at -20°C</td>
</tr>
<tr>
<td>W504</td>
<td>47J at -40°C</td>
</tr>
<tr>
<td>W505</td>
<td>47J at -60°C</td>
</tr>
</tbody>
</table>
The letter 'H' generally completes the third group and indicates that the Welding Process will be Hydrogen Controlled.

1.4.2) Shielding Gases:

The main function of a Shielding Gas in GMAW is to remove air from the weld zone thereby preventing contamination of the weld metal by Nitrogen, Oxygen and Water Vapour. These gases cause a variety of defects and put impurities into the weld metal.

The impurities in the weld metal can include Metal Oxides, Slag Inclusion, dissolved Hydrogen Atoms (causing brittleness) and Weld Porosity. The porosity that may result due lack of or insufficient shielding gas can readily be seen on the surface of welds, but also occur within the weld.

The selection of shielding gas affects the Welding Arc Characteristics, Bead Profile and levels of Spatter. No single shielding gas can be used by every welding process on every material type, hence commercially available shielding gases are generally a mixture of gases. Shielding gases for Low Carbon Steels at present are Argon Based Mixtures. The three major Shielding Gas Mixtures are:

1.4.2.1) Pure Argon:

A Pure Inert Gas such as Argon will protect the arc and weld metal from the atmosphere and is suitable for welding non-ferrous metals, however, it is not stable enough for welding low carbon steels because:

i) Argon is not a High Energy input gas, which enables ferrous metals to freeze rapidly. If the metal is not molten for long enough to 'wet out' the Weld Toe, undercut will result as illustrated in Fig 1.13.

ii) The arc in an Argon shielding gas tends to wander producing an irregular weld bead.

The above described problems are rectified by adding combinations of Oxygen \( \text{O}_2 \) and/or Carbon-dioxide \( \text{CO}_2 \).

1.4.2.2) Argon/CO\(_2\) Mixtures:

The Argon content varies between 75% - 90% whilst the \( \text{CO}_2 \) varies between 10% - 25% by volume. Increasing the \( \text{CO}_2 \) content tends to increase the heat of the arc and therefore also the depth of Weld Penetration.
1.4.2.3) **Argon/O₂ Mixtures:**

The Argon content varies between 95% - 99% whilst the O₂ varies between 1% - 5% by volume. Oxygen is added to stabilise the arc, improve the Weld Bead Profile, reduce Undercut and eliminate Spatter.

1.4.2.4) **Argon/O₂/CO₂ Mixtures:**

Typical gas composition ranges for Argon/O₂/CO₂ Mixtures are Argon (81% - 92%), O₂ (2% - 3%) and CO₂ (5% - 16%). The addition of O₂ to Argon/CO₂ improves the stability of Metal Transfer whilst increasing the CO₂ levels in the various gas mixtures increases the depth of penetration.

1.4.2.5) **Pure CO₂:**

CO₂ is used independently as a shielding gas, but on conventional welding machines produces very high spatter levels and heavily oxidised weld beads. Because CO₂ promotes oxidation, it fills the welding atmosphere with metal oxides which substantially reduces visibility in the welding area. Another limitation of using pure CO₂ is that a heated regulator is required to prevent the CO₂ from turning to Dry Ice as it leaves the cylinder.

An advantage of CO₂ is that it is cheap compared to the cost of Argon and Argon Based Mixtures and therefore can be used with conventional welding machines in situations where the appearance of the weld is not a priority concern. Also, with respect to conventional welding machines, CO₂ can only effectively be used in Spray Transfer Welding Mode (see Sec 1.5.2) and cannot really be used in Dip Transfer Welding Mode (see Sec 1.5.1). However, new Surface Tension Transfer Welding Machines [6] have been specifically designed for the utilisation of Pure CO₂ to produce good quality welds in Dip Transfer Mode, making it possible to use Pure CO₂ in both Dip and Spray Transfer Modes. This new development will enable Manufacturers to make significant savings in the cost of shielding gas.

Table 1.6 below gives details of some commercially available Shielding Gases from the BOC Company:

<table>
<thead>
<tr>
<th>Gas Type</th>
<th>Application</th>
<th>Mode</th>
<th>Composition</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argoshield 40</td>
<td>L</td>
<td>Spray</td>
<td>Argon/O₂</td>
<td>Fast, Clean appearance</td>
</tr>
<tr>
<td>Argoshield 50</td>
<td>SLH</td>
<td>Dip/Spray</td>
<td>Argon/O₂/CO₂</td>
<td>Versatile, Medium Heat Input</td>
</tr>
<tr>
<td>Argoshield 51</td>
<td>LH</td>
<td>Dip/Spray</td>
<td>Argon/O₂/CO₂</td>
<td>Versatile, High Heat Input, Penetration</td>
</tr>
</tbody>
</table>

S = Sheet Material, L = Light Section Material, H = Heavy Section Material
1.5) **Welding Transfer Modes:**

1.5.1) **The Dip Transfer Welding Mode:**

Dip Transfer is achieved by lower Voltages (13V - 23V) and Currents (60A - 220A) using Wire Diameters in the range of 0.6mm - 1.2mm. It is used mostly for the welding of thin sheet material (up to 4mm thick) or for Root Runs on thicker material.

Dip Transfer is characterised by repeated short-circuiting of the Electrode into the weld pool at a frequency of between 10 and 200 Cycles/Second. Typical Dip Transfer Voltage and Current traces are illustrated in Fig 1.7 below. It should be noted that the Dipping Frequency for the traces displayed is slower than normal, but nevertheless, clearly demonstrate the Cycles of Dip Transfer Welding.

![Voltage (V) v Time (mS)](image)

![Current (A) v Time (mS)](image)

Fig 1.7: Dip Transfer Voltage and Current Traces

Please note that the data for the above Parameter traces illustrated above was obtained by the ‘Shortmon’ Program for acquiring and analysing short bursts of welding data. The Program is described in detail in Chapter 7.
A typical Dipping Cycle is illustrated in Fig 1.8 below and Fig 1.9 illustrates an approximate state of the Electrode/Arc for each stage of the Dip as defined on the Voltage Trace in Fig 1.8:

Fig 1.8: The Voltage and Current in the Dipping Period

Fig 1.9: State of the Electrode/Arc in the Dip Cycle
The Events in the Dipping Cycle illustrated in Fig 1.8 are explained in detail below:

**Event 1:** The Arc at this Stage is ignited and the wire is feeding towards the weld pool as the electrode burnoff rate is less than the wire feed rate. The Voltage is constant (which is to be expected as the Welding Machine is a Constant Voltage Power Source) and Current is at the tail-end of an exponential drop from a peak value as can be seen in Fig 1.7.

**Event 2:** At this point the wire dips into the weldpool causing the short. The Arc is extinguished, the Voltage drops rapidly towards zero and Current starts to rise rapidly. The inductor in the Power Source ensures that the Current has a smooth, exponential rise to prevent excess spatter.

**Event 3:** The Voltage is now very small, but has still not approached zero because it is has not yet penetrated the oxides or other contaminants on the surface of the weldpool. The Current is still on the rise.

**Event 4:** The Oxide/Contaminant layer has been pierced and the Voltage reaches its lowest level (nearly zero, but not quite do to the resistance in the Electrode). The Current is still rising at this stage.

**Event 5:** The Current continues its exponential rise. The Voltage starts to rise because the rise in Current results in perpetually increasing Ohmic Heating in the Wire. The Resistance increases with the increase in Electrode Heating which, by Ohm's Law, also increases the Voltage.

**Event 6:** At this point the combination of heat input into the wire from the Power Input and the Weldpool causes a pinching effect which results in a 'necking' of the Wire Diameter near the Weldpool. This is followed by rapid burnback as the wire melts completely at the neck and the arc is reignited. As the wire burns back, the Voltage rises rapidly and the Current commences an exponential drop.

**Event 7:** Maximum burnback occurs here. At this point the burnoff rate is approximately equal to the Wire Feed Rate. The Voltage Peaks before returning to its regular value and the Current continues its exponential drop. Please note that in Fig 1.8, the Current appears to be rising at this stage, but this is caused by the large AC Ripple on the Transmig 350 EC Power Source. It can be observed from Fig 1.7 that after peaking, the Current does experience an exponential drop.

**Event 8:** The Voltage has nearly returned to its normal constant value, the Current is continuing its exponential drop and the Wire is feeding back towards the weldpool.
The Dipping Frequency is determined by the Voltage and Wire feed Rate Settings. The lower the Voltage/Current ratio, the higher will be the Dipping Frequency. Therefore, with respect to a Voltage setting, increasing the Wire Feed Rate will increase the Current but will also increase the Dipping Frequency.

1.5.2) **The Spray Transfer Welding Mode:**

Spray Transfer is achieved by higher Voltages (26V - 40V) and Currents (180A - 400A) using Wire Diameters in the range of 0.8mm - 1.6mm. It is used mostly for the welding of material of thickness greater than 5mm.

The Heat Input in Spray Transfer Mode is such that the Electrode Burnoff Rate is approximately equal to the Wire Feed Rate, resulting in a continuously burning Arc with a nearly constant Arc Length. Typical Spray Transfer Voltage and Current Traces (also obtained from the ‘Shortmon’ Program) are shown in Fig 1.10 below:

![Fig 1.10: Spray Transfer Voltage and Current Traces](image-url)
It can be seen from Fig 1.10, that the Parameter traces are much smoother in Spray Transfer due to the arc stability obtained. The variation that can be seen is entirely due to the large AC Ripple of the Transmig 350 EC Power Source. In Spray Transfer Mode, the Weld Metal is detached from the Electrode in droplet form and transferred across the arc to form the weld bead. The droplet Size decreases with increasing Welding Current [7].

1.6) **Welding Positions:**

The four welding positions are Flat, Horizontal, Vertical and Overhead as illustrated in Fig 1.11 below:

![Fig 1.11: GMAW Welding Positions](image-url)
Each different Welding Position requires a different Welding Procedure. A Straight Welding Technique can be used on the Flat, Horizontal and Overhead Positions but a Weaving Technique must be used if producing welds in the Vertical Position.

1.7) **Welding Types:**

Fig 1.12 below is a comprehensive illustration of the many weld types that can be produced using GMAW:

![Welder Types producable by GMAW](image)

**Fig 1.12: Weld Types producable by GMAW**

1.8) **Some Typical Welding Faults:**

1.8.1) **External Welding Defects:**

External Defects are those which can be viewed externally on a weld. These defects include:

i) Undercut and Overroll.
ii) Plate Misalignment.

iii) Incomplete or Excessive Penetration.

iv) Weld Craters, Blowholes and Spatter.

v) Irregular Bead Profile.

1.8.2) **Internal Welding Defects:**

Internal Defects are those which are inside the Weld and can generally only be detected using Ultrasonics, X-Rays or Destructive Weld Tests. These defects include:

i) Porosity.

ii) Weld Cracks.

iii) Lack of Side Wall Fusion and/or lack of Penetration.

Fig 1.13 below illustrates some of the External and Internal Defects listed above:
Chapter 2

Literature Survey and Project Aims

2.1) The Manual Welder:

To be able to automate the Welding Process, it is necessary to understand the processes and techniques utilised by Manual Welders in the production of quality welds.

In manual welding operations the Welder will set the Voltage, Current and Gas Flow Rate (GFR) prior to commencing a Welding Operation. The Settings selected will be based on experience and will be selected for the type of weld, the welding position, material type and material thickness. The Manual Welder cannot alter the Voltage, WFR and GFR settings during a Welding Operation.

During the welding process the Welder will use vision to monitor the Gun Standoff, the orientation of the Welding Gun, the Weld Travel Speed, visible components of the Weld Bead, the Welding Mode and the Arc Stability. An experienced Welder can also use the Audible Weld Acoustics to assess Arc Stability and Welding Mode.

Based on Visual and Acoustic Feedback, the Welder will assess the current state of the Welding Process and the position of the Welding Gun and can then update the position of the Weld Gun and take action to rectify any irregularities that may be present. Such corrective actions may be:

i) Increasing/decreasing the Weld Travel Speed to increase/decrease the Bead size.

ii) Shifting the Weld Gun to place the weld in the correct position.

iii) Overcoming burnthrough (or Excessive Penetration) by rapidly increasing the Standoff, thereby decreasing the Current.

An effective and reliable Autonomous (Robotic) GMAW System, must therefore to a large degree, simulate the actions of the Manual Welder.

In order to study Industrial Welding Techniques and understand the Manual Welding Process, practical GMAW courses were completed by the Author [2 - 5].
2.2) **What must be controlled in GMAW?**

As described in Section 2.1, control of the GMAW process is a combination of control of the Process Parameters and also the positioning of the Weld Gun relative to the workpiece. In Autonomous GMAW, it is therefore vital to monitor and control the following:

2.2.1) **GMAW Process Parameters:**

GMAW Process Parameters include:

i) Voltage.
ii) Current.
iii) Wire Feed Rate.
iv) Weld Travel Speed.
v) Gas Flow Rate.

It should be noted that the Electrode Class, Electrode Size and Shielding Gas Type have a considerable effect on the welding process, but these effects cannot be readily monitored in Real-time, so their affects are not considered as 'real-time' controllable parameters.

2.2.2) **Weld Gun Positioning:**

The Weld Gun Position is defined by:

i) The Standoff (Contact-tip to Workpiece Distance).
i) The Orientation of the Contact-tip relative to the workpiece.

2.3) **A Concept of an Autonomous GMAW Control System:**

Cook et al. [8] refers to a Welding System Output as ‘Direct Welding Parameters’ (DWP’s). These Parameters are the measurable properties of the weld produced which include the Bead Dimensions, Material Properties and the Material Structure. He also refers to ‘Indirect Welding Parameters’ (IWP’s) as the System Inputs that produce the Direct Welding Parameters. IWP’s include Voltage, Current, WFR, etc.

A certain set of IWP’s will produce a set of DWP’s. For Automated Welding to be successful, there must be a means for relating IWP’s to DWP’s in Real-time through the development of some sort of ‘Adaptive Model’. These Models would be implemented in an Autonomous GMAW System as briefly illustrated in Fig 2.1 overleaf:
Although the Control System illustrated in Fig 2.1 appears theoretically simple, the Control of Process Parameters and Weld Gun Positioning in Real-time is an extremely complex problem and will require a considerable research effort comprising of individuals with expertise in the areas of Welding, Robotics, Mathematics, Statistics, Physics, Electronics and Software Development. An anticipated route of the project is presented in Sec 2.6.

Before commencing this project it was necessary to undertake a study of progress in the area of Welding Automation. This has been undertaken with an emphasis on Welding Sensors and methods for Weld Modelling and Control.
2.4) **A Study of Welding Sensor Development:**

It should be noted that the Welding Sensors discussed in the following sections are only concerned with Real-time Weld Process Monitoring and not Sensors used before or after the Welding Process.

2.4.1) **Requirements for Welding Sensors:**

Nomura [9] states that Welding Sensors must be able to sense:

i) Welding Parameters (See Sec. 2.2.1).

ii) Arc Conditions

iii) Weld Pool Dimensions.

iv) Weld Bead Geometry.

v) The Position of the Welding Gun relative to the workpiece (See Sec 2.2.2).

Araya and Saikawa [10] further state that Welding Sensors must be able to detect:

i) Errors and variation in the workpiece preparation.

ii) Workpiece alignment errors.

iii) Workpiece distortion due to Heat Input.

v) Anomalies such as tackwelds and other surface phenomena.

Araya and Saikawa also stated that some of the welding phenomena that could cause disturbances to Weld Sensors are:

i) Arc light.

ii) Heat.

iii) Spatter and Fumes.

Welding Sensors clearly need to be, as far as is possible, free from the effects of the above stated disturbances. In the light of this, Araya and Saikawa added that a Welding Sensor must be:

i) Sufficiently precise for handling welding processes.

ii) Unaffected by the common disturbances of welding.

iii) Compact.

iv) Durable.

v) Reliable.

vi) Inexpensive.

vii) Easily maintained.

Welding Sensors can be divided into the following categories:

i) Indirect Welding Parameter (TWP) Monitoring.

ii) Contact Probes.

iii) Optical (Vision and Thermographic Imaging).

iv) Through-the-Arc.

v) Infrared.

vi) Ultrasonics.

vii) Audible Weld Acoustics.

Recent Research efforts to develop the above described Sensing methods are described in the following Sections.

2.4.2) **Indirect Welding Parameter (IWP) Sensing:**

2.4.2.1) **Voltage Sensing:**

Instantaneous values of Voltage can be obtained by placing connections to the Anode and Cathode sides of the Welding Circuit. The connections can be made at the Welding Set, but is not recommended as Resistance in the Lead and Return cables cause voltage drops which will distort the true Arc Voltage Reading [12], as illustrated in Fig 2.2 overleaf:
It can be seen from Fig 2.2 that the Voltage Drop measured between the Anode and the Cathode \((V_{AC})\) is:

\[
V_{AC} = I(R_E + R_A)
\]

As \(R_E\) is small compared to \(R_A\), measuring the Voltage across the Welding Gun and the Workpiece will give a good estimate of the Arc Voltage. The Voltage across the whole Welding Circuit \((V_{TOTAL})\) is:

\[
V_{TOTAL} = I(R_E + R_A + R_L + R_R)
\]

It can clearly seen that if the Voltage is measured at the Welding Set the Voltage Drop across the Lead and Return cables would be added to the true Arc Voltage. Nevertheless, this Voltage drop would be constant and therefore if measuring the Voltage at the Welding Set, the Voltage Reading would need to be reduced by the Voltage across the Lead/Return cable to obtain the Arc Voltage.

The Voltage can range from 10V - 40V in GMAW. If the Voltage Reading is to be stored directly onto a Computer, this will be achieved through an Input/Output (I/O) Card. If, for example, the I/O Card has a maximum
Analogue Input range of 10V, then a Potential Divider will be required to reduce the Voltage to a Range suitable for passing into the I/O Card.

2.4.2.2) Current Sensing:

The Welding Current can be measured by either a Shunt (a low resistance in parallel) or a Hall Effect Sensor connected to either the Lead or Return Cable.

If using a Shunt, the current would be determined by measuring the Voltage across the Shunt. This Voltage is linearly proportional to the Welding Current. The Hall Effect Sensor produces a Voltage value linearly proportional to the Welding Current.

The Hall Effect Sensor is significantly easier to install than a Shunt as it is fitted by simply sliding it over the Cable whereas the Shunt requires cutting into the Cable for installation. Another obvious advantage of the Hall effect Sensor is that it can be readily transferred to other cables whereas the Shunt is a dedicated fitting to one cable.

2.4.2.3) Wire Feed Rate Sensing:

The Wire Feed Rate can be measured by connecting a Tachogenerator to the Wire Electrode. The Tachogenerator converts the Wire Feed Speed into a proportional Voltage reading which can be entered into a Computer via an I/O Card.

Another method available for Wire Feed Rate measurement is an Optical Encoder connected coaxially to one of the Wire Feed Rollers which feeds the Electrode into the Weld. The Optical Encoder enables the time between pulses to be determined and as the number of pulses/revolution of the Encoder is known, the time between pulses determined can be related directly to the linear distance travelled in this time by the circumference of the Wire Feed Roller. Knowing the time between pulses and the linear distance travelled by the Roller circumference during this period enables the Wire Feed Rate to be easily calculated.

An advantage of the Tachogenerator over the Optical Encoder is that it is flexible and can readily be transferred to other Wire Feed Unit. The Optical Encoder requires dedicated fittings for each Wire Feed Unit to which it is installed and can therefore only be used if the Fittings for a particular Wire Feed Unit exist. The Optical Encoder has very delicate and weak electronic connection points which are very easily broken. Using the Optical Encoder Method also creates difficulties in changing Wire Feed Rollers when using different Electrode sizes as the Wire Feed Rollers could only be accessed if the Encoder is removed.
Please note that an Optical Encoder was originally installed on our Weld Monitoring System, but will be replaced by the more flexible Tachogenerator.

2.4.2.4) **Weld Travel Speed Sensing:**

The method for Weld Travel Speed Sensing would very much depend on the Welding Apparatus used. At present there is no direct sensing method available for measuring the Travel Speed of Manual Welders. In Automated Welding Operations, methods available include Tachogenerators, Optical Encoders and Distance Transducers (used with Time to determine the Travel Speed).

If welding with Robots (which may be following complex welding paths), Travel Speeds will have to be calculated as a function of the Kinematics of the Robot (or, in other words, as a function of the time and joint motions for the Robot to move from the present set of coordinates to the next set of coordinates).

2.4.3) **Tactile Sensors:**

The term ‘Tactile’ refers to a Sensor that has physical contact with the workpiece.

The Simplest Tactile Sensor is a spring loaded guide wheel as illustrated in Fig 2.3 below [13]. The device simply utilises a rail placed above the workpiece on which the Welding Head is placed. The Welding Head consists of the Guide Wheel and Welding Torch fixed relative to each other. The Floating Torch Support enables the Guide Wheel to follow the contours of the workpiece and hence maintain a constant Standoff.
A more sophisticated Tactile Sensor is the Displacement Transducer illustrated in Fig 2.4 below [9]. The Displacement Transducer functions by converting the displacement of the Transducer into a linearly proportional voltage. This Sensor can therefore be utilised for contour detection and hence computer control of the Standoff Setting.

![Diagram of Displacement Transducer]

**Fig 2.4: The Displacement Transducer**

Other forms of Tactile Sensors include devices with a simple on/off operation such as Limit Switches. Limit Switches could be used in Mechanised Straight Line Welding for controlling the length of welding.

### 2.4.4) Vision Sensors:

Araya and Saikawa [10] divided the use of Vision Sensing into four clearly defined areas as listed below:

- **i)** Point Sensors.
- **ii)** Linear Sensors.
- **iii)** Structured Laser Light Sensors.
- **iv)** Area Sensors.

These Vision Sensor Types are illustrated in Fig 2.5 overleaf:
2.4.4.1) **Point Sensors:**

The Point Sensor is simply a Photo Transistor which oscillates across the Weld Seam. The quantity of light reflected from the workpiece is detected by the Photo Transistor and the difference between the light reflected by the workpiece and the light reflected from the workpiece joint or gap can be detected, revealing the position of the Weld Seam.

2.4.4.2) **Linear Sensors:**

As can be seen from Fig 2.5(b), the Linear Sensor is placed at a fixed angle from a point light source. This means that the distance $\Delta H$ will be directly and linearly proportional to $\Delta h$ and therefore this sensor can be used to determine the Standoff, assuming that the weld gun is fixed relative to the sensor unit.
Assume now that the unit can be rotated around a vertical axis, enabling 3D Scanning. The Linear Sensor can now also be used to map the Weld Joint Geometry and hence locate the centre of the joint.

A sensor for Seam Tracking based upon the Linear Sensor was developed by ASEA Robotics [14] and is illustrated in Fig 2.6 below:

![ASEA Seam Tracker based on the Linear Sensor](image)

**Fig 2.6: ASEA Seam Tracker based on the Linear Sensor**

2.4.4.3) **Slit Line Laser Sensors:**

The Slit Line Laser Vision Process, utilised mostly for Seam Tracking, is illustrated in Fig 2.7 overleaf [15]:

Referring to Fig 2.7, a beam of Laser Light is projected onto the workpiece surface (1) which in turn is reflected into a CCD Camera (2). The picture received by the Camera is sent to an Image Processor (3) which determines the Joint Profile information and sends this information to the Computer (4). The Computer analyses the data (5) with a view to updating the Welding Gun Position. The Welding Gun is moved to its correct position and orientation by the Controller.
The principal researchers for the Slit Line Vision method were Agapakis [16-18] and Umeaguku [19].

2.4.4.4) Area Sensors:

In contrast to Slit Line Imaging, Area Vision Sensing captures and analyses large areas of the Image. It is used typically with Infrared Cameras for Thermographic Analysis of the Weld Pool Area.

Infrared Sensing (discussed in more detail in Sec. 2.4.6) can be utilised to determine by Isotherm Processing, parameters such as the position and the width of the weld pool and can therefore be used for direct measurement of Weld Bead Geometry Characteristics including Bead Width, Penetration and also defects such as Lack of Fusion. Infrared Sensing can also be used for Seam Tracking by analysing the shape of the Thermal Image.

2.4.5) Through-the-Arc Sensing:

It appears that Through-the-Arc Sensing was originally researched by Cook [20] who proposed that as the Current increases/decreases with decreasing/increasing Standoff, scanning the Arc across the varying geometry of the Weld Joint could enable a profile of the joint to be obtained by analysing the variations in the Voltage/Current Signals. This principle is illustrated in Fig 2.8 overleaf [9]:

![Diagram of the Slit Line Laser Vision Process](image-url)

**Fig 2.7: The Slit Line Laser Vision Process**
It is quite clear that the major use of Arc Sensing is Seam Tracking, as the centre of the weld joint can easily be determined as the minimum Current Readings as the Arc scans across the joint.

Through-the-Arc Sensing has been further researched by Fujimara et al. [21] and by Kim and Na [22-23] who have developed new techniques for using Through-the-Arc Sensing for Seam Tracking and Standoff Control.

<table>
<thead>
<tr>
<th>Weaving operation</th>
<th>Shift from welding line</th>
<th>Welding current</th>
<th>Power spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>Shift to left</td>
<td>WR 0</td>
<td>P</td>
</tr>
<tr>
<td>Right</td>
<td>Shift to left</td>
<td>WR 0</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>undefined</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shift to right</td>
<td>WR 180</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Shift to right</td>
<td>WR 180</td>
<td>P</td>
</tr>
</tbody>
</table>

*) Current waves and phase angles for weaving wave

A new method for determining the Weld Bead Geometry using Arc Sensing has recently been developed by den Ouden and Xiao [24]. They have demonstrated using Gas Tungsten Arc Welding (GTAW) that the weldpool can easily be triggered into oscillation by Arc Current Pulses and that the Oscillation Frequency can be extracted from the Arc Voltage signals. It was further discovered that partially penetrated weld pools oscillate with a frequency of 100Hz to 350Hz whilst fully penetrated weld pools oscillate at much lower frequencies in the order of 25Hz to 100Hz. From this, den Ouden and Xiao have mathematically related the Weldpool Width to Weldpool Oscillation Frequency for both fully and Partially Penetrated Weldpools and have also clearly developed a method for Complete Penetration detection.

As stated this method was developed using GTAW and it has yet to be determined whether Weldpool Frequency can be utilised for Bead geometry Prediction using GMAW.

2.4.6) Infrared (IR) Sensing:

IR Sensing for Welding has been principally researched by Chin [25-32].
As previously stated, Infrared Sensing can be utilised for Bead Measurements including Bead width and Penetration. It can also be used to determine the Heat Affected Zone (HAZ) and defects such as Lack of Fusion.

The above mentioned Phenomena are determined by analysing the Isotherms obtained from Infrared Imaging of the weld pool. Fig 2.9 [29] below illustrates Isotherm plots of weld pool temperatures used for Penetration Measurement. In particular, they show images for 10%, 30% and 70% Penetration (presumably for Bead-on-plate Welding). The plot for 10% Penetration has a 5X Magnification.

Chin et al. [29] found that the Beadwidth of the Weld is linearly related to the width of the Thermal Image of the Weld Pool (Fig 2.10(a)) and also found that the Log of the Percentage Penetration is linearly related to the Thermal Area of the Isotherm Image of the Weldpool (Fig 2.10(b)):
Chin et al. [30] have also investigated the use of Infrared Sensing for Seam tracking by analysing the distortion of the Thermal Image of the Weldpool of a V-joint Butt Weld as the Arc moves away from the joint centre. This was investigated by taking 50 Infrared Frames (Images of the Weldpool) of a Weld Run produced at an angle to the Butt Weld Seam, as illustrated in Fig 2.11 below:

Fig 2.11: Infrared Seam Tracking: Experimental Procedure

Fig 2.12 (a) below illustrates the uniform Isothermal Image as the weld passes over the centre of the Bead (Frame 25), but also illustrates in Fig 2.12 (b), the distorted Isotherm Image (Frame 50) when the Weld Gun is significantly off-centre, thereby indicating the possibility of using Infrared Sensing for Seam Tracking.

Fig 2.12: Isotherm Images for Seam Tracking Experimentation
2.4.7) **Ultrasonic Sensing:**

Numerous attempts have been made to utilise Ultrasonics for Seam Tracking, Penetration Measurement and Weld Defect Detection [33-38]. However, a major limitation of Ultrasonics is the requirement for the Ultrasonic Transducer to be in the proximity (or in contact with) the workpiece. This means that any uneven surface caused by misalignment or Heat Distortion of the workpiece could severely hamper the effective use of Ultrasonics.

2.4.8) **Acoustic Sensing:**

As stated, the skilled Manual Welder often utilises Audible Weld Acoustics to determine the state of the Welding Process [39].

Audible Weld Acoustics can be used to determine Welding Mode [40] as the noise emitted by the various Welding Modes varies significantly (Dip Transfer is far more noisy than Spray Transfer due to the drastic changes in Energy that occur during a Dip Weld Cycle). Acoustics can also be utilised to determine Dipping Frequency in Dip Transfer Welding using FFT analysis. To a limited degree, Audible Weld Acoustics may also be used to determine weld defects such as burnthrough.

Norrish and Chawia [41] utilised Audible Weld Acoustics as a method for Quality Assessment of Flux Cored Arc Welding (FCAW) Consumables, but concluded that acoustics do not provide any extra information than can be obtained from the more easily measured Voltage and Current signals.

Another major problem with Acoustics is the external noise which may result in analysis errors.

2.4.9) **A Brief Analysis of Sensing Methods for GMAW:**

It appears that a range of sensing methods have been individually developed, but no individual sensing method or system can monitor all the phenomena required for truly Autonomous GMAW. Integration of the sensing methods discussed remains a goal yet to be accomplished. As many sensing methods (e.g. Vision, Infrared and Ultrasonics) require fairly bulky Hardware and require relatively long computation periods for analysis of the information they provide, it would be an extremely difficult (if not impossible) task to integrate these sensing methods for Real-time Control using Computer Technology currently available.

It would appear that the most versatile sensing method is Through-the-Arc Sensing as it utilises the Voltage and Current Signals to provide very important information as to the state of the Welding Process without
complex Sensing Hardware and computationally expensive Analysis Systems. Through-the-Arc Sensing can also readily be utilised in any welding position.

2.5) Modelling and Control of the GMAW Process:

Welding Sensors discussed in Sec. 2.4 only provide information as to the state of the welding process. This information needs to be processed by some technique to determine what changes to the welding process must be made to rectify any welding irregularities detected by Sensor Data Processing.

This section studies research efforts made in attempting to develop Modelling and Control techniques for Real-time GMAW Control. A discussion of some of these techniques now follows:

2.5.1) Mathematical Modelling:

Numerous Physical Models [42-58] (i.e. Models that are developed on purely Mathematical and Physical Principles) have been developed to understand the GMAW Arc and Metal Transfer Processes. However these Models generally utilise complex numeric analyses (such as the Finite Element Method and Difference Models) with computing times that are far too long for their use in Real-time Control.

It appears that for Real-time Control, the most suitable models will be Empirical and Semi-Empirical types where the effects of difficult to measure parameters such as Shielding Gas Type, gas Flow Rate and Electrode Composition can be included in experimentally and statistically determined coefficients.

Typical examples of Empirical and Semi-Empirical Models include the Least-Squares Current Predictor developed by Kim and Na [22-23] and various Statistical Models developed by Ogunbiyi [59].

More details of Mathematical Models for GMAW Parameter Prediction can be found in Chapter 9.

2.5.2) Artificial Intelligence:

The term Artificial Intelligence refers in this thesis to the use of Artificial Neural Networks (ANN's) and Fuzzy Logic techniques for GMAW Modelling and Control.

Attempts have been made to use Artificial Neural Networks for GMAW Parameter Estimation.
Cook et al. [60-61] attempted to use an ANN to map IWP's (Voltage, Current, Wire Feed Rate and Weld Travel Speed) to DWP's (Bead Width, Penetration, Bead Height and Weld Area). Comparison of Actual DWP's with the Predicted DWP's yielded errors mostly between 5 - 10%, but the Penetration errors were mostly in the order of 20%. The maximum error recorded was around 45%.

Rock et al. [62] developed a Neural Network for Seam Tracking by Vision Sensor. They reported that with 65% noise (which presumably refers to interference produced by welding such as Smoke and Spatter) the system worked with a 70% confidence level and with a 10% confidence level with 90% noise. As it is difficult to determine what could be considered as normal noise levels for GMAW, an assessment of the success of these experiments cannot be made.

Cocca [63] attempted to use a Neural Network for DWP Estimation and found that the Networks worked well when presented with the data with which they were trained, but did not function very well when presented with non-training data.

Ogunbiyi [59] developed Neural Networks to test their performance against Statistical Models but found that the performance of Neural Networks offered no advantages over Statistical Models. Other researchers have indicated that the Neural Network is best used as a Classifier rather than a Parameter Estimator.

It is considered that a major problem with Neural Networks is that users tend not to understand the mathematical principles on which they work, but rather treat them as 'magic boxes' that can somehow produce a correct output for a given input.

Most tests attempting to use the ANN as a Parameter Estimator appear to have been undertaken with Bead-on-Plate Welds. As Bead-on-Plate Welding is not a realistic welding situation it is difficult to evaluate whether the results are satisfactory. Tests need to be undertaken using more realistic welding situations such as Fillet Welds or Root Runs on Butt Welds where satisfactory and unsatisfactory welds can be clearly defined. Only in these circumstance can ANN's be realistically tested as Parameter Estimators.

It is also important to note that Parameter Estimators must, within reason, be completely reliable and it does not appear that ANN's will be able achieve this.

Fuzzy Logic is another avenue of Artificial Intelligence researched for GMAW Control. Kim and Na [64] and Fujimura et al. [65] appear to have successfully used Fuzzy Logic for Seam Tracking.
2.5.3) **Modern Control Theory:**

Some researchers have attempted to use a Control Theory approach for adaptive control of the GMAW Process.

Hale and Hardt [66-67] used a Transfer Function approach to relate outputs (Bead Width and Bead Height) to inputs (Wire Feed Rate and Weld Travel Speed).

Song and Hardt [68] appear to have also successfully developed a method for Weld Depth Estimation using a Discrete-time Deadbeat (or One Step Ahead) Control Algorithm.

2.5.4) **Real-time Rule-Based Dynamic Expert Systems:**

A Rule-Based Dynamic Expert System refers to the use of Linguistic Rules in a Knowledge-Base to control the Welding Process in real-time.

A typical Rule in Real-time Knowledge-Base may be of the form:

\[
\text{If the Predicted Penetration is less than the Desired Penetration} \\
\text{THEN} \\
\text{Conclude that the Penetration is too small.}
\]

This following Rule could then be:

\[
\text{If the Penetration is too small} \\
\text{THEN} \\
\text{Increase the Wire Feed Rate by X mm/s}
\]

Real-time Expert Systems have been developed [69-71], however it is not clear how effective they are when compared to other processes such as Statistical Modelling.

A potential problem with Rule Based Systems is that any conflict in the Rules could result in divergence from a solution with potentially catastrophic results. Very careful planning must therefore be done in the development of Rule based Systems to ensure that no conflicting decisions can occur.

With the example rule displayed on the previous page, the convergence to the solution is iterative and may take quite a few monitoring cycles to rectify the irregularity. This has Real-time implications in that the Rule Based method might be considerably slower than a Statistical or other type
of Model which could determine and rectify an irregularity in a single monitoring cycle.

2.5.5) A Brief Analysis of GMAW Modelling and Control Techniques:

It would appear from the Literature Survey conducted, that the most promising method for Real-time Control of the GMAW Process are Statistical Models as originally developed by Ogunbiyi [59] and Kim and Na [22-23]. The observed advantages of Statistical Models are:

i) Most Direct Welding Parameters (DWP’s) can be statistically modelled as functions of Indirect Welding Parameters (IWP’s).

ii) The Models are usually not mathematically complex and therefore require relatively little computing time for Parameter Estimate Calculations.

iii) Welding phenomena which cannot easily be measured, such as the effects of consumables, are included in the Models through experimentally determined coefficients.

It appears therefore that one approach to the development of a truly Autonomous GMAW System maybe to use easily measured parameters (e.g. Voltage, Current, Wire Feed Rate and Travel Speed) to determine the state of the Welding Process and Bead Profile by using indirect methods such as Statistical and other forms of Mathematical Modelling.

It has therefore been decided to utilise Statistical Modelling as the Basis for the Autonomous GMAW Control Strategies.

2.6) Thesis Aims:

The ultimate aim of the Welding Automation Project (of which this work forms a part) is to develop an Autonomous GMAW System capable of producing Structural Quality Welds to AS1554. To be able to achieve this some intermediate project stages must be successfully accomplished. These intermediate stages of the project are illustrated in Fig 2.13 overleaf.

The Route of work for this thesis as illustrated in Fig 2.13 and is explained in more detail below:

i) Development of Weld Testing Facilities:
The first Stage of work in this thesis is the development and implementation of Weld Testing Facilities for Butt and Fillet Welds. This is essential as welds produced will need to be tested to ensure their quality.
ii) Development of GMAW Monitoring and Control Systems:
The next Stage will see the development of a GMAW Experimental Facility (MWEF). Before being able to control the Welding Process, it is absolutely necessary to be able to observe and fully understand the Welding Process. This can only be achieved if one can effectively monitor the GMAW Process. It is also important to develop techniques for Computer Control of the Welding Parameters. The GMAW Experimental Facility will therefore be developed as testbed for Weld Monitoring and Control Techniques and then as an effective means of studying the GMAW Process as a necessary prelude to the development of Control Strategies.

iii) Development of Rapid Modelling Facilities:
As stated, Control Strategies will be developed using Statistical Models. A current disadvantage of Statistical Models is that the Experimental Processes to determine their coefficients are extremely time consuming. A solution to this problem is to automate the Modelling Process. A Facility will therefore be created that enables rapid on-line automatic model experimentation and calculation of model coefficients. The Least-Squares Models originally developed by Kim and Na [22-23] will be utilised as a test method for the development of this prototype Rapid Modelling Facility.
Chapter 3

The Gas Metal Arc Welding Experimental Facility (MWEF)

(Specification and Introductory Description)

This Chapter provides an introduction to the MWEF developed at the University of Wollongong. Before commencing the development of the System it was necessary to justify its development with respect to possible benefits to Industry by aiding the improvement of Strategies for Welding Automation and also improving the GMAW Process and Consumables. After the justification for the proposed development of the MWEF, a Specification was devised for a MWEF that would enable the Project Goals to be achieved. The Chapter commences with the justification for the development of the MWEF, provides the Specification for the System and then proceeds to give an introductory description of the developed MWEF.

3.1 Justification for the Development of the MWEF:

The justification for the Development of the MWEF lies in the short and long term goals of the project which were discussed in Chapter 2 but are summarised here for the convenience of the reader. The project Goals are:

i) The development of a GMAW Experimental Facility that enables effective study of the GMAW Process.

ii) The development of Facilities to provide rapid on-line development of Mathematical Models for different Welding Machines and Consumables that may be utilised in Automated Welding Operations.

iii) The development of Control Strategies for Autonomous Gas Metal Arc Welding based on Statistical Models.

iv) The eventual integration of the above mentioned Control Strategies into an Autonomous Robotic Welding System.

The achievement of the above stated goals lies in the development of a facility that allows the GMAW process to be effectively studied as it is necessary to understand and model the GMAW Process before effective real-time Control Strategies can be developed.
To effectively generate Physical or Empirical Models of the Welding Process, it is necessary to accurately and reliably relate the System Output with the System Input. As stated, Cook [8] refers to System Outputs as Direct Welding Parameters (DWP’s) and generally refers to the Measurable Dimensions and Material Properties of the Weld. The System Inputs are referred to as Indirect welding Parameters (IWP’s) and includes all the Parameters that directly affect the DWP’s. This is illustrated in Fig 3.1 below but please note that this diagram contains only a representative list of Indirect and Direct Welding parameters to illustrate this classification System:

![Fig 3.1: Indirect and Direct Welding Parameters](image)

It can therefore be seen that if effective study and modelling of the GMAW Process is to be achieved, then a Facility must exist that can accurately and reliably monitor the IWP’s described in Fig 3.1. In addition, an Experimental Facility must also include Materials Testing Facilities to obtain the DWP’s described in Fig 3.1 and also to ensure that Welds produced can satisfy the Quality Requirements of AS1554.

Such a facility could also be developed with flexible Sensing and Weld Gun Clamping Systems that will allow the rapid installation and testing of a variety of Welding Machines and Consumables and would also enable the rapid generation of on-line Mathematical Models of the characteristics of Welding Machines and Consumables.
It is expected that this Facility would also aid the Manufacturers of Welding Equipment and Consumables by substantially cutting the development time of their products and would therefore also reduce development costs.

3.2 System Specification for the MWEF:

The MWEF will possess the following features:

3.2.1) The Power Source:

The Power Source will be a commercially available Gas Metal Arc Welding Machine with a Power Capacity of 35V, 350A and the capacity for Welding with Electrodes up to 1.2mm in Diameter.

The Power Source should also have Analogue (Potentiometer) Control of both the Voltage and Wire Feed Rate to enable Computer Control of these Input Parameters.

3.2.2) The Welding Table and Weld Gun Clamp:

The System will be configured in way such that the workpiece to be welded will move under a stationary Weldgun (in contrast to Manual Welding Operations where the Welder moves the Weldgun over a stationary workpiece).

Welding Table will:

i) Have 2 DOF allowing Horizontal Longitudinal Motion for Welding Operations and Horizontal Longitudinal/Transverse Motion for initial positioning of the workpiece under the Welding Gun.

ii) Allow a maximum weld length of 450mm with a width of 350mm over which Welds may be produced.

iii) Have a Computer Controlled Travel Speed of 100 - 500 mm/min.

iv) Be mounted on either Linear Bearings or will be mounted on the Saddle of a specially modified Lathe.

v) Include a removable Welding Jig which will be clamped to the Welding Table and will be large enough to allow 450mm of Weld Length over a width of 350mm. The purpose of the Welding Jig is to provide an interface between the Weldgun and the Welding Table which may be easily removed and replaced should it be damaged.
The Weld Gun Clamp will:

i) Allow manual positioning of the Weldgun over the Workpiece.

ii) Possess 3 DOF which will included Gun Roll Movement, Gun Pitch Movement and Vertical Standoff Positioning. Fig 3.2 below illustrates Weld Gun Roll and Pitch.

iii) Taking into account the designs of different Weldguns, allow a Standoff distance of up to 30mm to be set.

3.2.3) Sensing Systems:

Sensors will be required to measure Welding Voltage, Welding Current, Wire Feed Rate and the Weld Travel Speed. Table 3.1 below provides an indication of the Type of Sensor required and the Parameter Ranges over which they will be required to operate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Possible Sensor Type</th>
<th>Sensing Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Potential Divider</td>
<td>0V - 40V</td>
</tr>
<tr>
<td>Current</td>
<td>Hall Effect Sensor</td>
<td>0A - 800A</td>
</tr>
<tr>
<td>Wire Feed Rate</td>
<td>Optical Encoder</td>
<td>50mm/s - 200mm/s</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>Optical Encoder</td>
<td>100mm/min - 500mm/min</td>
</tr>
</tbody>
</table>
The Data produced by the Sensors must be sampled simultaneously to avoid time differences between the Sampled Sets of Data. This is important as it will enable the System User to compare Parameter Traces with confidence that the sets of sampled data are exactly time-correlated.

3.2.4) **Computer Requirements:**

A Computer is required for Control of Data Acquisition, Weld Parameter Control and Analysis of Weld Feedback Data.

The Computer will have the following attributes:

- **Type:** PC (IBM Compatible).
- **Speed:** 66MHz minimum.
- **Memory:** 8MB RAM, 350MB HD.
- **Monitor:** SVGA.
- **Other:** Minimum of 3 Expansion Slots for Data Acquisition Cards.

3.2.5) **Data Acquisition Card:**

The Data Acquisition will be achieved through PCL812PG Data Acquisition Card. This card not only has the Capacity to Capture Data, but can also be utilised for Computer Control of Weld Parameters.

3.2.6) **Control Requirements:**

Table 3.2 below describes the Control Requirements for the MWEF:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Ranges</th>
<th>Initially Automatic Control</th>
<th>Initially Manual Setting</th>
<th>In Future Automatic Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>0v - 40 v</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>WFR</td>
<td>50mm/s - 200mm/s</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>100mm/min - 500mm/min</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>Travel (Long)</td>
<td>0mm - 450mm</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>Travel (Trans)</td>
<td>0mm - 350mm</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standoff</td>
<td>0mm - 30mm</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gun Roll</td>
<td>+/-90° (from Vertical)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gun Pitch</td>
<td>+45° (from Vertical)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gas Flow Rate</td>
<td>0l/min - 20l/min</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
With respect to Table 3.2, ‘Automatic Control’ means that the Parameter will be directly controlled by Computer or by some other Automation device such as a Programmable Logic Controller (PLC). ‘Manual Setting’ means that Operator will set the Parameters manually prior to the commencement of welding. Some Parameters will initially be set manually but may at some future time be adapted for automatic control. Whether or not Automatic Control is installed for Parameters currently set manually will depend on future experimental requirements.

The System must also allow the Operator the choice of operating the entire System in either Manual or Automatic Mode. In Manual Mode, the entire operation of the System is directly controlled manually by the Operator, whereas in Automatic Mode, the operation of the System is controlled by the Computer and any other Controllers which may be installed.

3.2.7) **Time Correlation of High Speed Photography with Sensor Data:**

An important component of the MWEF will be High Speed Photography of the Welding Process. It would enable further understanding of the Welding process if data obtained from the Sensors (i.e. Voltage, Current, Wire Feed Rate and Weld Travel Speed) could be directly time-correlated with the Visual Images of the Welding Process produced by High Speed Photography.

The High Speed Camera has the capability to send a electronic signal to the computer which may be utilised to commence Weld Data Sampling at the exact time that the Camera commences filming. If the Sampling Rate for Data Acquisition is set to equal the camera filming speed, then time-correlation of Sampled Data and Visual Images could be achieved.

An Electronic Communication Link between the High Speed Camera and the Computer will therefore be installed.

3.2.8) **Data Acquisition and System Control Software:**

Software will be written to:

i) Control Weld Data Acquisition from the Sensing Systems.

ii) Control the Weld Input Parameters.

iii) Enable the User to visually observe Parameter Traces and obtain a Graphical on-line Analysis of the Welding Data obtained.
It is important to develop System Software that is not only ‘User Friendly’ but that is also as far as is possible ‘Idiot Proof’, protecting the operator from making mistakes which could result in damage to the Facility. The Software will therefore be developed as Graphical User Interfaces (GUI’s) and will be Mouse controlled and Menu driven to minimise Keyboard Input.

3.3 **A Brief Description of the Developed MWEF:**

The developed MWEF was finally developed upon a converted lathe. It is felt that construction of the Facility upon Linear Bearings would have produced a superior facility, but at the time that construction of the MWEF began, very little funding had been obtained and therefore construction of the Facility upon a converted lathe was the only realistic option available.

A basic illustration of the MWEF System upon the modified Lathe Bed is shown in Fig 3.3 below:

---

**Fig 3.3: Welding Testbed Layout**
A diagram of the developed Data Acquisition and Control System is illustrated in Fig 3.4 below:
Two Software Packages, ‘Shortmon’ and ‘Longmon’ were developed for use with the MWEF and are described below:

A) The ‘Shortmon’ Program:

The ‘Shortmon’ Program has been developed to acquire short burst of weld data (less than 2 seconds). Data captured includes Weld Voltage, Current, Wire Feed Rate and Weld Travel Speed.

The ‘Shortmon’ Program enables:

i) The Traces of Parameters to be studied graphically on-line in both the Time and Frequency Domains.

ii) Correlation of Acquired Weld Data with High Speed Weld Visualisation to obtain a better understanding of the GMAW Process.

B) The ‘Longmon’ Program:

The ‘Longmon’ Program was devised for the Monitoring of Welding Parameters over longer time periods (up to 2 minutes). As with the ‘Shortmon’ Program it captures Data including the Weld Voltage, Current, Wire Feed Rate and Weld Travel Speed.

‘Longmon’ displays Feedback Parameter data on the Screen as it is captured thereby allowing the operator to view the state of the Welding Process as the Weld progresses.

In addition, ‘Longmon’ allows alteration of Weld Parameters during a Welding Run.

The ‘Longmon’ Program enables:

i) The stability and behaviour of Weld Parameter settings to be tested over long welding periods.

ii) The effects of workpiece profile variations on Weld Parameters to be studied.

iii) A study of the effect of changing one or more Weld Parameters on other Weld Parameters.

Both ‘Shortmon’ and ‘Longmon’ are Graphical User Interfaces, providing a user friendly interface between the User and the MWEF. As well as acquiring, displaying and analysing Weld Data, both of these programs allow the user to set Weld Parameters from the Computer.
The MWEF is described in detail in subsequent Chapters.

Chapter 4 describes Weld Test Facilities that have been set up to ensure that any Production type Weld Runs can be tested to ensure that the Quality of Welding meets the requirements of AS1554.

Chapter 5 deals with the development of the Mechanical components of the Facility and the installation of the Welding Apparatus.

Chapter 6 provides details of the Installation and Computer Interfacing of the Sensing Systems, the Computer Control of Voltage, Wire Feed Rate and Weld Travel Speed, the Communication Link between the High Speed Camera and the Computer for synchronised data capture and finally, the PLC control of Weld Length, Weld Starting and Stopping and Operating Mode.

Chapter 7 describes in detail the function and facilities of the ‘Shortmon’ Program.

Chapter 8 describes in detail the function and facilities of the ‘Longmon’ Program.
Chapter 4

Weld Testing Facilities

It is assumed for this Chapter that the Reader is familiar with Destructive Mechanical Testing Methods utilised in Weld Testing. If the Reader is not familiar with these Methods, please study AS1554 and AS2205 before proceeding.

4.1) Justification for Weld Testing Facilities:

As one of the important aims of the project is the autonomous production of Structural Quality Butt and Fillet Welds to AS1554, it is necessary to test welds to ensure that the Automated Weld Procedures produce welds that meet the required standards. Weld Test Facilities have therefore been established to test Complete Penetration Butt Welds with Material Thickness (MT) <= 25mm and Fillet Welds with Leg Length (S) <= 25mm.

4.2) Weld Test Facility Development:

The Welds Test Facilities were developed to the required capacity using the following Weld Types:

4.2.1) Butt Welds:

Two Complete Penetration 25mm Double-V Butt Welds were produced and tested. The Workpieces were prepared to AS1554 Table4.4(A) Type B-C 3.

4.2.2) Fillet Welds:

Two 25mm Equal Leg Fillet Welds (AS 1554 Table 4.4(C) Type F1) were produced and tested.

4.3) Weld Tests:

4.3.1) Butt Weld Tests:

The following tests will be undertaken for Butt Welds of Type B-C 3. Please Note that all individual Testpieces were designed for the Butt Weld Testpieces described in Section 4.2.1.
4.3.1.1) **Transverse Butt Tensile Test (AS2205.2.1):**

The Tensile Test provides an indication of the behaviour of a Weld under Tension. Two opposing forces induced by a Tensile Testing Machine subject a specially prepared Specimen to Tensile Forces which increase until fracture.

The Tensile Test measures a range of Mechanical Properties which include Yield Stress, Ultimate Tensile Strength (UTS), Fracture Load and Ductility through the Percentage Elongation of the Specimen.

Tensile Tests are undertaken on the Tensile Testing Machine (Instron: Model 8033) provided by courtesy of the Department of Civil and Mining Engineering.

4.3.1.2) **Transverse Guided Bend Test (AS2205.3.1):**

The Transverse Guided Bend Test yields an indication of Weld Ductility, but can also reveal defects such as a lack of Root and Side Wall Fusion.

The Specimen is bent through 180° using a special round Forming Tool as shown in Fig 4.1 below:

An acceptable weld should bend with minimal Fracturing, Cracking and lack of Root or Side-wall Fusion. A Weld fails the Bend Test if defects such as Cracks and Lack of Fusion are longer than 3mm in length.

The Bending Jig illustrated in Fig 4.1 was designed and Manufactured at the University of Wollongong and is used in a Form
4.3.1.3) **Macro Test (AS2205.5.1):**

The Macro Test enables physical viewing of Weld Bead Geometry, the Heat Affected Zone (HAZ) and defects within the Weld. With respect to Butt Welds, Components of the Butt Weld Geometry which can be measured using the Macro Test are illustrated in Fig 4.2 below:

1. Parent metal
2. Reinforcement
3. Fusion zone
4. Weld face
5. Weld metal
6. Toe
7. Heat-affected zone (HAZ)
8. Root penetration

**Fig 4.2: Components of the Butt Weld Geometry**

If the geometry of the Weld Preparation and the Root Gap are known, then the Macro Examination can also be utilised to determine other geometric characteristics such as the maximum Side Wall Fusion. The Weld Area can also be readily measured utilising Macro Examinations.

A Macro Test is produced by removing a cross section of the Weld Testpiece, grinding and polishing the section face to be viewed and then etching the polished surface with a 2% Nital Solution. Polishing is undertaken by using Course to Fine Grades of Wet and Dry Abrasive Papers. Grades of Abrasive Paper include P100, P240, P600 and P1200. The Nital Solution is manufactured by mixing 2% Nitric Acid in 98% Ethanol by volume.
A polished and Etched Macro Specimen can be viewed with the naked Eye, but is best viewed under a Profile Projector or Microscope. Computerised Image Analysis Systems can also be utilised to analyse the Weld under examination and are particularly useful for obtaining Bead Geometry measurements.

The Weld Area can be obtained manually by following a Planimeter around the perimeter of a magnified tracing of the Weld Profile.

If a Profile Projector is used for viewing, Transparent Templates of the Weld Preparation can be superimposed over the Weld Profile to determine the difference between the minimum and maximum Side Wall Fusion as illustrated in Fig 4.3 below:

The Transparent Weld Preparation Profile Template is placed over the Weld Profile as shown to measure the Maximum SWF.

Fig 4.3 Measurement of Maximum SWF.

All Macro Examinations to date have been undertaken on a Nikon V12 Profile Projector with Weld Profiles recorded by manual tracing. This method is very time consuming and is not really appropriate as a method for analysing and recording Weld Profiles on a regular basis. Since completing this section of the thesis, Image Analysis Software has been acquired enabling Computer Analysis of Weld Bead Dimensions.

4.3.1.4) **Hardness Tests (AS2205.6.1):**

As specified by AS2205, the Vickers Hardness Test with an Applied Load of 5Kg was used for all Butt Weld Hardness Tests.
The Hardness Test is a measure of a material's resistance to indentation. A diamond indenter is forced under a load into the surface of the Test Specimen and the diagonals of the diamond indentation are measured. Using special tables which are specific for the Applied Load (i.e. 5Kg for this application), the average diagonal length is converted into a Vickers Hardness Value.

In order to obtain a thorough indication of Hardness behaviour across the Weld, a series of Hardness Tests are performed in a line moving from the Weld Metal, through the Heat affected Zone and then terminating in the Parent Metal. This procedure is undertaken in Positions A,B,D,E as shown in Fig 4.4 below. The Hardness Test run for Position C commences in the Parent Metal, passes through the Weld Root and then through to the Parent Metal on the other side of the Weld as also illustrated in Fig 4.4.

![Fig 4.4 Vickers Hardness Test Positions.](image)

The Vickers Pyramid Hardness Tester was made available by courtesy of the Department of Materials Engineering.

4.3.1.5) Charpy V-Notch Impact Test (AS2205.7.1):

The Impact Test is a measure of the resistance of a Weld to shock impact. The Charpy Impact Test is specified by AS2205 with a Potential Energy setting of 310 Joules.

The Charpy Tester is provided by courtesy of the Department of Civil and Mining Engineering.

All Specimens for the Butt Weld Tests were prepared as specified in AS2205. Samples of Butt Weld Test Results can be found in Appendix D.

4.3.2) Fillet Weld Tests:

The following tests will be undertaken for Fillet Welds of Type F1. Please note that all individual Testpieces were designed for the Fillet Weld Testpieces described in Section 4.2.2.
4.3.2.1) **Fillet Break Test (AS2205.4.2):**

A Fillet Break Test is achieved by subjecting the Fillet Weld to an applied force resulting in fracture across the weld material. This is illustrated in Fig 4.5 below.

The Fillet Weld Break Test is used to physically view weld defects including Lack of Fusion, Pososity, Inclusions and Incomplete Penetration.

The Break Tests were achieved using a 60 Ton Hydraulic Press manufactured by the Department of Mechanical Engineering.

![Fillet Weld Break Test Setup](image)

**Fig 4.5: The Fillet Weld Break Test Setup**

4.3.2.2) **Macro Test (AS2205.5.1):**

As with Butt Weld Macro Tests, the Macro Test also enables physical viewing of the Fillet Weld Bead Geometry, the Heat Affected Zone (HAZ) and defects within the Weld. Components of the Fillet Weld Bead Geometry which may be determined by a Macro Test are illustrated in Fig 4.6 overleaf.

Fillet Weld Macros are produced using the same techniques as those utilised to produce Butt Weld Macros.
All Specimens for the Fillet Weld Tests were prepared as specified in AS2205. Samples of Fillet Weld Test Results can be found in Appendix III.

4.4) **Extraction of Test Specimens from Weld Testpieces:**

Specimens for Butt and Fillet Weld Tests are extracted from the main Testpieces as illustrated in Appendix I. Please note that for all specimens, the specimen thickness includes a 2mm cutting allowance.

4.5) **Weld Procedure Development and Qualification:**

Weld Procedures will be qualified using the following Stages:

**Stage 1:** Weld Testpieces will be prepared to AS1554.1 Table 4.4(A) for Complete Penetration Butt Welds and AS1554.1 Table 4.4(C) for Fillet Welds.

**Stage 2:** If required, testpieces will be pre-heated as required by AS1554.1 Sec 5.3.
Stage 3: The Testpieces will be welded with the same number of weld runs, welding techniques and machine settings that would be utilised in production weld runs.

Stage 4: The completed welds will be subjected to the tests described in Section 4.3.

Stage 5: A Welding Procedure will be assessed as qualified if the weld quality fully complies with the standard as described in AS1554.1 Sec 4.6. If the weld quality does not comply with the required standard then the welding procedure needs to be reevaluated and Stages 1 through 4 repeated.
Chapter 5

Development of Welding Systems for the MWEF

The basic layout of the Welding System of the MWEF was illustrated in Fig 3.3 but has also been inserted here for the convenience of the reader.

![Welding System Layout](image)

It can be clearly seen from the above diagram that the Welding System consists of the following components:

1) **Welding Equipment (Power Source, Welding Gun, Leads, etc).**
2) **Weld Gun Clamp Support.**
3) **Weld Gun Clamp.**
4) **Welding Table (Lathe Saddle).**
5) **Welding Jig.**
Engineering Drawings of the Weld Gun Clamp Support, the Weld Gun Clamp and the Welding Jig can be found in Appendix VI. The Reader is advised to study these drawings before proceeding with this Chapter.

5.1 Welding Equipment:

The Power Source eventually selected and installed in the MWEF was a Transmig 350 EC GMAW Machine with a Transmatic Wire Feed Unit.

This machine has the following characteristics:

1) 35V, 400A Power Supply
2) Wire Diameter size of up to 1.2mm
3) Analogue (Potentiometer) Control of Voltage and Wire Feed Rate.

The above listed characteristics satisfy the Specification for a Power Source as described in Section 3.2.1 and was adequate as far as requirements for this thesis were concerned, however, the Transmig 350 EC is an old machine (circa 1984) and in the course of experimentation, deficiencies were found with respect to its suitability for adaption to Automated Welding Operations. These deficiencies were:

1) The Power Source cannot easily be converted for Solid-state Computer Control of the Voltage and Wire Feed Rate as to achieve this would require a major redesign of the System Electronics. The way that Computer Control was eventually achieved was to connect Stepper Motors to the Voltage and Wire Feed Rate Potentiometers. Although this has enabled Computer Control of these Parameters, Parameter alteration is slow compared to a Solid-state System because of the time it takes for the Stepper Motor to move the Potentiometers to their correct positions. Parameter alteration time can take up to 2 seconds if both Voltage and Wire Feed Rate are considerably altered. At a Weld Travel speed of 300mm/min, 10mm of Weld would be produced during this period.

2) The Transmig 350 also has slow dipping frequencies at normal Dip Transfer settings (approx 20 - 50 Dips/Second). As a rule-of-thumb, Current readings for 10 Dips are required to obtain a good estimate of the true Average Current. Sampling times of 0.3 to 0.5 Seconds are therefore required to obtain the required data. Assuming a Weld Travel Speed of 300mm/min, 1.5 to 2.5mm of Weld Travel will have been completed during Data Sampling Period.

The time for a GMAW Control Cycle using the Transmig 350 EC can be given as:

\[ C = A + D + M \]
where: \( C = \) Total Control Cycle Time.
\( A = \) The Data Acquisition Time.
\( D = \) Data Analysis and Parameter Modification Calculations Time.
\( M = \) Time for physical Modification of Parameters.

All of the Above times are measured in seconds.

Assume a worst case scenario, substitute \( A=0.5\)s, \( D=0.1\)s and \( M=2.0\)s into (1):

\[
C = 0.5s + 0.1s + 2.0s
\]

\[
\therefore \ C = 2.6s
\]

The total Weld Travel travelled during the Control Cycle Time can be given by:

\[
S = C(TS/60)
\]

where: \( S = \) Weld Travel (mm).
\( TS = \) Travel Speed (mm/min).

Assuming \( TS=300\)mm/min and substituting \( C \) into (2):

\[
S = 2.6(300/60)
\]

\[
\therefore \ S = 13\text{mm}
\]

Assuming this scenario could realistically occur in a real-time Automated Welding Situation, a minimum of 13mm of defective weld would be produced before any detected irregularities could be corrected. This is clearly not acceptable and we can therefore conclude that the Transmig 350 Power Source is not suitable for Automated Dip Transfer Welding Operations.

The Transmig 350 Operating Characteristics can be found in Appendix IV. It will be seen that for any particular setting the Voltage Drop is 2.25 Volts per 100 Amps

5.2 The Weld Gun Clamp Support:

(Please refer to the Drawing ‘Weld Gun Clamp Support’ in Appendix VI).

The function of the Weld Gun Clamp Support is to secure and support the Weld Gun Clamp Unit at the correct position over the Welding Table.
The Weld Clamp Support is fabricated from essentially a Vertical Leg (Drawing Part No 1) and a Horizontal Leg (Drawing Part No 2) to form a Cantilever. The Weld Gun Clamp Unit (Drawing Part No 11) is secured to the Support on the Flange Plate (Drawing Part No 6) at the end of the Horizontal Leg. The Support is secured to the rear of the Lathe Bed using M12 Caphead Bolts.

The Vertical and Horizontal Legs were manufactured from Rectangular Hollow Section (RHS) whilst all other components were manufactured from Mild Steel Plate and Sheet.

An effort was made to ensure maximum stiffness of the support. Calculations were made using Castiglianos theorem to verify that there would be no significant deflection of the Support when the Weld Gun Clamp Unit is attached to it.

5.3 The Weld Gun Clamp:

(Please refer to the Drawing ‘Welding Gun Clamp’ in Appendix VI).

The function of the Weld Gun Clamp is to secure the Welding Gun at its correct position relative the Welding Jig (or the Workpiece secured to the Welding Jig).

The Weld Gun Clamp has 3 DOF. 2 DOF, the Pitch of the Weld Gun and Vertical Movement can be achieved by Slider movement (Drawing Part No 3) whilst the remaining DOF, the Gun Roll can be achieved by rolling the Gun in the Gun Clamp Assembly (Drawing Part No 5).

The Slider is secured to the Slider Clamp Bar (Drawing Part No 2) using the Slider Clamp Assembly (Drawing Part No 4). The Slider Clamp can be loosened when Weld Gun position alteration is required and is then tightened when the Weld Gun is at the correct position.

The Welding Gun Clamp Unit was designed to be detachable as it is intended to replace the manually set Clamp with a Robotic Welding Head for experiments with Welding Automation.

The unit is manufactured from Mild Steel Plate and Sheet except for the Slider which is (although not stated on the drawing) manufactured from aluminium. The Slider was manufactured from aluminium to save weight so that Welding Gun adjustments can be achieved more accurately with less physical effort.

Although not shown on the drawing, the original casing of the Welding Gun has been removed and replaced with a Cylindrical Perspex Casing for location in the Gun Clamp Assembly and also for easy Gun Roll positioning. The Gun Clamp Assembly has also been fitted with Shields to protect the Perspex Casing from Spatter and Heat generated from the Welding Process.
5.4) **The Welding Base:**

The Welding Base is the platform on which the Welding Jig is situated and is basically the Saddle of the Lathe.

Having 2 DOF, the Welding Base has Computer Controlled Longitudinal movement provided by the Leadscrew of the lathe, and Manual Transverse Motion provided by the Saddle Cross-slide.

5.5) **The Welding Jig:**

(Please refer to the Drawing ‘Weld Jig’ in Appendix VI)

The Welding Jig is placed on the Welding Base to provide a platform for Workpieces and occupies the position on the Lathe Saddle usually occupied by the Tool Post. Indeed, the Welding Jig is actually secured to the Cross-slide by T-Bolts using the same channels utilised to secure the Tool Post.

This Jig was originally designed for the Butt and Fillet Weld Testpieces described in Section 3.2 but has since been modified to also accommodate Bead-on-Plate Testpieces and Welding Jigs used for Weld Modelling and Testing (See Chapters 9 and 10).

It will be observed from the Drawing that there is a channel in the centre of the Jig. This has been included to allow for Spatter, Burnthrough and Penetration when producing Butt Welds.

All components of the Welding Jig were manufactured from Mild Steel Plate and Sheet.
This Chapter deals with the Data Acquisition and Control Systems of the MWEF. The following System Components are described:

1) The System Computer.
2) The Data Acquisition Card.
3) The Sample and Hold Data Acquisition and Storage System
4) Sensing Systems for Weld Voltage, Current, Wire Feed Rate and Weld Travel Speed.
5) Computer Control of the Voltage, Wire Feed Rate and Weld Travel Speed.
6) Communication Link between the High Speed Camera and the Computer.
7) Computer Algorithms for Sampling Rate Control.
8) A Computer Algorithm for Weld Data Acquisition.
9) PLC Control of Weld Length, Weld Start/Stop and Operating Mode.

6.1) **The System Computer:**

The Computer selected for the MWEF was a Compaq Prolinea Minitower which has the following features:

a) Intel 486 CPU (66MHz).

b) 8 Megabytes RAM.

c) 350 Megabyte Hard Disk.

d) 5 Expansion Bays (3 for Cards, 2 for Disk Drives).

f) 1 3.5-inch Floppy Disk Drive.

e) SVGA Monitor.

In addition, a Seikosha SL-75 Colour Graphics Dot Matrix Printer was acquired for Screen Dumps from the System Software (Described in Chapter 7).

6.2) **The PCL812 PG Input/Output Card:**

The PCL812 PG I/O Card is the interface between the Computer and the MWEF. This Section provides details of this card and how it is utilised for Data
Acquistion and System Control. Please note that in describing this Card, not all its features are discussed, but only those that are relevant to the MWEF. It should also be noted that Technical Information presented was obtained from the User Manual for the PCL812 PG Card [72].

6.2.1 **A Brief Summary of Features of the PCL812PG Card:**

A Brief Summary of the Features of the PCL812 PG Card utilised for the MWEF is given below:

1) 16 Analogue Input Channels
2) 2 12 bit D/A Output Channels.
3) 16 Digital Input Channels.
4) 16 Digital Output Channels.
5) Software Triggered A/D Input.
6) An Intel 8253-5 Programmable Timer/Counter.
7) Hardware Configurable Base Address Settings.

6.2.2 **Connector Pin Assignments:**

The PCL812PG Card has four external Connector Ports for Analogue/Digital Input/Output. The Diagrams below illustrate how the Card Inputs and Outputs are organised within these Ports. Please also refer to the Card I/O Wiring Diagram in Appendix V.

**Connector 1 (CN1) - Analogue Input:**

Connector Port 1 contains the Pins for the Analogue Input Channels 0 - 9 (A.GND = Analogue Ground).

<table>
<thead>
<tr>
<th>A/D 0</th>
<th>1</th>
<th>2</th>
<th>A.GND</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D 1</td>
<td>3</td>
<td>4</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 2</td>
<td>5</td>
<td>6</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 3</td>
<td>7</td>
<td>8</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 4</td>
<td>9</td>
<td>10</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 5</td>
<td>11</td>
<td>12</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 6</td>
<td>13</td>
<td>14</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 7</td>
<td>15</td>
<td>16</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 8</td>
<td>17</td>
<td>18</td>
<td>A.GND</td>
</tr>
<tr>
<td>A/D 9</td>
<td>19</td>
<td>20</td>
<td>A.GND</td>
</tr>
</tbody>
</table>
Connector 2 (CN2) - Analogue Input and Analogue Output:

Connector Port 2 contains the Pins for the Analogue Input Channels 10 - 15 and also Analogue Output Channels 1 and 2.

<table>
<thead>
<tr>
<th>A/D 10</th>
<th>1</th>
<th>2</th>
<th>A.GND</th>
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<tr>
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<td>5</td>
<td>6</td>
<td>A.GND</td>
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<tr>
<td>A/D 13</td>
<td>7</td>
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<td>A.GND</td>
</tr>
<tr>
<td>A/D 14</td>
<td>9</td>
<td>10</td>
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</tr>
<tr>
<td>A/D 15</td>
<td>11</td>
<td>12</td>
<td>A.GND</td>
</tr>
<tr>
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<td>13</td>
<td>14</td>
<td>A.GND</td>
</tr>
<tr>
<td>D/A 2</td>
<td>15</td>
<td>16</td>
<td>A.GND</td>
</tr>
<tr>
<td>V.REF 1</td>
<td>17</td>
<td>18</td>
<td>A.GND</td>
</tr>
<tr>
<td>V.REF 2</td>
<td>19</td>
<td>20</td>
<td>A.GND</td>
</tr>
</tbody>
</table>

Connector 3 (CN3) - Digital Output:

Connector Port 3 contains the Pins for Digital Output Channels 0 - 15.

<table>
<thead>
<tr>
<th>D/O 0</th>
<th>1</th>
<th>2</th>
<th>D/O 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/O 2</td>
<td>3</td>
<td>4</td>
<td>D/O 3</td>
</tr>
<tr>
<td>D/O 4</td>
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<td>D/O 14</td>
<td>15</td>
<td>16</td>
<td>D/O 15</td>
</tr>
<tr>
<td>D.GND</td>
<td>17</td>
<td>18</td>
<td>D.GND</td>
</tr>
<tr>
<td>+5V</td>
<td>19</td>
<td>20</td>
<td>+12V</td>
</tr>
</tbody>
</table>

Connector 4 (CN4) - Digital Input:

Connector Port 4 contains the Pins for Digital Input Channels 0 - 15.

<table>
<thead>
<tr>
<th>D/I 0</th>
<th>1</th>
<th>2</th>
<th>D/I 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/I 2</td>
<td>3</td>
<td>4</td>
<td>D/I 3</td>
</tr>
<tr>
<td>D/I 4</td>
<td>5</td>
<td>6</td>
<td>D/I 5</td>
</tr>
<tr>
<td>D/I 6</td>
<td>7</td>
<td>8</td>
<td>D/I 7</td>
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<tr>
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<td>D/I 9</td>
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</tr>
<tr>
<td>+5V</td>
<td>19</td>
<td>20</td>
<td>+12V</td>
</tr>
</tbody>
</table>
6.2.3) **Hardware Configurable Settings:**

The PCL812PG Card has certain Operating Parameters that require manual pre-setting on the Card prior to its use. The positions of the Setting Switches are illustrated in the Card layout drawing in Appendix V. The Hardware Settings required on the Card for use with the MWEF are as follows:

6.2.3.1) **The I/O Port Base Address Setting:**

**Switch Name:** SW1, Positions A(876543).

The PCL812PG Card requires 16 consecutive address locations in I/O space. This can be seen by referring to section 6.2.4 which describes the Register Structure and Format of the Card. Valid Base addresses are from 200H to 3F0H as illustrated in Table 6.1 below:

<table>
<thead>
<tr>
<th>I/O Address Range (Hex)</th>
<th>Switch Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A8 A7 A6 A5 A4 A3</td>
</tr>
<tr>
<td>200 - 20F</td>
<td>0 0 0 0 0 X</td>
</tr>
<tr>
<td>210 - 21F</td>
<td>0 0 0 0 1 X</td>
</tr>
<tr>
<td>220 - 22F</td>
<td>0 0 0 1 0 X</td>
</tr>
<tr>
<td>230 - 23F</td>
<td>0 0 0 1 1 X</td>
</tr>
<tr>
<td>300 - 30F</td>
<td>1 0 0 0 0 X</td>
</tr>
<tr>
<td>3F0 - 3FF</td>
<td>1 1 1 1 1 X</td>
</tr>
</tbody>
</table>

Please note with respect to Table 6.1 that 0 = ON and 1 = OFF and A4 - A8 are PC bus address lines.

The Base Address setting selected was 220H which is also the default (factory) setting.

6.2.3.2) **Wait State Selection:**

**Switch Name:** SW1, Positions W0, W1.

Some high speed Computers need wait states to be added to the I/O to achieve stable data transfer. The PCL812PG Card can be configured with wait state delays of 0, 2, 4 or 6 for each transfer of data. Table 6.2 overleaf illustrates the Switch Positions for the required delay (again 0 = On and 1 = OFF):
Table 6.2: Wait State Delay Settings

<table>
<thead>
<tr>
<th>Switch Position</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Time Delay</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

The Compaq Prolinea Computer did not need any Wait State Delays therefore both Switches 7 and 8 are set to ON.

6.2.3.3) Trigger Source Selection:

**Jumper Switch Name:** JP1

The A/D Conversion Trigger Source can be either an Internal Programmable pacer or an External Pulse Signal. As all A/D Conversions will be Software Triggered, the Jumper Switch JP1 was set to the Internal Trigger Setting.

6.2.3.4) Users Counter Input Clock Selection:

**Jumper Switch Name:** JP2

The Programmable Timer/Counter (used for Sampling Interval Control - see Section 6.7.2) has 3 Channels each with 16 Bit Counters. Channels 1 and 2 are configured as internal pacer controlled but Channel 0 is available for User applications. Channel 0 can therefore be configured for control by either the internal 2MHz clock or by an external clock.

As the Internal 2MHz clock would suffice for the System Control requirements, the Jumper Switch JP2 was set for the Internal Clock.

6.2.3.5) D/A Reference Source Selection:

**Jumper Switch Name:** JP3, JP4

The Reference Voltage of the 2 D/A Converters can be either internally or externally generated. The Reference Voltage Source for D/A Channel 1 and 2 are selected by Jumper switches JP3 and JP4 respectively.
For the MWEF, both D/A Channels utilise the Internal Reference Voltage Sources and therefore JP3 and JP4 are set for Internal Reference Voltages

6.2.3.6) D/A Internal Reference Voltage Selection:

**Jumper Switch Name**: JP8

There are 2 D/A Voltage Ranges determined by the Setting of JP8, ie. 0 - +5V and 0 - +10V. If the D/A Voltage Range utilised is 0 - +5V then the Internal Reference Voltage is -5V. However, if the D/A Voltage Range is 0 - 10V then the Internal Reference Voltage is -10V.

As the D/A Voltage requirements for the MWEF are less than 5V, JP8 is set to the 0 - +5V Setting.

6.2.3.7) A/D Input Voltage Range Selection:

**Jumper Switch Name**: JP9

The A/D Converter Input Voltage Range Setting can be either +/-5V or +/-10V.

The Analogue Voltage Inputs from the Sensors requires that JP9 be set to the +/-10V Range.

6.2.4) The PCL812PG Register Structure:

As stated in Section 6.2.3.1, The PCL812PG requires 16 consecutive addresses in I/O space for I/O Operations. The addresses start with the Base Address set as described in Section 6.2.3.1. Table 6.3 overleaf is an I/O Port Address Map showing the location of each Register and Drivers relative to the Base Address and also describes the Register Usage.

The use of these Addresses and Registers for Weld Data Acquisition and Control Operations will become apparent later in this Section and in later Sections as Sensor Systems and Weld Parameter Control is described.

Please also note that as the Base Address has been set to 220H, all of the Registers described overleaf will be relative to this address. Hence, if the Register location is ‘Base + 7’ then the actual Register location is ‘220H + 7’.

Also with respect to Table 6.3, ‘Read’ refers to Input Operations and ‘Write’ refers to Output Operations.
<table>
<thead>
<tr>
<th>Location</th>
<th>Read</th>
<th>Write</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base + 0</td>
<td>Counter 0</td>
<td>Counter 0</td>
</tr>
<tr>
<td>Base + 1</td>
<td>Counter 1</td>
<td>Counter 1</td>
</tr>
<tr>
<td>Base + 2</td>
<td>Counter 2</td>
<td>Counter 2</td>
</tr>
<tr>
<td>Base + 3</td>
<td>N/U</td>
<td>Counter Control</td>
</tr>
<tr>
<td>Base + 4</td>
<td>A/D Low Byte</td>
<td>CH1 D/A Low Byte</td>
</tr>
<tr>
<td>Base + 5</td>
<td>A/D High Byte</td>
<td>CH1 D/A High Byte</td>
</tr>
<tr>
<td>Base + 6</td>
<td>D/I Low Byte</td>
<td>CH2 D/A Low Byte</td>
</tr>
<tr>
<td>Base + 7</td>
<td>D/I High Byte</td>
<td>CH2 D/A High Byte</td>
</tr>
<tr>
<td>Base + 8</td>
<td>N/U</td>
<td>Clear Interrupt Request</td>
</tr>
<tr>
<td>Base + 9</td>
<td>N/U</td>
<td>Gain Control</td>
</tr>
<tr>
<td>Base + 10</td>
<td>N/U</td>
<td>MUX Control</td>
</tr>
<tr>
<td>Base + 11</td>
<td>N/U</td>
<td>Mode Control</td>
</tr>
<tr>
<td>Base + 12</td>
<td>N/U</td>
<td>Software A/D Trigger</td>
</tr>
<tr>
<td>Base + 13</td>
<td>N/U</td>
<td>D/O Low Byte</td>
</tr>
<tr>
<td>Base + 14</td>
<td>N/U</td>
<td>D/O High Byte</td>
</tr>
<tr>
<td>Base + 15</td>
<td>N/U</td>
<td>N/U</td>
</tr>
</tbody>
</table>

Note: N/U = Not Used, Base = 220H, Each Address = 1 Byte

The remainder of this Section describes the Functions of the Registers listed in Table 6.3 in more detail:

6.2.4.1) The A/D Data Registers:

The A/D Registers use Address BASE+4 and BASE+5.

Data Format (A/D Low Byte and Data):

<table>
<thead>
<tr>
<th>BASE + 4:</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD7</td>
<td>AD6</td>
<td>AD5</td>
<td>AD4</td>
<td>AD3</td>
<td>AD2</td>
<td>AD1</td>
<td>AD0</td>
</tr>
</tbody>
</table>

Data Format (A/D High Byte and Data):

<table>
<thead>
<tr>
<th>BASE + 5:</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>DRS</td>
<td>AD11</td>
<td>AD10</td>
<td>AD9</td>
<td>AD8</td>
</tr>
</tbody>
</table>

It will be noted that an A/D Conversion will result in a 12-bit Digital Number (AD0 - AD11) with AD0 being the Least Significant Bit (LSB) and AD11 being the Most Significant Bit (MSB).
The least significant 8 Bits are stored in the A/D Low Byte Register (BASE + 4). That is, AD0 - AD7 are stored in Bits D0 - D7 respectively.

The most significant 4 Bits are stored in the A/D High Byte Register (BASE + 5). That is, AD8 - AD11 are stored in Bits D0 - D4 respectively.

The Data Ready Signal (DRS) is set at ‘1’ until an A/D Conversion is completed, at which point it is set to ‘0’. The DRS Bit is set to ‘1’ again when the A/D Low Byte Register (BASE + 4) is read.

6.2.4.2) **The MUX Control Register:**

The MUX (an abbreviation for Multiplexer) Control Register is a write only register using Address BASE+10 and is utilised to set the A/D Channel from which an A/D Conversion is required.

**Data Format:**

<table>
<thead>
<tr>
<th>BASE + 10</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel No</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>CL3</td>
<td>CL2</td>
<td>CL1</td>
<td>CL0</td>
</tr>
</tbody>
</table>

CL3 - CL0 is the Multiplexer Channel Number which can be from A/D Channel 0 (AD 0) - A/D Channel 15 (A/D 15).

6.2.4.3) **The Digital I/O Registers:**

The PCL812PG Card has 16 Digital Input Channels and 16 Digital Output Channels. Digital Input (D/I) Ports are at BASE+6 and BASE+7 whilst Digital Output (D/O) Ports are at BASE+13 and BASE+14.

**Data Format (Digital Inputs):**

<table>
<thead>
<tr>
<th>BASE + 6</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Read Port) D/I Low Byte</td>
<td>DI7</td>
<td>DI6</td>
<td>DI5</td>
<td>DI4</td>
<td>DI3</td>
<td>DI2</td>
<td>DI1</td>
<td>DI0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BASE + 7</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Read Port) D/I High Byte</td>
<td>DI15</td>
<td>DI14</td>
<td>DI13</td>
<td>DI12</td>
<td>DI11</td>
<td>DI10</td>
<td>DI9</td>
<td>DI8</td>
</tr>
</tbody>
</table>
Data Format (Digital Outputs):

<table>
<thead>
<tr>
<th>BASE + 13</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Write Port)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D/O Lo Byte)</td>
<td>DO7</td>
<td>DO6</td>
<td>DO5</td>
<td>DO4</td>
<td>DO3</td>
<td>DO2</td>
<td>DO1</td>
<td>DO0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BASE + 14</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Write Port)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D/O Hi Byte)</td>
<td>DO15</td>
<td>DO14</td>
<td>DO13</td>
<td>DO12</td>
<td>DO11</td>
<td>DO10</td>
<td>DO9</td>
<td>DO8</td>
</tr>
</tbody>
</table>

Each Bit of a Digital Input or Output Register can either be ‘1’ (ie. ON) or ‘0’ (ie. OFF).

6.2.4.4) The D/A Output Registers:

The D/A Output Registers Write Only Registers uses Addresses BASE+4 and BASE+5 for D/A Channel 1 and BASE+6 and BASE+7 for D/A Channel 2.

Data Format (D/A Channel 1):

<table>
<thead>
<tr>
<th>BASE + 4</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/A 1 Lo Byte</td>
<td>DA7</td>
<td>DA6</td>
<td>DA5</td>
<td>DA4</td>
<td>DA3</td>
<td>DA2</td>
<td>DA1</td>
<td>DA0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BASE + 5</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/A 1 Hi Byte</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>DA11</td>
<td>DA10</td>
<td>DA9</td>
<td>DA8</td>
</tr>
</tbody>
</table>

Data Format (D/A Channel 2):

<table>
<thead>
<tr>
<th>BASE + 6</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/A 2 Lo Byte</td>
<td>DA7</td>
<td>DA6</td>
<td>DA5</td>
<td>DA4</td>
<td>DA3</td>
<td>DA2</td>
<td>DA1</td>
<td>DA0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BASE + 7</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/A 2 Hi Byte</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>DA11</td>
<td>DA10</td>
<td>DA9</td>
<td>DA8</td>
</tr>
</tbody>
</table>
It will be observed that D/A Output is a 12-Bit Digital Number with the least significant 8 Bits (DA0 - DA7) being in the D/A Channel Low Byte and the most significant 4 Bits (DA8 - DA11) being in the D/A Channel High Byte.

As the Digital Number to be converted to an Analogue Voltage can only be 12 Bits, the maximum value this number can be is 4096, Therefore, all Digital Numbers in the D/A Output Registers must be either the maximum 4096 or some Integer Number that is a Fraction of 4096.

The Digital Number for Analogue conversion can be calculated as:

\[
\text{Digital Number} = \left(\frac{\text{Desired Voltage}}{\text{Max Voltage}}\right) \times 4096
\]

where the Max Voltage is Pre-set using the Jumper Switch JP8 and has been set to 5V for the MWEF (See Section 6.2.3.6).

6.2.4.5) The Gain Control Register:

The Gain Control Register is a Write-Only Register using Address BASE+9 and is utilised to set the Gain of the Analogue Input Programmable Amplifier.

Data Format:

<table>
<thead>
<tr>
<th>BASE + 9</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>R2</td>
<td>R1</td>
<td>R0</td>
</tr>
</tbody>
</table>

Gain Definition:

<table>
<thead>
<tr>
<th>R2</th>
<th>R1</th>
<th>R0</th>
<th>GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Invalid</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Invalid</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Invalid</td>
</tr>
</tbody>
</table>
As the Analogue Input cannot be greater than the Maximum Input Voltage or less than the Minimum Input Voltage (ie +/-5V or +/-10V, as set by Jumper Switch JP9 - See Section 6.2.3.7), the Analogue Input Voltage Range must be scaled down if the Programmed Gain is greater than 1. This can be seen by looking at the formula for Analogue Input Range (AIR) as a function of the Maximum Input Voltage (MIV) and Gain

\[
\text{Maximum Input Voltage} = \frac{%6.2.3.7}{\text{AIR}} = \frac{\text{Maximum Input Voltage}}{\text{Gain}}
\]

As the Gain Increases, the AIR must be reduced to ensure that the Input Voltage after amplification does not exceed the Maximum Input Voltage. Table 6.4 below provides Input Ranges for the various Gain Settings.

<table>
<thead>
<tr>
<th>Gain</th>
<th>AIR (+/-5V MIV)</th>
<th>AIR (+/-10V MIV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+/-5V</td>
<td>+/-10V</td>
</tr>
<tr>
<td>2</td>
<td>+/-2.5V</td>
<td>+/-5V</td>
</tr>
<tr>
<td>4</td>
<td>+/-1.25V</td>
<td>+/-2.5V</td>
</tr>
<tr>
<td>8</td>
<td>+/-0.625V</td>
<td>+/-1.25V</td>
</tr>
<tr>
<td>16</td>
<td>+/-0.3125V</td>
<td>+/-0.625V</td>
</tr>
</tbody>
</table>

For Analogue Inputs from the MWEF Sensors, the Gain is always set to 1 and as the Jumper Switch JP9 is set to the Max Input Voltage Range of +/-10V.

6.2.4.6) The Mode Control Register:

The Mode Control Register is a Write-Only Register using address BASE+11 and is utilised to control the Operating Modes of the PCL812PG Card.

**Data Format:**

<table>
<thead>
<tr>
<th>BASE + 11</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Reg</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>S2</td>
<td>S1</td>
<td>S0</td>
</tr>
</tbody>
</table>
If the Jumper Switch JP1 is pre-set to the Internal Trigger Source (See Section 6.2.3.3) then the following Operating Modes can be set:

<table>
<thead>
<tr>
<th>S2</th>
<th>S1</th>
<th>S0</th>
<th>Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Disable Software and Pacer Trigger</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Enable Software Trigger and Program Transfer only.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Enable Pacer Trigger and DMA Transfer only.</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Enable Pacer Trigger and Program Transfer or Interrupt Transfer.</td>
</tr>
</tbody>
</table>

All Data Acquisition Routines use Software Control of Triggering and Data Transfer. The Mode Control Register is therefore always set to '1'.

6.2.4.7) **Programmable Timer/Counter Registers:**

The four Registers located at addresses BASE+0, BASE+1, BASE+2 and BASE+3 are used by the Intel 8253 Programmable Timer/Counter installed on the PCL812PG Card. The function of each Register is:

- **BASE + 0** Counter 0 Read/Write
- **BASE + 1** Counter 1 Read/Write
- **BASE + 2** Counter 2 Read/Write
- **BASE + 3** Counter Control Word

The Intel 8253 Timer is utilised for Sampling Interval Control during Data Acquisition. Counter 0 was used for this operation as Channels 1 and 2 are reserved for Internal Card use.

Details of how these Registers are used can be found in Section 6.7 which describes the Routines for Sampling Rate Control.

6.2.5) **A/D Conversion:**

As stated in Section 6.2.3.7, the Analogue Input Range is +/-10V. When an Input Voltage is applied to the A/D Converter it is converted to a Digital Value within the range 0 - 4096 (ie. an Integer 12-Bit Number)
where $0 = -10V$ and $4096 = +10V$. Fig 6.1 below illustrates the Analogue to Digital Conversion with the PCL812PG Card:

It can be seen that the Converted Digital Value is linearly proportional to the Input Voltage. As all Input Voltage from the MWEF Sensor Systems will be positive, the Datum Voltage value must be zero at which point the Digital Value is 2048. It can be seen from Fig 6.1 that for a Voltage V, the A/D Converter will produce a Digital Integer X, but the true Digital Value (DV) for the Sensor Input would be:

$$DV = X - 2048$$

An integer value requires 2 Bytes of Memory for storage. With the PCL812PG Card, an A/D Conversion is stored as the Low Byte in Address Location BASE+4 and the High Byte in Address Location BASE+5 (See Section 6.2.4.1). The DV is therefore calculated by Software and stored in Computer Memory as:

$$DV = ((\text{High Byte} \times 256) + \text{Low Byte}) - 2048$$

6.3) The Sample and Hold Data Acquisition and Storage System:

The Sample and Hold (S&H) Data Acquisition and Storage System is a link between the System Sensors and PCL812PG Card and has the specific function
of collecting simultaneous (i.e. time-correlated) data from the Sensors and storing this data whilst it is collected by the PCL812PG Card as controlled by the System Software. Fig 6.2 below compares the Sample and Hold Data Collection System to Data Collection with the Sensors connected directly to the PCL812PG Card:
Fig 6.2 illustrates Data Sampling from four Sensors (designated S1, S2, S3 and S4) with and without the S&H System. It can be seen from Fig 6.2 (A) that Sampled Data without an S&H System is not time-correlated. This may not be significant at High Sampling Speeds, but at lower Sampling Speeds it is quite feasible that the state of the Welding Process could change from the T1 to T4 and therefore the Data obtained from S4 cannot be reliably correlated with data from S1.

With the S&H System installed, the problem of time-correlation is eliminated as all Sensors are sampled simultaneously and data stored ready for collection by the PCL812PG Card. This is illustrated by Fig 6.2 (B) where all Sensors are simultaneously sampled at T1 and the data is then collected by the PCL812PG card from periods T2 to T5.

The S&H System installed has four Channels to which Sensors may be connected. As five Sensor Channels are required (i.e. Voltage, 2 Current Sensors, Wire Feed Rate and Travel Speed), 2 S&H boards have been installed with Voltage, Current and Wire Feed Rate Sensing Systems connected to S&H Board 1 and the Weld Travel Speed Sensing System connected to S&H Board 2. There are three free channels on S&H Board 2 which may be utilised in the future.

The S&H Systems are activated by Software (See Section 6.8).

6.4) Sensing Systems (Voltage, Current, Wire Feed Rate and Travel Speed):

6.4.1) The Voltage Sensor System:

The Voltage Sensor is simply a Potential Divider placed across the Welding Arc and is illustrated in Fig 6.3 below:
The Voltage supplied to the S&H System is given by:

\[ V = \frac{V(\text{arc})}{R} \]

where:

\[ R = \frac{(R1 + R2)}{R2} \]

\[ R = 109.0 \text{ for the Resistance values selected.} \]

The Voltage divider is necessary as \( V(\text{arc}) \) varies from 15V to 35V but the Input Range to the PCL812PG Card has been set at +/-10V (See Section 6.2.3.7) therefore \( V(\text{arc}) \) must be scaled down before it can be supplied to the Card. This is achieved by the Potential Divider.

Once the Voltage Value (V) has been read into Computer Memory, this value can be converted back to the true \( V(\text{arc}) \) reading by multiplying the Input Voltage by the R value, ie:

\[ V(\text{arc}) = RV \]

where V is calculated from the A/D Conversion as:

\[ V = \frac{\text{Digital Value (DV)}}{2047} \]

Voltage Input is connected to A/D Channel 2 (A/D 2) of the PCL812PG Connector 1 (CN1) for Analogue Inputs via the S&H System (See Section 6.2.2).

The accuracy of the Voltage Sensor was verified using an Oscilloscope.

6.4.2 The Current Sensing System:

The Welding Current is measured by two 400Adc Hall Effect Transducers (Type: RS 245-174) connected to the Return Cable of the Welding System. Although the mean Current Reading never exceeds 400A, individual Current Peaks in Dip Transfer Mode can exceed this value and
to capture the true value of these Peak Values, two Current Transducers have been installed. The Sensors are connected to the Return Cable in parallel as shown in Fig 6.4 below:

![Current Sensors Arrangement](image)

It can be seen from Fig 6.4 that the return Cable is split at the point where the Current Sensors are installed, effectively dividing the Current.

The Total Welding Current is therefore:

\[
\text{Weld Current} = \text{Current Reading 1} + \text{Current Reading 2}
\]

The Current Sensor Outputs have a range 0 - 10V which, after A/D Conversion by the PCL812PG Card is converted proportionally by the System Software to a Current value in the range 0 - 400A with an Accuracy of +/-1%. The Current Values are therefore calculated from the A/D Conversions as:

\[
\text{Current Reading (1,2)} = \left(\frac{\text{Digital Value (DV1,DV2)}}{2047}\right) \times 400
\]
Current Sensor 1 is connected to A/D Channel 0 (A/D 0) of the PCL812PG Card and Current Sensor 2 is connected to A/D Channel 1 (A/D 1), both via the S&H System. Both of these A/D Channels are on Connector 1 (CN1) for Analogue Inputs (See Section 6.2.2).

6.4.3) The Wire Feed Rate Sensing System:

Wire Feed Rate (WFR) Sensing is achieved by axially connecting an Encoder to a Wire Feed Roller. Connected to the Encoder is a System that determines the time between Encoder Pulses. As the Linear Distance travelled by the Circumference of the Wire Feed Roller between Encoder Pulses is known, the Wire Feed Rate can be easily determined.

The Encoder Type utilised for the WFR Sensing System is a Clarostat Optical Rotary Encoder (Model 601 - PCTerminal (Horizontal)) which produces 128 pulses/revolution.

As the Diameter of the Wire Feed Roller is 40mm, the linear distance travelled by the Circumference of the Roller (S) per Encoder Pulse is:

\[ S = \frac{40\pi}{128} = 0.981747 \text{mm} \] .................................(1)

Knowing S, we now only have to determine the Time between Encoder Pulses (T) to be able to calculate the WFR. Fig 6.5 below illustrates the System utilised to measure the Time between Encoder Pulses:

![Diagram](image)

Fig 6.5 System for Measurement of Time Between Encoder Pulses on the Wire Feed Rate Sensing System.

The Encoder pulse is received by the Miniboard [73] (which is itself an independent Control System). The Miniboard will then start a count at increments of 128\(\mu\)S which will terminate when the Miniboard receives the next Pulse from the Encoder.
The count for the period between Pulses is then sent from the Miniboard as an 8-Bit Digital Output (0 - 256) to the D/A Converter where it is converted to an Analogue Voltage in the Range 0 - 10V. The D/A Converter is Connected to A/D Channel 3 (A/D 3) on Connector 1 (CN1) of the PCL812PG Card via the S&H System where the Analogue Voltage Signal will be converted to a Digital Integer.

It should be noted that the Digital Integer, after it has been read in from the PCL812 Card and converted to the Digital Value (as described in Section 6.2.5) will have a value in the Range 0 - 2047. This Digital Value when compared to the Actual Count between Pulses (C) sent from the Miniboard (Range 0 - 256), has been magnified by a Factor of 8. Therefore, the Digital Value obtained from the A/D Converter of the PCL812PG Card must be divided by 8 to return this value to the correct value of C, ie:

\[ C = \text{Digital Value (DV)}/8 \] ..................................(2)

Time between Pulses (T) is therefore:

\[ T = 128 \times 10^{-6} \times C \] ..................................(3)

The WFR is given simply by:

\[ \text{WFR} = \frac{S}{T} \] .......................................(4)

Substituting (1)(3) int (4), the Equation for the WFR (in mm/s) as used in Software is:

\[ \text{WFR} = 61359.232/\text{Digital Value (DV)} \] ...............(5)

A Diagram of the mechanical installation of the WFR Encoder System can be found in the Drawing entitled 'Wire Feed Rate Encoder Assembly' in Appendix VI.

It can be clearly seen that if the actual Count between Pulses (C) can range from 1 to 256 (8 - 2047 through a PCL812PG A/D Converter) and the count occurs at 128\(\mu\)S intervals, then the Range of Time between Pulses that can be measured is:
and therefore the measurable WFR range (from (5)) is:

\[ 29.975 \text{mm/s} \leq \text{WFR} \leq 7669.904 \text{mm/s} \]

The specified WFR range is:

\[ 50 \text{mm/s} \leq \text{WFR} \leq 200 \text{mm/s} \]

and therefore the installed WFR Sensing System is more than adequate for this requirement.

6.4.4) The Weld Travel Speed Sensing System:

The Hardware for measuring the Weld Travel Speed is identical to that installed for Wire Feed Rate measurement (See Section 6.4.3) except for the Encoder Type and the method by which the Weld Travel Speed is actually calculated.

The Encoder for Travel Speed measurement is a Stationary Slotted Through Scan Type (RS 304-560) which is mounted on the Lathe Saddle directly over an Encoder Wheel (90mm Dia and 60 Pulses/Revolution) mounted on the rotating Lathe Saddle Handle. This Arrangement is illustrated in the Drawing ‘Encoder Support Assembly’ and the Drawing ‘Encoder Wheel Assembly’ in Appendix VI.

The Distance travelled by the circumference of the Encoder Wheel per Encoder Pulse (S) is given by:

\[ S = \frac{90\pi}{60} = 1.5\pi \text{ mm} \]

The time between Encoder Pulses for the Travel Speed System is identical to that for the Wire Feed Rate System, ie.

\[ T = 128 \times 10^{-6} \times \text{Digital Value (DV)}/8 \]

As with the measurement of the Wire Feed Rate, once we know S and the Time between Encoder Pulses (T) we can determine the TS, but the
The difference here is that the Weld Travel (i.e. the distance travelled by the Lathe Saddle) for a given time is not equal to the Linear Distance travelled by the circumference of the Encoder Wheel. Therefore the Weld Travel Speed must be linked to the Linear Encoder Speed by a Constant of Proportionality, i.e.:

\[ TS = \frac{KS}{T} \] ...........................................(3)

Substituting (1)(2) into (3) and multiplying by 60 to convert the Units of the Equation from mm/sec to mm/min:

\[ TS = \frac{17671458.68K}{Digital \ Value \ (DV)} \] ...............(4)

A value for K was determined by relating the Linear Speed of the Circumference of the Encoder Wheel to the actual Travel Speed of the Welding Table. K was determined as:

\[ K = 0.006808775 \]

and the Equation for TS (in mm/min) utilised in Software is therefore:

\[ TS = \frac{120320.986}{Digital \ Value \ (DV)} \] ...............(5)

The range for the Time between Pulses is identical to that for the WFR Sensing System. The measurable TS range in mm/min (from (5)) is therefore:

\[ 58.78\text{mm/min} \leq TS \leq 15040.12\text{mm/min} \]

The specified TS range is:

\[ 100\text{mm/min} \leq TS \leq 500\text{mm/min} \]

and therefore the installed Travel Speed Sensing System is more than adequate for this requirement.

The Travel Speed Sensing System is connected to A/D Channel 4 (A/D 4) on Connector 1 (CN1).
6.5) **Computer Control of Welding Parameters:**

The MWEF at present has Computer Control of 3 Welding Parameters which are Voltage, Wire Feed Rate (WFR) and Weld Travel Speed (TS).

Before commencing this Section, the Reader is advised to study Drawing entitled ‘Voltage/Wire Feed Rate Controller Assembly’ in Appendix VI. It can be clearly seen from the stated Drawing that the Voltage and Wire Feed Rate are controlled by Stepper Motors connected via Gearboxes to the Potentiometers for Voltage and WFR Control.

The Stepper Motors utilised are Type RS332-947 (12V, 7.5° Step Angle, 4-Phase, Bi-directional) and are connected to Gearboxes of Type RS336-444. This combination results in a Step Angle of 0.3° being applied to the Voltage/Wire Feed Rate Potentiometer. More accurate combinations of Motor and Gearbox are available, but an increase in Accuracy requires more Steps to move a given distance, thereby reducing the speed of movement. The combination selected was therefore one that allowed sufficient Parameter Setting Accuracy but also allows Parameter Setting at an acceptable speed.

It will also be noted on the Controller Assembly Drawing that there is a Control Lever (Part No 4) fixed to the Connector (Part No 3) which coaxially connects the Stepper Motor Gearboxes to the Potentiometer Spindle. The Control lever serves two major functions, which are:

i) To allow manual setting of the Welding Parameters if the Computer Control System is not functioning or the MWEF is being operated in Manual Mode.

ii) To allow the Computer to set the Voltage/Wire Feed Rate to Datum Settings on System Startup. This is achieved by reversing the Potentiometer movement until the Control Levers activate Limit Switches (affixed to the MIG Control Box and connected to the Computer) at which point Stepper Motor movement is halted. This is illustrated if Fig 6.6 below:

![Fig 6.6: Datum Setting of Voltage/Wire Feed Rate Potentiometers](image-url)
The equations that determine the number of Stepper Motor Steps to achieve a required Setting were calibrated and calculated from the Datum Positions described on the previous page.

All the Parameters are set using Sliders in the Graphical User Interface (GUI) Software packages ‘Shortmon’ and ‘Longmon’ described in Chapters 7 and 8. The GUI Slider setup is illustrated in Fig 6.7 below:

Please note with respect to Fig 6.7 that there is an additional Slider for the Computer Setting of the Standoff (L). Computer Control of this Parameter was not installed at the time of writing this thesis, but will be an important part of future work and was therefore included in the Software.

Before commencing with the details and algorithms for Parameter Control, it is also necessary to describe how data is read from and written to the PCL812PG Card.

Data is written to the PCL812PG Card 1 Byte at a time and is achieved using the following command format (in psuedocode):

```plaintext
writebyte(Port-Address, Byte)
```

where ‘Port-Address’ is the address to be written to and ‘Byte’ is the data to be written to the Port Address. The Port Address will be the Base Address (220H for the MWEF) plus the Address Offset (ie BASE+X, where X can be 0 to 15) and the Byte is an 8-Bit Integer Number.
Data is also read from the PCL812PG Card 1 Byte at a time and is achieved using the following command format (in psuedocode):

```
Byte = readbyte(Port-Address)
```

where 'Port-Address' is the address to be read from and 'Byte' is the data read from the Port Address. The Port Address for reading will also be the Base Address (220H for the MWEF) plus the Address Offset (ie BASE+X where X can be 0 to 15) and the Byte is an 8-Bit Integer Number. See Table 6.3 for further details of Port Addresses and Functions.

### 6.5.1) Weld Voltage Control:

The connections that have been setup to/from the PCL812PG Card for the Voltage Stepper Motor Control are illustrated in Table 6.5 below:

<table>
<thead>
<tr>
<th>Port Address</th>
<th>Port Function</th>
<th>Port Bit</th>
<th>Bit Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D3 (DO11) Stepper Motor Move/Rest</td>
<td></td>
</tr>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D2 (DO10) Stepper Motor Direction</td>
<td></td>
</tr>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D4 (DO12) Stepper Motor Halt</td>
<td></td>
</tr>
<tr>
<td>BASE + 7</td>
<td>D/I High Byte</td>
<td>D0 (DI8) Voltage Setting at Datum</td>
<td></td>
</tr>
</tbody>
</table>

With respect to the Port Bits of Port Address BASE+14 (D/O High Byte) described in Table 6.5, Port Bit D3 controls the motion of the Stepper Motor and is set to ‘1’ for activating the Stepper Motor for one step and is set to ‘0’ for resting between steps. Port Bit D2 controls the direction of Stepper Motor movement and is set to ‘0’ for Forward Motion (Clockwise) and ‘1’ for Reverse Motion (Anti-clockwise). Port Bit D4 is set to ‘0’ whilst the Stepper Motor is in action, and is set to ‘1’ when Stepper Motor movement is completed.

Port Address BASE+7 (D/I High Byte) is utilised to check if the Voltage Setting is at its Datum setting. The Limit Switch for checking this is connected to Port Bit DO which is set to ‘0’ when the Control Lever (See Fig 6.6) has activated this switch, meaning that the Voltage has reached the Datum Setting. Port Bit DO is set at ‘1’ when the Voltage is at any other Setting.

Illustrated overleaf are the Command Formats for Voltage Increase (Forward Stepper Motion) in Table 6.6, Voltage Decrease (Reverse Stepper Motion) in Table 6.7 and Checking for Setting at the Datum Position in Table 6.8:
Table 6.6: Command Formats for Voltage Increase

<table>
<thead>
<tr>
<th>Add = BASE + 14</th>
<th>Port Status (Bit Settings)</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>D7</td>
<td>D6</td>
</tr>
<tr>
<td>Forward one Step</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rest between Steps</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stepper Motor Halt</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.7: Command Formats for Voltage Decrease

<table>
<thead>
<tr>
<th>Add = BASE + 14</th>
<th>Port Status (Bit Settings)</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>D7</td>
<td>D6</td>
</tr>
<tr>
<td>Reverse one Step</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rest between Steps</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stepper Motor Halt</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.8: Command Formats for Voltage Datum Setting Check

<table>
<thead>
<tr>
<th>Add = BASE + 7</th>
<th>Port Status (Bit Settings)</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>D7</td>
<td>D6</td>
</tr>
<tr>
<td>Setting at Datum</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Setting not at Datum</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A basic Algorithm for Forward Stepper Motor movement is:

Comment: Routine Initialisation.
base = 220H
step_count = 0

Comment: Stepper Motor Movement Routine.
while (step_count < steps_required)
BEGIN
    writebyte((base+14), 8) REM Move one step forward.
    2mS Delay
    writebyte((base+14), 0) REM Rest between Steps.
    2mS Delay
    step_count = step_count + 1
END

Comment: Stepper Motor Halt Routine.
writebyte((base+14), 16)
2mS Delay
writebyte((base+14), 16)
2mS Delay
Conversely, a basic Algorithm for Reverse Stepper Motor movement is:

*Comment: Routine Initialisation.*
base = 220H
step_count = 0

*Comment: Stepper Motor Movement Routine.*
while (step_count < steps_required)
BEGIN
  writebyte((base+14), 12)  REM Move one step backward.
  REM 2mS Delay
  writebyte((base+14), 4)   REM Rest between Steps.
  REM 2mS Delay
  step_count = step_count + 1
END

*Comment: Stepper Motor Halt Routine.*
writebyte((base+14), 16)
REM 2mS Delay
writebyte((base+14), 16)
REM 2mS Delay

The 2mS delay in the Routines is to provide time for an action to be performed before moving on to the next action.

When the Software Packages are initially run on the Computer, an initialisation routine is performed that returns the Voltage to its Datum Setting. This is achieved by the following Routine:

*Comment: Routine Initialisation.*
base = 220H
step_count = 0
Read System Clock for Start Time

*Comment: Stepper Motor Movement Routine.*
while (((readbyte(BASE+7) AND 1) <> 0)) AND (In Time))
BEGIN
  writebyte((base+14), 12)  Move one step backward.
  REM 2mS Delay
  writebyte((base+14), 4)   Rest between Steps.
  REM 2mS Delay
  Read System Clock
  Calculate Elapsed Time since Start Time
  if (elapsed_time < 10seconds)
    THEN In Time ELSE Out of Time
END
Voltage Datum Setting Routine (Contd...)

Comment: Stepper Motor Halt Routine.

writebyte((base+14), 16)
2mS Delay
writebyte((base+14), 16)
2mS Delay

The above routine will decrease the Voltage until it reaches the Datum Setting and the Limit Switch is activated. Until the Datum Setting is reached, the Port Bit DO of Port Address BASE+7 will be set at ‘1’, resulting in repetition of the while loop and Reverse Stepping Motion because the statement ‘readbyte(BASE+7) AND 1 <> 0’ is TRUE.

As soon as the Limit Switch is activated Port Bit DO will move to ‘0’ and the statement ‘readbyte(BASE+7) AND 1 <> 0’ will now be FALSE, resulting in termination of the while loop and Stepper Motor Reverse Motion.

One must also consider that if the Stepper Motor Controller was not switched on or there is some sort of Controller Failure that prevented Stepper Motor movement, The Voltage would never reach the Datum Setting, the Limit Switch would never be activated and the Program would be permanently marooned in the while loop. To overcome this problem, a Timer Routine has been included which enables termination of the while loop if the Datum Setting has not been reached within 10 seconds.

The Linear Equation (determined empirically) for relating the Number of Stepper Motor Steps from the Voltage Datum Setting to a required Voltage Setting is:

\[
\text{Voltage}_\text{Steps} = \frac{(\text{Required}_\text{Voltage} - 14.223671)}{0.025229}
\]

where ‘14.22367’ is the Datum Voltage Setting and ‘0.025229’ is the Voltage Change per Stepper Motor Step of 0.3°.

It should be noted that the calculated values of Step movements required using the above Linear Equation, will be a real and not an integer value. A Routine is therefore required to round down or round up the Step number to the nearest integer value. Rounding up and rounding down is done to retain accuracy and repeatability in Settings, thereby ensuring that a Voltage Setting by the Stepper Motor System will always be repeated for a given GUI Voltage Slider Setting.
The Routine for calculating an integer value of the number of Steps required from the Datum Voltage Setting is:

**Comment: Linear Equation for Voltage Steps Calculation.**
Voltage_Steps = (Required_Voltage - 14.223671)/0.025229

**Comment: Rounding Routine.**
if (Voltage_Steps - rounddown(Voltage_Steps) >= 0.5) then Voltage_Step_Setting = roundup(Voltage_Steps)
else Voltage_Step_Setting = rounddown(Voltage_Steps)

Once the Voltage has reached the Datum Setting, it is then automatically set to the minimum GUI Voltage Slider Setting (ie. 15V). For the required Voltage Setting of 15V, the Linear Equation calculates the Voltage Steps to be 30.77 Steps. The Rounding Routine will then round up this value to set the required Voltage Step Setting as 31 Steps. Using the Basic Routine for Forward Stepper Motor movement, the Voltage is now set to 15V.

Once the Voltage has been moved off the Datum Setting, any future Voltage Setting must be made relative to its Previous Voltage Setting. For this reason, when the Voltage has been set, the Voltage Step Setting will now be assigned as:

Previous_Voltage_Step_Setting (PVSS) = Voltage_Step_Setting (VSS)

Therefore, after the Voltage has been moved from the Datum Setting to 15V, the Previous Voltage Step Setting is set to 31 Steps.

As stated, any Voltage Setting will require Stepper Motor movement from the previous Voltage Setting. Therefore, the required movement in terms of the number of required Steps will be:

Required_Steps = VSS - PVSS

if VSS > PVSS,

or

Required_Steps = PVSS - VSS

if PVSS > VSS.

Once the Voltage has been set to the GUI Slider minimum of 15V, the User is now free to increase or decrease the Voltage to any Settings within a 15V - 35V range utilising the Routine described overleaf:
Comment: Calculate the Voltage Steps.
Voltage_Steps = (Required_Voltage - 14.223671)/0.025229.

Comment: Determine the Integer Voltage Step Setting.
if (Voltage_Steps - rounddown(Voltage_Steps) >= 0.5)
then Voltage_Step_Setting = roundup(Voltage_Steps)
else Voltage_Step_Setting = rounddown(Voltage_Steps)

Comment: Ensure Voltage Setting does not go below 15V
if (Voltage_Step_Setting < 31)
then Voltage_Step_Setting = 31

Comment: Routine for Increasing the Voltage Setting.
if (VSS > PVSS)
BEGIN
    Required_Steps = VSS - PVSS
    Step_Count = 0
    while (Step_Count < Required_Steps)
        BEGIN
            writebyte((BASE+14), 8)
            2mS Delay
            writebyte((BASE+14), 0)
            2mS Delay
        END
    END
END

Comment: Routine for Decreasing the Voltage Setting.
if (VSS < PVSS)
BEGIN
    Required_Steps = PVSS - VSS
    Step_Count = 0
    while (Step_Count < Required_Steps)
        BEGIN
            writebyte((BASE+14), 12)
            2mS Delay
            writebyte((BASE+14), 4)
            2mS Delay
        END
    END
END

Comment: Halt Stepper Motor
writebyte((BASE+14), 16)
2mS Delay
writebyte((BASE+14), 16)
2mS Delay

Comment: Set VSS to PVSS
PVSS = VSS
6.5.2) **Wire Feed Rate (WFR) Control:**

The connections that have been setup to/from the PCL812PG Card for the WFR Stepper Motor Control are illustrated in Table 6.9 below:

<table>
<thead>
<tr>
<th>Port Address</th>
<th>Port Function</th>
<th>Port Bit</th>
<th>Bit Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D1 (D09)</td>
<td>Stepper Motor Move/Rest</td>
</tr>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D0 (D08)</td>
<td>Stepper Motor Direction</td>
</tr>
<tr>
<td>BASE + 14</td>
<td>D/O High Byte</td>
<td>D4 (D012)</td>
<td>Stepper Motor Halt</td>
</tr>
<tr>
<td>BASE + 7</td>
<td>D/I High Byte</td>
<td>D1 (D19)</td>
<td>Voltage Setting at Datum</td>
</tr>
</tbody>
</table>

With respect to the Port Bits of Port Address BASE+14 (D/O High Byte) described in Table 6.9, Port Bit D1 controls the motion of the Stepper Motor and is set to ‘1’ for activating the Stepper Motor for one step and is set to ‘0’ for resting between steps. Port Bit D0 controls the direction of Stepper Motor movement and is set to ‘0’ for Forward Motion (Clockwise) and ‘1’ for Reverse Motion (Anti-clockwise). Port Bit D4 is set to ‘0’ whilst the Stepper Motor is in action, and is set to ‘1’ when Stepper Motor movement is completed.

Port Address BASE+7 (D/I High Byte) is utilised to check if the WFR Setting is at its Datum setting. The Limit Switch for checking this is connected to Port Bit D1 which is set to ‘0’ when the Control Lever (See Fig 6.6) has activated this switch meaning that the WFR has reached the Datum Setting. Port Bit D1 is set at ‘1’ when the WFR is at any other Setting.

Illustrated below and overleaf are the Command Formats for WFR Increase (Forward Stepper Motion) in Table 6.10, WFR Decrease (Reverse Stepper Motion) in Table 6.11 and Check for Setting at the Datum Position in Table 6.12:

### Table 6.10: Command Formats for WFR Increase

<table>
<thead>
<tr>
<th>Add = BASE + 14</th>
<th>Port Status (Bit Settings)</th>
<th>Action</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Forward Step</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>writebyte(Add, 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rest between Steps</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>writebyte(Add, 8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stepper Motor Halt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>writebyte(Add, 16)</td>
</tr>
</tbody>
</table>

### Table 6.11: Command Formats for WFR Decrease

<table>
<thead>
<tr>
<th>Add = BASE + 14</th>
<th>Port Status (Bit Settings)</th>
<th>Action</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reverse Step</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>writebyte(Add, 3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rest between Steps</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>writebyte(Add, 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stepper Motor Halt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>writebyte(Add, 16)</td>
</tr>
</tbody>
</table>
Table 6.12: Command Formats for WFR Datum Setting Check

<table>
<thead>
<tr>
<th>Add = BASE + 7</th>
<th>Port Status (Bit Settings)</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setting at Datum</td>
<td>0 0 0 0 0 0 0 0</td>
<td>readbyte(Add)</td>
</tr>
<tr>
<td>Setting not at Datum</td>
<td>0 0 0 0 0 1 0 1</td>
<td>readbyte(Add)</td>
</tr>
</tbody>
</table>

A basic Algorithm for Forward Stepper Motor movement is:

Comment: Routine Initialisation.
base = 220H
step_count = 0

Comment: Stepper Motor Movement Routine.
while (step_count < steps_required)
BEGIN
  writebyte((base+14), 2)  // Move one step forward.
  2mS Delay
  writebyte((base+14), 0)  // Rest between Steps.
  2mS Delay
  step_count = step_count + 1
END

Comment: Stepper Motor Halt Routine.
writebyte((base+14), 16)
2mS Delay
writebyte((base+14), 16)
2mS Delay

Conversely, a basic Algorithm for Reverse Stepper Motor movement is:

Comment: Routine Initialisation.
base = 220H
step_count = 0

Comment: Stepper Motor Movement Routine.
while (step_count < steps_required)
BEGIN
  writebyte((base+14), 3)  // Move one step backward.
  2mS Delay
  writebyte((base+14), 1)  // Rest between Steps.
  2mS Delay
  step_count = step_count + 1
END
Comment: Stepper Motor Halt Routine.
writebyte((base+14), 16)
2mS Delay
writebyte((base+14), 16)
2mS Delay

The 2mS delay in the Routines is to provide time for an action to be performed before moving on to the next action.

When the Software Packages are run on the Computer, an initialisation routine is performed that returns the WFR to its Datum Setting. This is achieved by the following Routine:

Comment: Routine Initialisation.
base = 220H
step_count = 0
Read System Clock for Start Time

Comment: Stepper Motor Movement Routine.
while (((readbyte(BASE+7) AND 2) <> 0)) AND (In Time))
BEGIN
  writebyte((base+14), 3) Move one step backward.
  2mS Delay
  writebyte((base+14), 1) Rest between Steps.
  2mS Delay
  Read System Clock
  Calculate Elapsed Time since Start Time
  if (elapsed_time < 10seconds)
  THEN In Time ELSE Out of Time
END

Comment: Stepper Motor Halt Routine.
writebyte((base+14), 16)
2mS Delay
writebyte((base+14), 16)
2mS Delay

The above routine will decrease the WFR until it reaches the Datum Setting and the Limit Switch is activated. Until the Datum Setting is reached, the Port Bit D1 of Port Address BASE+7 will be set at ‘2’, resulting in repetition of the while loop and Reverse Stepping Motion because the statement ‘readbyte(BASE+7) AND 2 <> 0’ is TRUE.

As soon as the Limit Switch is activated Port Bit D1 will move to ‘0’ and the statement ‘readbyte(BASE+7) AND 2 <> 0’ will now be FALSE, resulting in termination of the while loop and Stepper Motor Reverse Motion.
As with the Voltage Setting, one must also consider that if the Stepper Motor Controller was not switched on or there some sort of Controller Failure that prevented WFR Stepper Motor movement, the WFR would never reach the Datum Setting, the Limit Switch would never be activated and the Program would be permanently marooned in the while loop. Again, to overcome this problem, a Timer Routine has been included in the WFR Datum Setting Routine which enables termination of the while loop if the Datum Setting has not been reached within 10 seconds.

The Linear Equation (determined empirically) for relating the Number of Stepper Motor Steps from the WFR Datum Setting to a required WFR Setting is:

\[
WFR_{Steps} = \frac{(\text{Required}_{WFR} + 17.098192)}{0.327701}
\]

where ‘17.098192’ is the Datum WFR Setting and ‘0.327701’ is the WFR Change per Stepper Motor Step of 0.3° (WFR is in mm/s).

It should be noted that the calculated values of Step movements required using the above Linear Equation, will be a real and not an integer value. As with the Voltage Setting, a Routine is therefore required to round down or round up the Step number to the nearest integer value. Rounding up and rounding down is done to retain accuracy and repeatability in Settings, thereby ensuring that a WFR Setting by the Stepper Motor System will always be repeated for a given GUI WFR Slider Setting.

The Routine for calculating an integer value of the number of Steps required from the Datum WFR Setting is:

**Comment: Linear Equation for WFR Steps Calculation.**

\[
WFR_{Steps} = \frac{(\text{Required}_{WFR} + 17.098192)}{0.327701}
\]

**Comment: Rounding Routine.**

if (WFR_{Steps} - rounddown(WFR_{Steps}) >= 0.5)
then WFR_{Step Setting} = roundup(WFR_{Steps})
else WFR_{Step Setting} = roundown(WFR_{Steps})

Once the WFR has reached the Datum Setting, it is then automatically set to the minimum GUI WFR Slider Setting (ie. 50mm/s). For the required WFR Setting of 50mm/s, the Linear Equation calculates the WFR Steps to be 205.19 Steps. The Rounding Routine will then round down this value to set the required WFR Step Setting as 205 Steps. Using the Basic Routine for Forward Stepper Motor movement, the WFR is now set to 50mm/s.
Once the WFR has been moved off the Datum Setting, any future WFR Setting must be made relative to its Previous WFR Setting. For this reason, when the WFR has been set, the Voltage Step Setting will now be assigned as:

\[
\text{Previous\_WFR\_Step\_Setting (PWSS) = WFR\_Step\_Setting (WSS)}
\]

Therefore, after the WFR has been moved from the Datum Setting to 50mm/s, the Previous WFR Step Setting is set to 205 Steps.

As stated, any WFR Setting will require Stepper Motor movement from the previous WFR Setting. Therefore, the required movement in terms of the number of required Step will be:

\[
\text{Required\_Steps} = \text{WSS} - \text{PWSS} \quad \text{if} \quad \text{WSS} > \text{PWSS},
\]

or

\[
\text{Required\_Steps} = \text{PWSS} - \text{WSS} \quad \text{if} \quad \text{PWSS} > \text{WSS}.
\]

Once the WFR has been set to the GUI Slider minimum of 50mm/s, the User can now increase or decrease the WFR to any Settings within a 50mm/s - 200mm/s range utilising the Routine described below and continued overleaf:

\text{Comment: Calculate the WFR Steps.}
WFR\_Steps = (\text{Required\_WFR} + 17.098192)/0.327701.

\text{Comment: Determine the Integer WFR Step Setting.}
if (WFR\_Steps - \text{rounddown}(WFR\_Steps) >= 0.5)
then WFR\_Step\_Setting = \text{roundup}(WFR\_Steps)
else WFR\_Step\_Setting = \text{rounddown}(WFR\_Steps)

\text{Comment: Ensure WFR Setting does not go below 50mm/s}
if (WFR\_Step\_Setting < 205)
then WFR\_Step\_Setting = 205

\text{Comment: Routine for Increasing the WFR Setting.}
if (WSS > PWSS)
BEGIN
\text{Required\_Steps} = \text{WSS} - \text{PWSS}
Step_Count = 0
while (Step_Count < Required_Steps)
BEGIN
    writebyte((BASE+14), 2)
    2mS Delay
    writebyte((BASE+14), 0)
    2mS Delay
END
END

Comment: Routine for Decreasing the WFR Setting.
if (WSS < PWSS)
BEGIN
    Required_Steps = PWSS - WSS
    Step_Count = 0
    while (Step_Count < Required_Steps)
    BEGIN
        writebyte((BASE+14), 3)
        2mS Delay
        writebyte((BASE+14), 1)
        2mS Delay
    END
END

Comment: Halt Stepper Motor
writebyte((BASE+14), 16)
2mS Delay
writebyte((BASE+14), 16)
2mS Delay

Comment: Set WSS to PWSS
PWSS = WSS

6.5.3) Weld Travel Speed Control:

As stated, the Saddle on the Lathe provides the Weld Travel. The Welding Travel Speed is controlled by the Lathe Leadscrew connected via the Lathe Gearing System to a 3-Phase, 230V-50Hz AC Motor.

The Speed of the AC Motor is controlled by a Danfoss Variable Speed Drive (VSD) Unit which supplies a 3-Phase Voltage at a proportional Frequency to the AC Motor. The amplitude and frequency of the applied Voltage is controlled by a DC reference Voltage (0V - 5V) supplied to the Danfoss VSD as an Analogue Voltage Signal from D/A Channel 1 (D/A 1) of the PCL812PG Card.
A simplified Diagram of the Travel Speed Control System is shown if Fig 6.8 below:

![Diagram](image)

**Fig 6.8: Weld Travel Speed Control System**

The Danfoss VSD utilises the Analogue DC Voltage from the PCL812PG Card to produce an AC Voltage with a Frequency directly proportional to the AC Voltage which is supplied to the AC Motor. A simplified Diagram of the function of the Danfoss DSV in Power Conversion is given in Fig 6.9 below:

![Diagram](image)

**Fig 6.9: Variable Speed Drive Controller**

In Fig 6.9, an AC Input to the VSD (which will be a typical Mains Voltage of 230V, 50Hz) is Rectified to form a DC Signal. The Rectified Signal is then Inverted back into an AC Signal at the desired Voltage and
Frequency levels. The Inverted AC Signal is then applied to the AC Motor.

The Voltage/Frequency levels of the Inverted AC Signal are controlled by the Inversion Controller which utilises the Reference DC Voltage from the PCL812PG Card to set The Inversion Voltage/Frequency level. The Voltage/Frequency Setting of the Inverted AC Signal is linearly and directly proportional to the DC Reference Voltage.

The Weld Travel Speed was calibrated by comparing measured Weld Travel Speeds with corresponding Digital Values (in the range 0 - 2047) sent from the Computer to the VSD through the PCL812PG D/A Converter. The Linear Equation relating Travel Speed Digital Setting (TSDS) to the Weld Travel Speed (TS) is:

\[
\text{TSDS} = \text{round}((\text{TS}+15.201558) / 0.248934)
\]

It will be remembered from Section 6.2.4.4 that Output from the PCl812PG Card via a D/A Converter requires the Digital Setting to be a 12-Bit Integer number with the High and Low Bytes being sent to the D/A Converter independently.

For D/A Channel 1 (D/A 1), the Digital Setting High Byte is to Port Address BASE+5 whilst the Low Byte is sent to Port Address BASE+4.

The Routine to set the Weld Travel Speed is given below:

Comment: Calculate TSDS.
\[
\text{TSDS} = \text{round}((\text{TS}+15.201558) / 0.248934)
\]

Comment: Separate TSDS into High Byte and Low Byte.
LowByte = (00FFH AND TSDS)
HighByte = TSDS rightshifted by 8 Bits

Comment: Send High and Low Bytes to D/A Channel 1 (D/A 1).
writebyte(BASE+4, LowByte)
writebyte(BASE+5, HighByte)

When the Speed Setting has been sent out to the VSD, the Welding Travel Speed will be set to the desired level.
6.6) **Communication Link between the High Speed Camera and the Computer:**

A Communication Link has been installed between the High Speed Camera and the Computer that enables the Camera to send a signal to the Computer to start the Data Acquisition Process at the exact moment that the Camera commences its filming run.

![Fig 6.10: HS Camera/Computer Communication Link](image)

The Communication Link is connected to D/I Low Byte, PortBit D10 on Connector 4 (CN4) at Port Address BASE+6. A Basic Circuit Diagram of the Communication Link is shown in Fig 6.10 below:

It will be seen from Fig 6.10 that the D/I 0 is connected to a Transistor in the High Speed Camera, but also to D/I 19 which is a 5V Power Supply. When the Transistor is off, D/I 0 will have 5V applied across it, ie. it will be set high and if read by Software will be set to ‘1’.

When the Camera Filming Run is started, the Transistor is switched on, and the Voltage at D/I 0 goes low and will, if read by Software, now be set to ‘0’.

The Software therefore has a routine that will delay Program execution whilst D/I 0 is set to ‘1’, but will exit the delay when the Camera is activated causing D/I 0 to be set to ‘0’. The Software then proceeds immediately to the Data Acquisition routines.

The Routine for the Software Delay is given below:

```c
while ((readbyte(BASE+6) AND 1) = 1)
```
6.7) **Computer Algorithms for Sampling Rate Control:**

The Sampling Rate is Controlled by routines that utilise the Programmable Counters on the Intel 8253 Timer/Counter Chip which is the Timer installed on the PCL812PG Card. Before dealing with the Algorithms for Sampling Rate Control, it is therefore necessary to describe the Intel 8253 Timer/Counter.

6.7.1) **The Intel 8253 Timer/Counter:**

The Intel 8253 Timer/Counter consists of three independent 16-Bit Counters (Counter 0 - 2) with each Counter possessing a Clock Input, Control Gate and an Output. It can be programmed to operate in one of six modes. The PCL812PG Card provides an internal (ie. on-board) 2MHz Frequency Input to the Counters.

Counters 1 and 2 are cascaded and operated in fixed divider configuration. Counter 2 is connected to the 2MHz Frequency Input and the Output of Counter 2 is connected to the Input of Counter 1.

Counter 0 is not reserved by the PCL812PG Card for Internal use and is therefore free for User utilisation.

The Intel 8253 uses four Registers which are at the Port Addresses listed below:

<table>
<thead>
<tr>
<th>Port Address</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE + 0</td>
<td>Counter 0 Read/Write</td>
</tr>
<tr>
<td>BASE + 1</td>
<td>Counter 1 Read/Write</td>
</tr>
<tr>
<td>BASE + 2</td>
<td>Counter 2 Read/Write</td>
</tr>
<tr>
<td>BASE + 3</td>
<td>Counter Control Word</td>
</tr>
</tbody>
</table>

The Counters have a 16 Bit Structure and reading/writing the Count from/to the Counters is split into independent reading/writing of the Least Significant Bit (LSB) and the Most Significant Bit (MSB).

The Counter Control Word Enables the User to select the Required Counter, Read/Write Operation, Operation Mode and Counting Mode. Details of the use of the Counter Control Word are given below and overleaf.

**Data Format of the Control Word Register:**

<table>
<thead>
<tr>
<th>BASE + 3</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>SC1</td>
<td>SC0</td>
<td>RW1</td>
<td>RW0</td>
<td>M2</td>
<td>M1</td>
<td>M0</td>
<td>BCD</td>
</tr>
</tbody>
</table>
The Tables below provide details of the options that make up the format of the Counter Control Word:

**SC1 & SC0: Select Counter**

<table>
<thead>
<tr>
<th>SC1</th>
<th>SC0</th>
<th>Counter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Illegal</td>
</tr>
</tbody>
</table>

**RW1 & RW2: Select the Read/Write Operation**

<table>
<thead>
<tr>
<th>RW1</th>
<th>RW1</th>
<th>Read/Write Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Counter Latch</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Read/Write LSB</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Read/Write MSB</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Read/Write LSB first, then MSB</td>
</tr>
</tbody>
</table>

**M2, M1 & M0: Select the Operation Mode**

<table>
<thead>
<tr>
<th>M2</th>
<th>M1</th>
<th>M0</th>
<th>Operation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 - Interrupt on Terminal Count</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1 - Programmable One Shot</td>
</tr>
<tr>
<td>X</td>
<td>1</td>
<td>0</td>
<td>2 - Rate Generator</td>
</tr>
<tr>
<td>X</td>
<td>1</td>
<td>1</td>
<td>3 - Square Wave Rate Generator</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4 - Software Triggered Strobe</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>5 - Hardware Triggered Strobe</td>
</tr>
</tbody>
</table>

**BCD: Select Binary or BCD Counting**

<table>
<thead>
<tr>
<th>BCD</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Binary Counter (16 Bits)</td>
</tr>
<tr>
<td>1</td>
<td>Binary Coded Decimal (BCD) Counter (4 Decades)</td>
</tr>
</tbody>
</table>

With respect to BCD selection, if it is set to Binary, the Count can be any number from 0 to 65535 (64K). If it is set to BCD (binary Coded Decimal), the Count can be set at any number from 0 to 9999.
6.7.2) **Algorithms for Sampling Rate Control:**

The Control Word Options (See Section 6.7.1 on preceding pages) were selected as follows:

i) **Counter:** Counter 0.
   
   (SC1 = 0, SC0 = 0)

ii) **Read/Write Operation:** Read/Write LSB first, then MSB.
   
   (RW1 = 1, RW0 = 1)

iii) **Operation Mode:** Mode 3 - Square Wave Rate Generator.
   
   (M2 = 0, M1 = 1, M0 = 1)

iv) **BCD:** Binary.

   (BCD = 0)

Table 6.13 below illustrates how the Counter Control Word is set at Port Address BASE+3 for use by the Intel 8253 Timer/Counter:

<table>
<thead>
<tr>
<th>Table 6.13: Counter Control Word Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Status (Bit Settings)</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>SC1 SC0 RW1 SW0 M2 M1 M0 BCD Command</td>
</tr>
<tr>
<td>0 0 1 1 0 1 1 0 0</td>
</tr>
</tbody>
</table>

Once the Counter Control Word has been set, the selected Counter can then be loaded with a Count Value (0 to 65535). Once the Count Value is loaded the Counter decrements the Count Value with each Clock Pulse (at a rate of 2MHz or 2000000 Clock Pulses/second) until it reaches zero at which point the Count Value is reloaded into the Counter and again decremented, thereby repeating the process. It should be noted that with the Operation Mode selected (ie. Mode 3 - Square Wave Rate Generator), the Count Value is decremented by 2 for every Clock Pulse.

The Counter can therefore be used to control the Sampling Interval by equating a Count Value to the Sampling Interval required. This can be done using the Equation below:

\[
Count \ Value = \frac{(Decrement/Clock \ Pulse) \times \text{Clock Frequency}}{\text{Sampling Rate}}
\]
As the Clock Frequency is 2MHz and the Decrement/Clock Pulse is 2, the Equation now becomes:

\[
\text{Count Value} = \frac{40000000}{\text{Sampling Rate}}
\]

where:

\[
\text{Sampling Rate} = \frac{1}{\text{Sampling Interval}}
\]

It can be clearly seen that the time taken for the Count Value to be decremented to zero will equal the Sampling Interval.

To enable this System to be utilised for Sampling Rate Control, two Routines were written in Assembler Language and linked to the main Software Packages. These Routines are:

i) **The Priming Routine:**

The Priming Routine is used to set the Counter Control Word and load the Count Value (CV). The Routine to achieve this is illustrated below:

*Comment: Counter Control Word Setting.*
writebyte((BASE+3), 54)

*Comment: Load Count Value (CV) in Counter 0.*
writebyte(BASE+0, CV_lowbyte)
writebyte(BASE+0, CV_highbyte)

ii) **The Polling Routine:**

The Polling Routine is utilised to detect when the decremented Count Value has reached zero. The Routine to do this is given below:

*Comment: Initialise by Reading in Count Value (CV).*
CV_lowbyte = readbyte(BASE+0)
CV_highbyte = readbyte(BASE+0)
Comment: Polling Routine.
DO
BEGIN

Comment: Assign CV to Previous Count Value (PCV)
PCV = CV

Comment: Read in Count Value (CV).
CV_lowbyte = readbyte(BASE+0)
CV_highbyte = readbyte(BASE+0)

END
WHILE (PCV > CV)

By studying the Polling Routine above, it can be seen that the Program will remain in the DO-WHILE loop whilst ever the Previously Polled Count Value (PCV) is greater than the Current Count Value (CV). This situation will occur until the Count Value has reached zero and the original Count Value is reloaded in the Counter, at which point the Current Count Value (CV) will be greater than the Previous Count Value (PCV) indicating that the Sampling Interval time has elapsed.

The routines were checked by sampling a 10Hz Sine Wave Input to the PCL812PG Card via a Signal Generator. The Frequency Setting was accurate to 10Hz +/-0.02Hz. Data was collected for Sampling Rates varying from 1000Hz to 10000Hz in steps of 1000Hz for a 1 Second Period. The Data collected was saved to Files.

The Sampling Rates were confirmed by loading the Data File into MS Excel and checking the Number of Samples for 5 Sine Wave Cycles as described below:

Assume that the Sampling Rate has been set to 5000Hz and sampled for the Period of 1 Second. This would imply that 5 Cycles of a 10Hz Sine Wave should occupy exactly 2500 Samples in the Data Array. By loading the Data Files into MS Excel the number of samples collected for 5 Cycles can be obtained by locating the zero-crossing point for the first Cycle and then counting the Samples to the zero-crossing point at the end of the fifth Cycle. For 5000Hz, the Sample Count should be exactly 2500.

Using the above described method, it was confirmed that the Priming and Polling Routines provided a exact Sampling Interval for any Sampling Rate that provided an Integer Count Value (ie. 1KHz, 2KHz, 4KHz, 5KHz, 8KHz and 10KHz). The other Sampling Rates tested (ie. 3KHz, 6KHz, 7KHz and 9KHz) do not produce an exact Integer Count Value, therefore, when the Count Values for
these Sampling Rates are rounded to integer values for loading into the Counter, inaccuracies (up to 0.8%) resulted in the Sampling Interval Times.

6.8) **A Computer Algorithm for Weld Data Acquisition:**

The Weld Data Acquisition Routine is utilised to acquire Data from the Welding Process including Weld Voltage, Weld Current, Wire Feed Rate and Weld Travel Speed.

Before actual Data Acquisition can occur, the PCL812PG Card has to be setup for Data Acquisition. This is achieved by the Routine described below:

```
Comment: Setup PCL812PG Card for Data Acquisition.
BASE = 220H Set the BASE Address.
writebyte(BASE+13, 0) Clear D/O Low Byte.  
writebyte(BASE+11, 1) Set Mode Control to Enable Software Trigger.  
writebyte(BASE+9, 0) Set the Gain to 1.
```

The above Routine initially sets the Base Port Address to 220Hex.

The Digital Output Low Byte at BASE + 13 is then cleared. This is essential as the Sample and Hold (S&H) Data Acquisition System is connected to and activated by Digital Output Low Byte Port at Address BASE + 13, Port Bit DO 0. The S&H System is activated by setting high Port Bit DO 0 (ie. changing the Port Bit DO 0 setting from ‘0’ to ‘1’). If Port Bit DO 0 is already high, then setting Bit DO 0 high by software will have no effect with respect to activating the S&H System. Bit DO 0 is therefore set low in the Setup Routine to ensure that when the S&H System is utilised in the first data acquisition cycle, setting Bit DO 0 high will have the effect of activating the S&H System for Data Acquisition.

The third line of the Setup Routine sets the Control Mode to Enable Software Trigger and Software Transfer only. This means that A/D Conversions of Sensor Data can only be triggered from commands in the Users Software (See Section 6.2.4.6).

Finally, the Gain for Analogue Input is set to 1 (See Section 6.2.4.5).

After the PCL812PG has been setup for Data Acquisition, the Software moves into the Data Acquisition Routines as described overleaf:
Comment: Data Acquisition Routine.

AC = 1
Call Priming Routine

WHILE (AC <= samples_required)
BEGIN

Comment: Activate the S&H System for Data Acquisition.

writebyte(BASE+13, 1) Activate S&H System
10μS Delay Delay for S&H Data Acquisition
writebyte(BASE+13, 0) Set Bit DO 0 low

Comment: Read in Digital Value for Current Sensor 1.

writebyte(BASE+10, 0) Set MUX to A/D Channel 0
writebyte(BASE+12, 1) Software Trigger for A/D Conversion

Wait while Data Ready Signal (DRS) at BASE+5, Port Bit D4 is 0
(fie. while A/D Conversion on A/D 0 is occurring)
WHILE (read byte(BASE+5) AND 4) = 0)

hibyte = read byte(BASE+5) Read hibyte Current Sensor 1
lobyte = read byte(BASE+4) Read lobyte Current Sensor 1

Comment: Read in Digital Value for Current Sensor 2.

writebyte(BASE+10, 1) Set MUX to A/D Channel 1
writebyte(BASE+12, 1) Software Trigger for A/D Conversion

Assign hibyte and lobyte for Current Sensor 1 to current1 Array
while A/D Conversion occurs on A/D Channel 1
current1(AC) = ((hibyte x 256) + lobyte) - 2048

WHILE (read byte(BASE+5) AND 4) = 0)

hibyte = read byte(BASE+5) Read hibyte Current Sensor 2
lobyte = read byte(BASE+4) Read lobyte Current Sensor 2

Comment: Read in Digital Value for Voltage Sensor.

writebyte(BASE+10, 2) Set MUX to A/D Channel 2
writebyte(BASE+12, 1) Software Trigger for A/D Conversion

Assign hibyte and lobyte for Current Sensor 2 to current2 Array
while A/D Conversion occurs on A/D Channel 2
current2(AC) = ((hibyte x 256) + lobyte) - 2048
WHILE (readbyte(BASE+5) AND 4) = 0)

hibyte = readbyte(BASE+5)  \textit{Read hibyte Voltage Sensor}
lobyte = readbyte(BASE+4)  \textit{Read lobyte Voltage Sensor}

\textit{Comment: Read in Digital Value for WFR Sensor.}

writebyte(BASE+10, 3)  \textit{Set MUX to A/D Channel 3}
writebyte(BASE+12, 1)  \textit{Software Trigger for A/D Conversion}

Assign hibyte and lobyte for Voltage Sensor to Voltage Array while A/D Conversion occurs on A/D Channel 3
voltage(AC) = ((hibyte x 256) + lobyte) - 2048

WHILE (readbyte(BASE+5) AND 4) = 0)

hibyte = readbyte(BASE+5)  \textit{Read hibyte WFR Sensor}
lobyte = readbyte(BASE+4)  \textit{Read lobyte WFR Sensor}

\textit{Comment: Read in Digital Value for Travel Speed (TS) Sensor.}

writebyte(BASE+10, 4)  \textit{Set MUX to A/D Channel 4}
writebyte(BASE+12, 1)  \textit{Software Trigger for A/D Conversion}

Assign hibyte and lobyte for WFR Sensor to WFR Array while A/D Conversion occurs on A/D Channel 4
wfr(AC) = ((hibyte x 256) + lobyte) - 2048

WHILE (readbyte(BASE+5) AND 4) = 0)

hibyte = readbyte(BASE+5)  \textit{Read hibyte TS Sensor}
lobyte = readbyte(BASE+4)  \textit{Read lobyte TS Sensor}

Assign hibyte and lobyte for TS Sensor to TS Array
ts(AC) = ((hibyte x 256) + lobyte) - 2048

\textit{Comment: Increment Array Counter (AC).}
AC = AC + 1

\textit{Comment: Call Polling Routine to detect end of sampling Interval.}
Call Polling Routine

\textbf{END}

The Data read in utilising the above routine will be Digital Numbers in the range 0 - 2047. These Digital Numbers need now to be converted to their actual
Parameter Values. The Routine described below performs this function using the Parameter Formulae derived in Section 6.4

Comment: Routine for Actual Parameter Reading Calculation.

AC = 1 \hspace{1cm} \textit{Set Array Counter (AC) to 1}

\textbf{WHILE} (AC <= samples\_required) \\
\hspace{1cm} \textbf{BEGIN}

\hspace{2cm} \textit{Current Calculation:}
\hspace{2cm} current(AC) = (current1(AC) + current2(AC))/2047 \times 400

\hspace{2cm} \textit{Voltage Calculation:}
\hspace{2cm} voltage(AC) = voltage(AC)/2047 \times 109.0

\hspace{2cm} \textit{Wire Feed Rate:}
\hspace{2cm} wfr(AC) = 61359.232/wfr(AC)

\hspace{2cm} \textit{Travel Speed Calculation:}
\hspace{2cm} ts(AC) = 120320.986/ts(AC)

\hspace{2cm} \textit{Increment the Array Counter (AC):}
\hspace{2cm} AC = AC + 1

\hspace{1cm} \textbf{END}

The actual Data Acquisition Routines in the System Software also have Failure Detection Routines included to:

i) Ensure that false readings will not be given in the event of Sensor Failure.

ii) Prevent the Software from crashing in the event of Sensor Failure.

iii) Prevent entry into the Data Acquisition Routines if the Data Acquisition Hardware is not switched on.

6.9) PLC Control of Weld Length, Weld Start/Stop and Operating Mode:

A Programmable Logic Controller (PLC) is utilised to control the Weld Length, Weld Starting and Stopping and the Operating Mode (ie. Manual or Automatic). The MWEF Control Panel is illustrated in Fig 6.11 overleaf:
Table 6.14 below describes the functions of the Components of the MWEF Control Panel illustrated in Fig 6.11 above.

<table>
<thead>
<tr>
<th>Comp</th>
<th>Description</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Toggle Switch 1</td>
<td>Sets the Weld Length to 400mm if ON</td>
</tr>
<tr>
<td>S2</td>
<td>Toggle Switch 2</td>
<td>Sets the Weld Length to 200mm if ON</td>
</tr>
<tr>
<td>S3</td>
<td>Toggle Switch 3</td>
<td>Sets the Weld Length to 100mm if ON</td>
</tr>
<tr>
<td>S4</td>
<td>Toggle Switch 4</td>
<td>Sets Travel Speed Control Mode (Computer/Manual)</td>
</tr>
<tr>
<td>B1</td>
<td>Button Switch 1</td>
<td>Resets the System after Welding if in Automatic Mode</td>
</tr>
<tr>
<td>B2</td>
<td>Button Switch 2</td>
<td>Starts Weld Travel if in Manual Mode</td>
</tr>
<tr>
<td>B3</td>
<td>Button Switch 3</td>
<td>Starts Welding if in Manual Mode</td>
</tr>
<tr>
<td>B4</td>
<td>Button Switch 4</td>
<td>Starts Welding/Weld Travel if in Automatic Mode</td>
</tr>
<tr>
<td>MS</td>
<td>Mode Switch</td>
<td>Sets the Control Mode (Automatic/Manual)</td>
</tr>
<tr>
<td>POT</td>
<td>Precision Pot</td>
<td>Controls Weld Travel Speed if in Manual Mode</td>
</tr>
<tr>
<td>L1</td>
<td>Light 1</td>
<td>ON if Automatic Control Mode is selected.</td>
</tr>
<tr>
<td>L2</td>
<td>Light 2</td>
<td>ON if the System Power is on.</td>
</tr>
<tr>
<td>ES</td>
<td>Emergency Stop</td>
<td>Halts Welding/Weld Travel when pressed.</td>
</tr>
</tbody>
</table>
With respect to table 6.14 on the previous page, if none of the Weld Length Switches (ie. S1, S2 and S3) are ON, then the default Weld Length is 40mm. If more than one Weld Length Switch is ON, then the PLC selects the default Weld Length. The Weld Lengths stated have been selected and set for their suitability for use with the 'Shortmon' (See Chapter 7), ‘Longmon’ (See Chapter 8), and ‘Weldmod’ (See Chapter 10) Programs.

In Automatic Mode, the Operation of the MWEF is entirely Computer/PLC controlled whereas in Manual Mode, the Welding Parameters are set manually by the Operator prior to the Welding Operation. Only the Weld Length is PLC controlled in both Manual and Automatic Mode.
Chapter 7

The ‘Shortmon’ Weld Monitoring Package

7.1) Introduction to the ‘Shortmon’ Program:

The ‘Shortmon’ Package is a Mouse-driven Graphical User Interface (GUI) developed to enhance and accelerate Welding Research by providing a User-friendly means by which the Welding Researchers can Monitor, View, Analyse and Store short bursts of Weld Data in both the Time and Frequency Domains. The package is written in the ‘Borland C’ Programming Language.

The ‘Shortmon’ Package possesses the following facilities:

i) Ability to monitor the Weld Voltage, Current, Wire Feed Rate and Weld Travel Speed. The Facility exists in Software to also measure Audible Weld Acoustics although the Hardware for this has not been installed at the time of writing the thesis.

ii) 10000 Samples for each of the above mentioned Parameters can be acquired and stored in Parameter Data Arrays in Computer Memory. The Sampling Frequency can be set from 1KHz to 10KHz. An Additional Array is setup to store the Time of each Parameter Set relative to the Start of Monitoring.

iii) The Parameter Traces can be viewed in the Time Domain as individual Parameters or in a General View which allows the User to view up to three Parameters Traces simultaneously. The Software allows the User to set the Time Period to be viewed (referred to as the Plot Time) which can vary from 10mS to the complete Sampling Period.

iv) The Parameter Traces can also be viewed in the Frequency Domain, again either as individual Parameters or in a General View with the Frequency Analysis of up to three Parameters displayed simultaneously.

v) Parameter Data can be saved in Files in a format that enables the data to be further analysed off-line in Software Packages such as MS-Excel and Matlab. Please note that only the Data for the current Plot Time Period is saved and not the whole Parameter Data Array.

vi) A Run Report can also be displayed which gives a statistical summary of the last Weld Run.

vii) All Graphical Displays can be Printed by a Screen Dump to the Printer.
viii) The Software allows the User to start Data Acquisition instantaneously or with a delay awaiting a signal from the High Speed Camera.

ix) The User can set the Welding Parameters including the Voltage, Wire Feed Rate and Weld Travel Speed. The facility has also been included in the Software for setting the Standoff, however the Hardware to achieve this has not yet been installed.

x) The User can configure the Software by setting the Welding Consumables utilised, Shielding Gas Flow Rate (GFR) and the Data Acquisition Sampling Rate.

7.2) ‘Shortmon’ Initialisation:

On ‘Shortmon’ startup, the Voltage is set to the datum value of 15V (see Section 6.5.1) and the Wire Feed Rate is set to its datum value of 50mm/s (see Section 6.5.2). If there is a fault in the System that prevents the completion of this setup routine, a message is displayed stating the possible cause of malfunction and initialisation is then re-attempted. If after the second attempt the Datum settings cannot be achieved, the Program is terminated.

7.3) The ‘Shortmon’ Control Panel:

Once the Initialisation Routine has been successfully completed, the ‘Shortmon’ Control Panel is displayed on the Monitor (see Appendix VII, Visual 1). It can be seen from this Screen Dump that the Control Panel contains a Menu Bar and a Set of Blocks into which the various Functions of the ‘Shortmon’ Software are divided. The Options on the Menu Bar and the Functions of the individual Blocks are described below:

7.3.1) The Setup Option (Menu Bar):

The Setup Option on the Menu Bar allows the User to inform ‘Shortmon’ what Consumables will be utilised. The Consumable Options that can be set include:

i) Electrode Class.

ii) Electrode Diameter.

iii) Shielding Gas Type.

The Setup is a Page-through Routine with one Page per Consumable Option. The User can set the required Consumable Option by simply clicking on the Option displayed on the Page.
7.3.2) **The System Setup (Menu Bar):**

The System Setup Option on the Menu Bar is utilised to set options which are critical to the function of the Program.

The System Setup options are:

i) **Sampling Rate (Default Setting: 5KHz):**

The Sampling Rate can be set from 1KHz to 10KHz in discrete intervals of 1KHz.

ii) **The Plot Time Window (Default Setting: 10mS):**

This sets the Weld Data Time Window which may be viewed. As previously stated, this time may vary from 10mS to full Time Period of Data obtained. Please note that the Plot Time can only be altered once a Weld Run has been completed.

iii) **The Material Thickness (Default Setting: 3mm):**

The Material Thickness can be set from 3mm to 25mm in intervals of 1mm. This feature is redundant at present, but will be important when the Hardware for Automatic Standoff Control is installed as the Standoff will be set relative to a fixed Datum and therefore the Material Thickness will have to be known by the Software to enable correct setting of the Standoff.

iv) **The Gas Flow Rate (Default Setting: 14litres/min):**

The Gas Flow Rate can be set from 10l/min to 20l/min in intervals of 1 l/min. This variable is also redundant at the moment except that the GFR Setting is printed in the Run Summary and sent to File when the Data is saved. The GFR is manually set at the moment, but is anticipated that at some stage in the future, Electronic GFR Control Equipment will be installed at which point this setting will be used to set the GFR.

The System Setup Box is illustrated in Fig 7.1 overleaf. It will be noticed that the Parameters are set using Counters. The setting of a Parameter can be incremented by clicking on the up-arrow and conversely, Parameters can be decremented by clicking on the down-arrow.

The Parameters set with the System Setup are Automatically set to the Default Values on running the Software and can only be altered by the User via the System Setup Box.
7.3.3) **Individual Parameter Plots (‘Parameters’ Block):**

Graphical Displays of Voltage, Current, Wire Feed Rate, Travel Speed and Acoustic Traces can be viewed in either the Time or Frequency Domains. Typical Individual plots can be found in Appendix VII for Dip Transfer Time Domain Voltage (Visual 3), Dip Transfer Time Domain Current (Visual 4), Dip Transfer Frequency Domain Voltage (Visual 5), Dip Transfer Frequency Domain Current (Visual 6), Spray Transfer Time Domain Voltage (Visual 9), Spray Transfer Time Domain Current (Visual 10), Spray Transfer Frequency Domain Voltage (Visual 11) and Spray Transfer Frequency Domain Current (Visual 12).

The Parameter Plots are activated by clicking on the Time or Frequency Domain Button for the required Parameter.

7.3.4) **The Special Functions (‘Special’ Block):**

The first Option in the ‘Special’ Block is the General Graph Function which allows plots of up to three different Parameters simultaneously in either the Time or Frequency Domains. The Parameters that can be viewed include Voltage, Current, Wire Feed Rate, Weld Travel Speed, Acoustics, Arc Resistance and the Heat Input.
As the Arc Resistance and Heat Input are also important and useful Parameters, the ‘Special’ Block also contains an option for individual viewing of these Parameters in the Time Domain.

The Arc Resistance (R) is calculated by:

\[ R = \frac{V}{I} \]

and Heat Input (H) is calculated by the Australian Standards Definition:

\[ H = 60VI/1000TS \]

Other Functions in this Block include the Run Report and the Data Save Options.

Typical General Plots can be found in Appendix VII for Dip Transfer Time Domain (Visual 7), Dip Transfer Frequency Domain (Visual 8), Spray Transfer Time Domain (Visual 13) and Spray Transfer (Visual 14). A typical Run Report can be seen in Appendix VII, Visual 2.

7.3.5) The Action Functions (‘Actions’ Block):

The Actions Block consists only of the Data Acquisition functions which may be activated by clicking on the Button for Run Mode A or Run Mode B.

When Run Mode A is selected, Data Acquisition commences as soon as the User selects that Option, however, when Run Mode B is selected, Data Acquisition is delayed until an Electronic Signal is received from the High Speed Camera as described in Sec 6.6. The Signal is sent from the High Speed Camera when the Filming Run commences to enable time-correlated Electronic Data Acquisition with the Weld Visualisation.

The Weld Data is acquired using the Data Acquisition routines described in Sec 6.8.

7.3.6) Parameter Setting (‘Settings’ Block):

‘Shortmon’ enables Computer Setting of the Voltage, Wire Feed Rate, Weld Travel Speed and (when the Hardware is installed) Standoff.

Parameter Setting is achieved by positional adjustment of Graphical Sliders which simulate the function of Analogue Sliders often utilised in
Electronic and Acoustic Equipment. Each Slider can move vertically within a Screen Height of 100 Pixels. The units, ranges and sensitivity of the Sliders for each Parameter are given in Table 7.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Volts</td>
<td>15V</td>
<td>35V</td>
<td>0.2V/Pixel</td>
</tr>
<tr>
<td>WFR</td>
<td>mm/s</td>
<td>50mm/s</td>
<td>200mm/s</td>
<td>1.5mm/s/Pixel</td>
</tr>
<tr>
<td>TS</td>
<td>mm/min</td>
<td>150mm/min</td>
<td>450mm/min</td>
<td>3mm/min/Pixel</td>
</tr>
<tr>
<td>Standoff</td>
<td>mm</td>
<td>10mm</td>
<td>30mm</td>
<td>0.2mm/Pixel</td>
</tr>
</tbody>
</table>

One can exit the ‘Shortmon’ Program by simply clicking on ‘Exit’ in the Menu Bar.

7.4) Individual/General Time Domain Parameter Plots:

The Parameter Traces are extracted and plotted from the Parameter Data Arrays for the set Graph Time as illustrated in Fig 7.2 below:

It can be seen from Fig 7.2 that the Parameter Data Array starts at $t = 0$ and terminates at the end of the Sampling Period (SP), i.e. $t = SP$. It can also be seen that there is a Datum in the Parameter Data Array which is a Time value positioned central to the Start Time (ST) and End Time (ET) to be plotted. This Datum is initially set to the central Time Value in the Parameter Data Arrays. The
The Start Time and End Time Plot Positions in the Parameter Data Arrays are determined by the simple Algorithm listed below.

**Comment: Algorithm for ST and ET Calculation:**

\[ ST = DT - \left( \frac{PT}{2} \right) \]
\[ ET = ST + PT \]

As stated in Sec 7.3.2, the Default Plot Time is 10mS, but this can be altered to higher Plot Time Settings up to the Sampling Period. It will be observed in the Screen Dumps for the Time Domain Individual and General Plots that there is a Tool Bar at the Top Left of the Graph Page as illustrated in Fig 7.3 below:

![Fig 7.3: Tool Bar (Time Domain Plots)](image)

The Functions of each Option on the Tool Bar is given below:

7.4.1) **Tool Bar Option 1: Plot Datum Left Shift:**

This Option allows the User to Shift the Datum Time in the Array to the left as illustrated in Fig 7.4 below and overleaf.

![Fig 7.4 (a): Plot with Original Datum Postion](image)
It can be seen from Fig 7.4 that the Datum is shifted to left in the Parameter Data Array by a Left Shift Time Setting (LS) resulting in a Parameter Plot for a new ST and ET but the same PT. LS is Coarse Set by a Counter in increments of 10mS up to 500mS and can also be Fine Set by a Counter in increments of 1mS up to 10mS with the Total LS Value being the Sum of the Coarse and Fine Settings.

It is possible that Datum Shifting could move ST to a Point where it has passed the start of the Parameter Data Array (ST < 0), as illustrated in Fig 7.5 below:
If the situation described in Fig 7.5 occurs, a routine in the software simply shifts ST to the start of the Parameter Data Array (ST = 0) as illustrated in Fig 7.6 below:

The simple algorithm utilized to rectify Left Shift Overshoot Error is given below:

\[ \text{Comment: If } ST < 0 \text{ then Shift Plot Array to } ST = 0 \]

\[
\begin{align*}
ST &= 0 \\
ET &= ST + PT \\
DT &= PT/2
\end{align*}
\]

7.4.2) **Tool Bar Option 2: Plot Datum Right Shift:**

A Plot Datum Right Shift is achieved by the same method as the Datum Left Shift, except that the Datum is now moved to the right of the Original Datum Position.

As Left Shifting can result in moving ST beyond the Start of the Parameter Data Array (ST < 0), so can Datum Right Shifting result in ET being pushed past the End of the Parameter Data Array (ET > SP), as illustrated in Fig 7.7 overleaf:
If the above situation occurs then another Routine in Software simply moves the Plot Array to a position such that ET = SP by the Algorithm given below:

*Comment: If ET > SP then shift Plot Array to ET = SP*

- \[ ET = SP \]
- \[ ST = ET - PT \]
- \[ DT = ST + DT/2 \]

7.4.3) **Tool Bar Option 3: Plot Time Alteration:**

This Option enables the User to increase or decrease the Plot Time as illustrated in Fig 7.8 below and overleaf:
The usefulness of Plot Time Alteration is that the User can increase the Plot time to view a longer period of the Weld, but can also reduce the Plot Time to study, for example, individual Dipping Periods when welding in Dip Transfer Mode. The Plot Time is set by a Counter in 10mS increments with settings ranging from 10mS up to the Sampling Period.

With Plot Time Alterations, it is possible, depending on the Datum Position, that the Start Time of the Plot Array could be moved past the Start of the Parameter Data Array (ST < 0) or the End Time of the Plot Array could be moved past the end of the Parameter Data Array (ET > SP). These situations are rectified using the same Algorithms as used to correct the Left and Right Shift Overshoot.

7.4.4) Tool Bar Option 4: Screen Dump:

When this Option is selected a Screen Dump of the Plot is sent to the Printer by executing DOS Interrupt 0x5.

Error Messages have been included in the Software that inform the User if the Printer is switched off, out of paper or off-line.
7.4.5) **Tool Bar Option 5 (General Plots Only): Parameter Selection:**

Selecting this Parameter Selection Option produces a Menu that enables the User to select up to three Parameters to be viewed simultaneously in the General Graph Plot. The Parameters which may be viewed include Voltage, Current Wire Feed Rate, Travel Speed, Acoustics, Resistance and Heat Input.

The Parameter Range on the Graph Scale is also automatically determined for the Maximum and Minimum Parameter Values in the Data covered by the Plot Time. Also printed on the Plot is the Start and End Times of the Plot in the Parameter Data Array.

In addition to the Parameter Plot, the following Statistics are calculated and displayed for the Plotted Data on the Individual Parameter Plots but not on the General Plots due to lack of screen space:

i) The Mean (or Average) Parameter Value.

ii) The Maximum Parameter Value.

iii) The Minimum Parameter Value.

iv) The Parameter Data Range (ie. Max Value - Min Value).

v) The Sampling Interval (Seconds).

vi) The Sampling Frequency (Hz).

vii) The number of Parameter Samples plotted.

7.5) **Individual/General Frequency Domain Parameter Plots:**

Frequency Domain Plots are obtained by taking a Fast Fourier Transform (FFT) of a Section of the Data in the Parameter Data Array. The size of the Data Section (DS) is a Power of 2:

\[ DS = 2N = 2^n \quad \text{where: } 5 \leq n \leq 11 \]

The FFT Routine was obtained from ‘Numerical Recipes in C’ [74] Sec 12.2 - 12.3 and is the Routine used for the FFT of a Single Real Function. The Input to the Array contains 2N Real Samples and the Output Array contains the positive half of its Complex Fourier Transform. The real-valued first and last components of the FFT are returned in the first two elements respectively of the Output Array.
Fig 7.9 below illustrates the Time Domain Input and subsequent Frequency Domain Output of the FFT Routine.

![Fig 7.9: Input and Output Arrays for FFT.](image)

Once an FFT has been completed, the Real FFT Data is extracted from the FFT Array and rearranged in a separate Real FFT Array in increasing order of Frequency. The Real FFT Array has N-1 Real FFT Values. Power Spectrum Estimation (PSE) is then calculated for each component of the Real FFT Array by:

\[ P(f_k) = \frac{|X_k|^2}{N^2} \]

where:

- \( k \): Real FFT Array Position \( 1 \leq k \leq N \)
- \( P(f_k) \): The PSE for the Frequency at point \( k \) in the Real FFT Array.
- \( X_k \): The Real FFT value at point \( k \) in the Real FFT Array.
As with the Time Domain Plots, there is a Datum in the Parameter Data Array which is a Time Value central to the Data Points extracted for the FFT calculations as illustrated in Fig 7.10 below.

The FFT Data Period (FDP) will depend on the number of Points set for the FFT calculation. The Algorithm for determining the FFT Plot Start Time (FST) and End Time (FET) is given below:

\[
\text{Comment: Algorithm for FST and FET Calculation:} \\
\text{FST} = \text{FDT} - \left(\frac{\text{FDP}}{2}\right) \\
\text{FET} = \text{FST} + \text{FDP}
\]

As with the Time Domain parameter Plots, there is also a Tool Bar on the Individual and General Frequency Domain Plots, as illustrated in Fig 7.11 below.
The Functions for each Option on the Frequency Domain Tool Bar are given below:

7.5.1) **Tool Bar Option 1: FFT Plot Datum Left Shift:**

This Option allows the User to shift the FFT Datum to the Left allowing an FFT to be taken of a Time Period left of the original FFT Datum Setting (FDT) and has the same Left Shift Overshoot Elimination Algorithm (i.e. if \( FST < 0 \)) as that entered for the Time Domain Left Shift Option. The Left Shift FDP Overshoot Algorithm is listed below (also refer to Fig 7.10 for Symbol Details):

*Comment: If \( FST < 0 \) shift FDP to \( FST = 0 \).*

- \( FST = 0 \)
- \( FET = FDP \)
- \( FDT = FET/2 \)

7.5.2) **Tool Bar Option 2: FFT Plot Datum Right Shift:**

This Option allows the User to shift the FFT Datum (FDT) to the right allowing an FFT to be taken of a Time Period right of the original FFT Datum Setting and has the same Right Shift Overshoot Elimination Algorithm (i.e. if \( FET > SP \)) as that entered for the Time Domain Right Shift Option. The Right Shift FDP Overshoot Algorithm is listed below (also refer to Fig 7.10 for Symbol Details):

*Comment: If \( FET > SP \) shift FDP to \( FET = SP \).*

- \( FET = SP \)
- \( FST = FET - FDP \)
- \( FDT = FST + FDP/2 \)

7.5.3) **Tool Bar Option 3: FFT Points Setting:**

With this Option the User may set the required number of FFT Points ranging from 32 Points to 4096 Points in intervals to the power of 2.

As with the Plot Time Alterations in the time Domain Plots, it is again possible, depending on the FFT Datum Position and the number of FFT Points, that the FFT Start time (FST) could be moved past the start of the Parameter Data Array (FST < 0) or the FFT End Time (FET) could be moved past the end of the Parameter Data Array (FET > SP). These situations are again rectified using the same Algorithms used to correct the Left and Right Overshoot.
7.5.4) **Tool Bar Option 4: Screen Dump:**

This Option is exactly the same as the corresponding Option in Time Domain Plots in that when it selected, a Screen Dump of the FFT Plot is sent to the Printer through the execution of DOS Interrupt 0x5.

7.5.5) **Tool Bar Option 5 (General FFT Plots Only): Parameter Selection:**

This Option allows the user to select and view the FFT’s of up to three Parameters. The Parameters for which FFT’s may be calculated includes Voltage, Current, Wire Feed Rate, Travel Speed, Arc Resistance and Heat Input and any of these parameters may be selected for the General FFT Plot.

The PSE Scales on the FFT Plots start at zero with the Maximum Scale Value determined by the Maximum PSE value in the Plot.

In addition to the FFT Plot, the following Statistics are displayed with the Individual Parameter FFT Plots and also with the General FFT Plots:

i) The FFT Start Time in the Parameter Data Array (FST).

ii) The FFT End Time in the Parameter Data Array (FET).

iii) The FFT Data Period (FDP).

iv) The Sampling Interval.

v) The number of FFT Points.

7.6) **The Run Report:**

The Run Report provides a Summary of the last Weld Run. It is important to note that the Report is produced for the Data contained within the current Plot Time only and not for the whole Parameter Data Array. The Report contains the following information.

i) The Voltage, Wire Feed Rate, Weld Travel Speed and Standoff Settings.


iii) Consumable details including the Electrode Class and Type, Shielding Gas Type and Gas Flow Rate.
iv) The Mean, Maximum, Minimum and Range Values for the Feedback Voltage, Current, Wire Feed Rate, Weld Travel Speed and Acoustics. The Range is the difference between the Maximum and Minimum Parameter values.

v) The Sampling Interval, Sampling Frequency, number of Samples for which the Statistics determined in (iv) above were obtained.

vi) The Start Time (ST), End Time (ET) and Plot Time (PT) of the current Plot Window within the Parameter Data Array.

7.7) The Save Option:

The ‘Shortmon’ Program allows the User to save the required data to Hard or Floppy Disk. Please note that, as with the Run Report, only the data within the Current Plot Window is saved and not the complete Parameter Data Array.

When the Save Option is selected, the User enters a Filename of up to 8-Characters, but does not include the extention because ‘Shortmon’ saves the data to three separate files and automatically adds the extensions to the filename entered. The following files are created when saving data in ‘Shortmon’:

i) The Weld Feedback Data File:

The Weld Feedback Data file is saved as: filename.sdt

This file contains the Weld Feedback Data for the current Plot Window including Voltage (V), Current (I), Wire Feed Rate (W), Weld Travel Speed (S), Acoustics (A) and the Time of the Sample (T) relative to the start of the current Plot Window. The data is saved in the format displayed in Fig 7.12 below:

<table>
<thead>
<tr>
<th>V(1)</th>
<th>Tab</th>
<th>I(1)</th>
<th>Tab</th>
<th>W(1)</th>
<th>Tab</th>
<th>S(1)</th>
<th>Tab</th>
<th>A(1)</th>
<th>Tab</th>
<th>T(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(2)</td>
<td>Tab</td>
<td>I(2)</td>
<td>Tab</td>
<td>W(2)</td>
<td>Tab</td>
<td>S(2)</td>
<td>Tab</td>
<td>A(2)</td>
<td>Tab</td>
<td>T(2)</td>
</tr>
<tr>
<td>V(n-1)</td>
<td>Tab</td>
<td>I(n-1)</td>
<td>Tab</td>
<td>W(n-1)</td>
<td>Tab</td>
<td>S(n-1)</td>
<td>Tab</td>
<td>A(n-1)</td>
<td>Tab</td>
<td>T(n-1)</td>
</tr>
<tr>
<td>V(n)</td>
<td>Tab</td>
<td>I(n)</td>
<td>Tab</td>
<td>W(n)</td>
<td>Tab</td>
<td>S(n)</td>
<td>Tab</td>
<td>A(n)</td>
<td>Tab</td>
<td>T(n)</td>
</tr>
</tbody>
</table>

n = Number of Sample Sets in the Sampling Period

Fig 7.12: ‘Shortmon’ Feedback Data File Format.
It can be seen from Fig 7.12 that the data is saved with a 'Tab' between each Data Item. This is to enable the File to be used for Off-line analysis with Applications Packages such as Excel and Matlab.

ii) **The Plot File:**

The Plot File is saved as: filename.plt

This File contains the Plotting Information including the Start Time (ST), End Time (ET) and Plot Time (PT) of the Plot Window in the Parameter Data Array. Also included in this File is the Sampling Interval and the Sampling Frequency.

iii) **The Miscellaneous File:**

The Plot File is saved as: filename.smi

The File contains the Data and Time of the last Weld Run. Also saved in this File is the Workpiece Material Type and the Consumable details including Electrode Class, Electrode Size, Shielding Gas Type and Gas Flow Rate.
Chapter 8

The 'Longmon' Weld Monitoring Package

8.1) Introduction to the 'Longmon' Program:

The 'Longmon' Package is a Mouse-driven GUI developed to provide a User-friendly Tool for Monitoring and Studying the Behaviour of the Welding Process over longer Welding periods. It is also written in the 'Borland C' Programming Language.

The 'Longmon' Package possesses the following Facilities:

a) The ability to monitor Weld Voltage, Current, Wire Feed Rate and Weld Travel Speed. The Facility for the monitoring of Audible Weld Acoustics has also been included but as already stated, the Hardware for this activity has not been installed at the time of writing.

b) The 'Longmon' Package obtains from 100 up to 2000 Parameter Sets in a Sampling Period and Graphically plots the Mean Parameter Values in Real-time as the Weld progresses. The Sampling Frequency can be set from 1KHz to 10KHz. The Facility also exists to setup a Rest Period inbetween Sampling Periods if required.

c) The User can set the Voltage, Wire Feed Rate and Weld Travel Speed by GUI Sliders. The facility has also been included for GUI Slider setting of the Standoff, but the Hardware to achieve this has yet to be installed.

d) The Welding Parameters can be altered during the Welding Run enabling the effects of Parameter Alteration on the Welding Process to be studied. Up to five Parameter Alterations can be made per Run.

e) A Histogram can be printed of the Parameter Alterations made during a Weld Run. This information includes the Parameter Settings after Alteration and also the time into the Weld Run when the Parameter Alteration occurred.

f) The Scales on the Parameter Graphs can be altered after a Weld Run to obtain maximum resolution for the Parameter Trace.

g) The Parameter Traces can be Printed as a Screen Dump.

h) The User can configure the Software for Consumables utilised, the Gas Flow Rate and the Workpiece Thickness.
8.2) ‘Longmon’ Initialisation:

The Initialisation Routine for ‘Longmon’ is identical to that of the ‘Shortmon’ Package. On ‘Longmon’ startup, the Voltage is set to the datum value of 15V (see Section 6.5.1) and the Wire Feed Rate is set to its datum value of 50mm/s (see Section 6.5.2). If there is a fault in the System that prevents the completion of this setup routine, a message is displayed stating the possible cause of malfunction and initialisation is then re-attempted. If after the second attempt the Datum settings cannot be achieved, the Program is terminated.

8.3) The ‘Longmon’ Screen Layout:

Once the Initialisation Routine has been successfully completed, The ‘Longmon’ Screen Page is displayed on the Monitor (See Appendix VIII, Visual 1). The Screen Page consists of a Menu Bar, the GUI Sliders for Parameter Setting and Screen Locations for the Real-time Plotting of the Voltage, Current, Wire Feed Rate, Weld Travel Speed and Acoustic Feedback. The Function of each Option on the Menu Bar is discussed in Sec 8.4 and Parameter Setting using the GUI Sliders in Sec 8.5.

8.4) The ‘Longmon’ Menu Bar:

8.4.1) The Configuration Setup (Setup):

This Option is identical to the Option of the same name in the ‘Shortmon’ Program in that it presents a Page-through Menu for setting the Consumable Options including the Electrode Class, Electrode Diameter and the Shielding Gas Type. Each Option Page consists of Click-on Boxes and the User may enter a selection by simply clicking on the appropriate Box.

8.4.2) The Graph Axis Range Setup (Range):

Due to the often unpredictable nature of Weld Parameter Feedback, all the axes of the Real-time Parameter Plots during a Weld Run range from a default minimum value up to a default maximum value. The default Plot Ranges for each Parameter are listed in Table 8.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default Graph Axis Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>15 V - 35V</td>
</tr>
<tr>
<td>Current</td>
<td>0A - 400A</td>
</tr>
<tr>
<td>Wire Feed Rate</td>
<td>50mm/s - 200mm/s</td>
</tr>
<tr>
<td>Weld Travel Speed</td>
<td>150mm/min - 450mm/min</td>
</tr>
<tr>
<td>Weld Acoustics</td>
<td>0dB - 150dB</td>
</tr>
</tbody>
</table>
These settings can be seen in Appendix VIII, Visual 1 which displays the Screen Page after initialisation but before the first weld run.

However, on completion of a weld run, these Axis Ranges will not provide the optimum resolution for the Parameter traces plotted. The Graph Axis Range Setup therefore enables the User to set the maximum and Minimum Axis Settings for each Parameter so that the optimum resolution can be obtained for each Parameter Plot.

The Optimum Axis settings are set using a Page-through Routine with one page for each Parameter Setting and also a final page for setting Maximum and Minimum Time Values on the Horizontal Axis. There are two Counters on each Page that enable the User to set the Minimum and Maximum Axis Values for the Parameter of the current Page. The Page-through Routine displays an Error Message if the Minimum Axis Setting is greater than or equal to the Maximum Axis Setting.

Visual 3 in Appendix VIII illustrates a Dip Transfer Weld Run as recorded in Real-time with the Default Parameter Settings and Visual 4 illustrates the same Weld Run after Parameter Axis Modification. Visuals 5 and 6 in Appendix VIII illustrate a Spray Transfer Weld Run before and after Parameter Axis Modification.

As the Graph Axis Range Setup enables the User to set the Axis Ranges for the Parameter Plots of a Weld Run, this Option can only be activated once a Weld Run has actually taken place.

### 8.4.3) The System Setup (Setup):

As with the 'Shortmon' Program, the System Setup Option in the 'Longmon' Program is utilised to set options which are critical to the function of the 'Longmon' Program.

The System Setup options are:

i) **Sampling Frequency (Default Setting: 5KHz):**
   The Sampling Rate can be set from 1KHz to 10KHz in discrete intervals of 1KHz.

ii) **The Run Time (Default Setting: 20 Seconds):**
    The Run Time is the Period over which Data Acquisition will occur and will be the Maximum Time value on the Parameter Plots. The Run Time can vary from 5 Seconds up to 120 Seconds in increments of 1 Second. The maximum Run Time may be extended if demanded by future research requirements.
iii) The Sample Count (Default Setting: 1000 Sample Sets):
The Sample Count is the Number of Parameter Sample Sets acquired in a Sampling Period. After the Sampling Period, the Data collected is averaged to produce Mean Parameter Values which are then plotted. The number of Sampling Periods completed in a Weld Run will depend on the Sample Count Setting, the Sampling Frequency, the Weld Travel Speed and the Interval Setting (described in (v) below). The Sample Count can vary from 100 up to 2000 Sample Sets in increments of 100 Sets.

iv) The Material Thickness (Default Setting: 3mm):
The Material Thickness can be set from 3mm to 25mm in intervals of 1mm. This feature is redundant at present, but will be important when the Hardware for Automatic Standoff Control is installed as the Standoff will be set relative to a fixed Datum and therefore the Material Thickness will have to be known by the Software to enable correct setting of the Standoff.

v) The Interval Setting (Default Value: 0 mS):
The Interval Setting is a rest period inbetween Sampling Periods and can vary from 0mS to 5000mS in increments of 10mS. It is unlikely that Interval will ever be used but was included in case it was required for future experimental work.

iv) The Gas Flow Rate (Default Setting: 14litres/min):
The Gas Flow Rate can be set from 10l/min to 20l/min in intervals of 1l/min. This variable is also redundant at the moment except that the GFR Setting is printed on Screen Dumps of Parameter Plots and sent to File when the Data is saved.

When the System Setup Option is selected, a System Setup Box, identical to that for the System Setup in the ‘Shortmon’ Program (See Fig 7.1) will appear on the Screen and the above described Parameters can be set by the Counters displayed for each Parameter.

8.4.4) The Data Acquisition Routine (Run):

When this Option is selected, the Program enters the Data Acquisition Routine and acquires, averages and then plots Parameter Data in real-time as the Weld Progresses. The Run Option is described in detail in Sec 8.6.

8.4.5) The Data Save Routine:

The Data Save Routine saves to File the Averaged Parameter Values for each Sampling Period in the last Weld Run. Other information is also saved to File and is discussed in detail in Sec 8.7.
8.4.6) **The Plot Option (Plot):**

When selected, the Plot Option sends a Screen Dump of the Parameter Traces to the Printer by executing DOS Interrupt 0x5. This option is activated after completion of the first Weld Run.

Error Messages are printed if the Printer is switched off, out of paper or off-line.

8.4.7) **The Histogram Option (Hist):**

As stated, the 'Longmon' Program enables in-weld alteration of Weld Parameters. These Parameter alterations are recorded and can be viewed by selecting the Histogram Option. A typical Histogram is shown in Fig 8.1 below:

<table>
<thead>
<tr>
<th>Event</th>
<th>U (V)</th>
<th>W (mm/s)</th>
<th>TS (mm/min)</th>
<th>L (mm)</th>
<th>Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.00</td>
<td>80.0</td>
<td>300</td>
<td>16.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>21.00</td>
<td>108.1</td>
<td>300</td>
<td>16.0</td>
<td>8.4</td>
</tr>
<tr>
<td>2</td>
<td>25.50</td>
<td>108.1</td>
<td>300</td>
<td>16.0</td>
<td>13.3</td>
</tr>
<tr>
<td>3</td>
<td>25.50</td>
<td>108.1</td>
<td>248</td>
<td>16.0</td>
<td>17.7</td>
</tr>
</tbody>
</table>

**Fig 8.1: Parameter Settings Histogram**

It can be seen from Fig 8.1 that 3 Parameter Alterations were made during the Weld Run and the Parameter Settings at each alteration recorded together with the Time into the Weld Run that the alterations were made. The Histogram prints out the Original Parameter Settings (Event 0) followed by the Parameter Alterations (Events 1, 2 and 3). The Histogram Data can also be sent to the Printer by clicking on the Print Button.

This option is also only activated after the first Weld Run. Should no Parameter Alterations be made during a Weld Run, the Histogram will only display the Original Parameter Settings (Event 0).
8.4.8) The Delay Option:

In normal use of the ‘Longmon’ Program, the User will start the Welding Process and then activate the Data Acquisition Routines by clicking on the ‘Run’ Option. When the User selects the ‘Run’ Option the Program will automatically go straight into the Data Acquisition Routine.

However, there are circumstances where it is necessary to commence Data Acquisition at the exact moment when the Welding Process starts. An example of this is the use of the Current/Standoff Model Verification Jig (See Fig 9.10 and drawing entitled ‘Current/Standoff Model Verification Jig’ in Appendix VI) for verification of Standoff Models where the Weld Run commences at a specified point on the Jig and the Data Acquisition must also commence at this same point to ensure correlation of Parameter Feedback with the Actual Standoff at any point.

To enable the correlated commencement of Data Acquisition and the Weld Run, a Delay has been included in the Software that prevents entry into the Data Acquisition Routine until the Delay Routine detects that the Welding Process has started.

The Delay is simply a Software loop that checks to see if the Voltage and Wire Feed Rates have risen above Threshold values and the loop will only terminate when the readings for both Parameters have risen above their respective Threshold values. The Threshold for the Voltage is set to 15V and the Threshold for the Wire Feed Rate is 50mm/s.

On selecting the Delay Option, a Click-on Box is displayed on the screen which enables the User to toggle between Activation and Deactivation of the Delay Routine.

8.5) The GUI Sliders for Parameter Setting:

As in the ‘Shortmon’ Program, Parameter Setting is achieved by positional adjustment of the GUI Sliders. In the ‘Longmon’ Program, each Slider can move vertically within a Screen Height of 80 Pixels as compared to the Screen Height of 100 Pixels for the ‘Shortmon’ Program, resulting in slightly reduced sensitivity of the Sliders in ‘Longmon’. The reduced Screen Height in ‘Longmon’ was necessary because of the lack of Screen Space. The units, ranges and sensitivity of the Sliders for each parameter are given in Table 8.2 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Volts</td>
<td>15V</td>
<td>35V</td>
<td>0.25V/Pixel</td>
</tr>
<tr>
<td>WFR</td>
<td>mm/s</td>
<td>50mm/s</td>
<td>200mm/s</td>
<td>1.875mm/s/Pixel</td>
</tr>
<tr>
<td>TS</td>
<td>mm/min</td>
<td>150mm/min</td>
<td>450mm/min</td>
<td>3.75mm/min/Pixel</td>
</tr>
<tr>
<td>Standoff</td>
<td>mm</td>
<td>10mm</td>
<td>30mm</td>
<td>0.25mm/Pixel</td>
</tr>
</tbody>
</table>
The Sliders are utilised to set Parameters before a Weld Run, but are also utilised for in-weld Parameter alterations.

8.6) The 'Longmon' Data Acquisition Algorithm:

The Flowchart in Fig 8.2 illustrates the Algorithm used for Data Acquisition, Parameter Averaging and Data Plotting:

![Flowchart Image]

Fig 8.2: 'Longmon' Algorithm for Data Acquisition, Averaging and Plotting

Note:
See Sec 6.8 for details of Raw Weld Data Acquisition and Real Parameter Value calculation.
If the Delay is set to 'Active', then the Graph Axis will be plotted on the screen (as illustrated in Appendix VIII, Visual 2), but Data Acquisition will be delayed until the Welding Process is started.

During the execution of the Algorithm illustrated in Fig 8.2, the Parameter Data collected for each Sampling Period is averaged and then stored in Mean Parameter (MP) Arrays at the current Memory Location Pointer (k). This is further illustrated in Fig 8.3 below:

**Fig 8.3: Acquired Data Organisation in the 'Longmon' Program**

Please note with respect to Fig 8.3 that individual Sampling Period and Mean Parameter Arrays are created for the Voltage, Current, Wire Feed Rate, Weld Travel Speed and Acoustics Feedback as illustrated in Fig 8.4 below:

**Fig 8.4: Parameter Array Structures in 'Weldmod'**
8.7) The Save Option:

The ‘Longmon’ Program allows the User to save to File the Mean Parameter Values for each Sampling Period in the last Weld Run.

When the Save Option is selected, the User enters a Filename of up to 8-Characters, but does not include the extension because ‘Longmon’ saves the data to three separate files and automatically adds the extensions to the filename entered. The following files are created when saving data with ‘Longmon’:

i) The Parameter Data File:

The Weld Feedback Data file is saved as: filename.Idt
This file contains the Averaged Parameter Values for each Sampling Period in the last Weld Run with the record for each Sampling Period containing the Mean Voltage (V), Current (I), Wire Feed Rate (W), Weld Travel Speed (S) and Acoustics (A) Parameter Data together with the Time acquired at the end of the Sampling Period (T) relative to the start of Data Acquisition. The data is saved in the format displayed in Fig 8.5 below:

```
V(1) Tab I(1) Tab W(1) Tab S(1) Tab A(1) Tab T(1)
V(2) Tab I(2) Tab W(2) Tab S(2) Tab A(2) Tab T(2)
V(m-1) Tab I(m-1) Tab W(m-1) Tab S(m-1) Tab A(m-1) Tab T(m-1)
V(m) Tab I(m) Tab W(m) Tab S(m) Tab A(m) Tab T(m)
```

\[ m = \text{Number of Sampling Periods in the Weld Run} \]

**Fig 8.5: ‘Longmon’ Feedback Data File Format.**

It can be seen from Fig 8.5 that ‘Longmon’ Data is saved in exactly the same format as the ‘Shortmon’ Data File. This is also to enable ‘Longmon’ Data Files to be used for Off-line analysis with Generic Application Packages.

ii) The Histogram File:

The Histogram File is saved as: filename.hst
iii) The ‘Longmon’ Miscellaneous File:

The ‘Longmon’ Miscellaneous File is saved as: filename.lmi

The File contains the Date and Time of the last Weld Run. Also saved in this File is the Sampling Frequency, Sample Count, Interval Setting, Graph Time, Workpiece Material Type and the Consumable details including Electrode Class, Electrode Size, Shielding Gas Type and Gas Flow Rate.
Chapter 9

Investigation into the use of the MWEF for Real-time Condition Monitoring and Irregularity Detection

This Chapter illustrates the uses of the MWEF for furthering understanding of the Welding Process and also for the development of Real-time Control Strategies. To achieve this, the following series of experiments was performed to investigate the effects of Welding phenomena and irregularities on the Welding Process:

i) A study of the effects of In-Weld Parameter alteration.

ii) The Effects of Standoff variation on Voltage and Current readings.

iii) The effects of Surface Contaminants on Parameters and Weld Stability.


v) Detection of Isolated Transient Irregularities.

The procedures and results for the above stated sets of experimentation are presented in the following sections of this Chapter.

9.1) Studies of the Effects of In-Weld Parameter Alteration:

As stated, the ‘Longmon’ program allows In-Weld Parameter Alteration which enables the effect of Parameter alterations to be studied on-line and in Real-time. Visual 7 in Appendix VIII illustrates a Weld Run where the Parameters have been altered. The effects of the Parameter alterations can clearly be seen on the Real-time plots. Table 9.1 displays the Histogram of Parameter Alteration Events as illustrated in Appendix VIII Visual 8. The Parameter altered in a particular Event is shown in italics (and in red in the Software Histogram). The time into the Weld Run that a Parameter Alteration Event occurred is given in the last column.

<table>
<thead>
<tr>
<th>Event</th>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>TS (mm/min)</th>
<th>L (mm)</th>
<th>Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>24.00</td>
<td>160.6</td>
<td>386</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>30.50</td>
<td>160.6</td>
<td>386</td>
<td>20.0</td>
<td>7.2</td>
</tr>
<tr>
<td>2</td>
<td>30.50</td>
<td>113.8</td>
<td>386</td>
<td>20.0</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>30.50</td>
<td>113.8</td>
<td>285</td>
<td>20.0</td>
<td>19.3</td>
</tr>
<tr>
<td>4</td>
<td>30.50</td>
<td>149.4</td>
<td>285</td>
<td>20.0</td>
<td>29.1</td>
</tr>
</tbody>
</table>

WFR = Wire Feed Rate, TS = Travel Speed, L = Standoff
Explanations of the resulting Parameter Feedback for each Event as observed in Appendix VIII, Visual 7) are given below:

**Event 0:** The Original Parameters set before commencing of the Weld Run:

It will be observed that the Voltage reading (about 21.0V) is much less than the Voltage Setting (24.0V). As discussed in Sec. 1.3 and illustrated in Fig. 1.4, for a particular Voltage Setting there will be an almost linear drop in the Voltage as the Current increases. For the Transmig350 EC Machine there is a Voltage drop of 2.25V/100A (i.e. for a particular Voltage setting, the Voltage will decrease by 2.25V for an increase in Current of 100A). As the Current Reading is high (about 295A) it can therefore be expected that a significant difference between the set and measured Voltage could occur. It should be remembered that the Voltage Setting is just simply a dial setting and will only approximately equal the actual Voltage for a small Current range on the V-I Slope.

**Event 1:** The Voltage Setting is increased from 24.00V to 30.50V:

The real Voltage increases from 21.0V to about 27.0V. It will be observed that the Current also increases substantially. This is due to the Arc Characteristics which dictate that with an increase in the Voltage Setting, there must also be a linear increase in the Welding Current as illustrated in Fig 9.1 below:

![Fig 9.1: Effect of Voltage Increase on the Current Reading](image)

It can be clearly seen that the increase in Voltage induces an increase in Current from 295A to about 340A.
Event 2: The Wire Feed Rate is reduced from 160.6mm/s to 113.8mm/s:

The Wire Feed Rate is directly related to the Current as discussed in Sec. 1.3 and illustrated in Fig. 1.5. As the Wire Feed Rate is substantially reduced it can be expected that the Current will also be substantially reduced as occurs with a Current drop from 340A down to circa 285A.

Event 3: The Weld Travel Speed is reduced from 385mm/min to 285mm/min:

It can be seen that due to the inertia of the Welding Table, it takes about 1.5 seconds for the Weld Travel Speed to decelerate from 385mm/min to 285mm/min. It will also be observed that altering the Travel Speed has no observable effect on the Voltage and Current.

Event 4: The Wire Feed Rate is increased from 113.8mm/s to 149.4mm/s

In contrast to Event 2, increasing the Wire Feed Rate has the effect of increasing the Current as can be observed by the increase in Current from 285A up to circa 330A.

It can be seen that the facility for In-Weld alteration can be used as a tool for exhibition and study of the effects of parameter alteration on other welding parameters.

The In-Weld Parameter alteration facility of the ‘Longmon’ Program can also be used for the assessment of GMAW Power Sources and Consumables by determining the following:

i) V-I Characteristics:

V-I Characteristics can be obtained for a range of Voltage settings by stepping through a range of WFR settings for each Voltage setting. The Voltage will decrease as the WFR and hence Current increases. The Voltage readings can then be plotted against Current readings to obtain the V-I Slopes from which can be determined the V-I Characteristic.

ii) WFR-Current Characteristics:

The relationship between WFR and Current can be determined by stepping through a range of WFR settings for a selected Voltage setting. The WFR settings can then be plotted against corresponding Current readings for the relationship between WFR and Current.

iii) Arc Characteristics

Arc Characteristics can be determined by stepping through a range of Voltage settings for a selected WFR setting. Plotting the Voltage against the resulting
Current readings enables the Arc Characteristic line to be determined.

9.2) The Effect of Standoff Variations on Voltage and Current Readings:

Another use of the ‘Longmon’ Program, and one which is of importance to the aims of this thesis, is the effect of varying Standoff on Voltage and Current Readings. Visuals 9 and 10 of Appendix VIII illustrate the result of experiments undertaken using the ‘Longmon’ Program to investigate this phenomena.

In Visual 9, ‘Longmon’ was to used to monitor Weld Parameters over a stepped specimen as illustrated in Fig 9.2 overleaf:

It can be seen from Fig 9.2 that as the Weld Gun passes over a step the Standoff is increased by 4mm. It can also be seen from Visual 9 of Appendix VIII, that as the Weld Gun passes over a step, the Current is almost instantaneously reduced whilst the Voltage is slightly increased (as one would expect for the Voltage/Current characteristics of the Transmig 350 EC as displayed in Appendix IV). Table 9.2 below displays the approximate Current Readings for each step in the testpiece:

<table>
<thead>
<tr>
<th>Step No</th>
<th>Standoff (mm)</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>28.9</td>
<td>314</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>29.8</td>
<td>288</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>30.2</td>
<td>274</td>
</tr>
</tbody>
</table>
Visual 10 of Appendix VIII illustrates a Weld Run for the same Voltage, Wire Feed Rate and Original Standoff Settings as the Weld Run displayed in Visual 9 except that for this experiment, the Weld was produced over a Gradient Descent by using the Current/Standoff Model Verification Jig illustrated in Fig 10.10 (and also in Appendix VI). The Standoff also increases from 16mm to 24mm over the same Weld Length of 200mm.

It can be seen from Visual 10 that as the weld progresses, there is an almost linear decrease in Current and linear increase in Voltage with the linear increase in Standoff. The starting and terminating Voltage and Current Readings are almost identical to those obtained for the Stepped Testpiece.

The linearity of the relationship between Current and Standoff indicates that the Current Feedback may be utilised for predicting the Standoff value in Automated Welding Operations.

9.3) **The effects of Surface Contaminants on Parameters and Weld Stability:**

Surface Contaminants create a Resistance in the welding circuit and can therefore significantly affect the Welding Voltage and Current and hence also the Weld Bead Geometry. Contaminants can also lead to inclusions in the Weld Bead which would adversely affect the physical properties of the weld.

To test the effects of Surface Contaminants on the Welding Process, a series of experiments was performed with various contaminants as described in Table 9.3 below:

<table>
<thead>
<tr>
<th>Set</th>
<th>Contaminants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Descaled and degreased plain metal surface</td>
</tr>
<tr>
<td>2</td>
<td>Scaled but degreased metal surface</td>
</tr>
<tr>
<td>3</td>
<td>Painted Surface (Undercoat and Gloss Enamel Finish)</td>
</tr>
<tr>
<td>4</td>
<td>Bearing Grease</td>
</tr>
</tbody>
</table>

**Experimental Constants:**

Material: 8mm x 100mm x 250mm MS Bar (Grade 250)  
Electrode: Autocraft LW1 (1.2mm Dia)  
Shielding Gas: Argoshield 50 (GFR = 14l/min)  
Voltage Setting=22V, WFR Setting=75mm/min  
Travel Speed Setting=300mm/min, Standoff Setting=16mm

In order to obtain a firm basis of comparison between normal welding conditions and those induced by surface contaminants, it is necessary to obtain parameter feedback for Stable Welding Conditions over a descaled and degreased surface. The parameters to achieve stable welding conditions were obtained using the
'Shortmon' Program and are given in Table 9.3.

Each Set of contaminants are monitored over 5 weld runs using both the 'Shortmon' and 'Longmon' Programs. The Details of the setup and functions of each program are given below:

i) **Use of the 'Shortmon' Program:**

The 'Shortmon' Program is used to monitor the dipping frequency, weld stability and details of irregularities whilst welding over the surface contaminants.

The 'Shortmon' Sampling Rate=5KHz and the Weld Length=40mm.

ii) **Use of the 'Longmon' Program:**

As Real-time weld monitoring of Dip Transfer Welding will be undertaken in data acquisition windows covering approximately 10 dips, the 'Longmon' Program is utilised to evaluate the real-time response of a monitoring system to the detection of surface contaminants.

The 'Longmon' Sampling Rate=5KHz with a Sampling Window of 2500 Samples. These Settings were selected because of the low dipping frequency of the Transmig 350 EC (circa 20 Hz) where to obtain approximately 10 dips, a Sampling Window of 2500 Samples would be required at 5KHz. The Weld Length is 200mm with a Surface Contaminant Length of 100mm in the centre of the weld run. About 50mm of weld run over descaled and degreased surface is completed before and after the contaminated section to enable the start and end of the contaminated area to be detected.

It is possible that in Real-time weld monitoring, Transient Isolated Irregularities (i.e. irregularities that occur within one data acquisition window and are detected as irregularities in the means of parameter feedback for the window) could occur that would not significantly affect the overall welding process or weld bead profile and therefore would not require any modification of the process parameters.

However, on detecting an isolated irregularity, a control system might unnecessarily modify the process parameters only to detect from subsequent data acquisition windows that the modifications have adversely affected the welding process. It is therefore necessary in real-time control of the welding process to use a number of data acquisition windows for analysis of the current state of the welding process and monitor 'trends' for irregularity detection and not (in most cases) individual data acquisition windows.

This can be achieved by using a 'Rolling Average' which is an average of the means of the present data acquisition window and the means of a specified number of previous data acquisition windows. Isolated parameter irregularities are
effectively 'soaked up' in the Rolling Average and irregularities will therefore only be detected if they continue for a number of data acquisition windows. It is necessary to optimise the number of data acquisition windows in the Rolling Average as too few windows will not effectively eliminate isolated irregularities, but too many windows would cause significant delays in the detection of genuine irregularities. It was determined by experimentation that the optimum number (n) of data acquisition windows is 5 (for a Sampling Rate of 5khz and Sampling Window of 2500 Samples). The Rolling Average (RA) of any monitored parameter (P) is therefore calculated as:

\[
RA(k) = \left( \frac{\sum P_i}{n} \right) \quad \text{where:} \quad k -(n-1) <= i <= k
\]

Another important real-time consideration is the Response Time which is defined as the time difference between the detection of an irregularity and the time of the start of the irregularity. Irregularity Start Times will be determined from the raw data and as it is assumed that the Rolling Average would be utilised in Real-time Control Systems, all Irregularity Detection Times will be based upon the Rolling Average.

As stated earlier, the Transmig 350 EC is not suited to Real-time Dip Transfer Control because of its low dipping frequency of approximately 20Hz. More modern welding machines having higher dipping frequencies (circa 100Hz) will be able to control Dip Transfer welding in Real-time. As the data acquisition windows are set to allow approximately 10 dips using the Transmig 350 EC power source, it should be noted that it is assumed (but may not always be true) that response times recorded could be approximately 5 times longer than those that could be achieved using a more modern power source. Simulated response times for a more modern power source will therefore also be determined.

9.3.1) Surface Contaminant Experimentation:

The results of the experimentation for Surface Contaminants are presented in the following sections:

9.3.1.1) Descaled and Degreased Plain Metal Surface:

As stated, production of a set of welds on a descaled and degreased metal surface provides parameter feedback which can be compared to the parameter feedback obtained when welding over surface contaminants.

The weld runs were completed for the parameters displayed in Table 9.3. A statistical analysis of the data obtained from the 'Longmon' Program was taken for the Voltage and Current readings. As the statistical distribution of the Voltage and Current readings was determined to be Gaussian (Normal), welding conditions will be defined as normal if the means of Voltage and Current data acquisition windows lie within +/- 2 Standard Deviations (\(\sigma\)) of the respective Voltage and Current Distributions.
Normal welding conditions for Voltage are therefore defined by:

Voltage Upper Tolerance ($UT^{(V)}$) = $+2\sigma_{(V)}$
Voltage Lower Tolerance ($LT^{(V)}$) = $-2\sigma_{(V)}$

Normal welding conditions for Current are likewise defined by:

Current Upper Tolerance ($UT^{(I)}$) = $+2\sigma_{(I)}$
Current Lower Tolerance ($LT^{(I)}$) = $-2\sigma_{(I)}$

(It should be noted that other parameters affect the welding process and bead characteristics. However, assuming that we have a reasonably constant WFR, Travel Speed and Standoff, it is the Voltage and Current that can be utilised to detect irregularities and are therefore the parameters of major interest).

The Statistical Analysis for the monitored Voltage and Current Readings (obtained from the average of 140 Data Acquisition Windows) are given in Table 9.4 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ($\mu$)</th>
<th>SD ($\sigma$)</th>
<th>UT ($\mu+2\sigma$)</th>
<th>LT ($\mu-2\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>21.7398V</td>
<td>0.099V</td>
<td>21.9377V</td>
<td>21.5417V</td>
</tr>
<tr>
<td>Current</td>
<td>184.4014A</td>
<td>2.2945A</td>
<td>188.9903A</td>
<td>179.8125A</td>
</tr>
</tbody>
</table>

The Statistical Analysis for the Rolling Average of Voltage and Current Readings is given below in Table 9.5:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ($\mu$)</th>
<th>SD ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>21.7366V</td>
<td>0.0841V</td>
</tr>
<tr>
<td>Current</td>
<td>184.5545A</td>
<td>1.3707A</td>
</tr>
</tbody>
</table>

It can be seen that the Standard Deviations of the Rolling Averages in Table 9.5 are significantly smaller than the Standard Deviations calculated for the Raw Monitored Data. Fig. 9.3 overleaf provides a comparative plot of Raw and Rolling Averaged data for a weld run monitored over descaled material using the 'Longmon' Program. It can be clearly seen that isolated irregularities (i.e. out-of-tolerance readings) occur with the Voltage at 19.34 Secs and also with the Current at 10.93 Secs and 19.34 Secs. These irregularities are isolated and do not affect the welding process. It can be clearly seen that the Rolling Average is always in the tolerance range and effectively eliminates the effect of the irregularities.
Fig 9.3: Typical V-I Characteristics on Welding Descaled Surfaces

Fig 9.4: Transient V-I Signals obtained for Welding over Descaled Surfaces
It can be seen from the transient V-I plots in Fig 9.4 that the welding process is reasonably stable with approximately 17 Short Circuits (or Dips) per second.

As stated, the data obtained for normal stable welding conditions over descaled and degreased material will now be used as a basis of comparison with welding over contaminated surfaces.

9.3.1.2) Scaled Material Surface:

The first Surface Contaminant that shall be studied is the Mill Scale that is present on Low Carbon Steel as normally supplied to the customer.

Mill Scale is a surface layer consisting of three Oxides, i.e. Ferrous Oxide or Wustite (FeO), Magnetite or Ferrous-Ferric Oxide (Fe₃O₄) and Ferric Oxide or Hematite (Fe₂O₃). Mill Scale is composed of layers richest in Oxygen at the scale surface and richest in iron at the metal surface. Ferrous Oxide, the layer next to the metal surface constitutes about 85% of the scale thickness, the Magnetite about 10%-15% and the Wustite about 0.5%-2%. Mill scale thickness can vary from between 0.4μm to 4.7μm.

It was observed from both the ‘Shortmon’ and ‘Longmon’ Runs that there was no significant difference between the Characteristics of Welding over Descaled Material and those observed when welding over the Mill Scale. The V-I Characteristics for weld run over Mill Scale are displayed in Fig 9.5 overleaf. It will be observed that the Voltage is mostly bordering on the Lower Tolerance line. However, it should be remembered that the first and last 50mm of the 200mm weld length was over descaled plate with the central 100mm of the weld being over Mill Scale. As no significant difference was observed between V-I characteristics of the Descaled and Undescaled sections, it can be concluded that the low Voltage levels were to do some other phenomena such as a slight inaccuracy in the Standoff setting.

It was also observed from transient data monitored by the ‘Shortmon’ Program, that the average Dipping Frequency was around 17 Dips/Second and is therefore not significantly different from the average Dipping Frequency observed when welding over Descaled Material. It will also be observed from a typical transient plot in Fig 9.6 overleaf that the welding process is also reasonably stable.

It can therefore be concluded that welding over Undescaled Material does not significantly affect the welding process as monitored by the MWEF. However, the Mill Scale might cause inclusions in the Weld Bead which could affect the physical properties of the weld. This set of experimentation has therefore indicated a limitation of the MWEF in that, with respect to welding over undetectable surface contaminants, it cannot directly detect the development of weld faults such as inclusions.
Fig 9.5: Typical V-I Characteristics for Descaled/Undescaled Surfaces

Fig 9.6: Transient V-I Signals for welding over Undescaled Surfaces
9.3.1.3) Painted Material Surface:

To investigate realistic effects of painted metal surfaces on the welding process, descaled and degreased material was painted with an Undercoat (Metal Primer-Red Oxide Flat) and then coated with Gloss Enamel (Epoxy Gloss Enamel-Ocean Blue).

The V-I Characteristics are shown in Fig 9.7 overleaf. It can be clearly seen that the painted surface causes a resistance to the flow of Current resulting in a substantial Voltage increase (up to a mean reading of 23.5344V) and a substantial decrease in the Current (down to a mean reading of 172.6992A).

A statistical analysis of the monitored Voltage and Current readings over the Painted surface is given in Table 9.6 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (µ)</th>
<th>SD (σ)</th>
<th>UT (µ+2σ)</th>
<th>LT (µ−2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>23.5344V</td>
<td>0.6681V</td>
<td>24.8706V</td>
<td>22.1982V</td>
</tr>
<tr>
<td>Current</td>
<td>172.6992A</td>
<td>4.3948A</td>
<td>181.4888A</td>
<td>163.9096A</td>
</tr>
</tbody>
</table>

It can be seen from Table 9.6 that the Standard Deviations for Voltage and Current Readings when welding over paint are substantially larger than those calculated for the Voltage and Current readings when welding under normal conditions over descaled plate (see Table 9.4). This larger variation is most likely caused by process instability as a result of the additional resistance induced by the paint. Variation may also be caused by variation in the thickness of the paint layers which may well cause variations in the resistance to welding current and hence also variations in Voltage and Current Readings.

The effect of the variations in the process parameters induced by the paint can also be clearly seen in the weld produced through an increase in reinforcement and decrease in Bead Width. As levels of penetration are determined by the welding current, it is anticipated that the substantial reduction in mean current levels when welding over paint will result in a reduction in the penetration levels.

The instability of the welding process when welding over a painted surface can be clearly seen in the plot of V-I Transient Signals displayed in Fig 9.8. Dipping Frequency is irregular and increases from a normal Dipping Frequency of around 17 Dips/Second to an average of around 43 Dips/Second. The higher Dipping Frequency can be explained by comparing the Heat Input Characteristics for normal welding conditions to those observed for welding over a painted surface. It is observed that the Heat Input over painted surfaces during the arcing period drops to levels well below those obtained for normal welding conditions (see Fig 9.13) and the arc can therefore not be sustained for the periods observed for normal periods resulting in reduced arcing time and hence a higher dipping frequency.
Fig 9.7: Typical V-I Characteristics for Descaled/Painted Surfaces

Fig 9.8: Transient V-I Signals for welding over Painted Surfaces
9.3.1.4) **Surface coated in Bearing Grease:**

The effects of Surface Grease on the welding process was investigated by coating the material surface with Bearing Grease (Sapphire Longlife Multifunction Bearing Grease).

The V-I Characteristics are shown in Fig 9.9 overleaf. It can be clearly seen that Grease also causes a resistance to the flow of Current resulting in Voltage increases (up to a mean reading of 25.7807V) and a reduction in the Current (down to a mean reading of 151.3883A).

A statistical analysis of the monitored Voltage and Current readings over the Greased surface (from 80 Samples) is given in Table 9.7 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (μ)</th>
<th>SD (σ)</th>
<th>UT (μ+2σ)</th>
<th>LT (μ−2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25.7807V</td>
<td>2.0777V</td>
<td>29.9361V</td>
<td>21.6253V</td>
</tr>
<tr>
<td>Current</td>
<td>151.3883A</td>
<td>7.7721A</td>
<td>166.9325A</td>
<td>135.8441A</td>
</tr>
</tbody>
</table>

It can be seen from Table 9.7 that the Standard Deviations for Voltage and Current Readings when welding over Grease are even larger than those calculated for the Voltage and Current Readings when welding over paint (see Table 9.6). This even larger variation in parameters is again partially caused by process instability as a result of the additional resistance induced by the Grease but may also be caused by comparatively larger variations in the thickness of the grease layers which may in turn cause larger variations in the resistance and hence also larger variations in Voltage and Current Readings.

The instability of the welding process when welding over the greased surface can be again clearly seen in the plot of V-I Transient Signals displayed in Fig 9.10. Dipping Frequency is irregular and averages around 27 Dips/Second. It will also be observed that at certain intervals the current flow is substantially or completely blocked and the Voltage moves towards its open-circuit reading. The higher than normal Dipping Frequency is again caused by a drop in Heat Input below normal levels as the arc cannot be sustained for normal periods and a higher dipping frequency therefore occurs. It will be observed that the dipping frequency when welding over grease (27 Dips/Second) is lower than that observed for welding over paint (43 Dips/Second). It appears that this may be caused by the lengthy periods of interference to the welding process when the Current is substantially or completely blocked by the grease.
Fig 9.9: Typical V-I Characteristics for Descaled/Greased Surfaces

Fig 9.10: Transient V-I Signals for welding over Greased Surfaces
9.3.2) **A Discussion of Methods for Contaminant Detection:**

There are four methods of analysing Voltage and Current for the detection of interference to the Welding Process from Surface Contaminants which are discussed in the following sections:

9.3.2.1) **Tolerance Limits:**

It will be remembered from Sec 9.3.1.1 that Upper and Lower tolerance levels were established for Voltage and Current readings for normal welding conditions over descaled and degreased materials. It is clear that when these tolerances are significantly exceeded for a specified range of successive data acquisition windows, there is an irregularity in the welding process. As most Surface Contaminants will (in most cases) create a resistance, they may be detected by a significant rise in the Voltage above the Upper Voltage Tolerance and conversely, a significant drop in the Current below the Lower Current Tolerance value.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Mean (µ) (V)</th>
<th>SD (σ) (V)</th>
<th>UT (µ+2σ) (V)</th>
<th>LT (µ-2σ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descaled</td>
<td>21.7398</td>
<td>0.0990</td>
<td>21.9377</td>
<td>21.5417</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>21.5539</td>
<td>0.0984</td>
<td>21.7507</td>
<td>21.3571</td>
</tr>
<tr>
<td>Paint</td>
<td>23.5344</td>
<td>0.6681</td>
<td>24.8706</td>
<td>22.1982</td>
</tr>
<tr>
<td>Grease</td>
<td>25.7807</td>
<td>2.0777</td>
<td>29.9361</td>
<td>21.6253</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Mean (µ) (A)</th>
<th>SD (σ) (A)</th>
<th>UT (µ+2σ) (A)</th>
<th>LT (µ-2σ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descaled</td>
<td>184.4014</td>
<td>2.9945</td>
<td>188.9903</td>
<td>179.8125</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>184.1162</td>
<td>2.3396</td>
<td>188.7954</td>
<td>179.4370</td>
</tr>
<tr>
<td>Paint</td>
<td>172.6992</td>
<td>4.3948</td>
<td>181.4888</td>
<td>163.9096</td>
</tr>
<tr>
<td>Grease</td>
<td>151.3883</td>
<td>7.7721</td>
<td>166.9325</td>
<td>135.8441</td>
</tr>
</tbody>
</table>

The Voltage and Current Tolerances are displayed in Tables 9.8 and 9.9 as obtained for normal welding conditions over descaled material. It can also be seen from Tables 9.8 and 9.9 that, whilst the mill scale has no significant effect on the welding process, welding over painted and greased surfaces adversely affects the process parameters and weld stability. The Voltage readings for painted and greased surfaces significantly exceed the Upper Voltage Tolerance whilst the Current readings are well below the Lower Current Tolerance level. It can therefore be concluded that the Tolerance levels derived for normal welding conditions may be used for the detection of surface contaminants.

The surface grease is observed to be more disruptive to the welding process than the painted surfaces, probably because the layers of grease on the
material were thicker than the layers of paint but could also be due to
greater resistive properties. As stated in Sec 9.3.1.3 and Sec 9.3.1.4, the
larger Standard Deviations of parameters observed when welding over
grease and paint are clearly due to process instability created by the
contaminants but may also be due to variations in the thickness of the
contaminant layers.

9.3.2.2) Parameter Derivatives:

Another method for contaminant detection is utilisation of the first
derivative (or rate of change) of the Voltage \((dV/dT)\) and Current \((dI/dT)\)
parameters with respect to time.

When the welding process reaches a surface contaminant, changes in
parameter readings will occur as described in sec 9.3.1. It may therefore be
feasible to use the rate of parameter change in the rolling average to detect
changes in the welding process before the tolerance limits are reached.

The derivative of the Rolling Average of the Voltage readings is given by:

\[
dV_{(RA)}/dT = (V_{(RA)}[k] - V_{(RA)}[k-1])/(T[k] - T[k-1])
\]

and the derivative of the rolling average of the Voltage readings is given by:

\[
dI_{(RA)}/dT = (I_{(RA)}[k] - I_{(RA)}[k-1])/(T[k] - T[k-1])
\]

where:

\(V_{(RA)}[k]\) = the Rolled Average of Voltage for the current data acquisition
window.

\(V_{(RA)}[k-1]\) = the Rolled Average of Voltage for the previous data acquisition
window.

\(I_{(RA)}[k]\) = the Rolled Average of Current for the current data acquisition
window.

\(I_{(RA)}[k-1]\) = the Rolled Average of Current for the previous data acquisition
window.

\(T[k]\) = the Time of the current data acquisition window relative to the
start of data acquisition.

\(T[k-1]\) = the Time of the previous data acquisition window relative to
the start of data acquisition.
Figs 9.11 and 9.12 below display the First Derivatives for the Rolling Averages of Voltage and Current readings for normal welding conditions over descaled material (see Fig 9.3), painted material (see Fig 9.7) and greased material (see Fig 9.9).

**Fig 9.11: Derivative of the Rolling Average of Voltage Readings**

**Fig 9.12: Derivative of the Rolling Average of Current Readings**
It can be clearly seen from Figs 9.11 and 9.12 that the Derivatives of the Rolled Averages of Voltage \((V_{(RA)})\) and Current \((I_{(RA)})\) readings at the point where the welding process reaches the surface contaminants is substantially larger than those calculated for normal welding conditions over descaled material. Whilst the Derivative of \(I_{(RA)}\) for normal welding conditions is more erratic than the corresponding Derivative of \(V_{(RA)}\), the Derivatives for both \(V_{(RA)}\) and \(I_{(RA)}\) for normal welding conditions are clearly distinguishable from the Derivatives obtained for the start of welding over the stated surface contaminants. It can therefore be concluded that the Derivatives of \(V_{(RA)}\) and \(I_{(RA)}\) can be used for the detection of surface contaminants by using Upper and Lower Tolerance values of \(dV_{(RA)/dT}\) and \(dI_{(RA)/dT}\) which, if exceeded, will indicate the start of a welding irregularity.

The Tolerance value of \(dV_{(RA)/dT}\) obtained for normal welding conditions is:

\[
\text{Tol}(dV_{(RA)/dT}) = +/- \text{MAX}(dV_{(RA)/dT})
\]

if \( \text{MAX}(dV_{(RA)/dT}) > \text{ABS} \left( \text{MIN}(dV_{(RA)/dT}) \right) \)

else

\[
\text{Tol}(dV_{(RA)/dT}) = +/- \text{ABS} \left( \text{MIN}(dV_{(RA)/dT}) \right)
\]

if \( \text{ABS}(\text{MIN}(dV_{(RA)/dT})) > \text{MAX}(dV_{(RA)/dT}) \)

and the Tolerance for \(dI_{(RA)/dT}\) obtained for normal welding conditions is:

\[
\text{Tol}(dI_{(RA)/dT}) = +/- \text{MAX}(dI_{(RA)/dT})
\]

if \( \text{MAX}(dI_{(RA)/dT}) > \text{ABS} \left( \text{MIN}(dI_{(RA)/dT}) \right) \)

else

\[
\text{Tol}(dI_{(RA)/dT}) = +/- \text{ABS} \left( \text{MIN}(dI_{(RA)/dT}) \right)
\]

if \( \text{ABS}(\text{MIN}(dI_{(RA)/dT})) > \text{MAX}(dI_{(RA)/dT}) \)

\(\text{Tol}(dV_{(RA)/dT})\) was found to be 0.1V/Sec and \(\text{Tol}(dI_{(RA)/dT})\) is 2.5A/Sec for normal welding conditions. Should these tolerance levels be exceeded then it will be assumed that an irregularity exits in the welding process. Surface Contaminants can be detected by a rapid rise in the Voltage and a corresponding reduction in the Current. There will therefore also be a substantial positive rise in \(dV_{(RA)/dT}\) at the start of the surface contaminant complemented by a negative increase in \(dI_{(RA)/dT}\) which will exceed the tolerance derivative limits and hence contribute to the detection of the Contaminant.
9.3.2.3) **Dipping Frequency:**

It was observed that the Dipping Frequency increased dramatically when welding over substantial Surface Contaminants. Table 9.10 below compares the mean Dipping Frequency observed for normal welding conditions with those observed when welding over Contaminants.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Dipping Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Contaminant</td>
<td>17</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>17</td>
</tr>
<tr>
<td>Paint</td>
<td>43</td>
</tr>
<tr>
<td>Grease</td>
<td>27</td>
</tr>
</tbody>
</table>

It can be clearly seen that there is a large increase in the Dipping Frequency for the substantial Contaminants (i.e. Paint and Grease) indicating that Dipping Frequency can be utilised for detection of welding over Contaminants.

As stated, the Higher Dipping Frequencies observed when welding over Contaminants is caused by reduced Heat Input during the arcing period.
which results in shorter arcing times because the arc can not be sustained for
the normal arcing period. Fig 9.13 on the previous page compares the Heat
Inputs observed for welding over Surface Contaminants to those observed
for normal welding conditions. It can be clearly seen that the Heat Inputs for
welding over contaminated material are lower than those observed for
normal welding conditions.

It will also be observed from Fig 9.13 that the Heat Inputs for welding over
the greased surface are lower than those observed for welding over paint. In
many instances the Heat Input is reduced to zero because the Current is
blocked by the grease. The Current blockages cause significant delays to the
welding process and hence explain the lower Dipping Frequency observed
for grease (27 Dips/Sec) when compared to the Dipping Frequency
observed for welding over paint (43 Dips/Sec).

It should be clear that use of the Dipping Frequency as a medium for
detecting welding irregularities can only be utilised when welding in Dip
Transfer Mode.

It should also be noted that with respect to real-time control, a rapid increase
in Standoff will also cause an increase in Voltage and corresponding
decrease in Current as verified in Sec 9.1. A real-time control strategy is
therefore required to differentiate between parameter deviation when
welding over a Contaminant and parameter deviations due to an increase in
Standoff. To compare the effects of Standoff variation on Voltage and
Current characteristics with the characteristics observed for Surface
Contaminants, additional experimentation was completed to determine the
effect of varying Standoff on the V-I Characteristics and Dipping
Frequencies using the same settings as those utilised in the Contaminant
experimentation described in Sec 9.3.1. The Standoff was varied from
12mm to 24mm in steps of 4mm and the welding process was monitored
using the ‘Shortmon’ Program for each step.

The results for the above described experimentation are illustrated in Fig
9.14 overleaf. It can be seen that over an increase in Standoff (L) from
12mm to 24mm, the Voltage increases from 21.4V to 22.4V and the
Current is reduced from 198A down to 166A. On studying the V-I
characteristics for welding over paint (see Fig. 9.7), it can be clearly seen
that if the Standoff were to suddenly increase to 24mm, the V-I
characteristics would be in the range that could be expected for welding
over painted surfaces. It can therefore be concluded that one cannot reliably
differentiate between welding over contaminated surfaces or an increase in
Standoff using the V-I characteristics alone.

It can be seen from Fig 9.14 that the Dipping Frequency varies little over
the variation in Standoff with a drop from 17 Dips/Sec @ L=24mm down
to 15Dips/Sec @ L=12mm. The Dipping Frequency when welding over the
painted surface however leaps from the normal 17 Dips/Sec up to around
43 Dips/Sec. It can therefore be seen that Dipping Frequency may be a
critical parameter for distinguishing between increase in Standoff and welding over surface contaminants.

It should again be noted that this experimentation was completed on the Transmig 350EC Welding Machine which has a low Dipping Frequency (circa 20Hz). In order to completely verify the use of Dipping Frequency as a diagnostic parameter as described above, it will be necessary to ensure that Dipping Frequency variations can be effectively detected with Power Sources having higher stable Dipping Frequencies (circa 100Hz). This experimentation can only be undertaken with a more modern Power Source which was not available at the time of completing this thesis.

9.3.2.4) **Arc Resistance:**

As most contaminants have the effect of creating an additional resistance in the welding circuit, using the mean Arc Resistance for a data acquisition window could also be an appropriate a very quick indication of the stability of the welding process.
For each contaminant, the mean, maximum and minimum Resistance values for the data presented in Sec 9.3.1 are calculated from the Monitored Data as:

Mean Resistance: \[ R_{(\mu)} = \frac{V_{(\mu)}}{I_{(\mu)}} \]

Maximum Resistance: \[ R_{(\text{Max})} = \frac{V_{(\mu+2\sigma)}}{I_{(\mu-2\sigma)}} \]

Minimum Resistance: \[ R_{(\text{Min})} = \frac{V_{(\mu-2\sigma)}}{I_{(\mu+2\sigma)}} \]

The Resistance values calculated for each Contaminant are displayed in Table 9.11 below:

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>( R_{(\mu)} ) (( \Omega ))</th>
<th>( R_{(\text{Max})} ) (( \Omega ))</th>
<th>( R_{(\text{Min})} ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Contaminant</td>
<td>0.118</td>
<td>0.122</td>
<td>0.114</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>0.117</td>
<td>0.121</td>
<td>0.113</td>
</tr>
<tr>
<td>Paint</td>
<td>0.136</td>
<td>0.152</td>
<td>0.122</td>
</tr>
<tr>
<td>Grease</td>
<td>0.170</td>
<td>0.220</td>
<td>0.130</td>
</tr>
</tbody>
</table>

It can be seen from Table 9.11 that the Resistance Ranges for contaminated and uncontaminated surfaces are distinguishable from each other (although the \( R_{(\text{Min})} \) for the Painted surface is approximately equal to \( R_{(\text{Max})} \) for the uncontaminated surface). It should be noted that the Resistance Ranges in Table 9.11 were calculated using raw Monitored Data. As Rolled Averages of Voltage and Current will be utilised for Real-time Monitoring, the Mean, Maximum and Minimum values of Resistance for Rolled Averages of \( V_{(RA)} \) and \( I_{(RA)} \) were also calculated as:

Mean Resistance: \[ R_{(RA),(\mu)} = \frac{V_{(RA),(\mu)}}{I_{(RA),(\mu)}} \]

Maximum Resistance: \[ R_{(RA),(\text{Max})} = \frac{V_{(RA),(\mu+2\sigma)}}{I_{(RA),(\mu-2\sigma)}} \]

Minimum Resistance: \[ R_{(RA),(\text{Min})} = \frac{V_{(RA),(\mu-2\sigma)}}{I_{(RA),(\mu+2\sigma)}} \]

Table 9.12 overleaf displays the Resistance Ranges calculated from Rolled Averages of Voltage \( (V_{(RA)}) \) and Current \( (I_{(RA)}) \). It can be seen that Resistance Ranges are more clearly defined and indicates the effectiveness of the Resistance as an additional diagnostic parameter.
It should be noted that the Resistance does not provide any more information than the Voltage and Current with respect to irregularity detection. The Resistance can however be utilised as a check to confirm the detection of irregularities and can also be utilised as an indication of the severity of the contaminant on the welding process.

9.3.3) **Response Times for Contaminant Detection:**

Response time is defined as the difference between the time of detection of an irregularity and the time of the actual start of the irregularity. The time of the start of the irregularity is referred to as the Datum Time. With respect to real-time monitoring using data acquisition windows, the point of irregularity detection is taken as the data acquisition window prior to the one at which the irregularity actually commences because the irregularity could have commenced at any point between these windows. It will be remembered from Sec. 8.6 and Fig. 8.2 that time of the current data acquisition window is obtained at the end of actual data acquisition and that the time between the current and following windows will comprise of the Data Processing and Plotting Time for the current window and the Data Acquisition Time for the following (k+1) window as illustrated in Fig 9.15 below.

![Fig 9.15: Data Acquisition Window Sequences](image-url)
It can be clearly seen from Fig. 9.15 that each window consists of a period for Data Acquisition (Ta), Data Processing (Tc) and Data Plotting (Tp) on the Monitor. It can also be clearly seen that the Window Time Acquisition occurs directly after the Data Acquisition phase and that the Window Time is therefore calculated as:

\[ Tw(k+1) = Tc(k) + Tp(k) + Ta(k+1) \]

It will also be observed that an irregularity could commence at any time between \( T(k) \) and \( T(k+1) \) and therefore \( T(k) \) is used as the Datum Time value with respect to determining the Response Time of an irregularity. The irregularity will be detected at Window \( W(k+n) \) and therefore the Response Time (\( Tr \)) is given as:

\[ Tr = T(k+n) - Tk \]

The time period for each window depends on the Sampling Frequency, Samples/Window, Data Processing Time and Plotting Time. For the Computer installed on the MWEF (Compac Prolinea MT 4/66MHz) and the settings for this set of experimentation (2500Samples/Window @ 5kHz), the Window Period was found to be approximately 0.66Sec which was comprised of:

- Data Acquisition Period (Ta) (Sec): 0.500
- Data Processing and Plotting Periods (Tc +Td) (Sec): 0.160
- Data Acquisition Window Period (Tw) (Sec): 0.660

It is also clear that the Minimum Response Time (\( Tr_{\text{min}} \)) must be one Data Acquisition Window Period which in this case is 0.660Sec. It should also be remembered at this point that the long Data Acquisition Period is required because of the low Dipping Frequency (20Hz) of the Transmig 350EC Power Source which requires 0.500Sec of Monitoring Time to obtain data for the 10 dips required for a reasonable Current average to be obtained. Table 9.13 and 9.14 overleaf illustrate the Response Times of Voltage and Current respectively for the Transmig 350EC when welding over Paint and Grease. The Tables provide Response Times for Rolling Averages and Derivatives and also compares Weld Travel (S) for the quickest Response Time at TS=300mm/min and TS=600mm/min.
Table 9.13: Voltage Response Time (Tr) and Weld Travel (S) Values

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Tr ( (V_{RA}) )</th>
<th>Tr ( (dV_{RA}/dT) )</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paint</td>
<td>1.320 ((2Tw))</td>
<td>0.660 ((Tw))</td>
<td>3.30</td>
<td>6.60</td>
</tr>
<tr>
<td>Grease</td>
<td>1.320 ((2Tw))</td>
<td>0.660 ((Tw))</td>
<td>3.30</td>
<td>6.60</td>
</tr>
</tbody>
</table>

Units: Tr = Seconds, S = mm

Table 9.14: Current Response Time (Tr) and Weld Travel (S) Values

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Tr ( (I_{RA}) )</th>
<th>Tr ( (dI_{RA}/dT) )</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paint</td>
<td>1.320 ((2Tw))</td>
<td>0.660 ((Tw))</td>
<td>3.30</td>
<td>6.60</td>
</tr>
<tr>
<td>Grease</td>
<td>1.320 ((2Tw))</td>
<td>0.660 ((Tw))</td>
<td>3.30</td>
<td>6.60</td>
</tr>
</tbody>
</table>

Units: Tr = Seconds, S = mm

It can be seen from Tables 9.13 and 9.14 that, for this set of experimentation, there is no difference between the Response Times of Voltage and Current. It is however observed that the Derivatives of Rolling Averages can indicate an Irregularity before the Rolling Average. This is to be expected as when an irregularity occurs, there will be a change of gradient of the Rolling Average before the Rolling Averages exceed Tolerance values.

Australian Standards require that weld defects will not be longer than 3mm in length and to ensure quality, we will therefore specify that defects should be rectified within 2mm of Weld Travel. It can be seen that the Transmig 350EC Power Source cannot be used to control welding in the Dip Transfer Mode as the Weld Travel Values determined for the minimum Response Times well exceed the 2mm Defect Length Tolerance.

In real-time monitoring of the welding process, it can be clearly seen that the quick response time is crucial to the early detection and (if possible) elimination of an irregularity. Assuming the criteria that, when welding in the Dip Transfer Mode, data for 10 Dips must be acquired to obtain reasonable accurate Parameter Averages, Simulated Response Times and corresponding Weld Travel Values will be determined for Power Sources with Dipping Frequencies \( (Fd) \) of 50Hz, 100Hz and 150Hz. As the Dipping Frequency increases, the Data Acquisition Period can be reduced and for the same Sampling Frequency, the number of samples required can be reduced which will clearly lead to a proportional reduction in Data Processing Time. It will also be assumed that a Computer of the near future will operate at 200MHz which means that Data Processing speeds could be around three times as fast as the 66MHz Computer currently installed on the MWEF. Table 9.15 overleaf illustrates possible Window \((Tw)\) times for a 200MHz Computer utilising the stated Dipping Frequencies.
The data displayed in Table 9.15 above was calculated using the following procedure:

**Step 1:** Determine the Data Acquisition Time \( (T_a) \) for 10 Dips as follows:

\[ T_a = \frac{10}{F_d} \]

**Step 2:** Determine the Number of Samples \((N)\) in the Data Acquisition Window for a set Sampling Frequency \((F_s)\) using:

\[ N = T_a \cdot F_s \]

**Step 3:** Calculate the Data Processing and Plotting Time \((T_c + T_p)\) relative to the value of \(T_c + T_p\) @ \(F_d=20\text{Hz}\) (i.e. 0.0533Sec): 

\[ T_c + T_p = 0.0533\left(\frac{N}{2500}\right) \]

**Step 4:** Calculate the Total Data Acquisition Window Period \((T_w)\) as:

\[ T_w = T_a + T_c + T_p \]
Table 9.16: Simulated Response Times (Welding over Paint)

<table>
<thead>
<tr>
<th>Fd (Hz)</th>
<th>Tr (V_{RA})</th>
<th>Tr (dV_{RA}/dT)</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.1066</td>
<td>0.5533</td>
<td>2.765</td>
<td>5.533</td>
</tr>
<tr>
<td>100</td>
<td>0.4424</td>
<td>0.2212</td>
<td>1.106</td>
<td>2.212</td>
</tr>
<tr>
<td>150</td>
<td>0.2214</td>
<td>0.1107</td>
<td>0.553</td>
<td>1.107</td>
</tr>
</tbody>
</table>

Response Times (Current)

<table>
<thead>
<tr>
<th>Fd (Hz)</th>
<th>Tr (I_{RA})</th>
<th>Tr (dI_{RA}/dT)</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.1066</td>
<td>0.5533</td>
<td>2.765</td>
<td>5.533</td>
</tr>
<tr>
<td>100</td>
<td>0.4424</td>
<td>0.2212</td>
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<td>2.212</td>
</tr>
<tr>
<td>150</td>
<td>0.2214</td>
<td>0.1107</td>
<td>0.553</td>
<td>1.107</td>
</tr>
</tbody>
</table>

See Tables 9.13, 9.14 and 9.15 for descriptions of Units and Symbols

Table 9.17: Simulated Response Times (Welding over Grease)

<table>
<thead>
<tr>
<th>Fd (Hz)</th>
<th>Tr (V_{RA})</th>
<th>Tr (dV_{RA}/dT)</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.1066</td>
<td>0.5533</td>
<td>2.765</td>
<td>5.533</td>
</tr>
<tr>
<td>100</td>
<td>0.4424</td>
<td>0.2212</td>
<td>1.106</td>
<td>2.212</td>
</tr>
<tr>
<td>150</td>
<td>0.2214</td>
<td>0.1107</td>
<td>0.553</td>
<td>1.107</td>
</tr>
</tbody>
</table>

Response Times (Current)

<table>
<thead>
<tr>
<th>Fd (Hz)</th>
<th>Tr (I_{RA})</th>
<th>Tr (dI_{RA}/dT)</th>
<th>S (300mm/min)</th>
<th>S (600mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.1066</td>
<td>0.5533</td>
<td>2.765</td>
<td>5.533</td>
</tr>
<tr>
<td>100</td>
<td>0.4424</td>
<td>0.2212</td>
<td>1.106</td>
<td>2.212</td>
</tr>
<tr>
<td>150</td>
<td>0.2214</td>
<td>0.1107</td>
<td>0.553</td>
<td>1.107</td>
</tr>
</tbody>
</table>

See Tables 9.13, 9.14 and 9.15 for descriptions of Units and Symbols

It can be seen from Tables 9.16 and 9.17 that a Dipping Frequency (Fd) of 50Hz cannot detect an irregularity within the 2mm Tolerance. At a Dipping Frequency of 100Hz, detection of contaminants is achieved well within the 2mm Tolerance at a Travel Speed of 300mm/min, but the Weld Travel for irregularity detection at 600mm/min is slightly over Tolerance but could be accepted as it is well within the 3mm maximum Fault Length allowed by Australian Standards. All irregularities are detected within 2mm at a Dipping Frequency of 150Hz.
9.4) **The Effect of Root Gap on the Welding Process:**

In addition to the detection of surface contaminants, it is also important to be able to detect the effects of other weld preparation defects, of which one of the most obvious is excessive Root Gap which can result in either Excessive Penetration or Burnthrough.

Excessive Root Penetration can be defined as a continuous Weld Bead with a Root Penetration larger than the Penetration Range obtained from normal welding conditions. Burnthrough can be described as a discontinuity in the Weld Bead characterised by an absence of weld metal that would normally physically bridge the joint.

Excessive Penetration and Burnthrough occur under two conditions which are:

i) Excessive Heat Input.

ii) The Root Gap is too large.

To investigate the effects of Root Gap on the Welding Process, a set of Butt Welds were completed on 2mm thick Sheet Steel with varying Root Gaps. For this set of experimentation, the following conditions were specified:

i) The Voltage and Wire Feed Rate settings were maintained at the respective levels determined for optimal Bead Characteristics with no Root Gap.

ii) There was no change in the Standoff (i.e. Contact-Tip to Workpiece Distance) Setting. It should be noted however, that with a Root Gap, there would be a variation in the Contact-Tip to Weldpool Distance as the Weldpool will tend to sag on welding over a Root Gap.

iii) In the light of the experimental constraints listed in (i) and (ii) above, it was assumed that irregularities in parameter feedback were solely due to the effects of Root Gap.

A series of initial experiments was performed to determine the Root Gap Width at which continuous Burnthrough occurs. This experimentation was undertaken with the experimental constants displayed in Table 9.18. The metal plates were positioned with a linear increase in Root Gap ranging from 0.0mm to 1.0mm over the material length.

It was observed that Excessive Penetration occurred up to a Root Gap of around 0.6mm at which point periodic Burnthrough commenced and became more severe as the Root Gap approached 1.0mm. The increase in Root Penetration followed by points of Burnthrough can be clearly distinguished on the Voltage
Traces in Fig 9.16 and can also be clearly seen on the Photograph of the Weld Bead in Fig 9.17.
The Excessive Penetration/Burnthrough experiments were therefore performed to the criteria illustrated in Table 9.18 below.

### Table 9.18: Root Gap Experimentation Setup

<table>
<thead>
<tr>
<th>Root Gap (G):</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G = 0.00\text{mm} ) to ( 1.00\text{mm}: \text{Step} = 0.25\text{mm} )</td>
</tr>
</tbody>
</table>

**Experimental Constants:**

<table>
<thead>
<tr>
<th>Material: 2mm x 100mm x 250mm MS Sheet (2 Off/Weld Run)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode: Autocraft LW1 (0.9mm Dia)</td>
</tr>
<tr>
<td>Shielding Gas: Argoshield 50 (GFR=14l/min)</td>
</tr>
<tr>
<td>Voltage Setting=22V, WFR Setting=70mm/s</td>
</tr>
<tr>
<td>Trace Speed Setting=400mm/min, Standoff Setting=16mm</td>
</tr>
<tr>
<td>Total Weld Length=200mm, Root Gap Length=80mm</td>
</tr>
</tbody>
</table>

It should be noted that half of the specified Root Gap width is machined into one specimen, so that when two specimens are placed together for welding, the specified Weld Gap is central to the weld line. The Root Gap Length is machined in the centre of the specimen length and will be also be centrally placed in the weld run. This will therefore allow approximately 60mm of weld run over no Root Gap both before and after the Root Gap welding (of 80mm length) to enable sufficient comparative data to be obtained.

The specimens were clamped to a special jig to minimise distortion and maintain the experimental conditions. As, for this set of experimentation, the sampling window has been reduced from 2500 Samples to 1000 Samples, the Rolling Averages of the monitored data were calculated for 12 data acquisition windows to obtain smoother average readings.

Tolerance values for the Voltage, Current and Root Penetration readings of normal welding conditions (i.e. for a Closed Butt Weld) were determined for +/- 2 Standard Deviations of the mean values, as displayed in Table 9.19 below:

### Table 9.19: Normal (Tolerance) Parameter Ranges for No-Gap Welding.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (( \mu ))</th>
<th>SD (( \sigma ))</th>
<th>( \sigma + 2\mu )</th>
<th>( \sigma - 2\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>19.6839</td>
<td>0.1237</td>
<td>19.9313</td>
<td>19.4366</td>
</tr>
<tr>
<td>Current (I)</td>
<td>104.3106</td>
<td>1.9167</td>
<td>108.1440</td>
<td>100.4772</td>
</tr>
<tr>
<td>Root Pen (mm)</td>
<td>0.395</td>
<td>0.088</td>
<td>0.575</td>
<td>0.219</td>
</tr>
</tbody>
</table>

In completing the experimentation for the range of Rootgaps, it was observed that
Burnthrough occurred only for Gaps of 0.75mm and larger whilst Excessive Penetration occurred at a Rootgaps up to 0.5mm.

It should also be noted that this experimentation was designed to include a separate thesis on the effect of Root Gap on Audible Weld Acoustics [75]. The specimens were designed for use with the 'Longmon' Program only and therefore no transient data was obtained. It will be shown in this section that Excessive Penetration/Burnthrough can be detected using the mean Voltage and Current readings obtained from data acquisition windows, but it is also felt that the transient parameter signals will also yield additional information for the detection of the stated phenomena. It is therefore recommended that further experimentation be undertaken using the 'Shortmon' Program to identify the uses of transient Voltage and Current signals for the detection of Excessive Penetration and Burnthrough.

9.4.1) **Excessive Penetration Detection:**

As stated, welding over a Root Gap causes a sagging of the weld pool which, on solidification of the weld metal, results not only in increased Root Penetration, but also in reduced Reinforcement and Bead Width.

Fig 9.18 below provides a comparison of rolled Voltage and Current Averages compared to Root Penetration for Zero Gap, 0.25mm Gap and 0.5mm Gap.

![Fig 9.18: V-I Traces and Root Penetration on Welding over Root Gaps](image)
It can be seen from Fig 9.18 that there is a drop in Voltage as the welding process moves over the Root Gap. At a first glance, it would actually be expected that the Voltage would rise over a Gap because the sagging weldpool would cause an increase in stickout, effectively increasing the Standoff and hence also the Voltage. The Voltage Drop clearly contradicts the expected result. It will also be observed that the Current remains reasonably constant for all Gap Widths. It was expected that the Current would drop when moving over a Root Gap because of the resistance caused by the increase in Stickout. However, no change in the Current was observed as the welding process passed over the Root Gap. These phenomena are not at present understood.

It was also observed that the depth and length of Undercut increased with increasing in Root Gap.

9.4.1.1) Methods for Excessive Penetration Detection:

It is clear (at least from the experimentation that has been done thus far) that the Voltage is the Primary Parameter for Excessive Penetration detection. Although the Voltage deviations on welding over a Gap is small compared to the more catastrophic parameter deviations observed when welding over surface contaminants, they are nevertheless characteristic and, because of the constant Current trend on passing over a Gap, can be distinguished from a genuine decrease in Standoff where the Voltage will decrease, but there will also be a corresponding increase in Current.

A discussion now follows on the methods which may be used for detection of Root Gap and hence Excessive Penetration.

9.4.2.1.1) Detectable Voltage Drop:

By studying the Voltage traces in Fig 9.18 it can be deduced that using the Voltage Tolerance Crossing is not a reliable method for detection of Excessive Penetration. It will be observed that whilst the Voltage Drop at a Root Gap of 0.5mm is fairly substantial at about 0.4V, the Voltage Drop for a Root Gap of 0.25mm is only around 0.2V and only crosses the Lower Tolerance value because of a relatively low normal Voltage level at circa 19.50V. However, it will also be observed that for both Root Gap Widths, there is definite deviation from normal Voltage levels that could be utilised to indicate Excessive Penetration.

9.4.2.1.2) Parameter Derivatives:

Fig 9.19 overleaf illustrates the Derivative of Rolled Voltage Averages \( (dV_{RA}/dT) \) for Zero Gap and for Root Gaps of 0.25mm and 0.5mm respectively.
The Derivatives were calculated using the equations given in Sec. 9.3.2.2.

It can be seen for the Derivative Plot of Closed Butt Welding (Gap=0.00mm) in Fig 9.19 that there is a balance of +ve and -ve Gradients indicating reasonably stable and normal welding conditions. However the Derivative plots on starting the pass over 0.25mm and 0.5mm Gaps are characterised by a series of mostly negative Gradient values.

Figs 9.20 and 9.21 overleaf compares the Voltage Gradient trends with the Rolled Voltage Averages for Root Gaps 0.25mm and 0.5mm respectively from the point at which the welding process moves over the start of the Root Gap to the approximate point of maximum Voltage drop. It will be observed that the negative gradient trends that occur on passing over a Root Gap can be easily detected and can therefore be utilised to detect Excessive Penetration.

Please note that the Derivatives of the Rolled Current Averages for Zero Gap, 0.25mm Gap and 0.5mm Gap were also studied but provided no useful information with respect to Excessive Penetration detection and therefore no Current Derivative Plots are included in this thesis.
Fig 9.20: $V_{(RA)}$ and $dV_{(RA)}/dT$ for a 0.25mm Root Gap

Fig 9.21: $V_{(RA)}$ and $dV_{(RA)}/dT$ for a 0.5mm Root Gap
9.4.1.2) **Response Times for Excessive Penetration Detection:**

The Response Time with respect to Excessive Penetration detection can be defined as the time required to detect and confirm the presence of the Excessive Penetration relative to the time at which the welding process moved over the Root Gap.

The Parameter Response to welding over a Root Gap is slower than the Responses observed for Surface Contaminants and Burnthrough (as will be seen in Sec 9.4.2). This is because the rise in Root Penetration is a relatively gradual phenomenon, as can be observed on the Root Penetration plot in Fig 9.18.

The detection of the start of Excessive Root Penetration can therefore only be detected and confirmed after the analysis of a number of data acquisition windows taken from the onset of welding over a Root Gap. Temporary changes in the Gradient sign (as can be observed in Fig 9.20) will cause a variation in the number of data acquisition windows required to confirm the onset of a Root Gap and Excessive Penetration. It is for this reason that one cannot accurately assess the Response Time for Excessive Penetration detection.

9.4.2) **Burnthrough Detection:**

If the Root Gap is too wide or the Heat Input is too great, the Weldpool may not be maintained resulting in a failure to bridge the gap between weldpieces with deposited weldmetal.

It will be observed from Fig 9.22 overleaf that Burnthrough is characterised by downward Voltage Spikes of the Monitored Voltage Data (at points A, B and E). It was also observed that for normal welding conditions, the difference between the Monitored and Rolled Voltage Averages was never greater than 0.3V. As the difference between the Rolled Voltage Average and the Monitored Voltage Spike at Burnthrough is never less than 0.5V, it may be possible to utilise Monitored and Rolled Voltage Averages to detect a Burnthrough situation using the relationship shown below:

\[
\text{If } V_{(RA)(k)} - V_{(Mon)(k)} \geq V_{(Th)} \text{ THEN Assume Burnthrough}
\]

where:

\(V_{(RA)}\) = the Rolled Voltage Average at Data Acquisition Window ‘k’.
\(V_{(Mon)}\) = the Monitored Voltage Average for Data Acquisition Window ‘k’.
\(V_{(Th)}\) = the Threshold Voltage Difference for Burnthrough detection.
**Fig 9.22: Voltage and Voltage Derivative Plots over a 0.75mm Root Gap**

**Fig 9.23: Photograph of a Weld Run with a 0.75mm Root Gap**
The Voltage Threshold \( V_{(th)} \) will be determined experimentally.

It can also be seen from Fig 9.22 that Burnthrough can also be identified by downward Spikes of the Derivative of the Rolled Voltage Average \( (dV_{(RA)}/dT) \). The Derivatives were again calculated using the derivative equations found in Sec. 9.3.2.2.

It was also observed from the Rolled Voltage Derivative plot, that the blunted Spikes at points C and D closely corresponded to points in the weld run where there was a severe reduction in Bead Width and Bead Height with a large increase in Undercut. It appears that at these points, Burnthrough was just about to, but did not, occur (probably due sufficient Surface Tension in the Weldpool to prevent Burnthrough).

A photograph of the weld run can be seen in Fig 9.23. The points of the actual and near Burnthough events highlighted in Fig 9.22 can be clearly identified.
9.5) **Isolated Transient Welding Irregularity Detection:**

A Isolated Transient Welding Irregularity can be defined as an irregularity that occurs (i.e. starts and terminates) over a period of time that is less than the period of Data Acquisition in a Data Acquisition Window. If it is again assumed that real-time monitoring will be undertaken utilising Data Acquisition Windows then provision will need to be integrated into the Data Acquisition Routine to detect and analyse a Transient Irregularity.

Samples of possible Transient Irregularities that can occur in real welding situations have been captured with time-correlated Electronic and Visual Monitoring and are discussed in the following sections:

9.5.1) **Extinguished/Weakened Arc:**

For various reasons, it is possible that the arc can be extinguished or weakened during welding. This leads to a temporary situation where the current is blocked and rapidly drops whilst the voltage tends towards its Open Circuit value. An example of Arc Extinguishing/Weakening can be seen in Fig 9.24 below. A sequence of visual events at the point of arc extinguishing/weakening is shown in Fig 9.25 with the events highlighted in Fig. 9.24. It is possible the Arc was extinguished/weakened because of a Gas Explosion in the wire which caused instantaneous separation of a the large droplet at the end of the wire (see Fig 9.25 (B)) which in turn resulted in a large increase in the Arc Length and hence also an increase in the Arc Resistance.

![Fig 9.24: Transient V-I Characteristics of Extinguished/Weakened Arc](image-url)
It can be clearly seen from Fig 9.25 that as the droplet (see Fig 9.25 (A)) is violently separated from the wire (see Fig 9.25 (B)), the Arc Length is instantaneously increased from nearly 0mm to around 2.4mm. The Arc Resistance is therefore temporally increased resulting in the weakening or extinguishing of the Arc and hence also resulting in an increase in Voltage and corresponding decrease in Current. In figs 9.25 (C) and (D), show that the Arc Length is temporally maintained as the Voltage rises and the Current drops. As highlighted in Fig 9.24, the Voltage rises to around 35.2V and the Current drops to around 30.453A before regulating to normal readings.

The Electronic Data was monitored using the 'Shortmon' Program with a Sampling Rate of 5kHz. The High Speed Photography was taken at 2500 Frames/Sec. The sample of weld shown in Fig 9.24 is for 0.010mSec of weld stating at 0.442 Seconds into the Monitored Data Array. The Experimental Constants for the weld run are displayed in Table 9.20 below:

Table 9.20: Experimental Constants (Sec 9.5.1)

<table>
<thead>
<tr>
<th>Voltage = 20V, WFR = 50mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Speed = 300mm/min, Standoff = 12mm</td>
</tr>
<tr>
<td>Electrode = Autocraft LW1 (1.2mm Dia)</td>
</tr>
<tr>
<td>Shielding Gas = Argoshield 50 (GFR=14l/min)</td>
</tr>
<tr>
<td>Material = 8mm x 100mm x 250mm</td>
</tr>
</tbody>
</table>

9.5.2) Uncharacteristic Dipping in Globular Transfer Welding Mode:

Globular Transfer is achieved with V-I Settings in a range that is inbetween the Dip and Spray Transfer Welding Modes. The Metal Transfer is achieved through large irregular droplets. Ideally, Arc Shorting or Dipping should not occur in Globular Transfer, but occasionally does.

Fig 9.26 overleaf illustrates an uncharacteristic dip whilst welding in the Globular Transfer Mode and Fig 9.27 displays time-correlated visualisation at selected stages of the dipping cycle as highlighted in Fig 9.26.

The events for each stage are discussed below and overleaf:

Point A (Fig 9.27 (A)):
The globule at the end of the wire is just about to dip into the weldpool.

Point B (Fig 9.27 (B)):
The globule is now just made contact with the weldpool causing a short circuit. The Voltage now rapidly drops towards zero and the Current start to rise.
Point C (Fig 9.27 (C)):

The globule is now firmly dipped into the weldpool. The Voltage is now almost zero and the Current is continuing its rise.

Point D (Fig 9.27 (D)):

Necking in the wire commences due to the Pinch Force induced at higher Current levels. The Voltage starts to rise slowly, partly due to increasing Resistance created by Ohmic Heating in the wire as the Current rises, but possibly also due to the Necking which will increase the Resistance as the effective area of the wire decreases.

Point E (Fig 9.27 (E)):

Severe Necking has now occurred and the globule is about to separate from the wire.

Point F (Fig 9.27 (F)):

The globule has now detached from the wire and the Arc has reignited. It will
be observed there is violent of molten material at the end of the wire. This is probably caused by a Vapour Jet Force. Norrish [13] explains that at higher Currents there is significant vapourisation of the surface of a molten droplet in the root arc area. Thermal Acceleration of the vapour particles into the arc plasma results in a force that opposes droplet transfer. It is possible that force is also responsible for the repulsion of the molten metal at the wire end. The Voltage starts to rise rapidly whilst the Current now starts to drop.

**Point G (Fig 9.27 (G)):**

The molten globule is now continuing its absorption by the weldpool. It also appears that the metal repulsed at the end of the wire is now being expelled as Spatter.

**Point H (Fig 9.27 (H)):**

The detached globule is now almost completely absorbed by the weldpool. The Spatter continues its outward flight.

The Electronic Data was monitored using the ‘Shortmon’ Program with a Sampling Rate of 5kHz. The High Speed Photography was taken at 5000 Frames/Sec. The sample of weld shown in Fig 9.26 is for 0.010mSec of weld stating at 0.442 Seconds into the Monitored Data Array. The Experimental Constants for the weld run are displayed in Table 9.21 below:

<table>
<thead>
<tr>
<th>Table 9.21: Experimental Constants (Sec 9.5.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage = 26V, WFR = 80mm/s</td>
</tr>
<tr>
<td>Travel Speed = 300mm/min, Standoff = 20mm</td>
</tr>
<tr>
<td>Electrode = Autocraft LW1 (1.2mm Dia)</td>
</tr>
<tr>
<td>Shielding Gas = Argoshield 50 (GFR=14l/min)</td>
</tr>
<tr>
<td>Material = 8mm x 100mm x 250mm</td>
</tr>
</tbody>
</table>
Chapter 10

Mathematical Modelling for Real-time GMAW
Parameter Estimation and Control

When developing Mathematical Models for Real-time GMAW it is necessary to consider the following phenomena:

a) Accuracy of the Models in Parameter Estimation.

b) The Computing Time taken for the Models to produce Parameter Estimates.

c) The Consumables and other variables which will affect the Welding Process.

Typically, as stated earlier in Section 5.1, an Automated Welding Control Cycle will have the following stages:

Stage 1: Data Acquisition.

Stage 2: Data Analysis.

Stage 3: Weld Irregularity Detection and Elimination.

To satisfy Quality Standards, weld irregularities should be corrected within 2mm of Weld Travel, which implies that the Welding Control Cycle must be completed within this distance.

If we now consider an Automated Welding Situation of, say, thin Mild Steel Sheet, produced at a Travel Speed of 600mm/min (or 10mm/s), it can be seen that 2mm of Weld Travel is completed in 0.2 seconds. The Welding Control Cycle must also therefore be completed in 0.2 seconds. If 0.1 seconds is allowed for Data Acquisition, then there is only 0.1 seconds left for Data Analysis and Weld Irregularity Detection/Elimination. As some Weld Irregularities will be detected by comparing Parameter Estimates to Actual Weld Data, it can be seen that the Mathematical Models utilised in Parameter Estimation must be simple and very fast.

10.1) Model Types:

There are three types of Model which may be utilised in Welding Research which are discussed overleaf:
10.1.1) **Physical Models:**

A Physical Model is one which has been derived from Physical and Mathematical Principles. Given consistent postulates based on physical experience, correct conclusions may be drawn about future experiments through the use of Physical Models.

10.1.2) **Semi-Physical Models:**

A Semi-Physical Model is one where a Parameter (Y) is related to a Physical Expression by an Experimentally determined Constant (K). ie.

\[ Y = K \cdot f(X_1, X_2, X_3, \ldots) \]

where \( X_1, X_2, X_3 \) and etc. are Variables in a Physical Expression determined by Physical and Mathematical Principles.

10.1.3) **Empirical Models:**

Empirical Models are those which are determined and verified solely by Statistical and Experimental Data. A typical Example of an Empirical Model could be a Least-Squares Model of the form:

\[ Y = AX_1 + BX_2 + CX_3 \]

Where \( Y \) is the Estimated Parameter, \( X_1, X_2 \) and \( X_3 \) are Parameter Variables and \( A, B \) and \( C \) are Experimentally determined Constants that relate \( X_1, X_2 \) and \( X_3 \) to \( Y \).

Physical Models are very important for understanding the Welding Process with off-line modelling, but are mostly unsuitable for Real-time Control because:

a) The affect of Welding Consumables (ie. Shielding Gas and Electrode), Material to be Welded and other influences on the Welding Process need to be included in Models to ensure accuracy. As these Parameters are very difficult to Model by Physical means, it is at present almost impossible to include their effects in Real-time Physical Models.

b) Physical Models often require computationally time-consuming methods such as Finite Element Analysis and other Numerical Techniques. These methods often require minutes and even hours to compute a solution, rendering them completely unsuitable for Real-time Control.
It appears therefore that the most suitable Model Types for Real-time Control would be Semi-Physical and Empirical Models where the effects of difficult to determine influences such as the Consumables and Workpiece Material are catered for by the Experimentally determined Constants in the Equation.

An important research aim of the project is the development of Strategies for the Autonomous Control of the Standoff \( (L) \). It has been demonstrated by Kim and Na [22-23] that the Standoff is almost linearly related to the Current and that the Current can be readily modelled by an Empirical Non-Linear Least-Squares Model of the form:

\[
I = K_1 + K_2V + K_3W + K_4L + K_5VW + K_6WL + K_7VL
\]

where \( I \) = Current, \( V \) = Voltage, \( W \) = Wire Feed Rate and \( L \) = Standoff.

The Model is referred to as ‘Non-Linear’ for reasons that will become apparent later in the Chapter. Of all the approaches studied for Autonomous Control, that utilised by Kim and Na appeared to be the most realistic with respect to Real-time Control. According to Kim and Na the Model produced a reasonably accurate estimate of the Current as a function of Voltage, Wire Feed Rate and Standoff Feedback, but would also, due to the simplicity of the Model, require little computational time to calculate a Parameter Estimate. If this approach did produce accurate estimates of Parameters, then it would be an ideal tool for Real-time Control. It was therefore decided to attempt to develop Control Strategies based on this approach.

10.2) Verification of the Kim-Na Least-Squares Current Prediction Model:

Kim and Na utilised a \( 2^3 \) Factorial Combination of Parameters to obtain their Current Predictor. As stated, the Parameters utilised in Current Prediction included Voltage, Wire Feed Rate and Standoff and these are set at two levels in varying combinations as illustrated in Table 10.1 below:

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( V_0 )</td>
<td>( W_0 )</td>
<td>( L_0 )</td>
</tr>
<tr>
<td>1</td>
<td>( V_1 )</td>
<td>( W_1 )</td>
<td>( L_1 )</td>
</tr>
</tbody>
</table>

\( V \) = Voltage, \( W \) = Wire Feed Rate, \( L \) = Standoff

The Parameters are then organised into an Experimental Matrix in the form of a \( 2^3 \) Factorial Combination, as shown in Table 10.2 overleaf:
Table 10.2: $2^3$ Factorial Combination of Parameters.

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>$V$ (V)</th>
<th>$W$ (mm/s)</th>
<th>$L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i=1$</td>
<td>$V_0$</td>
<td>$W_0$</td>
<td>$L_0$</td>
</tr>
<tr>
<td>$i=2$</td>
<td>$V_0$</td>
<td>$W_0$</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$i=3$</td>
<td>$V_0$</td>
<td>$W_1$</td>
<td>$L_0$</td>
</tr>
<tr>
<td>$i=4$</td>
<td>$V_0$</td>
<td>$W_1$</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$i=5$</td>
<td>$V_i$</td>
<td>$W_0$</td>
<td>$L_0$</td>
</tr>
<tr>
<td>$i=6$</td>
<td>$V_i$</td>
<td>$W_0$</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$i=7$</td>
<td>$V_i$</td>
<td>$W_1$</td>
<td>$L_0$</td>
</tr>
<tr>
<td>$i=8$</td>
<td>$V_i$</td>
<td>$W_1$</td>
<td>$L_1$</td>
</tr>
</tbody>
</table>

As stated, the Non-Linear Least-Squares Current Model is of the form:

$$I = K_1 + K_2V + K_3W + K_4L + K_5VW + K_6WL + K_7VL$$

and now putting this Equation into Matrix form we get:

$$I_i = A_yK_j \quad \text{or} \quad [I] = [A][K]$$

where:

$$[A] = \begin{bmatrix}
1 & V_0 & W_0 & L_0 & V_0W_0 & W_0L_0 & V_0L_0 \\
1 & V_0 & W_0 & L_1 & V_0W_0 & W_0L_1 & V_0L_1 \\
1 & V_0 & W_1 & L_0 & V_0W_1 & W_1L_0 & V_0L_0 \\
1 & V_0 & W_1 & L_1 & V_0W_1 & W_1L_1 & V_0L_1 \\
1 & V_1 & W_0 & L_0 & V_1W_0 & W_0L_0 & V_1L_0 \\
1 & V_1 & W_0 & L_1 & V_1W_0 & W_0L_1 & V_1L_1 \\
1 & V_1 & W_1 & L_0 & V_1W_1 & W_1L_0 & V_1L_0 \\
1 & V_1 & W_1 & L_1 & V_1W_1 & W_1L_1 & V_1L_1 \\
\end{bmatrix}$$

$$[K] = \begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4 \\
K_5 \\
K_6 \\
K_7 \\
\end{bmatrix}$$

The Least-Squares Coefficients are now calculated as:


It is important to note at this stage, that the values of $V$, $W$ and $L$ in Matrix $A$ are the actual Sensor Feedback Readings for these Parameters and not the Machine Setting Values.
Least-Squares Models were determined for both Dip and Spray Weld Transfer Modes for five weld runs per setting. Each weld Run was sampled at 5KHz for 0.5 seconds using the 'Shortmon' Package. The settings and resulting Least-Squares Models are given below for Dip Transfer in Table 10.3 and Spray Transfer in Table 10.4.

**Table 10.3: Dip Transfer Settings and Non-Linear Least-Squares Model**

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>60</td>
<td>12</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

**Dip Transfer Non-Linear Least-Squares Current Model:**

\[
I = 291.7571 - 8.5861V + 2.0101W - 14.9770L - 0.0228VW + 0.0004WL + 0.6016VL
\]

**Experimental Constants:**

Electrode Type: Autocraft LW1 (1.2mm Dia), Travel Speed: 300mm/min
Shielding Gas Type: Argoshield 50, Gas Flow Rate: 14litres/min

**Table 10.4: Spray Transfer Settings and Non-Linear Least-Squares Model**

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>29</td>
<td>120</td>
<td>16</td>
</tr>
<tr>
<td>1</td>
<td>31</td>
<td>150</td>
<td>24</td>
</tr>
</tbody>
</table>

**Spray Transfer Non-Linear Least-Squares Current Model:**

\[
I = -277.1539 + 7.8553V + 2.6608W + 9.5482L - 0.0155VW - 0.0429WL - 0.3287VL
\]

**Experimental Constants:**

Electrode Type: Autocraft LW1 (1.2mm Dia), Travel Speed: 300mm/min
Shielding Gas Type: Argoshield 50, Gas Flow Rate: 14litres/min

It is important to note that the Models are only valid within the Parameter Ranges for which the Coefficients were determined. Please also note that the Experimental Constants included in the above Tables are standard for all Experimentatal Work undertaken.

It should also be noted that different Models are required for Dip and Spray Transfer Modes because of the varying Transfer Characteristics that occur.
Once the Models were determined for Dip and Spray Transfer, it is now necessary to verify them using a range of representative parameter settings within the parameter ranges for which the Models were developed. The parameter settings selected for Dip Transfer Model Verification are given in Table 10.5 below:

<table>
<thead>
<tr>
<th>Set</th>
<th>V (V)</th>
<th>W (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>100</td>
</tr>
</tbody>
</table>

$L = 12\text{mm to } 20\text{mm}: \text{Step } 2\text{mm for each Set}$

With respect to the Legend in Fig 10.1, the ‘E’ refers to Experimental Current Values obtained from the Current Sensor and the ‘M’ refers to the predicted Current Values from the Least-Squares Model.

It can be seen from Fig 10.1 that the Experimental Current Readings quite accurately match the Predicted Current Values from the Dip Transfer Non-Linear Least-Squares Model with the largest Error being 2.96% with Set 2 at $L=16\text{mm}$.

The parameter settings selected for the Non-Linear Spray Transfer Model Verification are given in Table 10.6 overleaf:
Table 10.6: Spray Transfer Model Verification Settings

<table>
<thead>
<tr>
<th>Set</th>
<th>V (V)</th>
<th>W (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>135</td>
</tr>
<tr>
<td>3</td>
<td>31</td>
<td>150</td>
</tr>
</tbody>
</table>

$L = 16\text{mm} \text{ to } 24\text{mm}: \text{Step } 2\text{mm for each Set}$

Fig 10.2: Spray Transfer Non-Linear Least-Squares Model (Verification)

It can also be seen from Fig 10.2 that the Experimental Current Readings quite accurately match the Predicted Current Values from the Spray Transfer Least-Squares Model with the largest Error being 3.0% with Set 2 at $L=16\text{mm}$.

It can therefore be concluded that the Kim/Na Model is verified as a Model that may be utilised as a Real-time Current Estimator.

An attempt was made to slightly improve upon the Original Non-Linear Least-Squares Current Predictor by removing the last three non-linear terms of the Equation. The Model is now therefore reduced from a Non-Linear least-Squares Model of the form:

$$I = K_1 + K_2V + K_3W + K_4L + K_5VW + K_6WL + K_7VL$$

to a Linear Least-Squares Model of the form:

$$I = K_1 + K_2V + K_3W + K_4L$$
and now again putting this Equation into Matrix form we get:

\[ I_i = A_j K_j \quad \text{or} \quad [I] = [A][K] \]

where the Matrices are now reduced to:

\[
[I] = \begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4 \\
I_5 \\
I_6 \\
I_7 \\
I_8 \\
\end{bmatrix} \quad [A] = \begin{bmatrix}
1 & V_0 & W_0 & L_0 \\
1 & V_0 & W_0 & L_1 \\
1 & V_0 & W_1 & L_0 \\
1 & V_0 & W_1 & L_1 \\
1 & V_1 & W_0 & L_0 \\
1 & V_1 & W_0 & L_1 \\
1 & V_1 & W_1 & L_0 \\
1 & V_1 & W_1 & L_1 \\
\end{bmatrix} \quad [K] = \begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4 \\
\end{bmatrix}
\]

As before, the Least-Squares Coefficients are now calculated as:


With the same data utilised for the generation of the Non-Linear Least-Squares Models, Linear Least-Squares Models were determined for both Dip and Spray Weld Transfer Modes. The resulting Linear Least-Squares Models are displayed below for Dip Transfer in Table 10.7 and Spray Transfer in Table 10.8.

### Table 10.7: Dip Transfer Linear Least-Squares Current Model

**Dip Transfer Linear Least-Squares Current Model:**

\[ I = 125.6917 - 0.6578V + 1.5600W - 2.4193L \]

### Table 10.8: Spray Transfer Linear Least-Squares Current Model

**Spray Transfer Linear Least-Squares Current Model:**

\[ I = 88.6752 + 4.7884V + 1.3558W - 5.5310L \]
For the experimental data obtained for the Dip Transfer Verification Settings (see Table 10.5) and Spray Transfer Verification Settings (See Table 10.6) the Linear Least-Squares Model was validated by comparing Experimental Current Values to those predicted by the Linear Least-Squares Models. The Results are displayed below in Fig 10.3 for Dip Transfer and Fig 10.4 for Spray Transfer.

It can be seen from Fig 10.3 that the Experimental Current Readings also quite accurately match the Predicted Current Values from the Dip Transfer Linear Least-Squares Model with the largest Error being 2.50% with Set 2 at $L=16\text{mm}$.
Fig 10.4 on the preceding page indicates that the Experimental Current Readings also quite accurately match the Predicted Current Values from the Spray Transfer Linear Least-Squares Model although the largest Error was 3.02% with Set 2 at L=16mm which is just slightly greater than the largest error for the Non-linear model.

A graphical comparison of the Predicted Current values for the Dip and Spray Transfer Linear and Non-linear models are shown in Fig 10.5 below and Fig 10.6 below:
It can be seen from both Fig 10.5 and Fig 10.6 that there is very little significant difference between the performance of the Linear and Non-Linear Models for both Dip and Spray Transfer. An analysis of the errors was also undertaken to further validate this conclusion. Table 10.9 below gives a statistical comparison of the mean Current Prediction Errors of each Experimental Set for both Dip and Spray Transfer Models with respect to the Experimental Current Readings.

<table>
<thead>
<tr>
<th>Set</th>
<th>Dip Transfer</th>
<th>Spray Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L Error (A)</td>
<td>N Error (A)</td>
</tr>
<tr>
<td>1</td>
<td>1.064</td>
<td>1.673</td>
</tr>
<tr>
<td>2</td>
<td>3.915</td>
<td>4.404</td>
</tr>
<tr>
<td>3</td>
<td>0.664</td>
<td>0.777</td>
</tr>
</tbody>
</table>

It can be seen from Table 10.9 that the Current Prediction Errors for the Linear Model are slightly smaller than those obtained for the Non-linear Model. The Linear Model will henceforth be utilised for Real-time Current Prediction Models.

10.3) **Development of a Least-Squares Model for Standoff Prediction:**

It has been assumed at this stage, that the concept of the Least-Squares Model is only valid for Current Prediction. The process of Model Validation and Comparison of Linear and Non-Linear Least-Squares Models will be repeated in an attempt to determine a Standoff Predictor which will be generated and verified with the data obtained for the Current Prediction Model. The Least-Squares Standoff Predictor will simply be a rearrangement of the Least-Squares Current Predictor.

The Non-Linear Least-Squares Standoff Predictor will therefore be of the form:

\[ L = K_1 + K_2 V + K_3 I + K_4 W + K_5 VI + K_6 WI + K_7 VW \]

and the Linear Least-Squares Standoff Predictor will be of the form:

\[ L = K_1 + K_2 V + K_3 I + K_4 W \]
Putting these Equations into Matrix form we get:

\[ L_4 = A_j K_j \quad \text{or} \quad [L] = [A][K] \]

where, for the Non-Linear Least Squares Model:

\[
[L] = \begin{bmatrix}
L_1 \\
L_2 \\
L_3 \\
L_4 \\
L_5 \\
L_6 \\
L_7 \\
L_8 \\
\end{bmatrix}
= \begin{bmatrix}
1 & V_0 & I_0 & W_0 \\
1 & V_0 & I_0 & W_1 \\
1 & V_0 & I_1 & W_0 \\
1 & V_0 & I_1 & W_1 \\
1 & V_1 & I_0 & W_0 \\
1 & V_1 & I_0 & W_1 \\
1 & V_1 & I_1 & W_0 \\
1 & V_1 & I_1 & W_1 \\
\end{bmatrix}
\begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4 \\
K_5 \\
K_6 \\
K_7 \\
\end{bmatrix}
\]

and for the Linear Least-Squares Model:

\[
[I] = \begin{bmatrix}
L_1 \\
L_2 \\
L_3 \\
L_4 \\
L_5 \\
L_6 \\
L_7 \\
L_8 \\
\end{bmatrix}
= \begin{bmatrix}
1 & V_0 & I_0 & W_0 \\
1 & V_0 & I_0 & W_1 \\
1 & V_0 & I_1 & W_0 \\
1 & V_0 & I_1 & W_1 \\
1 & V_1 & I_0 & W_0 \\
1 & V_1 & I_0 & W_1 \\
1 & V_1 & I_1 & W_0 \\
1 & V_1 & I_1 & W_1 \\
\end{bmatrix}
\begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4 \\
\end{bmatrix}
\]

Again, The Least-Squares Coefficients are now calculated as:

\[
\]

for both the Linear and Non-Linear Standoff Predictors.

The Non-Linear and Linear Least-Squares Standoff Predictors were determined for both Dip and Spray Transfer Modes and are displayed in Tables 10.10 and 10.11 overleaf followed by Graphs of Standoff Prediction versus Actual Standoff for the Linear and Non-Linear Models:
Table 10.10: Dip Transfer Least-Squares Standoff Models

Dip Transfer Non-Linear Least-Squares Standoff Model:
\[ L = -122.1539 + 7.8853V + 1.7217I - 2.4414W - 0.1011VI - 0.0003IW + 0.1502VW \]

Dip Transfer Linear Least-Squares Standoff Model:
\[ L = 44.3481 - 0.0469V - 0.3781I + 0.5939W \]

Table 10.11: Spray Transfer Least-Squares Standoff Models

Spray Transfer Non-Linear Least-Squares Standoff Model:
\[ L = 110.0070 - 0.3261V - 0.8172I + 0.4831W + 0.0153VI + 0.0015IW - 0.0242VW \]

Spray Transfer Linear Least-Squares Standoff Model:
\[ L = 14.7975 + 0.8850V - 0.1766I + 0.2411W \]

Once the Standoff Models were determined they were now verified using exactly the same procedure and data that was used to verify the Current Models.

Past research [59] indicates that it is extremely difficult to obtain a very accurate Standoff Prediction because:

a) The curviness of the wire may cause variations in the point at which the wire makes contact with the Contact Tip. Variations in the point of wire contact in the Contact Tip result in variations in the effective Wire Stickout leading to variations in Wire Resistance and therefore also variations in the Current and Voltage.

b) Variations in the Wire Feed Rate would also directly affect the Current levels.

Past Research [59] also indicates that a reasonable Standoff Model will be able to determine the Standoff to within +/-2mm of the True Standoff. Fig 10.7 (overleaf) displays the plots for Dip Transfer Linear and Non-Linear Model Standoff Predictions whilst Fig 10.8 (also overleaf) displays the plots for the Spray Transfer Linear and Non-Linear Standoff Model Predictions. The Graphs also display the upper and lower Tolerance lines for the actual Standoff values (Upper Tolerance = L + 2 and Lower Tolerance = L - 2).
It can be seen from both Fig 10.7 and Fig 10.8 that, with the exception of Set 2 for the Dip Transfer Standoff Model, all Predictions fall within the +/-2mm Tolerance band. An analysis of the errors was also undertaken to determine which Model Type (ie. Linear or Non-Linear) produced on average the most accurate Standoff Predictions. Table 10.12 overleaf gives a comparison of the mean Standoff Prediction Errors of each Experimental Set for both Dip and Spray Transfer Models with respect to the Actual Standoff Settings.
Table 10.12: Errors for Linear (L) and Non-Linear (N) Standoff Models

<table>
<thead>
<tr>
<th>Set</th>
<th>L Error (mm)</th>
<th>N Error (mm)</th>
<th>L Error (mm)</th>
<th>N Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5997</td>
<td>0.7887</td>
<td>0.8474</td>
<td>1.0033</td>
</tr>
<tr>
<td>2</td>
<td>1.5032</td>
<td>1.7914</td>
<td>1.2246</td>
<td>0.7788</td>
</tr>
<tr>
<td>3</td>
<td>0.2007</td>
<td>0.4896</td>
<td>0.5175</td>
<td>0.7091</td>
</tr>
</tbody>
</table>

By inspection, it can be seen from Table 10.12 that the performance of the Linear Standoff Prediction Models is, for most settings, superior to that of the Non-Linear Models. The Linear Standoff Model will therefore be utilised in the development of Real-time Standoff Predictors.

10.4) **Verification of Linear Standoff Models as Real-Time Standoff Predictors:**

The Standoff Models determined in Sec 10.3 were generated from data collected using the ‘Shortmon’ Package at 5KHz and a Sampling Period of 0.5 Seconds. As stated at the beginning of this chapter, weld irregularities should be corrected within 2mm of Weld Travel and therefore, depending in the Weld Travel Speed, the Sampling Period should be 0.1 Seconds (@ TS = 600mm/min for thin MS Sheet) to 0.2 Seconds (@ TS = 300mm/min for thicker MS Plate).

As an important future research interest is the Welding of thicker Mild Steel Plate, a range of Experiments was undertaken with the Sampling Period reduced to 0.2 Seconds. It was expected that this reduction in Sampling Interval would not significantly alter the Standoff Prediction performance of Spray Transfer Welding or Dip Transfer Welding at higher Dipping Frequencies (ie. where the number of Dips greater than 10 in the 0.2 Second Sampling Interval). The problem is likely to occur with Dip Transfer Welding at low Dipping Frequencies as Sampling could start and end at various points in the Dip Transfer Cycle resulting in false Parameter Readings after averaging.

![Fig 10.9: Parameter Averaging Errors](a.png)  
![Fig 10.9: Parameter Averaging Errors](b.png)
Fig 10.9 on the previous page displays Dip Transfer Current Traces over the Sampling Period of 0.2 Seconds. It can be seen from Fig 10.9 (a) that 2 complete Dip Cycles fit in the Sampling Period and hence the Calculated Current Average will be very near the True Current Average. However, in Fig 10.9 (b), there is only 1 complete and 2 incomplete cycles, which results in the Calculated Current Average being much higher than the True Current Average. Incorrect Averaging of Feedback Parameters such as the Current can also therefore clearly affect the Accuracy of Standoff Predictions from Least-Squares Models.

Experiments were undertaken to verify the Dip and Spray Transfer Linear Least-Squares Models with a Sampling Period of 0.2 Seconds and were performed using the ‘Longmon’ Program for Data Acquisition and the Current/Standoff Model Verification Jig illustrated in Fig 10.10 below (See also the Drawing entitled ‘Current/Standoff Model Verification Jig’ in Appendix VI).

The Current/Standoff Model Verification Jig (CSMVJ) was designed to test Current and Standoff Models for a gradient increase in Standoff over the Weld Length and is used with the Longmon Program where Current and Standoff Predictions can be obtained for each Sampling Period monitored.

In using the CSMVJ, the Contact Tip is set to the correct Standoff and Starting Point using the Setting Block. The Weld Length is PLC controlled at 200 mm and as the Weld progresses, the Standoff gradually increases until at the end of the

![Fig 10.10: Current/Standoff Model Verification Jig](image-url)
Weld Length the Standoff will have increased by 8mm. It can therefore be seen that both Dip and Spray transfer Models can be verified for a range of Standoff Values over the Standoff range for which the Models were originally developed.

The Actual Standoff value for any Sampling Period in the Weld Run is calculated as described below:

The Weld Travel at the end of a Sampling Period relative to the Weld Starting Point is given as:

\[ S(n) = S(n-1) + TS(n)(t(n) - t(n-1)) \]

where:

- \( n \): The current Sampling Period.
- \( S(n) \): Weld Travel at the end of the current Sampling Period.
- \( S(n-1) \): Weld Travel at the end of the previous Sampling Period.
- \( TS(n) \): Mean Weld Travel Speed for the current Sampling Period.
- \( t(n) \): Time at the end of the current Sampling Period from the start of Welding.
- \( t(n-1) \): Time at the end of the previous Sampling Period from the start of Welding.

Having now calculated the value \( S(n) \), the corresponding Standoff can be calculated using simple Trigonometry:

\[ L(n) = S(n)\tan\theta \]

where:

- \( L(n) \): The Standoff at the end of the current Sampling Period.
- \( \theta \): The Gradient of the Workpiece Support (See Fig 9.10).

\[ \theta = \frac{8}{200} = 0.04. \]
It has been determined experimentally that this method provides a Standoff with an accuracy of +/-0.1mm.

For verifying the Dip and Spray Standoff Models, a Matrix of Settings was established for each Welding Mode with ranges within and bordering on the range of Settings for which the Dip and Spray Transfer Standoff Models were originally developed (See Table 10.3 for Dip Transfer and 10.4 for Spray Transfer). One Weld Run on the CSMVJ was completed per Setting and for each Sampling Period, the Actual Standoff ($L_a$) was compared to the Predicted Standoff ($L_p$) to determine the Standoff Error ($\Delta L$). The Standoff Error is therefore determined by:

$$\Delta L = \text{ABS}(L_a - L_p)$$

where $\Delta L$ is the Absolute Value of the difference between $L_a$ and $L_p$.

10.4.1) **Verification of the Dip Transfer Linear Least Squares Standoff Model for Real-time Control:**

The Matrix of settings for verifying the Dip Transfer Linear Least-Squares Model as a Real-time Standoff Estimator is given in Table 10.13 below:

<table>
<thead>
<tr>
<th>V (V)</th>
<th>WFR (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>60 65 70 75 80 85 90 95 100</td>
</tr>
<tr>
<td>21</td>
<td>60 65 70 75 80 85 90 95 100</td>
</tr>
<tr>
<td>22</td>
<td>60 65 70 75 80 85 90 95 100</td>
</tr>
</tbody>
</table>

It can be seen from Table 10.13 that for Dip Transfer Model Verification, 27 Weld Runs were completed yielding a total of 3977 Sampling Periods for which Standoff Predictions were calculated. Table 10.14 below displays the result of this set of Experiments:

<table>
<thead>
<tr>
<th>$\Delta L$ (mm)</th>
<th>&gt; +/-2.5</th>
<th>&lt; +/-2.5</th>
<th>&lt; +/-2.0</th>
<th>&lt; +/-1.5</th>
<th>&lt; +/-1.0</th>
<th>&lt; +/-0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>1133</td>
<td>2844</td>
<td>2374</td>
<td>1875</td>
<td>1299</td>
<td>670</td>
</tr>
<tr>
<td>% Samples</td>
<td>28.49</td>
<td>71.51</td>
<td>59.69</td>
<td>47.15</td>
<td>32.66</td>
<td>16.85</td>
</tr>
</tbody>
</table>
The Results in Table 10.14 show that for the Dip Transfer Standoff Model, only 59.69% of the Standoff Predictions were within the +/- 2.0mm Error Tolerance, indicating that it is not really possible to obtain an accurate and reliable Standoff Prediction in Dip Transfer Mode for the Transmig 350 EC Welding Machine. This is due to the fact that, even for the higher WFR Settings within the above Matrix, the Dipping Frequency was not sufficient to give a reasonably stable Current Mean over the Sampling Period of 0.2 Seconds. Parameter Values could have been distorted because of the effects of incomplete Dip Cycles on Parameter Averaging, as illustrated in Fig 10.9.

Instabilities in the Dip Transfer Process (ie. variations in Dipping Frequency) would also cause significant variations in the Parameter Averages.

The variation in Parameter Averaging for the Sampling Periods for a Weld Run is illustrated in Fig 10.11 below which shows the Dip Transfer Current traces produced by ‘Longmon’ for Settings V=20V, WFR=60mm/s and V=20V, WFR=100mm/s:

![Fig 10.11: Dip Transfer Current Traces from the ‘Longmon’ Program.](image-url)
It can be seen from Fig 10.11 that the Current traces for Dip Transfer with a Sampling Period of 0.2 Seconds is extremely noisy although the linear decrease in current with the linear increase in Standoff is clearly distinguishable. It can also be clearly seen that the variation in Current Readings for WFR=100mm/s is less than that observed for WFR=60mm/s. This is probably due to the higher WFR causing an increase in Dipping Frequency resulting in more accurate Current Averaging. However, the amount of Current Variation for both Settings is sufficient to cause significant errors in Standoff Predictions.

The Low Dipping Frequency encountered is probably caused by the Machine Inductance.

Attempts were made to reduce the problem of Current Variation by utilising a Current Smoothing Algorithm that eliminates instabilities and Part Cycles from the Current Data as illustrated in Fig 10.12 below.

The Current Smoothing Algorithm functions by detecting the Dipping Peaks above a Threshold Current Value. If the Cycle Time between Peaks is less than the Threshold Cycle Time the Cycle is classed as an instability. Incomplete Cycles at the Start and end of the Current Data Sample are rejected.
Once instabilities and Incomplete Cycles have been eliminated from the Current Data Sample, the Data from the accepted Cycles is Averaged to produce a mean Current Value.

The Algorithm was subjected to some initial testing and did not appear to significantly reduce Current Variation in Dip Transfer. It is the Authors opinion that the successful implementation of the Algorithm could be achieved with a database of Current and Cycle Time Threshold Values that cater for the variation in Cycle Characteristics of different Machine Settings. However, Welding Machines more modern than the Transmig 350 EC have higher Dipping Frequencies (upto 200Hz (40Cycles in 0.2 Seconds)) thereby providing sufficient Cycles for Parameter Averaging and rendering the issue of Current Smoothing irrelevant.

As the Resistance in a Wire is directly proportional to the length of the Wire, another method which may be utilised for direct Standoff Prediction is the Resistance in the Electrode Wire at the end of the Dipping Period. The Resistance Trace of a Short in Dip Transfer Welding is displayed in Fig 10.13 below and demonstrates the point in the Cycle where the Resistance would be measured for use in Standoff Prediction:

This Resistance Measurement Point demonstrated in Fig 10.13 above can be easily detected in Real-time using Voltage and Current Measurements, with the Resistance in the Wire calculated by the simple Ohms Law Equation:
\[ R = \frac{V}{I} \]

In performing a preliminary feasibility test for this method, the Welding Machine was set at the randomly selected Dip Transfer Setting of \( V=20\, \text{V} \), \( WFR=70\, \text{mm/s} \) with the Standoff Settings varying from 12mm to 20mm in steps of 2mm. One Weld Run was completed for each Standoff Setting and monitored using the 'Shortmon' Program. Five Dips were then selected from the data of each Run and the Resistance determined for each selected Dip at the point in the Dipping Cycle where burnback was just about to occur.

The results of this experiment are displayed graphically in Fig 10.14 below:

It can be seen from Fig 10.14, that the Resistance of the Wire was found to be directly proportional to the Standoff and it appears that this method may be feasible for Standoff Prediction. However, it assumed that a significant amount of research work is needed to further verify the feasibility of this method and also for its development and implementation.

10.4.2) Verification of the Spray Transfer Linear Least Squares Standoff Model for Real-time Control:

The Matrix of settings for verifying the Spray Transfer Linear Least-Squares Model as a Real-time Standoff Estimator is given in Table 10.15 overleaf:
Table 10.15: Table of Machine Settings for the Verification of the Spray Transfer Linear Least-Squares Standoff Model as a Real-time Standoff Estimator

<table>
<thead>
<tr>
<th>V (V)</th>
<th>WFR (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>120 125 130 135 140 145 150</td>
</tr>
<tr>
<td>30</td>
<td>120 125 130 135 140 145 150</td>
</tr>
<tr>
<td>31</td>
<td>120 125 130 135 140 145 150</td>
</tr>
</tbody>
</table>

It can be seen from Table 10.15 that for the Spray Transfer Model Verification, 21 Weld Runs were completed yielding a total of 3067 Sampling Periods for which Standoff Predictions were calculated. Table 10.16 below displays the result of this set of Experiments:

Table 10.16: Spray Transfer Standoff Model Error Analysis

<table>
<thead>
<tr>
<th>ΔL (mm)</th>
<th>&lt; +/- 2.5</th>
<th>&lt; +/- 2.0</th>
<th>&lt; +/- 1.5</th>
<th>&lt; +/- 1.0</th>
<th>&lt; +/- 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>3067 3067 3050 2776 1509</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Samples</td>
<td>100 100 99.45 90.51 49.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 10.15: Spray Transfer Current Traces from the ‘Longmon’ Program.
The Results in Table 10.16 on the previous page show that for the Spray Transfer Standoff Model, 100% of the Standoff Predictions were within the +/-2.0mm Error Tolerance, indicating that this Model is suitable for Real-time Control of Standoff in the Spray Transfer Mode.

Fig 10.15 on the previous page displays some typical Spray Transfer Current Traces obtained by the ‘Longmon’ Program. The Linear decrease of Current with Linear increase in Standoff can be very clearly seen. It will also be observed that there is very little variation in the Current Trace when compared to the variation levels which can be observed for the Dip Transfer Current traces in Fig 10.11. This is clearly because of the smooth nature of Spray Transfer Welding where almost constant Voltage and Current Parameter Traces are obtained and no Dipping or other phenomena occur which cause heavily dynamic parameter changes to occur.
Chapter 11

The ‘Weldmod’ Program for On-line Modelling

11.1) Introduction to the ‘Weldmod’ Program:

The ‘Weldmod’ Program is a modified version of the ‘Longmon’ Program and has been developed as prototype Software for rapid on-line Weld Model generation. This version generates Models for Current and Standoff Predictions utilising the Linear Least-Squares Method described in Chapter 10.

It will be remembered from Chapter 10 that the Least-Squares Model is produced by a $2^3$ Factorial Combination of a two-level Set of Experimental Parameters. The Experimental Parameters Setup is again illustrated in Table 11.1 below whilst the Combination of Parameter Settings as ordered in the ‘Weldmod’ Program is illustrated in Table 11.2:

Table 11.1: Experimental Parameters Setup

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$V_0$</td>
<td>$W_0$</td>
<td>$L_0$</td>
</tr>
<tr>
<td>1</td>
<td>$V_1$</td>
<td>$W_1$</td>
<td>$L_1$</td>
</tr>
</tbody>
</table>

$V$ = Voltage, $W$ = Wire Feed Rate, $L$ = Standoff

Table 11.2: $2^3$ Factorial Combination of Parameters.

<table>
<thead>
<tr>
<th>Event No</th>
<th>L (mm)</th>
<th>V (V)</th>
<th>W (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$L_0$</td>
<td>$V_0$</td>
<td>$W_0$</td>
</tr>
<tr>
<td>2</td>
<td>$L_0$</td>
<td>$V_0$</td>
<td>$W_1$</td>
</tr>
<tr>
<td>3</td>
<td>$L_0$</td>
<td>$V_1$</td>
<td>$W_0$</td>
</tr>
<tr>
<td>4</td>
<td>$L_0$</td>
<td>$V_1$</td>
<td>$W_1$</td>
</tr>
<tr>
<td>5</td>
<td>$L_1$</td>
<td>$V_0$</td>
<td>$W_0$</td>
</tr>
<tr>
<td>6</td>
<td>$L_1$</td>
<td>$V_0$</td>
<td>$W_1$</td>
</tr>
<tr>
<td>7</td>
<td>$L_1$</td>
<td>$V_1$</td>
<td>$W_0$</td>
</tr>
<tr>
<td>8</td>
<td>$L_1$</td>
<td>$V_1$</td>
<td>$W_1$</td>
</tr>
</tbody>
</table>

The ‘Weldmod’ Program simply sets and monitors the Parameter Events in a single Weld Run and generates the Least-Squares Model instantaneously from the acquired data.

It will be observed from Table 11.2 that the Experimental Order in the ‘Weldmod’ Program is different to that for the Experimentation undertaken in Chapter 10 (see Table 10.2). This is because the Current/Standoff Modelling...
Jig (See the Drawing entitled ‘Current/Standoff Modelling Jig’ in Appendix VI) has been designed for single drop in Standoff over the length of the Weld Run. This means that the first four Parameter Events will be at Standoff $L_0$ on a Material Thickness of 16mm, after which the Material Thickness drops by 8mm effectively increasing the Standoff to $L_1$ for the final four Parameter Events. The Factorial Combination of Events have therefore been configured such that the Standoff Setting changes only once in the course of the Modelling Weld Run. The Stages of the ‘Weldmod’ Modelling Run are illustrated in Fig 11.1 below:

On commencing a Modelling Weld Run, a Startup Period of 5mm allows the Welding Process to stabilise before Data Acquisition commences. After this the Program Moves into the Modelling Routine which consists of alternating Event and Rest Periods. An Event Period is where Data is obtained for a Particular Parameter Event and the following Rest Period is where the Data for the Parameter Event is Processed and the Parameters for the next Parameter Event are set. The Terminating Routine (R8) Processes the Data obtained for the last Parameter Event and Resets the Parameters to their original settings (ie. the settings for the First Parameter Event). Details of the Weld Modelling Routine are given in Sec 11.2 below:

11.2) The Model Weld Run:

The Charts in Fig 11.2 overleaf illustrate the acquisition Analysis and Routing of Data in the Weldmod Program:
Fig 11.2 (A): Data Analysis and Routing in the ‘Weldmod’ Program
(for Event 1 of Model Weld Run 1)
Event 8: Sampling Period (SP) 1
Sample Set (1)
Sample Set (2)
Sample Set (3)
Sample Set(1998)
Sample Set(1999)
Sample Set(2000)

Mean Parameter (MP) Arrays:
Event 8
MP(1)
MP(2)
MP(3)

SP1 Mean

MP Mean

Mean Parameter
MP(m-2)
MP(m-1)
MP(m)

MP(m)

MP Mean

Parameter Setting Events

<table>
<thead>
<tr>
<th>Event</th>
<th>L</th>
<th>V</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L_0</td>
<td>V_0</td>
<td>W_0</td>
</tr>
<tr>
<td>2</td>
<td>L_0</td>
<td>V_0</td>
<td>W_1</td>
</tr>
<tr>
<td>3</td>
<td>L_0</td>
<td>V_1</td>
<td>W_0</td>
</tr>
<tr>
<td>4</td>
<td>L_0</td>
<td>V_1</td>
<td>W_1</td>
</tr>
<tr>
<td>5</td>
<td>L_1</td>
<td>V_0</td>
<td>W_0</td>
</tr>
<tr>
<td>6</td>
<td>L_1</td>
<td>V_0</td>
<td>W_1</td>
</tr>
<tr>
<td>7</td>
<td>L_1</td>
<td>V_1</td>
<td>W_0</td>
</tr>
</tbody>
</table>

Model Data (MD) Arrays

Event 1
Event 2
Event 3
Event 4
Event 5
Event 6
Event 7
Event 8

Run 1
Run 2
Run 24
Run 25

Fig 11.2 (B): Data Analysis and Routing in the ‘Weldmod’ Program
(for Event 8 of Model Weld Run 1)
Whilst Fig 11.2 provides details of the Data Analysis and Routing Procedures in the 'Weldmod' Program, the actual order in which the described Data Acquisition and Processing Operations are undertaken is explained later in this Section. It can be seen from Fig 11.2 that 'Weldmod' has the capacity for up to 25 Modelling Weld Runs. Whilst a Least-Squares Model can be generated with 1 Modelling Weld Run, Weld Models can be generated from multiple Modelling Weld Runs if it is felt that a more accurate Model will result.

It should be noted that Data collected in the Sampling Periods of each Event consist of Voltage, Current, Wire Feed Rate (WFR) and Travel Speed (TS) Readings and each Parameter has its own Single-Dimension Array in Computer Memory in which the Data for each Sample Set is stored. Clearly, the Mean Parameter Array also consists of a Single-Dimension Array for each of the Sampling Period Means of the above mentioned Parameters. The Model Data Array however consists of Single-Dimension Arrays for the Model Data Values of Voltage, Current, Wire Feed Rate, Travel Speed and Standoff. Mean Travel Speed Values are included in the Model Data Array but are not utilised in the Least-Squares Models. The Array Structures are illustrated in Fig 11.3 below:

| Sampling Period Arrays (2000 Locations/Parameter) |
| Voltage | Current | WFR | TS |
| Mean Parameter Arrays (20 Locations/Parameter) |
| Voltage | Current | WFR | TS |
| Model Data Arrays (25 Runs = 200 Locations/Parameter) |
| Voltage | Current | WFR | TS | Standoff |

Fig 11.3: Parameter Array Structures in 'Weldmod'

As the Standoff setting is determined by Workpiece Geometry (See Fig 11.1) and therefore known for each Event, the Standoff Values are therefore simply entered directly into the Model Data Array without the Data Acquisition and processing that the Voltage, Current and Wire Feed Rate Values require.

It should also be noted at this point that in the 'Weldmod' Software, the Data Acquisition Sampling Rate is set to 5KHz, the Sample Count for each Sampling Period is set to 2000 Samples/Parameter and the Weld Travel Speed is set to 300mm/min. These Parameters are software set and cannot be altered by the User in the current version of 'Weldmod'.

The number of Sampling Periods/ Parameter Event (m) is thirteen (13).
Before commencing a Weld Run, the following settings are to be completed by the User:

i) The Maximum and Minimum Voltage and WFR Settings must be set using the GUI Sliders described in Section 11.3.

ii) The Welding Mode (ie. Dip or Spray Transfer Welding) must be set as this will determine the Standoff values assigned to the Model Data Array during the Model Run. The Initial Standoff Setting is manually set to 12mm for Dip Transfer Welding and 16mm for Spray Transfer Welding.

iii) The Welding Gun must be positioned at the correct Location. This position is marked on the Current/Standoff Modelling Jig.

iv) The Data Acquisition Delay (As described in Sec 8.4.8) must be set to active. The default Delay setting is active and therefore need not be altered unless the Delay for some reason has been deactivated.

Once the prerequisite activities have been completed as described above, Model Weld Runs can now be undertaken. The flowchart in Fig 11.4 below provides a basic illustration of the flow of the Model Data Acquisition Routine:
It can be seen from Fig 11.4 that the Model Data Routine is divided into an Initialisation Routine followed by Event and Rest Periods (which are performed whilst the Event Count is less than 9). Descriptions of the functions of these Routines now follows:

11.2.1) **The Initialisation Routine:**

A detailed flowchart of the Initialisation Routine is illustrated in Fig 11.5 below:

![Initialisation Routine Flowchart](image)

**Fig 11.5: ‘Weldmod’ Model Data Routine (Initialisation Routine)**
The Initialisation routine will halt Program execution (if the Delay is set) until the Welding Process has started.

When the Welding Process has started, the Program moves into the Startup Period which allows 5mm of Weld Travel before the Model Data Acquisition Process begins. As stated, this is to enable the Welding Process to stabilise prior to commencing Data Acquisition. It can be seen from the Flowchart in Fig 11.5 that the Startup Period consists of a loop that calculates the Weld Travel Distance (S) for every Cycle and only terminates when S has reached 5mm.

The Weld Travel Distance (S) is calculated by:

\[ S = \frac{(Set\_TS)}{60} \times Weld\_Time \]

where:

Set\_TS: The Set Weld Travel Speed (300mm/min).
Weld\_Time: The Time Elapsed Since the Start of Welding (Seconds).

The Weld Time is the difference between the Current and Start Times obtained from the System Clock and is calculated using special ‘C’ Language Functions.

The final function of the Initialisation Routine is to set the ‘Plot Time’ to zero. The ‘Plot Time is the time of a Sampling Period of any Event relative to the start of the first Event. Please note that these ‘Plot Times’ exclude the Time taken for the Rest Period and only include the time of the Event Periods. This is discussed in more detail in Sec. 11.2.2.

It can be seen from Fig 11.4 that once the Initialisation Period has been completed, the Program then commences to collect Weld Data for the Model. As stated, this is achieved in 8 Parameter Event Periods with alternating Rest Periods where the data for the Event Period is processed and the Parameter values for the next Event are set. Section 11.2.2 provides details of the Event Period whilst section 11.2.3 deals with the rest Period.

11.2.2) The Event Period:

A detailed Flowchart of the Event Period Routine is illustrated in Fig 11.6 overleaf:
Fig 11.6: Model Data Routine (Event Period)

BEGIN

Get Initial Start Time (From System Clock)

Set $S = 0$

Set $k = 1$

Acquire Raw Weld Data over the Sampling Period

Calculate Real Parameter Values from the Raw Data Acquired

Calculate Mean Parameter Values and store in MP Arrays at Location K

Get Current Time (From System Clock)

Eqn 1 Calculate Current $S$

Get Start Time (From System Clock)

Eqn 2 Calculate Current Plot Time

Plot MP Values in MP Array at Location K

$k = k + 1$

B

Is $S + 2.2\text{mm} < 30\text{mm}$?

Yes

No

Get Start Time (From System Clock)

Get Current Time (From System Clock)

Calculate Current $S$

Is $S \geq 30\text{mm}$?

Yes

END

No

A

S = Weld Travel Distance.
k = MP Arrays Memory Location Pointer.
The Event Period is utilised to acquire Weld Data for a particular Parameter Setting Event.

On entering an Event Period for a Parameter Setting, the Program acquires a 'Initial Start Time' (IST) reading from the System Clock, the Weld Distance (S) is set to zero and the Mean Parameter (MP) Arrays Pointer (k) is set to 1 (i.e. the first location in the MP Arrays). Parameter Data is then acquired in a Sampling Period, averaged and then stored in the Mean Parameter Arrays at the Memory Location pointed at by the Array Pointer (k) (see also Fig 11.2). Raw Data is acquired and converted to actual Parameter Values as described in Sec 6.8.

After Data Acquisition the 'Current Time' (CT) reading is obtained from the System Clock and the Weld Distance Travelled up to this point in the Parameter Event is calculated by:

\[ S(k) = S(k-1) + \frac{TS(k)}{60} \times \text{Time}_\text{Inc} \] ...........................(Eqn 1)

where:

S(k): The Weld Distance for Cycle k relative to the Start of the Event.

S(k-1): The Weld Distance for the Model Data Acquisition Cycle (k-1) relative to the Start of the Event.

TS(k): The Mean Travel Speed for the Model Data Acquisition Cycle k.

Time_Inc: The Time Difference between the acquisition of the 'Current Time (CT(k)) and the 'Start Time' of the previous Data Acquisition Cycle (ST(k-1)) calculated by 'C' Language Functions.

The Mean Parameter Data for each Data Acquisition Cycle in the Parameter Event is plotted in real-time on Graphs for a Plot Time relative to the Start of Data Acquisition at the start of the first Event Period. The Plot time (PT) is calculated as:

\[ PT(k,EC) = PT((k-1),EC) + \text{Time}_\text{Inc} \] ...........................(Eqn 2)

The Plot Time only takes into account the Time utilised in the Event Periods and excludes Time utilised in the Rest Periods. This is achieved by calculating Plot Time in the Event Period Routine only. The Increase in Plot Time for the transition between Event Periods is:
PT(1,EC) = PT(m,(EC-1)) + Time Inc

where the 'Time Inc' is a calculated from the Initial Start Time (IST) and CT(k=1)

The Approximate Weld Distance (S) covered for each Data Acquisition Cycle is 2.2mm. Data Acquisition Cycles are continued for the Event Period whilst ever the condition:

\[ S + 2.2\text{mm} < 30\text{mm} \]

is True. When this condition is False, the Data Acquisition Loop is terminated and the Program enters the Event Terminating Loop which is performed until the Weld Travel Distance has reached 30mm. In this Loop, the Weld Travel Distance (S) is calculated by:

\[ S = S + \frac{\text{Set TS}}{60} \times \text{Weld Time} \]

where:

Set_TS: The Set Weld Travel Speed (300mm/min).
Weld_Time: The Time Elapsed since the Start of the Event Terminating Routine (Seconds) calculated as a function of the Routine CT and ST Values using 'C' Language Functions.

On entering the Event Terminating Loop:

\[ S = S(m,EC) \]

When the Event Period is completed the Program moves directly into the Rest Period.

11.2.3) The Rest Period:

The Rest Period is utilised to calculate and store the Averages of Data in the Mean Parameter Arrays at the correct Location in the Model Data Arrays and also set the Parameters for the next Event. A detailed Flowchart of the Rest Period Routine is illustrated in Fig 11.7 overleaf.
On entering the Rest Routine, a ‘Start Time’ reading is obtained from the System Clock which is utilised later in the Routine for determining the Weld Distance Travelled whilst the functions of the Rest Period are performed.
The Data in the Mean Parameter Arrays is Averaged and stored in the Model Data Arrays at the Correct Memory Location (see Fig 11.2). The Memory Location Pointer (P) for the Model Data Array (or the Location in the Model Data Arrays where the Data is stored) is a function of the Run Count (RC) and the Event Count (EC) and is calculated as:

\[ P = (RC \times 8) + EC \]

The Run Count is initially set to zero and is incremented by 1 at the completion every Model Weld Run. The Run Count is clearly multiplied by a Factor of 8 because there are 8 Events in a Model Weld Run.

After the Data for the Model Data Arrays has been processed the Program then moves on to assigning and setting the Parameters for the next Event.

The First Parameter Assignment is the Standoff Value. As stated, the Weld Mode (Dip or Spray Transfer) should have been set before commencing the Model Weld Run. Table 11.3 below provides the Standoff Assignments for particular Events:

<table>
<thead>
<tr>
<th>Table 11.3: Event Standoff Assignments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1 &lt;= EC &lt;= 4</td>
</tr>
<tr>
<td>5 &lt;= EC &lt;= 8</td>
</tr>
</tbody>
</table>

Please note that the Standoff Assignments are placed directly in the Standoff Array of the Model Data Arrays.

After the Standoff Assignment, the Voltage and Wire Feed Rate Values are set for the next Event in the order illustrated in Table 11.4 below:

<table>
<thead>
<tr>
<th>Table 11.4: Voltage and WFR Event Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event No</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>
After the Parameters for the next Event are set, the Weld Distance Travelled during Parameter Setting is calculated by:

\[ S = \frac{(Set\_TS)}{60} \times Rest\_Time \]  
\[ \text{(Eqn 1)} \]

where:

- **Set_TS**: The Set Weld Travel Speed (300mm/min).
- **Rest_Time**: The Time Elapsed Since the Start of the Rest Period (Seconds) calculated as the difference between the 'Current Time' and 'Initial Start Time' using C Functions.

If the Weld Distance (S) since entering the Rest Period has reached 20mm the Rest Period Routine will be terminated at this point. However if the Weld Distance calculated is less than 20mm, the Program enters a Terminating Loop which will be performed until the Weld Distance reaches 20mm. In this Terminating Loop, the Weld Distance is calculated by:

\[ S = S + \frac{(Set\_TS)}{60} \times Weld\_Time \]  
\[ \text{(Eqn 2)} \]

where:

- **Set_TS**: The Set Weld Travel Speed (300mm/min).
- **Weld_Time**: The Time Elapsed since the Start of the Rest Period Terminating Routine (Seconds) calculated as a function of the Routine 'Current Time' and 'Start Time' Values using 'C' Language Functions.

11.3) **The Modelling Routines:**

At present the 'Weldmod' Program can produce On-line Models for Current and Standoff Prediction. The Models are generated using the Least-Squares method described in Chapter 10 with Data extracted from the Model Data Arrays as illustrated in Fig 11.2.

10.3.1) **Linear Least-Squares Current Model Generation:**

Linear Least-Squares Current Model is of the form:

\[ I = K_1 + K_2V + K_3W + K_4L \]
and now again putting this Equation into Matrix form we get:

\[
[I] = [A][K]
\]

where for Current Model Generation the Matrices are constructed as:

\[
[I] =
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4 \\
I_5 \\
I_6 \\
I_7 \\
I_8 \\
I_{N-7} \\
I_{N-6} \\
I_{N-5} \\
I_{N-4} \\
I_{N-3} \\
I_{N-2} \\
I_{N-1} \\
I_N
\end{bmatrix}
\quad \text{and}
\begin{bmatrix}
A \\
A \\
A \\
A \\
A \\
A \\
A \\
A
\end{bmatrix}
\]

\[
[K] =
\begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
K_4
\end{bmatrix}
\]

where: \( N = 8RC \)

and the Least-Squares Coefficients for the Current Model are then calculated from:

\[
\]
11.3.2) **Linear Least-Squares Standoff Model Generation:**

Linear Least-Squares Standoff Model is of the form:

\[ L = K_1 + K_2V + K_3I + K_4W \]

and now again putting this Equation into Matrix form we get:

\[ [L] = [A][K] \]

where for Standoff Model Generation the Matrices are constructed as:

\[
\begin{bmatrix}
 L_1 \\
 L_2 \\
 L_3 \\
 L_4 \\
 L_5 \\
 L_6 \\
 L_7 \\
 L_8 \\
 L_{N-7} \\
 L_{N-6} \\
 L_{N-5} \\
 L_{N-4} \\
 L_{N-3} \\
 L_{N-2} \\
 L_{N-1} \\
 L_N
\end{bmatrix} =
\begin{bmatrix}
 1 & V_1 & I_1 & W_1 \\
 1 & V_2 & I_2 & W_2 \\
 1 & V_3 & I_3 & W_3 \\
 1 & V_4 & I_4 & W_4 \\
 1 & V_5 & I_5 & W_5 \\
 1 & V_6 & I_6 & W_6 \\
 1 & V_7 & I_7 & W_7 \\
 1 & V_8 & I_8 & W_8 \\
 1 & V_{N-7} & I_{N-7} & W_{N-7} \\
 1 & V_{N-6} & I_{N-6} & W_{N-6} \\
 1 & V_{N-5} & I_{N-5} & W_{N-5} \\
 1 & V_{N-4} & I_{N-4} & W_{N-4} \\
 1 & V_{N-3} & I_{N-3} & W_{N-3} \\
 1 & V_{N-2} & I_{N-2} & W_{N-2} \\
 1 & V_{N-1} & I_{N-1} & W_{N-1} \\
 1 & V_N & I_N & W_N
\end{bmatrix}
\]

where: \( N = 8RC \)
The Least-Squares Coefficients for the Standoff Model are then calculated from:

\[
\]

Details of how to start a Model Weld Run can be found in Sec 11.5.4 and details of Model Generation can be found in Sec 11.5.3.

11.4) The 'Weldmod' Screen Layout:

Once the initialisation routines (which are identical to those of the 'Shortmon' and 'Longmon' Programs where the Voltage is set to 15V and the Wire Feed Rate to 50mm/s) have been successfully completed, the 'Weldmod' Screen is displayed on the Monitor (See Appendix IX, Visual 1). It can be seen that the Screen layout is very similar to the original 'Longmon' Screen layout but there are some fundamental differences.

The 'Longmon' Screen includes a Menu Bar where the functions are activated directly by clicking on the Option on the Menu Bar. However, due to the increased number of functions in the 'Weldmod' Program a Pull-down Menu System has been written and installed. The User can select a Title on the Menu Bar at which point the Pull-down Menu under that Title is displayed and the User can activate a function by moving the Menu Cursor to the required Option.

Although there are four Sliders on the Screen Page, The function of the GUI Parameter Setting Sliders also differ in the 'Weldmod' Program in that they set the upper and lower Voltage and Wire Feed Rate Settings required for Least-Squares Model generation (see Table 11.1).

Four Screen locations are displayed on the Screen Page for Real time Plotting of the Voltage, Current, Wire Feed Rate and Weld Travel Speed Parameters. The Screen occupied by the Acoustics Plot in the 'Longmon' Program will, in the 'Weldmod' Program, print out the Voltage, Wire Feed Rate and Standoff Parameter Settings as the Modelling Run progresses.

The Function of each Option included in the Menu System is discussed in Sec 11.5 and Parameter Setting using the GUI Sliders in Sec 11.6.

11.5) The 'Weldmod' Menu Options:

As stated, the 'Weldmod' Program possesses a Pull-down Menu System. There are four Titles on the Menu Bar which activate functions as described overleaf:
11.5.1) **Menu Title 1: Options:**

i) **Option 1: Consumable Configuration Setup (Setup):**
The Configuration Option is a Page-through Routine that enables the User to enter the Consumable types that will be utilised in the Model Weld Runs. This Routine is identical to the Configuration Routine in the ‘Shortmon’ and ‘Longmon’ Programs.

ii) **Option 2: Graph Axis Range Setting (Range):**
The Range Setting Option allows the User to set the Graph Axis Ranges thereby increasing the resolution of Parameter Traces after a Model Weld Run (See Sec 8.4.1). This Option is only activated after the first Model Weld Run.

iii) **Option 3: The Delay Option (Delay):**
The Delay Option allows the User to activate or deactivate a Data Acquisition Delay. This Delay enables the User to enter the Data Acquisition Routine but prevents Data Acquisition until Welding has started (See Sec 8.4.8). By default, the Delay is set to activated in the ‘Weldmod’ Program.

iv) **Option 4: Weld Mode Setting (Mode):**
The Standoff Range for the Dip Transfer Welding Mode (12mm - 20mm) is less than that required for Spray Transfer (16mm - 24mm). As separate Models are required for the Dip and Spray Transfer Modes, the ‘Weldmod’ Software needs to know which Welding Mode a Model is to be generated for.

The Mode Option enables the User to set the Welding Mode for the next set of Model Weld Runs. If Dip Transfer is selected, the Original Standoff Setting is set to 12mm whereas the Original Standoff is set to 16mm if the Welding Mode is set as Spray Transfer.

v) **Option 5: The Reset Option (Reset):**
Selecting this Option has the effect of erasing all Model Data by resetting the Model Data Array Pointer and the Run-Count to Zero. This Option is only activated after the first Model Weld Run.

11.5.2) **Menu Title 2: Output:**

All the Options under this Menu Title are activated after the first Model Weld Run.

i) **Option 1: Screen Print (Plot):**
On selecting the Plot Option, a Screen Dump of Parameter Traces for the last Weld Run is sent to the Printer by executing DOS Interrupt 0x5.
ii) **Option 2: Data Save (Save):**
This Option saves the Model and other related data to File. Details of the File Saving Routine can be found in Sec 11.7.

iii) **Option 3: Model Weld Run Histogram (Hist):**
The Histogram displays the Feedback Model Data obtained for all 8 Parameter Setting Combinations of the last Weld Model run. Feedback Data displayed includes the Voltage, Current, Wire Feed Rate and Standoff. A typical Histogram of a Model Weld Run can be seen in Fig 11.8 below:

![Histogram for Run 1](image)

Fig 11.8: Model Run Histogram

A Printout of the Histogram can be obtained by clicking on the ‘Print’ Button. Each Histogram printout contains the Feedback Model Data (as displayed in Fig 11.8), the Input Settings and Consumable Details. A Sample Histogram printout can be found for a Dip Transfer Model Weld Run in Appendix IX, Visual 7 and for a Spray Transfer Model Weld Run in Visual 14.

11.5.3) **Menu Title 3: Model:**

i) **Option 1: Linear Least-Squares Current Model (Current):**
On selecting this Option a Linear Least-Squares Current Model is generated from Model Data (as described in Sec 11.3) and displayed as illustrated in Fig 11.9 overleaf:
Sample Printouts of Dip and Spray Transfer Current Models can be found in Appendix IX, Visuals 8 and 15 respectively.

ii) Option 2: Linear Least-Squares Standoff Model (Standoff):
Selection of this Option generates a Linear Least-Squares Standoff Model from the Model Data (as described in Sec 11.3) and displays the Model as illustrated in Fig 11.10 below:

Sample Printouts of Dip and Spray Transfer Standoff Models can be found in Appendix IX, Visuals 9 and 16 respectively.

Please note that Model Printouts can be obtained by simply clicking on the 'Print' Button on the Model Boxes illustrated in Figs 11.9 and 11.10.
Printouts contain the Model together with the Parameter Ranges and Consumable Types for which they are valid.

11.5.4) **Menu Title 4: Run:**

i) **Option 1: Start Model Weld Run (Run):**

Selecting this Option starts a Model Weld Run as described in Sec 11.3. If the Delay is set to active the screen will now appear as displayed in Appendix IX, Visual 2. At this stage the Software is in the Delay Loop awaiting the start of Welding. When Welding commences, a Model Weld Run is completed as described in Section 11.2. Model Weld Run Real-time Plots are displayed for Dip Transfer in Appendix IX, Visual 3 and for Spray Transfer in Visual 10.

i) **Option 2: Model Weld Run Delete (Delete):**

If for some reason, a User is not satisfied with the last Model Weld Run it can be deleted from the Model Data Arrays by selecting this option. This is achieved by decrementing the Memory Location Pointer for the Model Data Arrays (P) by 8 Locations and also by decrementing the Run Count (RC) by 1.

11.6) **The GUI Sliders for Model Parameters Setup:**

The GUI Sliders are utilised to setup the Maximum and Minimum Voltage and Wire Feed Rate Values that will be utilised in Model Data Acquisition and generation. The Sliders are illustrated in Fig 11.11 below, set up for Dip Transfer Model Weld Runs.

![GUI Sliders for Model Parameter Setting](image)
If the Higher Parameter Value is set at a Value that is lower than the Lower Parameter Setting, a Warning Message is displayed informing the User of the Error. ‘Weldmod’ will not allow a Model Weld Runs if a Higher Parameter Setting is lower than the Lower Setting value.

In order to maintain continuity of Settings for Models generated from Multiple Model Weld Runs, Model Parameters can only be set prior to the first Model Weld Run. If it is desired to alter Model Parameters after the first Model Weld Run, the User would have to reset the Software by selecting ‘Reset’ under the Menu Title ‘Options’ but it should be noted that the Data for completed Model Weld Runs would be deleted.

11.7) **The Save Option:**

The ‘Weldmod’ Program allows the User to save to File the data stored in the Model Data Arrays together with Parameter Settings and other important information on the last set of Model Weld Runs.

When the Save Option is selected, the User enters a Filename of up to 8-Characters, but does not include the extension because ‘Weldmod’ saves the data to three separate files and automatically adds the extensions to the filename entered. The following files are created when saving data with ‘Weldmod’:

i) **The Model Data File:**

The Weld Feedback Data file is saved as: **filename.mod**

This file contains the data in the Model Data Arrays with each record containing the mean Voltage (V), Current (I), Wire Feed Rate (W), Weld Travel Speed (S) and Standoff (L) Values for a particular Event. The data is saved in the format displayed in Fig 11.12 below:

```
| V(1) | Tab | I(1) | Tab | W(1) | Tab | S(1) | Tab | L(1) |
| V(2) | Tab | I(2) | Tab | W(2) | Tab | S(2) | Tab | L(1) |
|      |     |      |     |      |     |      |     |      |
| V(N-1) | Tab | I(N-1) | Tab | W(N-1) | Tab | S(N-1) | Tab | L(N-1) |
| V(N) | Tab | I(N) | Tab | W(N) | Tab | S(N) | Tab | L(N) |
```

**N = Events in the Model Data Arrays (8*RC)**

**Fig 11.12: ‘Weldmod’ Model Data File Format.**
ii) **The Parameter Settings File:**

The Parameter Settings File is saved as: filename.psf

This File contains the two levels of Parameter Settings as illustrated in Fig 11.1.

iii) **The ‘Weldmod’ Miscellaneous File:**

The ‘Longmon’ Miscellaneous File is saved as: filename.wmi

The File contains the Date of the Model Runs. Also saved in this File is the Workpiece Material Type and the Consumable details including Electrode Class, Electrode Size, Shielding Gas Type and Gas Flow Rate.

**Note:**

A set of Visuals and Printouts can be found for a Dip Transfer Model Weld Run in Appendix IX, Visuals 3 - 9 and for a Spray Transfer Model Weld Run in Appendix IX, Visuals 10 - 16.
Chapter 12

Discussion

12.1) Development of the GMAW Experimental Facility:

The implementation of a Welding Research Program at the University of Wollongong made necessary the design and development of GMAW Experimental Facility (MWEF) which includes the following facilities:

i) Electronic Monitoring of the Welding Process by measurement of Arc Voltage, Current, Wire Feed Rate and Weld Travel Speed.

ii) The Computer Setting and Control of Welding Parameters including Voltage, Wire Feed Rate and Weld Travel Speed.

iii) Graphical User Interface (GUI) Software Systems for integrated monitoring/analysis/viewing/saving of weld data and Computer setting/control of welding parameters.


A discussion of the above mentioned facilities is given below:

12.1.1) Electronic Monitoring of the Welding Process:

The Sensing Systems installed in the MWEF has enabled accurate real-time monitoring of the Welding Process.

The MWEF was originally intended as a facility for studying the welding process as a prelude to the development of effective real-time GMAW Control Strategies. However, interest has since been shown in using the facility as a testbed for Welding Machine and Consumable evaluation. As different Power Sources will be tested, the Weld Monitoring Systems must be flexible and easily installed on different machines.

12.1.1.1) The Voltage Sensing System:

The Voltage Sensing System on the MWEF consists of a potential divider placed across the arc. It is completely flexible and can easily be installed on Power Sources other than the Transmig 350EC to which it currently connected.
The accuracy of the Voltage Sensor was tested by installing a Fluke 77 Digital Multimeter in the Sensor circuit. By comparing Voltage settings of the Multimeter to those measured by the Voltage Sensor, it was found that the Voltage Sensing System is accurate to within +/-0.3%.

As the Voltage Sensor is connected at the Wire Feed Unit, the Lead Cable is in the Voltage Sensing circuit. It was determined that the Voltage Drop across the Lead Cable is negligible as Voltage measurements observed during the dipping cycle in Short Arc welding were very near to zero (i.e. < 0.001V).

12.1.1.2) The Current Sensing System:

The Current is monitored on the MWEF by a Hall Effect Sensor connected to the Return Cable of the Power Supply. It is therefore also completely flexible and can easily be installed on Power Sources other than Transmig 350EC to which they are currently connected. The Current Sensor is accurate to +/-1%

12.1.1.3) The Wire Feed Rate (WFR) Sensing System:

The WFR Encoder Sensing System (connected coaxially to the wire feed roller) functions by relating the time between encoder pulses to the linear distance travelled during this period by the surface of the wire feed roller which one can reasonably assume will equal the length of wire fed to the weld. The WFR is simply calculated a function of the length of wire fed to the weld and the time between encoder pulses during which that length of wire was fed.

On studying the WFR plots in Appendix VII, Visuals 7 and 13, it will be observed that:

i) the WFR is updated at discrete intervals with the frequency of update increasing with increasing WFR.

ii) differences between a current and subsequent WFR reading also occurs at discrete intervals.

iii) the discrete interval in WFR readings will increase with increasing WFR.

These observations indicate that the apparently large variations in WFR readings can be traced back to the Miniboard and DAC of the WFR Sensing System (please refer to Sec 6.4.3 and Fig 6.5). The Miniboard increments a Count (at 128μS intervals) between Encoder pulses and then outputs this Count as an 8-Bit Digital Number to the DAC. The accuracy of the Count will therefore clearly be +/- 1 Increment of the Counter. The DAC is also accurate to +/- 1 LSB of its input.
It will also be observed from Visuals 7 and 13 of Appendix VII, that there is rarely a difference of more than two discrete WFR values between a current and subsequent WFR readings. Taking into account the possible errors in accuracy of the WFR Sensing System, it is possible that a very small change in the WFR could quite conceivably result in a difference of two discrete increments or decrements in the WFR reading.

An analytical study of the relationship between the WFR and Miniboard Count between Encoder Pulses, Time between Encoder Pulses and the discrete WFR Increment/Decrement was completed and the results are displayed in Fig 12.1 below:

![Fig 12.1: WFR Sensing System Analysis](image)

It can clearly be seen from Fig 12.1 that the Count between Encoder Pulses and the Time between Encoder Pulses decreases with increasing WFR, but the Discrete WFR Increment/Decrement increases with the increasing WFR indicating that the accuracy of the WFR reading will decrease as the WFR increases. If we assume that an error of +/- 1 Count of the Miniboard between Encoder Pulses, with the largest error which occurring at WFR=200mm/s, the error in WFR readings will be in the range of +/-3%.
A check was also made to ensure that the WFR sensing System could update its readings within the target fault length of 2mm. At the slowest WFR setting of 50mm/s and a fast Travel Speed of 600mm/min, the WFR reading will be updated within 0.020Sec and 0.2mm of weld travel which is well within the maximum allowable fault length of 2mm.

Another problem, with respect to the flexibility criterion, is that the WFR Encoder Sensing System requires a set of unique dedicated fittings for its installation on each individual machine (see drawing in Appendix VI entitled 'Wire Feed Rate Encoder Assembly'). However, a set of fittings can be designed and manufactured within a period of a few days and therefore the WFR Encoder System can be considered flexible for the purposes of work that will be undertaken on the MWEF.

12.1.1.4) The Weld Travel Speed (TS) Sensing System:

The TS Sensing System is fitted to the Lathe Saddle Traverse Handle (see the drawings in Appendix VI entitled ‘Encoder Support Assembly’ and ‘Encoder Wheel Assembly’) and functions on the same principle as the WFR Encoder Sensing System.

Fig 12.2: TS Sensing System Analysis
It is therefore clear that the TS Sensing System will also be subject to the same limitations of accuracy as the WFR Sensing System. An analytical study of the relationship between the TS and Miniboard Count between Encoder Pulses, Time between Encoder Pulses and the discrete TS Increment/Decrement was also completed and the results are displayed in Fig 12.2.

As with the WFR Sensing System, it can again be clearly be seen from Fig 12.2 that the Count between Encoder Pulses and the Time between Encoder Pulses decreases with increasing WFR, but the Discrete TS Increment/Decrement increases with increasing TS. The largest error in TS readings will occur at TS=450mm/min in the range of +/-3%.

Tests using the the in-weld parameter alteration facility of the ‘Longmon’ Program indicates that if there were to be a sudden deceleration from a TS of 300mm/min, the TS drop would be fairly constant at about 5mm/min per TS update. This TS update period is sufficient to detect the deceleration before the TS drop significantly affects the welding process and bead geometry characteristics.

It has been observed from literature that there are many facilities that enable the Voltage, Current and WFR to be monitored in real-time, but none were observed that directly measure the Weld Travel Speed in real-time. Measurement of the Voltage, Current and Wire Feed Rate is sufficient for the real-time evaluation of the Welding Process where Bead Geometry will not be predicted.

However, measurement of the Weld Travel Speed is essential for real-time prediction of Bead-Geometry Characteristics. The integration of TS monitoring in the MWEF makes possible the efficient development and real-time testing of Bead Geometry Prediction Models.

12.1.2) **Computer Control of Welding Parameters:**

The Voltage, Wire Feed Rate and Weld Travel Speed can all be set and controlled by computer on the MWEF.

12.1.2.1) **The Voltage and Wire Feed Rate Control System:**

The Voltage and Wire Feed Rate are controlled by Stepper Motors coaxially connected to the Voltage/WFR Potentiometer Shafts on the Transmig 350EC Control Pendant.

As has been stated, this method of control has been satisfactory for the requirements of this thesis and have enabled accurate and repeatable setting
and control of the Voltage and WFR. However, this method of control would not be suitable for genuine real-time experimentation because of the time taken for the Stepper Motors to move the Potentiometers to the correct settings. To obtain real-time control of the Voltage and WFR, a more modern Welding Machine allowing solid-state computer control of the Voltage and WFR will need to be acquired.

Although not stated in the body of the thesis, an attempt was made to control Voltage and WFR through the installation of opto-isolators. It was discovered that to achieve control by this method would require substantial redesign of the control electronics of the Power Source which could not be achieved in the remaining thesis time and therefore the attempt was abandoned in favour of Stepper Motor control.

12.1.2.2) The Weld Travel Speed Control System:

The Weld Travel Speed is controlled by a Variable Speed Drive (VSD) which provides instantaneous change of Travel Speed. A slight delay in the change of the Travel Speed has been observed due to the inertia of the Welding Jig and Lathe Saddle on which the Jig is mounted. This problem could be reduced by the creation of a new welding base mounted on linear bearings which would eliminate the inertia caused by the Lathe Saddle.

12.1.3) MWEF Software Systems:

Graphical User Interface (GUI) Software Systems were produced for integrated monitoring and computer setting/control of the welding process. These Software Systems were written in the Borland C Programming Language.

It was decided to develop the Software using a Programming Language because:

i) Reports from users of Applications Packages indicated that, at the time of commencing the work on monitoring and control systems, available monitoring packages were limited in their scope of application, were difficult to implement and were often unreliable in service.

ii) There was concern that Application Packages might not be able to cater for the future software requirements of GMAW experimentation.

iii) Using available Applications Packages, it was not possible to commence data acquisition from a signal from the High Speed Camera.

iv) The GUI Functions and Modules necessary for the production of Software Systems had already been written prior to the commencement of the development of the MWEF. The integration of these functions in
development of monitoring/control packages was therefore feasible within a short period of time.

GUI Software Systems have therefore been developed that can adequately monitor, plot, analyse, save, set and control GMAW parameters. These packages can also be readily modified to cater for future experimental requirements.

The Software Packages produced for GMAW monitoring include the ‘Shortmon’ and ‘Longmon’ Programs. The functions of these two packages are discussed overleaf:

12.1.3.1) The ‘Shortmon’ Program:

The ‘Shortmon’ Package has been designed for the acquisition and study of short bursts of transient welding signals (upto 5 seconds) in both the time and frequency domains.

Unique features of the ‘Shortmon’ Program include:

i) An integrated GUI Screen for Monitoring, Plotting, Analysis and Parameter Setting (See Appendix 7, Visual 1).

ii) enabling the user to graphically ‘zoom’ in on a particular section of the monitored parameter arrays, the period of which may vary from as low as 5mS up to the complete monitoring period. This means that the transient parameter signals of particular welding phenomena and anomalies can be viewed and studied in detail.

iii) the facility to save either all the parameter data to file or only the data for particular periods of interest thereby saving only relevant data for future use and eliminating the use of disk space for data that is not relevant.

iv) in addition to plots of directly measured data, plots of the Heat Input (as defined by AS Standards) and Arc Resistance can be made. These parameters, calculated from the transient parameter data, have been included because of their regular use in Welding Research.

v) accurate, repeatable and User-friendly computer setting of Welding Parameters using GUI Sliders.

vi) the facility for the user to view the parameter data in both the time and frequency domain as either individual plots (see Appendix VII, Visuals 3, 4, 5, 6, 9, 10, 11 and 12) or in general plots (see Appendix VII, Visuals 7, 8, 13 and 14) where up to three parameters can be viewed simultaneously allowing visual correlation of the parameters.
vii) a run summary for the period of data currently under study see Appendix VII, Visual 2). The summary includes simple statistical data of the measured weld parameters, the parameter settings, consumable details, the sampling rate and the start and end time of the period under study relative to the start of data acquisition.

viii) a delay routine awaiting a signal from a high speed camera. The high speed camera sends a signal when it has reached it correct filming speed. This signal is received by the computer which enables the ‘Shortmon’ program to exit the delay routine and commence data acquisition, thereby enabling time correlation of monitored weld data with visual images obtained by the high speed camera.

12.1.3.2) The ‘Longmon’ Program:

The ‘Longmon Package has been designed for the acquisition and study of weld behaviour and stability of parameter settings over longer welding periods. It functions by acquiring windows of parameter data, the averages of which are plotted in real-time and stored in parameter arrays in computer memory. The ‘Longmon’ Program can monitor welding periods up to 120 seconds with no rest periods inbetween the data windows.

Unique features of the ‘Shortmon’ Program include:

i) integrated monitoring and setting of welding parameters (See Appendix VIII, Visuals 1 and 2).

ii) the facility for inweld parameter alteration. This enables real-time study of the effects of changing one welding parameter on other welding parameters. A Parameter Alteration Record can be displayed and printed after the weld run to review the parameters altered for correlation with the recorded parameter traces. A weld run with inweld parameter alteration can be seen in Appendix VIII, Visual 7 and with the Parameter Alteration Record in Visual 8.

iii) the facility for data window length alteration by altering either the Sampling Frequency and/or the Number of Samples monitored/window. The user can also set a rest period between sample windows thereby extending the length of the monitoring periods for weld runs where continous windowing is not essential.

iv) saving to file the parameter averages calculated for each data window acquired during the weld run.

Although not included in the current version of the Package, the ‘Longmon’ Program can be easily modified to include routines for a thorough statistical analysis of the parameters acquired in each data window which could be printed on request at the end of the weld run. Whilst weld stability can to
some degree be assessed from the variation of data window averages, this enhancement would enable a substantially more accurate assessment of the stability of the welding process which would clearly be useful for obtaining optimised parameter settings.

The ‘Longmon’ Program could also be utilised for real-time testing of Weld Models. For example, assume that a model for a Bead Geometry Parameter (X) is to be modeled as a function of Voltage (V), Current (I), Wire Feed Rate (W) and Weld Travel Speed (T), ie:

\[ X = f(V, I, W, T) \]

The above described model could be entered into the ‘Longmon’ Program which would produce an estimation of Parameter X after the completion of each data acquisition window. The parameter estimations of X could be compared to the actual values of parameter X in the weld produced during the weld run.

12.1.3.3) A General Discussion of the Software Systems:

It can be seen that the Software Systems developed enable most welding situations to be effectively monitored and studied, ranging from individual phenomena and anomalies occurring over periods of a few milliseconds to long term process stability measured over minutes.

Although the Software Systems were primarily designed as research tools, it is possible that the Software might also find applications in welding education.

The ‘Shortmon’ Program could be used to show the transient signals of the welding process to trainee welders which, if correlated with the audible weld acoustics, could enhance the welders understanding of the welding process and teach how to obtain parameter settings for stable welding conditions.

The ‘Longmon’ Program could be used to answer ‘what if’ questions from students. For example, the question might be asked ‘What would be the effect on parameter Y if parameter X were to be altered’. An instructor could very effectively answer this question by monitoring a weld run using the ‘Longmon’ Program, altering parameter X during the weld run using the GUI Slider and then observing in real-time the affect of this parameter alteration on parameter Y.

12.1.4) Correlation of High Speed Weld Visualisation with Electronic Monitoring:

Another unique function of the MWEF is the ability to time correlate electronically monitored weld data with visual weld images obtained from high
speed photographic visualisation.

As stated, this is achieved by a communication link between the High Speed Camera and the Computer utilised for electronic data monitoring. When the High Speed Camera has reached its correct filming speed (measured in frames/second), it will send a signal to the computer via the communication link. The ‘Shortmon’ Program is held in a delay loop until the signal is received from the Camera at which point the electronic data monitoring is commenced. As the filming progresses, timing marks are printed on the film at millisecond intervals which enables the exact correlation between monitored data and visual images.

This facility is important as it will enable effective study of welding phenomena which to this point have not been properly studied, understood or modelled. Phenomena that could be more effectively studied include the Arc Length, Metal Transfer and Arc Phenomena, The Dipping Period in Short Arc Transfer, Exploding Wire and the effect of consumables on the welding process.

12.2) **Condition Monitoring:**

To confirm that the MWEF as a System that may be effectively utilised for the development and implementation of Real-time GMAW Condition Monitoring and Control Strategies, a series of experiments (discussed in Chapter 9) was undertaken to determine the effect of:

i) Varying Standoff (Contact-tip to Workpiece Distance).

ii) Surface Contaminants.

iii) Root Gap

on Welding Parameters and Process Stability.

Isolated Transient Irregularities were also captured during welding experimentation and have therefore also been studied.

With respect to planned experimentation, it was observed that each induced irregularity had a unique set of identifiable features which could be used for Real-time Condition Monitoring and control of GMAW. These features are described in Table 12.1 overleaf.

The irregularities characterised in Table 12.1 above are not classed as Transient Irregularities because they occur over a period of more than one Data Acquisition Window. Although Burnthrough is detected within a single Data Acquisition Window, the cause of Burnthrough (i.e. excessive Weld Gap) might be a continuing fault and is therefore not an Isolated Irregularity.
Table 12.1: GMAW Weld Irregularity Characteristics

<table>
<thead>
<tr>
<th>Irregularity</th>
<th>Irregularity Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standoff Variation (Increase)</td>
<td>Measurable Voltage Increase/Current Decrease. Little change in Dipping Frequency (Dip Transfer Mode only).</td>
</tr>
<tr>
<td>Standoff Variation (Decrease)</td>
<td>Measurable Voltage Decrease/Current Increase. Little change in Dipping Frequency (Dip Transfer Mode only).</td>
</tr>
<tr>
<td>Surface Contaminant</td>
<td>Voltage Increase/Current Decrease. Detectable difference from normal welding conditions with Rolling Averages and Derivatives of Rolling Averages for both Voltage and Current. Substantial increase in Dipping Frequency (Dip Transfer Mode only).</td>
</tr>
<tr>
<td>Weld Gap (Excessive Pen)</td>
<td>Voltage Decrease detectable from the Derivative of the Rolled Voltage Average. No change in Current levels.</td>
</tr>
<tr>
<td>Weld Gap (Burnthrough)</td>
<td>Sharp downward Voltage Spike (2 Data Acquisition Windows in duration) of Monitored Data. The Magnitude of Voltage Spikes in Burnthrough are substantially greater than those observed for Transient Irregularities. Current remains reasonably Constant. In some cases, a 'warning' of imminent Burnthrough is obtained from Excessive Penetration detection characterised by a Voltage reduction trend.</td>
</tr>
<tr>
<td>Weld Gap (Near Burnthrough)</td>
<td>Possibly characterised by a 'blunted' downward Spike of Monitored Voltage data, occurring over 2 or more Data Acquisition Windows.</td>
</tr>
</tbody>
</table>

Transient Irregularities are isolated events which will usually occur within the period of a Data Acquisition Window and are not continuing faults. These Irregularities include Exploding Wire and uncharacteristic Dipping when welding in Globular or Spray Transfer Mode. These Irregularities do not affect the long term stability of the welding process and also do not affect the quality of the weld.
With respect to the experimentation with Root Gap for Excessive Penetration/Burnthrough detection, it should be noted that for Butt Welds, the root preparation (after tacking) will consist of a Root Gap, but, for thicker material, will also possess a Root Face. It may therefore be possible that Excessive Penetration/Burnthrough may also be caused solely by insufficient Root Face or a combination of too wide a Root Gap and a Root Face that is too small. Whilst it may not be possible to detect the excess in Root Gap and insufficient Root Face by Through-the-Arc Sensing alone, it has been determined that this Sensing method can detect the occurrence of Burnthrough and the onset of Excessive Penetration.

The observations of Parameter behaviour and weld stability on the occurrence of various weld irregularities can, after further confirmation with additional experimentation, be integrated into some form of Control System or Algorithm using Artificial Intelligence Techniques (such as Fuzzy Logic and Neural Networks), a set of Rules or more than likely, some form of Hybrid System. The best strategy for real-time control of the GMAW process can only be determined through thorough testing of the control methods stated.

12.3) Development of Mathematical Models for Real-time Control of the GMAW Process:

Models for real-time control of the GMAW Process must be reasonably accurate, consistently reliable and fast. Assuming a fast Weld Travel Speed (say 600mm/min) and a maximum of 2mm of fault length to satisfy weld quality requirements, it can be seen that cycle of data acquisition, analysis and weld irregularity elimination must be accomplished within a period of 0.2 seconds. In other words, in 0.2 seconds, sufficient weld data must be collected to enable an accurate assessment of the welding process, the real-time control models must calculate their predictions of the welding process and bead geometry, and finally, rules for weld irregularity detection, based upon the predictions of the real-time models, must detect any weld irregularities, determine updated parameter settings and output these updated settings to the welding system. It can therefore be seen that the models for real-time parameter prediction must be very fast and therefore also indicates that they should also be simple in their operation.

It was determined after studying a number of approaches to real-time control [14-71], that Through-the-Arc sensing offered the most flexible Sensing Method in that the Arc can be effectively monitored by relatively simple Arc Voltage, Current and Wire Feed Rate Sensors. Information as to the current state of the welding process and current bead geometry can be efficiently obtained from the feedback from Arc Sensing using Statistical Models. One approach which appeared to show promise as fast and accurate real-time parameter predictor is the Least-Squares Model originally utilised by Kim and Na [22-23] with a Current Prediction Model of the the form:

\[
I = K_1 + K_2V + K_3W + K_4L + K_5VW + K_6WL + K_7VL
\]

where \(I\) = Current, \(V\) = Voltage, \(W\) = Wire Feed Rate and \(L\) = Standoff.
Experimentation was undertaken (as described in Sec 10.2) to verify the Kim-Na Model displayed above. Separate Models were developed for both the Dip and Spray Transfer Welding Modes because of the different characteristics they possess. It was found that the Models developed produced Current Estimations that were accurate to within 3% (with an error of 2.96% for the Dip Transfer Model and 3.00% for the Spray Transfer Model) of the measured Current Readings thereby confirming the suitability of this Model as a Real-time Current Predictor. The small errors obtained were most likely caused by Sensor Error, small WFR fluctuations and also probably due to the effect of incomplete dipping cycles in the data arrays.

As the above model was evaluated for its potential for real-time use, it was decided, for the purposes of increasing the computational speed of the Model, to test the accuracy of the Model with the removal of the last three ‘non-linear’ terms, reducing the Model to the ‘linear’ form of:

\[ I = K_1 + K_2V + K_3W + K_4L \]

Using the same data as was used to verify the original Kim-Na Model, it was found that the ‘linear’ Models were on average slightly more accurate than the original ‘non-linear’ Kim-Na Models (with an error of 2.50% for the Dip Transfer Model and 3.02% for the Spray Transfer Model).

Current Prediction does not have much use in real-time control as the actual Current can be easily and accurately measured. It was therefore decided to attempt to create a Least-Squares Standoff Model by rearranging above Current Prediction Model to predict the Standoff as a function of the Voltage, Current and Wire Feed Rate. The Standoff is an important parameter to be able to predict with respect to welding automation because the contours of a workpiece may not always be known and the Standoff prediction would then be used for ‘terrain following’ by an Autonomous GMAW System. A ‘non-linear’ Least-Squares Standoff Model of the form:

\[ L = K_1 + K_2V + K_3I + K_4W + K_5VI + K_6WI + K_7VW \]

and the ‘linear’ Least-Squares Standoff Predictor will be of the form:

\[ L = K_1 + K_2V + K_3I + K_4W \]

were developed and tested as described in Sec 10.3. Past research [59] indicated that a variation of accuracy of up to +/-2mm from the Actual Standoff value should be expected from a Standoff Predictor and this was confirmed when the Predicted Standoff values were compared to the actual Standoff Settings. It was also observed that the ‘linear’ Standoff Model was on average more accurate than the ‘non-linear’
Standoff Model. The larger errors observed for Standoff predictions may be due mainly to the curviness of the wire resulting in variation in the point at which the wire makes contact with the contact tip, but also may be due to variations in the wire diameter and fluctuations in the WFR.

It should be noted that the data utilised for the development and testing of the Current and Standoff Predictors described above was obtained by monitoring at 5kHz over a 0.5 second period. The 0.5 second sampling period is not a realistic real-time sampling period so it was therefore decided to test the accuracy of the ‘linear’ Standoff Model by obtaining data at the Sampling Rate of 5kHz, but with the reduced Sampling Period of 0.2 seconds (as described in Sec 10.4). It was observed that the Standoff predictions for the Spray Transfer Model were consistently within the +/-2mm tolerance level, but only 59.7% of predictions were within tolerance for the Dip Transfer Model. The poor performance of the Dip Transfer Model at the Sampling Period of 0.2 seconds is due to the lower dipping frequency obtained with the Transmig 350EC Power Source (less than 10 dipping cycles during the 0.2 second sampling period), which resulted in the partial dip transfer cycles recorded at the beginning and end of the current data arrays causing significant variations of the calculated current average from the true current average (see Fig 10.9). It can therefore be concluded that to effectively use the Standoff Model for real-time Standoff control in Dip Transfer Mode, a Power Source is required with a higher dipping frequency of circa 100+ Cycles/Second.

As stated, another approach to Standoff Prediction is to use the Resistance of the electrode during the dipping cycle. As the Resistance of the electrode is directly and linearly proportional to the length of the Resistance, the Standoff may be calculated by determining the electrode resistance during the dipping cycle.

Initial experimentation has indicated that this method may be feasible and would provide a very powerful and efficient method of Standoff Prediction.

The Resistance is calculated as a function of the Voltage and Current at the point where the dipping cycle is about to end (i.e. when wire necking and burnback is just about to occur). This point can easily be determined as illustrated in Fig 10.13. It should be noted that due to varying arc conditions, there should be Gaussian variations in Resistance values for a particular Standoff setting. The Gaussian Resistance Functions for each Standoff Setting may also significantly overlap with the Gaussian Functions of neighbouring Standoff settings. Should this occur, it may be possible to develop a Fuzzy Standoff Predictor.

12.4) The ‘Weldmod’ Program for On-line Weld Modelling:

Up to the present, generation of Statistical Models have been achieved through manually performing a series of experiments to obtain the data from which the Models are developed.
The development of a Least-Squares Model (as described in Chapter 10 and in Section 12.3) is divided into 2 stages as described below:

i) The Data Acquisition Stage:

In this stage, the data that will be utilised to develop the model is collected. The data required for the Dip and Spray Transfer Least-Squares Models Current Predictor described in Sec 10.2 took approximately 4 hours each to collect, even with the use of the ‘Shortmon’ Program which enabled very rapid acquisition of data. The time was taken up by actual experimental runs, parameter alteration (which was achieved quickly for the Voltage and Wire Feed Rate Settings but was time consuming for the manual setup of the Standoff Setting), error and anomaly correction, unavoidable interruptions and occasionally, wire roll replacement.

ii) The Model Development Stage:

In the Model Development Stage, the data collected is entered into files which are then utilised by a Scientific/Mathematical Applications Package to generate the Coefficients of the required Model. For the Least-Squares Models developed in Sec. 10.2 this took up to 3 hours to complete for each model. The time was taken up by data entry into files, checking the data for errors, model coefficient generation and some of the situations described above such as unavoidable interruptions.

It can be seen that the manual generation of a statistical model can take up to a working day to complete and are therefore time consuming and expensive to produce. It should also be noted, that with respect to Statistical Models for Welding, they are only valid between certain parameter levels and only for a particular combination of welding consumables. If a range of statistical models are required for various consumable combinations and various parameter levels, it can be seen that to achieve this by manual development of Models might require a period running into weeks.

The ‘Weldmod’ Program for On-line Modelling can collect the Model Data and generate Least-Squares Model Coefficients in a single weld run and within a period of 90 seconds. This means that the period required to generate a Statistical Least-Squares Model has been reduced from a period of about 7 hours down to 90 seconds.

What is the significance of the development of On-line Modelling with respect to Welding Research and Industrial Welding Automation?

i) Welding Research:

Whilst the current/prototype version of the ‘Weldmod’ Program only generates Least-Squares Current and Standoff Predictors, it can be readily modified to include a generic Modelling Interface that will enable a range of user-defined models to be generated.
It can be clearly seen that On-line Modelling could save welding researchers a significant amount of time and also the tedium of repetitive experimentation, allowing researchers to spend their time on more productive activities. At a time when research funding in Australia, and indeed throughout the world, is being reduced, the elimination of unnecessary and unproductive activities such as lengthy experimentation, would be a significant benefit.

ii) Industrial Welding Automation:

Assume that a future adaptive GMAW System is totally or partially controlled by a range of statistical models which utilise weld parameter feedback to predict the current state of the welding process and bead geometry.

The statistical models for the above stated system will need to be initially developed, will also need to undergo periodic recalibration to maintain accuracy and the development of a new set of models will be required if the consumable combination or welding parameter levels are changed.

It can be clearly seen that the manual development or recalibration of a range of statistical models may take days, weeks or even months depending on the number of models in the system. This might result in a significant loss of production and income for the manufacturer as the welding unit could not be used whilst the modelling work was being completed. Added to these losses would be the expense of staff required to perform the modelling work.

The On-line Model Development System initially developed in this thesis would enable a manufacturer to initially develop Models, recalibrate the Models and develop models for new consumable combinations/parameter ranges very quickly and with a minimal loss of production and income. The On-line Modelling System could be adapted for use with various automated equipment including standard fixed-position welding manipulators, rotary pipe welding systems, cartesian/gantry welding systems and mobile welding robots.

12.4.1) Limitations of On-line Modelling:

Models may be created for both Indirect Welding Parameter (IWP) Prediction (e.g. Standoff) or Direct Welding Parameter (DWP) Prediction (e.g. Bead Width, Bead Height and Penetration).

A major problem with respect to the use of Rapid Modelling Techniques is that On-line Modelling can only be achieved if all the parameters in the Model can be readily measured in real-time by Sensory input or are otherwise known (as are the Standoff settings and Current readings in the prototype 'weldmod' System).

The majority of DWP's cannot, at present, be monitored in real-time and therefore need to be physically measured off-line. Provision must therefore be made in the
‘Weldmod’ software to allow IWP data collected during the Model Weld Run to be saved to file and then retrieved with corresponding DWP data at some future time. This also clearly means that Models involving DWP prediction will also take longer to develop.

Model Verification Software (MVS) can be created for automated testing of models. This Program would be a modification of the ‘longmon’ Program. The MVS will allow Model Input followed by automated testing of the models through Real-time Model Estimation of parameters based on IWP data obtained from an Automated Parameter Combination sequence covered in a single weld run. Estimated parameters can then be directly compared to actual parameters to determine the performance of the model. It can again be seen that models predicting IWP’s can be verified on-line but verification of DWP Estimators can only be completed with an off-line inspection of actual parameters obtained which again may take some time.

Despite the fact that the process of developing DWP Estimators cannot at present be fully automated, automated collection of IWP data with the ‘weldmod’ software and automated testing procedures with the MVS, will still result in a significant saving in time over fully manual data collection, model development and testing.
Chapter 13

Further Work

13.1) Possible Improvements to the MWEF:

Whilst the MWEF in its current state is suitable for Data Acquisition and Weld Modelling, it is not really suitable as a Facility for testing Real-time Automation Strategies due to the inadequacies in the Test Bed and Power Source which result in slow Parameter alteration time. The Sensors and Parameter Control Devices have dedicated fittings for the current Power Source and cannot be readily fitted to other Power Sources. In the light of these deficiencies, the following improvements for the MWEF are proposed:

13.1.1) Acquisition of a more modern Power Source:

The Transmig 350 EC was adequate for the experimentation required for this thesis, however, as stated, it does possess some shortcomings which limit its potential as a tool for development of Welding Automation Control Techniques. These limitations are:

i) In Dip Transfer Welding Mode, It has a low Dipping Frequency which limits accurate and stable Current Measurement for real-time Sampling Periods.

ii) The Voltage and Wire Feed Rate Settings can only be controlled with Stepper Motors which require unacceptably long periods to alter these Parameters.

iii) The AC Ripple in the Transmig 350 is very large making it difficult to detect Transition Points in Dip Transfer Welding.

It would therefore be desirable if a more modern Power Source could be installed that:

i) Enabled a higher Dipping Frequency (100 Cycles/Second)

ii) Enables Solid-State rapid Computer Control of Voltage and Wire Feed Rate.

iii) Has very little or no AC Ripple (which is achieved using an Inverter Type Power Source).
13.1.2) **Computer Control of Standoff Setting:**

At present, the Standoff from the Workpiece is manually set. It is important to achieve Automated Control of the Standoff to enable the development and testing of Standoff Control and Workpiece Contour Following Techniques. A Semi-Robotic Head will be developed with Computer Control of the Standoff Setting.

13.1.3) **An improved Welding Base:**

Effective Experimentation for the development of Welding Automation Techniques would also require accurate and instantaneous control of the Welding Table.

Although the current Welding Base on a Lathe Saddle is sufficient for straight weld experimentation, the Inertia of Lathe Saddle makes instantaneous control of Weld Travel Speed difficult. Also installation of Computer controlled Transverse Motion on the Saddle would be very difficult.

A more advanced Welding Base (preferably on Linear Bearings) must be installed to enable instantaneous control of both Lateral and Transverse Motion of the Welding Jig.

13.1.4) **Installation of a Linear Distance Transducer:**

It will be remembered from Sec 11.2 that the measurement of Weld Travel is essential for the function of the ‘On-line’ Modelling Program ‘Weldmod’.

At present, the Weld Travel is determined indirectly by calculation using the Weld Travel Speed Readings and time Values obtained from the Computer Clock.

Whilst this method proved to be sufficiently accurate, it should be noted that the ‘C’ Language Functions for Time Acquisition and Time Difference Calculations are only accurate to 1/100 Second. Consequently, as these Time Values are utilised in Weld Travel Calculations, a buildup of Errors can occur.

It is recommended that a Linear Distance Transducer be installed for Weld Distance Measurement as not only would it enable the elimination of errors in Weld Distance Measurement, but it would also result in the ‘Weldmod’ Program being more computationally efficient as all the Weld Distance Calculations using Weld Travel Speed and Time Values could be replaced with a simple input reading from the Distance Transducer.
13.1.5) **Flexible Sensing and Control Systems:**

At present the Voltage and Wire Feed Rate Sensor Fittings are dedicated to the current Power Source (the Transmig 350 EC) as are the Voltage and Wire Feed Rate Control Attachments. The Welding Gun Clamp can at present also hold only the Gun for the Transmig 350 Power Source.

The Voltage and Wire Feed Rate Sensor and Control Attachments need redesigning for flexibility of fitting on a range of Welding Machines (if possible). The Weld Gun Clamp must also be redesigned for the installation of a range of Welding Gun Types.

Flexibility of Sensor and Control Fittings will enable Weld Testing and Model Development for a range of Welding Machines.

13.1.6) **Improvements to the MWEF Software Systems:**

The Software Systems developed (i.e. The ‘Shortmon’ and ‘Longmon’ Programs) are able to effectively control and monitor the welding process and enable the user to study a weld run on-line in both the time and frequency domain.

However, there are certain improvements that can be made to the Software Systems which would increase their effectiveness as weld analysis tools. These potential improvements are:

i) Statistical Analysis tools could be developed and implemented in the ‘Shortmon’ Program to enable Dipping Frequency, the Current Peak to Current Mean Ratio, Arcing Time, Dipping Time and Droplet Detachment Rate to be determined on-line. Statistical Analysis tools could also be inserted in the ‘Longmon’ Program for calculation of statistical data described above for each data acquisition window and also for the calculation of parameter Means and Standard Deviations of parameters for the whole weld run.

ii) At present, the graphical display of the FFT’s in the ‘Shortmon’ Program can only be displayed across the entire Nyquist Frequency range. As the welding process is predominantly low frequency, the ‘Shortmon’ Program would benefit from routines that enable the User to ‘zoom in’ on, and study in more detail, a particular frequency range of interest.

iii) The ‘Shortmon’ Program would also benefit from a routine that enables instantaneous values of parameters to be obtained from both time and frequency domain plots.
13.2) **Possibilities for Future Work:**

The development of the MWEF with time correlation with high speed visualisation, together with the development of prototype Rapid On-line Weld Modelling Software, has opened up a range of possibilities for future research in Gas Metal Arc Welding. Some of these ideas are discussed in the following sections:

### 13.2.1) **On-line Power Source and Consumable Evaluation:**

It is anticipated that the MWEF, with the implementation of the improvements suggested in Section 12.1, will be adapted for On-line Testing and Evaluation of Commercial and Prototype Power Sources and Consumables.

### 13.2.2) **Development of Models and Strategies for Real-time GMAW Control:**

One of the indicators of the Quality of a Weld is its resulting Geometric Parameters (also referred to as Direct Welding Parameters (DWP’s)) as illustrated in Fig 4.2 for Butt Welds and Fig 4.6 for Fillet Welds. Indirect Weld Parameters (IWP’s) are those Input Weld Parameters that determine the Geometric Features of the Weld and include Voltage, Current, Wire Feed Rate, Weld Travel Speed and Standoff. Fig 3.1 illustrates the relationship of IWP’s to DWP’s.

At present it is very difficult to determine in real-time, the components of the Weld Bead Geometry using direct methods such as Vision, Thermographic Techniques and Ultrasonics. As the IWP’s mentioned above are easily measured in Real-time, it is therefore necessary to determine fast Real-time Empirical Models that enable indirect Estimation of the DWP’s utilising Feedback IWP’s during the Welding Process. The predicted DWP’s can then be compared to the desired DWP’s to determine the present quality of the weld.

An important part of future work is therefore the development of Real-time Empirical Models for the prediction of DWP’s together with Strategies for IWP modification should any Weld Irregularities be detected. These Models will be developed for Butt Welds on materials up to 25mm thick and also on Fillet Welds with Leg Lengths up to 25mm.

The Consumable Types utilised also have an important effect on the resulting Weld and therefore Models will need to be developed specifically for a unique set of Consumable Types and Gas Flow Rates.
The flowchart in Fig 13.1 below illustrates the proposed Modelling Process utilizing the facilities developed for this thesis:

The Modelling Process involves the initial design of a Candidate Model, the coefficients for which will be determined using the 'Weldmod'.
Program. The Model will then be tested thoroughly using a modified version of the ‘Longmon’ Program referred to in Sec 12.4.1 as the Model Verification Software (MVS). If the Model is not satisfactory after testing, the Candidate Model will need to be redesigned and the Modelling Process repeated.

The current version of the ‘Weldmod’ Program can be modified with the addition of a Model Input Interface that will enable a User to enter their own Model into the Program for coefficient calculation by a point-and-click operation on a menu window. A basic and preliminary design of the Model Input Interface is illustrated in Fig 13.2 below:

![Model Input Interface](image)

<table>
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<th>DWP:</th>
<th>Operands:</th>
<th>Coeffs:</th>
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<tr>
<td>V</td>
<td>B</td>
<td>+</td>
<td>k₁, k₇</td>
</tr>
<tr>
<td>I</td>
<td>H</td>
<td>-</td>
<td>k₂, k₈</td>
</tr>
<tr>
<td>W</td>
<td>P</td>
<td>*</td>
<td>k₃, k₉</td>
</tr>
<tr>
<td>T</td>
<td></td>
<td>/</td>
<td>k₄, k₁₀</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>^</td>
<td>k₅, k₁₁</td>
</tr>
</tbody>
</table>

Model No 1 Entry:

\[ I = k₁ + k₂ \cdot V + k₃ \cdot W + k₄ \cdot L \]

Model No 2 Entry:

\[ L = k₁ + k₂ \cdot V + k₃ \cdot I + k₄ \cdot W \]

Fig 13.2: Model Input Interface for the ‘Weldmod’ Program

The Model Input Interface illustrated above is highly simplistic and will be substantially more complex in reality. In this thesis we have only utilised the Least-Squares Modelling but not all situations can be affectively monitored using this method. To be an effective Modelling Tool the ‘Weldmod’ Program will need to cater for the Input and coefficient calculation of a range of Statistical Models. It can also be seen from Fig 13.2 that the
Interface will allow entry and coefficient calculation for multiple model entries.

It will be remembered from Sec 12.4.1 that DWP Predictors cannot be completely developed and tested on-line. Provision must therefore be made for this limitation in any further developments of the ‘Weldmod’ Program and in the development of the Model Verification Software (MVS).

13.2.3) Implementation of Real-time GMAW Strategies and Models in a Robotic Welding System:

The Strategies and Models for Real-time Control, described in Chapters 10 and 11, may at some point be implemented on a Robotic Welding System currently under development. This system will possess the capability of utilising the developed Models for estimation of the state of the Welding Process and Bead Geometry, and then utilise the Irregularity Elimination Strategies to determine any alterations to the IWP’s and position of the Welding Gun that would be required to eliminate Weld Irregularities.
Chapter 14

Conclusions

A Gas Metal Arc Welding Facility (MWEF) has been established with the following features:

i) Mechanical and Visual Testing of all Butt Weld Types up to a Material Thickness of 25mm and Fillet Welds with Leg Lengths up to 25mm.

ii) Mechanised Production of Butt, Fillet and Bead-on-Plate Welds.

iii) Weld Sensors have been developed and installed for Voltage, Current, Wire Feed Rate and Weld Travel Speed Measurement.

iv) Methods have been established and implemented for Computer Control of Voltage, Wire Feed Rate and Weld Travel Speed.

v) GUI Software has been produced for acquiring and studying short bursts of Welding Data ('Shortmon') and also for studying the behaviour and stability of Weld Settings over long Welding periods ('Longmon').

vi) Time Correlation of Weld Visualisation with Electronic Monitoring has been achieved allowing Frame to Sample correlated study of the Welding Process thereby enabling the physical effects of Welding Parameters to be correlated and studied with Visual Weld Images at any point in the Weld Sample obtained.

vii) The MWEF has been verified by extensive experimentation, as a system suitable for the investigation of welding phenomena and also for the development, testing and implementation of real-time GMAW Control strategies.

The System has been utilised to:

i) Derive on-line monitoring techniques for Surface Contaminant detection, Excessive Penetration and Burnthrough detection, Isolated Transient Irregularity detection and Standoff Estimation.

ii) Study and explain Isolated Transient Irregularities using time correlated Electronic Monitoring and Weld Visualisation.

iii) Prototype Software has been developed for rapid On-line Weld Modelling. Although this Software at present only produces Least-Squares
Models for Current and Standoff Prediction, it is anticipated that this Program will be utilised for more efficient Modelling of other Welding Parameters and Phenomena.
References


Please note that the following publications are not directly referenced in the thesis, but were utilised extensively in the completion of this project.


APPENDIX I

Specimen Cutting Positions

(Butt and Fillet Welds)
The above diagram displays the division of Butt Weld Testpieces into the various individual Testpieces as required by AS1554. A Standard Testpiece will yield:

a) 3 Tensile Tests
b) 3 Bend Tests
c) 6 Macro Tests
d) 3 Hardness Tests
e) 6 Charpy Tests
The above diagram illustrates the division of a Fillet Weld Testpiece into individual Testpieces as required by AS1554. A standard Fillet Weld Testpiece will yield 10 Macro Tests and 1 Fillet Weld Test.
APPENDIX II

Sample Test Results

(Butt Welds)
## TEST RESULTS (BUTT WELD)

<table>
<thead>
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<th>Date:</th>
<th>Matl Type:</th>
<th>Matl Thkns:</th>
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<tr>
<td>1</td>
<td>15.12.93</td>
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### MACRO TEST (AS2205.5.1)

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<th>BH (Min)</th>
<th>SWF (Max)</th>
<th>BW (Max)</th>
<th>BW (Min)</th>
<th>PEN</th>
<th>AREA (mm²)</th>
<th>Weld Faults</th>
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### TENSILE TEST (AS2205.2.1)

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<th>Area (mm²)</th>
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<table>
<thead>
<tr>
<th>Spec No</th>
<th>Yield Stress (MN/m²)</th>
<th>UTS (MN/m²)</th>
<th>Fracture Load (kN)</th>
<th>% Elongation</th>
<th>Comments</th>
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### CHARPY TEST (AS2205.7.1)

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### BEND TEST (AS2205.3.1)

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<td>2</td>
<td>Slight fracture at right Root and on upper-right V (&lt;3mm)</td>
<td>Pass</td>
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<tr>
<td>3</td>
<td>Slight fractures at Root and fracture on upper-left V (&lt;3mm)</td>
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**Abbreviations**

BH = Bead Height, BW = Bead Width, SWF = Side Wall Fusion, PEN = Penetration

*All Dimensional Measurements taken in Millimetres*
## Vickers Hardness Test (AS2205.6.1)

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<td>23.75</td>
</tr>
</tbody>
</table>

### Comments

N/A

### Vertical Scale:

1 mm = 4 kN Force

### Horiz Scale:

1 mm = 0.2 mm Extension

---

**FORCE - EXTENSION PLOT**

![Force-Extension Plot](image)

**Abbreviations:**

UTS = Ultimate Tensile Strength. GL = Gauge Length on Specimen
### MACRO TEST (AS2205)

<table>
<thead>
<tr>
<th>Run</th>
<th>Specimen No</th>
<th>Acid</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5% Nital Soln</td>
<td>5:1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BH (Max)</th>
<th>BH (Min)</th>
<th>SWF (Max)</th>
<th>BW (Max)</th>
<th>BW (Min)</th>
<th>PEN</th>
<th>AREA (mm²)</th>
<th>Weld Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.90</td>
<td>0.00</td>
<td>1.20</td>
<td>17.30</td>
<td>16.70</td>
<td>N/A</td>
<td>242.3</td>
<td>Cavitation: Root</td>
</tr>
</tbody>
</table>

### Weld Profile

**Abbreviations:**
- BH = Bead Height
- BW = Bead Width
- SWF = Side Wall Fusion
- PEN = Penetration

All Dimensions in Millimetres (mm)
Vickers Hardness Readings
(Run 1 : Specimen 2 : Posn A)
Vickers Hardness Readings

(Run 1 : Specimen 2 : Posn B)
Vickers Hardness Readings

(Run 1 : Specimen 2 : Posn C)

Displacement ("")
Vickers Hardness Readings

(Run 1 : Specimen 2 : Posn E)
Vickers Hardness Readings

(Run 1 : Specimen 2 : Posns A,B,D,E)
APPENDIX III

Sample Test Results

(Fillet Welds)
# TEST RESULTS (FILLET WELD)

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Date</th>
<th>Matl Type</th>
<th>Matl Thkns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MS Grade 250</td>
<td>25</td>
</tr>
</tbody>
</table>

## MACRO TEST (AS2205.5.1)

<table>
<thead>
<tr>
<th>Spec No</th>
<th>S (Vert)</th>
<th>S (Horiz)</th>
<th>SWF (Max)</th>
<th>SWF (Min)</th>
<th>TT Thkns</th>
<th>Reinf (Max)</th>
<th>Reinf (Min)</th>
<th>Area (mm²)</th>
<th>Weld Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.70</td>
<td>29.10</td>
<td>2.20</td>
<td>0.00</td>
<td>18.55</td>
<td>0.90</td>
<td>-0.60</td>
<td>399.9</td>
<td>Cavitation near Weld Face</td>
</tr>
<tr>
<td>2</td>
<td>24.30</td>
<td>29.60</td>
<td>2.40</td>
<td>0.40</td>
<td>19.10</td>
<td>1.10</td>
<td>-0.90</td>
<td>428.0</td>
<td>Cavitation near Weld Face</td>
</tr>
<tr>
<td>3</td>
<td>24.00</td>
<td>30.00</td>
<td>1.70</td>
<td>0.15</td>
<td>18.90</td>
<td>0.90</td>
<td>-1.00</td>
<td>407.2</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>25.10</td>
<td>28.70</td>
<td>2.20</td>
<td>0.00</td>
<td>19.10</td>
<td>1.10</td>
<td>-0.85</td>
<td>407.2</td>
<td>Cavitation near Weld Face</td>
</tr>
<tr>
<td>5</td>
<td>23.80</td>
<td>26.80</td>
<td>2.00</td>
<td>0.40</td>
<td>18.00</td>
<td>1.30</td>
<td>-0.70</td>
<td>389.3</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>26.00</td>
<td>28.10</td>
<td>1.90</td>
<td>0.20</td>
<td>19.25</td>
<td>0.85</td>
<td>-0.70</td>
<td>418.3</td>
<td>N/A</td>
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<tr>
<td>7</td>
<td>27.50</td>
<td>28.30</td>
<td>2.55</td>
<td>0.40</td>
<td>20.00</td>
<td>0.10</td>
<td>-1.20</td>
<td>430.1</td>
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</tr>
<tr>
<td>8</td>
<td>27.20</td>
<td>28.30</td>
<td>1.90</td>
<td>0.40</td>
<td>19.70</td>
<td>0.70</td>
<td>-1.00</td>
<td>430.6</td>
<td>N/A</td>
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<tr>
<td>9</td>
<td>26.50</td>
<td>28.00</td>
<td>2.20</td>
<td>0.30</td>
<td>19.40</td>
<td>1.60</td>
<td>-1.10</td>
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<td>0.20</td>
<td>19.95</td>
<td>0.70</td>
<td>-1.50</td>
<td>427.9</td>
<td>N/A</td>
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</table>

Angular Distortion of Joint from the Perpendicular (Degrees): 1.5

## BREAK TEST (AS2205.4.1)

<table>
<thead>
<tr>
<th>Root Penetration</th>
<th>Cavitation/Porosity</th>
<th>Inclusions</th>
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</thead>
<tbody>
<tr>
<td>OK</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Fusion (Vert/Horiz)  
Slight Lack of Fusion on Vertical Face for last run.  
Overall  
Undercut  
None  
None

**Abbreviations**

S = Fillet Weld Leg Length. SWF = Side Wall Fusion

All Dimensions are in Millimetres (mm), unless otherwise stated.
**MACRO TEST (AS2205.5.1)**

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Spec Number</th>
<th>Date</th>
<th>Weld Profile Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.2.94</td>
<td>5:1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S (Vert)</th>
<th>S (Horiz)</th>
<th>SWF (Max)</th>
<th>SWF (Min)</th>
<th>Throat Thkns</th>
<th>Reinf (Max)</th>
<th>Reinf (Min)</th>
<th>Area (mm²)</th>
<th>Ang Dist (°)</th>
<th>Weld Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.70</td>
<td>29.10</td>
<td>2.20</td>
<td>0.00</td>
<td>18.55</td>
<td>0.90</td>
<td>-0.60</td>
<td>399.9</td>
<td>1.5</td>
<td>Cavitation</td>
</tr>
</tbody>
</table>

**WELD PROFILE**

**Abbreviations:**

S = Fillet Weld Leg Length. SWF = Side Wall Fusion

All Dimensions are in Millimetres (mm), unless otherwise stated.
APPENDIX IV

Transmig 350 EC

Power Supply Characteristics
APPENDIX V

PCL812PG Input/Output Card

Card I/O Wiring Diagram
APPENDIX VI

GMAW Experimental Facility

Design Drawings
<table>
<thead>
<tr>
<th>NO</th>
<th>DESCRIPTION</th>
<th>MATERIAL</th>
<th>SIZE/TYPE</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BASE PLATE</td>
<td>MS (GD 250)</td>
<td>150<em>50</em>480</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>BOTTOM PLATE</td>
<td>MS (GD 250)</td>
<td>150<em>50</em>320</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>SIDE SUPPORT</td>
<td>MS (GD 250)</td>
<td>125<em>20</em>230</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>ROLLER</td>
<td>TS (K1045)</td>
<td>75<em>50</em>50</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>SHAFT</td>
<td>TS (K1045)</td>
<td>25*90</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>BEARING</td>
<td>PURCHASED NP 6305</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>FORMER</td>
<td>TS (K1045)</td>
<td>100<em>30</em>120</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>FORMER LOCN.Plate</td>
<td>MS (GD 250)</td>
<td>100<em>50</em>120</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>SHANK</td>
<td>MS (GD 250)</td>
<td>1/4*90</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>SPECIMEN LOCN.Plate</td>
<td>MS (GD 250)</td>
<td>90<em>50</em>3</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>CAPSCREW</td>
<td>PURCHASED</td>
<td>M10*25</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>DOWEL</td>
<td>MS (GD 250)</td>
<td>10*25</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>DOWEL</td>
<td>MS (GD 250)</td>
<td>6*15</td>
<td>4</td>
</tr>
<tr>
<td>14</td>
<td>DOWEL</td>
<td>MS (GD 250)</td>
<td>6.35*17</td>
<td>1</td>
</tr>
</tbody>
</table>

**NOTES:**
- BENDING JIG
  - SCALE 1:5
  - DATE: 5/11/93
  - Drawn: LAS
  - Set 1 of 8 Sheets
ALL DIMENSIONS IN MM

COMPONENTS:

<table>
<thead>
<tr>
<th>NO.</th>
<th>DESCRIPTION</th>
<th>MATERIAL</th>
<th>SIZE</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VERTICAL LEG</td>
<td>MS RHS</td>
<td>150 x 50 x 5 x 880</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>HORIZONTAL LEG</td>
<td>MS RHS</td>
<td>150 x 50 x 3 x 320</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>SECURING PLATE</td>
<td>MS PLATE</td>
<td>450 x 150 x 25</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>STIFFENER PLATE 1</td>
<td>MS PLATE</td>
<td>150 x 120 x 10</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>STIFFENER PLATE 2</td>
<td>MS PLATE</td>
<td>150 x 120 x 10</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>FLANGE PLATE</td>
<td>MS PLATE</td>
<td>200 x 150 x 20</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>COVER</td>
<td>MS SHT</td>
<td>100 x 50 x 3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>CAPSCREW</td>
<td>N/A</td>
<td>M9 x 25</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>DOWEL</td>
<td>SS</td>
<td>Ø10 x 40</td>
<td>4</td>
</tr>
<tr>
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<td>LATHE BED</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>11</td>
<td>WELD GUN CLAMP</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>

NOTES:
- WELD GUN CLAMP SUPPORT
- SCALE: 1"=6FS DATE: 9/6/94
- DRN: LAS SHT 1 OF 2 SHTS
<table>
<thead>
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<th>MATL</th>
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<th>QTY</th>
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<tbody>
<tr>
<td>1</td>
<td>ENCODER PLATE</td>
<td>M/S SHT</td>
<td>30 x 33 x 1.6</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>SUPPORT BRACKET</td>
<td>M/S SHT</td>
<td>45 x 25 x 3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>BACKING PLATE</td>
<td>M/S SHT</td>
<td>50 x 30 x 1.6</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>ANTI-SPATTER SHIELD</td>
<td>M/S SHT</td>
<td>200 x 120 x 1.6</td>
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ENCODER SUPPORT ASSEMBLY

Drn: L. A. Sanders
Date: 31/10/94
Scale: 2 x FS
Sht 1 of 5 Shts
<table>
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<th>NO</th>
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<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BASE</td>
<td>M/S PLATE</td>
<td>250 x 150 x 20</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>SUPPORT BRACKET</td>
<td>M/S SHT</td>
<td>3mm THK</td>
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</tr>
<tr>
<td>3</td>
<td>CONNECTOR</td>
<td>M/S ROD</td>
<td>DIA 12 x 30</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>CONTROL LEVER</td>
<td>M/S ROD</td>
<td>DIA 3 x 60</td>
<td>2</td>
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<tr>
<td>5</td>
<td>STEPPER MOTOR</td>
<td>N/A</td>
<td>RS (332-947)</td>
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</tr>
<tr>
<td>6</td>
<td>GEARBOX</td>
<td>N/A</td>
<td>RS (336-444)</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>CAPSCREW</td>
<td>N/A</td>
<td>M5 x 10</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>BOLT</td>
<td>N/A</td>
<td>M3 x 10</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>NUT</td>
<td>N/A</td>
<td>M3</td>
<td>4</td>
</tr>
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<td>MIG CONTROL BOX</td>
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VOLTAGE/WIRE FEED RATE CONTROLLER ASSEMBLY

Drn: L. A. Sanders
Date: 10/7/95
Scale: 1/2 x FS
Sht 1 of 4 Shts
<table>
<thead>
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<th>SIZE</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BASE PLATE</td>
<td>M/S PLATE</td>
<td>350 x 150 x 25</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>SUPPORT A</td>
<td>M/S BAR</td>
<td>250 x 40 x 20</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>SUPPORT B</td>
<td>M/S BAR</td>
<td>250 x 40 x 20</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>CAPSCREW</td>
<td>N/A</td>
<td>M10 x 15</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>CAPSCREW</td>
<td>N/A</td>
<td>M10 x 20</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>SET BLOCK A</td>
<td>M/S BAR</td>
<td>75 x 20 x 60</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>SET BLOCK B</td>
<td>M/S BAR</td>
<td>75 x 20 x 60</td>
<td>1</td>
</tr>
</tbody>
</table>

CURRENT/STANDOFF
MODEL VERIFICATION JIG

Drn: L. A. Sanders
Date: 15/10/95
Scale: 1/2 x FS
Sht 1 of 4 Shts
APPENDIX VII

The ‘Shortmon’

Weld Data Acquisition and Analysis Program

(Screen Dumps)
'Shortmon' Control Panel and Weld Run Report

1) 'Shortmon' Control Panel

2) Weld Run Report
Dip Transfer Individual Time Domain Plots

3) Individual Dip Transfer Time Domain Voltage Plot

4) Individual Dip Transfer Time Domain Current Plot
Dip Transfer Individual Frequency Domain Plots

5) Individual Dip Transfer Frequency Domain Voltage Plot

6) Individual Dip Transfer Frequency Domain Current Plot
Dip Transfer General Plots

7) General Dip Transfer Time Domain Plot

8) General Dip Transfer Frequency Domain Plot
Spray Transfer Individual Time Domain Plots

9) Individual Spray Transfer Time Domain Voltage Plot

10) Individual Spray Transfer Time Domain Current Plot
Spray Transfer Individual Frequency Domain Plots

11) Individual Spray Transfer Frequency Domain Voltage Plot

12) Individual Spray Transfer Frequency Domain Current Plot
General Spray Transfer Plots

13) General Spray Transfer Time Domain Plots

14) General Spray Transfer Frequency Domain Plots
APPENDIX VIII

The 'Longmon'

Weld Data Acquisition and Analysis Program

(Screen Dumps)
‘Longmon’ Initialisation

1) The ‘Longmon’ Screen on Startup

2) The ‘Longmon’ Screen setup for a Weld Run
Dip Transfer Weld Run

3) Dip Transfer Weld Run as Recorded in Real-Time

4) Dip Transfer Weld Run after Parameter Axis Modification
Spray Transfer Weld Run

5) Spray Transfer Weld Run as Recorded in Real Time

![Graphs showing voltage, current, WFR, time, SPL, and TS](image)

6) Weld run after Parameter Axis Modification

![Graphs showing voltage, current, WFR, time, SPL, and TS](image)
In-Weld Parameter Alteration

7) In-Weld Parameter Alteration Plot after Axis Modification

8) In-Weld Alteration Plot and Histogram Output
Parameter Behaviour with Standoff Variation

9) Parameter Variation with Stepped Specimen

10) Parameter Variation with a Specimen on a Gradient Descent
APPENDIX IX

The 'Weldmod'

On-line Weld Modelling Program

(Screen Dumps and Printed Output)
'Weldmod' Initialisation

1) The 'Weldmod' Screen Page on Startup

2) The 'Weldmod' Screen setup for a Model Weld Run
Dip Transfer Model Weld Run

3) Dip Transfer Model Weld Run Plot

4) Dip Transfer Model Weld Run Plot with Model Data Histogram Output
Dip Transfer Model Weld Run (Contd..)

5) Dip Transfer Model Weld Run Plot with Current Model Output

6) Dip Transfer Model Weld Run Plot with Standoff Model Output
7) Dip Transfer Weld Run Histogram

Histogram for Run 1

Date: Mon 4/3/1996
Time: 4:30 PM

Parameter Feedback Readings

<table>
<thead>
<tr>
<th>Event</th>
<th>V (V)</th>
<th>I (A)</th>
<th>W (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.41</td>
<td>164.8</td>
<td>56.8</td>
<td>12.0</td>
</tr>
<tr>
<td>2</td>
<td>19.49</td>
<td>238.6</td>
<td>99.9</td>
<td>12.0</td>
</tr>
<tr>
<td>3</td>
<td>22.08</td>
<td>171.1</td>
<td>59.9</td>
<td>12.0</td>
</tr>
<tr>
<td>4</td>
<td>20.48</td>
<td>237.0</td>
<td>100.3</td>
<td>12.0</td>
</tr>
<tr>
<td>5</td>
<td>20.86</td>
<td>151.8</td>
<td>59.9</td>
<td>20.0</td>
</tr>
<tr>
<td>6</td>
<td>20.45</td>
<td>211.5</td>
<td>99.5</td>
<td>20.0</td>
</tr>
<tr>
<td>7</td>
<td>22.42</td>
<td>152.2</td>
<td>59.7</td>
<td>20.0</td>
</tr>
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<td>8</td>
<td>21.50</td>
<td>212.8</td>
<td>99.4</td>
<td>20.0</td>
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</table>

Parameter Input Settings

<table>
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<th>V (V)</th>
<th>W (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
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<td>20.00</td>
<td>59.4</td>
<td>12.0</td>
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<tr>
<td>2</td>
<td>20.00</td>
<td>100.6</td>
<td>12.0</td>
</tr>
<tr>
<td>3</td>
<td>22.00</td>
<td>59.4</td>
<td>12.0</td>
</tr>
<tr>
<td>4</td>
<td>22.00</td>
<td>100.6</td>
<td>12.0</td>
</tr>
<tr>
<td>5</td>
<td>20.00</td>
<td>59.4</td>
<td>20.0</td>
</tr>
<tr>
<td>6</td>
<td>20.00</td>
<td>100.6</td>
<td>20.0</td>
</tr>
<tr>
<td>7</td>
<td>22.00</td>
<td>59.4</td>
<td>20.0</td>
</tr>
<tr>
<td>8</td>
<td>22.00</td>
<td>100.6</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Other Parameter Information

Weld Travel Speed (mm/min): 300.0
Electrode: Autocraft LW1 (1.2mm)
Shielding Gas: Argoshield 50 (GFR=14l/min)
Least-Squares Current Model

The Current Model \( I = f(V, W, L) \):

\[
I = 109.79360 + -0.07544V + 1.59872W + -2.66885L
\]

where \( I=\text{Amps, } V=\text{Volts, } W=\text{mm/s, } L=\text{mm} \).

The Model is valid for the following Parameter Input Ranges:

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>Standoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Range: 22.00</td>
<td>100.6</td>
<td>20.0</td>
</tr>
<tr>
<td>Lower Range: 20.00</td>
<td>59.4</td>
<td>12.0</td>
</tr>
</tbody>
</table>

The Model is valid for the following Consumable Types only:

- Electrode: Autocraft LW1 (Size=1.2mm)
- Shielding Gas: Argoshield 50 (GFR=14)
9) Dip Transfer Least-Squares Standoff Model

Least-Squares Stand-off Model

Date: Mon 4/3/1996                       Time: 4:30 PM

The Stand-off Model (I = f(V,W,L):

\[ L = 38.59545 + 0.04794V - 0.36239I + 0.58114W \]

where \( L=\text{mm}, \ V=\text{Volts}, \ I=\text{Amps}, \ W=\text{mm/s}. \)

The Model is valid for the following Parameter Input Ranges:

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>Standoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Range: 22.00</td>
<td>100.6</td>
<td>20.0</td>
</tr>
<tr>
<td>Lower Range: 20.00</td>
<td>59.4</td>
<td>12.0</td>
</tr>
</tbody>
</table>

The Model is valid for the following Consumable Types only:

Electrode: Autocraft LW1 (Size=1.2mm)
Shielding Gas: Argoshield 50 (GFR=14)
Spray Transfer Model Weld Run

10) Spray Transfer Model Weld Run Plot

11) Spray Transfer Model Run Plot with Model Data Histogram Output
Spray Transfer Model Weld Run (Contd.)

12) Spray Transfer Model Weld Run Plot with Current Model Output

13) Spray Transfer Model Weld Run Plot with Standoff Model Output
14) Spray Transfer Weld Run Histogram

Histogram for Run 1

Date: Tue 19/3/1996  Time: 4:14 PM

Parameter Feedback Readings

<table>
<thead>
<tr>
<th>Event</th>
<th>V (V)</th>
<th>I (A)</th>
<th>W (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.60</td>
<td>285.1</td>
<td>119.5</td>
<td>16.0</td>
</tr>
<tr>
<td>2</td>
<td>26.30</td>
<td>320.8</td>
<td>152.4</td>
<td>16.0</td>
</tr>
<tr>
<td>3</td>
<td>29.93</td>
<td>295.9</td>
<td>121.9</td>
<td>16.0</td>
</tr>
<tr>
<td>4</td>
<td>28.45</td>
<td>334.4</td>
<td>152.3</td>
<td>16.0</td>
</tr>
<tr>
<td>5</td>
<td>28.94</td>
<td>252.9</td>
<td>121.5</td>
<td>24.0</td>
</tr>
<tr>
<td>6</td>
<td>27.85</td>
<td>281.5</td>
<td>151.8</td>
<td>24.0</td>
</tr>
<tr>
<td>7</td>
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<td>260.6</td>
<td>121.1</td>
<td>24.0</td>
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<tr>
<td>8</td>
<td>30.01</td>
<td>293.2</td>
<td>151.7</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Parameter Input Settings

<table>
<thead>
<tr>
<th>Event</th>
<th>V (V)</th>
<th>W (mm/s)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.00</td>
<td>119.4</td>
<td>16.0</td>
</tr>
<tr>
<td>2</td>
<td>29.00</td>
<td>149.4</td>
<td>16.0</td>
</tr>
<tr>
<td>3</td>
<td>31.00</td>
<td>119.4</td>
<td>16.0</td>
</tr>
<tr>
<td>4</td>
<td>31.00</td>
<td>149.4</td>
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<td>29.00</td>
<td>119.4</td>
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<td>29.00</td>
<td>149.4</td>
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<td>7</td>
<td>31.00</td>
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</tr>
<tr>
<td>8</td>
<td>31.00</td>
<td>149.4</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Other Parameter Information

Weld Travel Speed (mm/min): 300.0
Electrode: Autocraft LW1 (1.2mm)
Shielding Gas: Argoshield 50 (GFR=141/min)
15) Spray Transfer Least-Squares Current Model

The Current Model \( I = f(V,W,L) \):

\[
I = 94.71021 + 4.52835V + 1.27559W - 5.43289L
\]

where \( I=\text{Amps} \), \( V=\text{Volts} \), \( W=\text{mm/s} \), \( L=\text{mm} \).

The Model is valid for the following Parameter Input Ranges:

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>Standoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Range: 31.00</td>
<td>149.4</td>
<td>24.0</td>
</tr>
<tr>
<td>Lower Range: 29.00</td>
<td>119.4</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The Model is valid for the following Consumable Types only:

- Electrode: Autocraft LW1 (Size=1.2mm)
- Shielding Gas: Argoshield 50 (GFR=14)
16) Spray Transfer Least-Squares Standoff Model

Date: Tue 19/3/1996

The Stand-off Model (I = f(V,W,L)):

\[ L = 16.75730 + 0.84357V - 0.181701 + 0.23259W \]

where \( L \) = mm, \( V \) = Volts, \( I \) = Amps, \( W \) = mm/s.

The Model is valid for the following Parameter Input Ranges:

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>WFR (mm/s)</th>
<th>Standoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Range: 31.00</td>
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<tr>
<td>Lower Range: 29.00</td>
<td>119.4</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The Model is valid for the following Consumable Types only:

Electrode: Autocraft LW1 (Size=1.2mm)

Shielding Gas: Argoshield 50 (GFR=14)