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Evaluation of standoff estimation methods in GMAW processes

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Evaluation of Standoff Estimation Methods in GMAW Processes

A thesis submitted in fulfilment of the requirements for the award of the degree

Master of Engineering (Honours)

From

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Australia

By
Gary So (BE.)
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Symbols

\( A \) = Cross-sectional area;
\( a_i \) = Constants;
\( C_i \) = Constants;
\( c_i \) = Constants;
\( d \) = Diameter;
\( I \) = Current;
\( j \) = Current density;
\( K_i \) = Constants;
\( L \) = Length;
\( MR \) = Melting rate of electrode wire;
\( R \) = Resistance;
\( r \) = radius;
\( T \) = Temperature;
\( t \) = Time;
\( V \) = Voltage;
\( v \) = Velocity;
\( WFR \) = Wire feed rate;
\( x \) = Axial distance;
\( z \) = Axial distance measured from molten tip, \( L - x \)

Greek letter

\( \gamma \) = Electrical resistivity of wire;
\( \rho \) = Density;
\( \phi \) = Constant potential drop at anode;
\( \Phi \) = Equivalent voltage for melting, Work function;

Subscript

\( a \) = Arc;
\( ave \) = Average;
\( bal \) = Ballast;
\( bk \) = Background;
\( CTWD \) = Contant tip-to workpiece distance;
\( d \) = Droplet;
\( e \) = Electrode extension;
\( liq \) = Liquid;
\( L-S \) = Liquid-solid interface;
\( max \) = Maximum;
\( min \) = Minimum;
\( SC \) = Short circuit;
\( sol \) = Solid;
\( x \) = Direction along electrode start from contact-tip;
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Automated and robotic Gas Metal Arc Welding (GMAW) processes are nowadays extensively used in many different industries due to their low cost, ease of operation and flexibility to different applications. The short-circuit transfer mode is widely used for joining thin sections and the spray transfer mode is extensively used for filling and joining thick sections. However, GMAW processes are susceptible to defects due to their operating characteristics [1]. Hence, quality of the components produced by automated and robotic GMAW is of prime importance.

The majority of automated and robotic GMAW applications still require the input from an experienced robot programmer or welder. In particular, the contact tip to work piece distance (CTWD), or so-called "standoff", is a variable, which has a significant influence on quality, including the mechanical and physical properties of the weld, yet it is difficult to maintain at its optimum value due to variations in work piece preparation, handling, jigging and distortion. Various authors [7-36] have developed methods to overcome this. This thesis will evaluate the applicability of different models often referred to in the literature [37-41] for standoff estimation and investigate the possibility of improvement by modifying these models. The models are classified as “theoretical models” and “empirical models”. Theoretical models are primarily based on the physical principles of the process. Experimental models that have been derived by fitting data to functions by using only a limited amount of knowledge of the structure of the process can also be used for standoff estimation. However, these usually require a significant amount of measurements and offer less insight into the process than theoretical models. Models of each category were investigated for their applicability to standoff estimation, theoretical methods based
on Halmoy's model [38] and Orszagh's model [39], and empirical methods based on Leneswich's [37], Kim & Na's [40] and Carvalho's [41] models.

Extensive experiments were carried out in both short circuit and spray transfer mode, using common welding conditions. Data were collected to derive and to validate the models. The results showed that Orszagh's and Carvalho's models performed similarly in short circuit transfer mode with less than +/- 1 mm offset from the actual standoff and a standard deviation of +/- 1 mm. Kim & Na's model resulted in the best standoff estimation during spray transfer, although the differences were less in this transfer mode. Carvalho's model is most suitable if one model is desired for both short circuit and spray transfer mode, however, different coefficients must be used.

Upon further investigation, a number of models were simplified and modified to evaluate whether improvements could be made. The modified Kim & Na's and Carvalho's models both used fewer coefficients (4 instead of 7) than the original models but turned out to have similar accuracy. It was therefore shown that numerically simpler algorithms could be used for standoff estimation, making it possible to implement the algorithms on line.
Chapter 1

Introduction
Gas metal arc welding (GMAW) is one of the most widely used welding processes in the world today. It has the advantage of flexibility, ease of operation and low cost. The short-circuit transfer mode is commonly used for joining thin sections and the spray transfer mode is generally used for joining thick sections. However, these transfer modes are susceptible to defects due to their operating characteristics [1]. Hence, the quality of components produced by automated and robotic GMAW is of prime importance.

For optimum quality, GMAW still requires the skill and experience of a qualified human operator but automated GMAW is being increasingly looked at to replace manual GMAW. An example of automated GMAW is a robotic welding cell equipped with a GMAW system, as shown in figure 1.1.

Figure 1.1 Robotic welding cell (*Hydro Tube Corp Robotic Welding*)
The components of a typical robotic welding cell are illustrated in figure 1.2. It consists of a robot arm or manipulator to move the welding torch, welding power supply, wire consumable and shielding gas. More complicated examples of robotic welding cells take advantage of the flexibility of two robots. One robot is designated to hold the work-piece and the other to do the welding. This allows the robot equipped with the welding torch to gain easier access to hard-to-reach positions [5, 44-45], providing greater flexibility in the welding of complicated objects.

![Figure 1.2 Components of a robotic welding cell](image1.png)

GMAW is, however, a highly complex process that so far has not been sufficiently described mathematically in order to be able to fully automate the process. Because of the complexity of the GMAW process and possible variations associated with work-piece handling, preparation and distortion, accurate online computer control systems are difficult to develop.
In particular, the contact tip to work piece distance (CTWD), or so-called "standoff", is a variable that has a significant influence on quality, including the mechanical and physical properties of the weld, yet it is difficult to maintain at its optimum distance due to process variations.
1.1 Transfer modes

GMAW is an electric arc welding process which uses the heat generated from an electric arc between the work-piece and a continuously fed current carrying filler wire to fuse the joint area. An inert shielding gas or gas mixture is employed within the process to provide protection to both the weld pool and the arc from outside contamination and to improve arc stability. This is illustrated in figure 1.3.

Essentially, there are two ways in which metal can be transferred across the arc and into the molten weld pool. These two modes are known as ‘short circuit’ and ‘free-flight’ transfer [1]. ‘Free-flight’ transfer can be further sub-divided into ‘spray’ ‘globular’ and ‘pulse’ transfer modes. These modes are influenced by parameters such as the magnitude and type of welding current and the diameter, composition and extension of the electrode. In this thesis, ‘short circuit’ and ‘spray’ transfer welding will be conducted and evaluated due to their wide application in industry. ‘Globular’
transfer is rarely used in industry due to its unstable characteristics. 'Pulse' transfer is a free flight transfer mode where a sudden current boost is used to detach the droplet from the wire. It is widely used in the welding industry. However, due to the complexity of 'pulse' transfer it was decided to limit this research to 'short circuit' and 'spray' transfer modes. Therefore, 'globular' and 'pulse' transfer are not addressed in this thesis.
1.1.1 Short circuit transfer

In ‘Short circuit’ mode, metal transfer occurs at the lowest range of welding current. Figure 1.4 illustrates the different stages of this transfer mode. An electric arc is formed by the potential difference between the anode (the filler wire) and the cathode (the work-piece). The arc diminishes when the filler wire makes contact with the weld pool, initiating a short circuit. Resistive heating within the filler wire and magnetic pinch effects generated during the short circuit cause a neck to form in the filler wire, which then ruptures, transferring material to the weld pool. The arc is then re-established. If the welding parameters are properly set, the short-circuiting cycle will occur at regular intervals at frequencies of 20 – 200 Hz. The weld bead formed is characteristically narrow and short in height with minimal penetration, making it suitable for the welding of thin sections.

Figure 1.4 Short-circuit mechanism and waveforms [10]
1.1.2 Spray transfer

Spray transfer occurs at a range above short-circuit mode, roughly 200 A welding current depending on wire diameter. Figure 1.5 illustrates the process of spray transfer. Once the arc is formed between the wire extension and work-piece, molten metal droplets smaller than, or equal to, the wire diameter is transferred within the arc at high frequency. The weld progresses as the welding torch is moved along the work-piece in such a way that the arc continues to touch down within the previously created weld pool. It is popular in use for filling large sections and building up material.

![Figure 1.5 Spray transfer mode](image)

Figure 1.5 Spray transfer mode [10]
1.2 Standoff

The distance between the end of the contact-tip and the work-piece is referred to as 'contact-tip to work-piece distance' (CTWD) or 'standoff', see figure 1.6. During short-circuiting, the solid wire dips into the weld pool and thus the wire extension is the same as the standoff. However, during spray transfer, the standoff consists of the wire extension plus the welding arc length resulting from a potential difference between the weld pool (anode) and solid wire (cathode).

Figure 1.6 Contact-tip to work-piece distance or ‘Standoff’

Standoff is an important welding parameter, which greatly affects the physical properties and quality of the resulting weld. Thus it would be useful if a reliable algorithm for predicting the standoff in real-time were available. In the next section, various methods described in the literature for measuring standoff will be presented.
1.3 Sensors

A number of methods have been developed by others to estimate standoff. These can be categorised into two groups, contact sensors and non-contact sensors. Contact types consists of tactile probes and electrode contact sensors, and non-contact types consists of electromagnetic, optical and arc phenomena sensors. They are briefly discussed below.

The tactile probe sensor is a transducer that outputs distance changes based on an electrical signal. A typical structure of a contact type probe is illustrated in figure 1.7.

![Figure 1.7 Contact probe sensor](image)

This structure uses a one degree-of-freedom differential transformer, which outputs an analog signal proportional to distance. These sensors are simple, robust and have been widely used for a long time.
The electrode contact sensor is a type which detects a change in electrical current or voltage flowing when a welding wire is placed in contact with a base material, as shown in figure 1.8.

![Figure 1.8 Electrode contact sensor](image)

This method has been developed for arc welding robots and is effective in detecting the deviation between a teach point and an actual point such as in poor assembly accuracy. It brings a welding torch near a welded member depending on the teach mode carried out prior to welding, detects the contact with the end of the electrode and then determines the position of the work piece. Applying a voltage of 50 Hz frequencies with 500V magnitude to the welding electrode is commonly used to detect current flow upon contact. When applied to automated manufacturing processes, it can increases the preparation time dramatically due to the measurements that must be carried out prior to welding.

The electro magnetic sensor is a non-contact type detector, which uses electromagnetic fields to determine distance. This sensor is not often used for welding due to the electromagnetic disturbances inherent in arc welding processes. However,
it is very simple in structure and hence widely used for the detection of position and displacement. A typical electromagnetic sensor is illustrated in figure 1.9a.

![Electromagnetic sensor diagram](image.png)

**Figure 1.9a Electro magnetic sensor [42]**

When a magnetic flux that interlinks a conductor is subject to change, an eddy current is generated in the conductor. As shown in figure 1.9a, if the distance between a flux generating coil and a conductor is changed, the magnitude of the eddy current is also changed, thereby altering the impedance of the coil. Since the relationship between
the impedance of the coil and the distance to be detected is affected by the electrical conductivity and magnetic permeability of the object as well as its geometric configuration, it is very difficult to define a theoretical dependence. Furthermore, the greater the work piece to sensor distance, the lower the sensitivity to object detection.

Various types of optical sensors have been designed to detect both visible and invisible light. They can be classified as point sensors, linear sensors or area (image) sensors, based on the shape of the light being received. The linear sensor is most often used for distance detection in welding, as shown in figure 1.10.

![Linear optical sensor](image)

**Figure 1.10 Linear optical sensor [42]**

This method uses a point light source, such as a semiconductor laser, which is irradiated on to a target and its light is detected with a linear sensor arranged at a fixed angle ($\theta$). Both the light emission and detection unit are integrated into a single package. The principle of operation is that a light receiving position changes by $\Delta h$ when the distance of the base material changes by $\Delta H$. Although very high accuracy can be achieved by such systems, these are rarely used in production due to their size and their reliability.
Arc phenomena sensors utilize the changes that occur in welding current and voltage waveforms induced by changes in torch height during welding, as shown in figure 1.11.

![Diagram of torch height and welding current](image)

**Figure 1.11 Arc phenomena sensor [42]**

Generally, these sensors are called an “arc sensors”, or “through-the-arc sensors”. During welding, they are less sensitive to disturbances, such as those due to electromagnetic effects. Therefore, this thesis focuses on arc phenomena sensors to estimate standoff. A number of models and functions that estimate torch height $H$ have already been developed. It is not known however how these models perform in practice for online estimation and whether they can be further improved.
1.4 Requirements of a standoff estimation method

The following requirements for a through-the-arc standoff estimation method can now be defined.

❖ The system must detect changes in standoff with sufficient accuracy; +/- 1 mm is deemed sufficient for most applications, such as in pipe welding and other joining processes [1, 5, 6 and 10].

❖ The method has to be suitable for on-line applications using a standard PC.

❖ It is desirable that the method is independent of the welding parameters set and transfer modes being used.
1.5 Problem Formulation

The objective of this thesis can now be formulated as: *evaluating the applicability of various standoff estimation methods in practice, and the possibility of improving accuracy by modification of the models.*

The following tasks were therefore identified.

- Identify and study available standoff estimation algorithms
- Evaluate the applicability of the various models for standoff estimation in practice in both short circuit and spray transfer GMAW
- Evaluate the possibility of further improving the accuracy of standoff estimation by modifying the various models
1.6 Outline of Thesis

An overview of various standoff strategies for different GMAW transfer modes and applicable sensors will be given in Chapter 2. Chapter 3 is dedicated to the algorithms that are generally referred to in the literature with regards to standoff estimation. A description of the experimental setup and data acquisition equipment used to perform the necessary experiments is given in Chapter 4. Chapter 5 presents the results for the different algorithms based on the various models. The modified models are then proposed, developed and evaluated in Chapter 6. The conclusions, recommendations and suggestions for future work are given in Chapter 7.
Chapter 2

Standoff Estimation Algorithms
In order to integrate a through-the-arc sensor into an automated welding system such as in the system shown in figure 2.1, the relationship between standoff and other welding parameters must be known. It is proposed that an identification algorithm can be used on-line to estimate such variables in real-time. A number of algorithms have been developed by various authors [11-20, 22-29, 37-41], and they can be classified as either “theoretical models” or “empirical models”. Theoretical models are primarily based on the physical principles of the process. Experimental models however, have been derived by fitting data to functions by using only a limited amount of knowledge of the structure of the process. These usually require a significant number of measurements and offer less insight into the process than theoretical models.

![Dual robot welding cell](image_url)

**Figure 2.1 Dual robot welding cell (Autotech Robotics, England)**

The models most often referred to are the models described by Halmoy [38], Orszagh [39], Leneswich [37], Kim & Na [40] and Carvalho [41]. These models will be discussed and evaluated for their applicability for on-line estimation.
2.1 Theoretical Models

2.1.1 Halmoy's model

Halmoy [38] derived a mathematical model using the current density \( j \), wire feed rate (WFR) and wire extension (\( L_e \)). These variables are related to the wire extension heat content \( H_{Le} \) as a function of \( L_e \cdot j^2 / WFR \). Halmoy stated that the heat content initially increases rapidly and non-linearly with \( L_e \cdot j^2 / WFR \), typical of low current processes. Above a heat content of approximately 4 J/mm\(^3\), as for high current processes, the relationship becomes a linearly increasing one. The relationship can be converted into a function of \( L_e \cdot j \) versus \( j / WFR \). Below 4 J/mm\(^3\), where short circuit transfer occurs, the relationships be approximated by a straight line, which results in the following model:

\[
L_e = K_1 \cdot \frac{1}{j} - K_2 \cdot \frac{1}{WFR} \quad [\text{mm}]
\]  

(2.1)

Where

- \( L_e \) = Length of wire extension [mm]
- \( K_{1,2} \) = Empirical constants [A/mm, mm\(^2\)/s]
- \( j \) = Averaged welding current density [A/mm\(^2\)]
- \( WFR \) = Averaged wire feed rate [mm/s]

The model (2.1) predicts wire extension. However, in short circuit transfer mode, this is almost equivalent to standoff, because of the relatively short arc (about 0.5 to 2
mm). It should be noted that the above-mentioned model uses the averaged current density and averaged wire feed rate to obtain the wire extension length and therefore uses data from the complete short circuit cycle. The constants of equation (2.1) depend only on filler material and shielding gas composition and it should, therefore, be possible to use equation (2.1) for a wide range of operating conditions and wire diameters.
2.1.2 Orszagh’s model

Another model that relates standoff to other welding parameters in short circuit transfer mode was developed by Orszagh [39]. He suggested estimating the wire extension using the instantaneous minimum welding resistance during a short circuit, as illustrated in figure 2.2. During a short circuit, CTWD is the same as the wire extension plus the molten metal bridge, as shown in figure 2.3. The standoff can be determined by measuring the resistance during the short-circuit period, when the wire is in contact with the weld pool via a liquid bridge. The minimum resistance during the short circuit is said to be directly related to the wire extension and, therefore, to the standoff. The model is expressed as follows:

![Minimum short-circuit resistance](image)

Figure 2.2 Minimum short-circuit resistance
Figure 2.3 Short-circuiting metal transfer

\[ R_{sc} = R_1 + R_s + R_b \quad \text{Short-circuit resistance} \quad [\Omega] \quad (2.2) \]

Where

\[ R_1 = \gamma(T_1) \int_{0}^{l_1} \frac{1}{A_1(x)} \, dx \quad \text{Resistance of liquid bridge} \quad [\Omega] \quad (2.3) \]

\[ R_s = \frac{1}{\pi \tau_s} \int_{l_1}^{l_1+l_2} \gamma(T(x)) \, dx \quad \text{Resistance of solid part} \quad [\Omega] \quad (2.4) \]

\[ R_b = \text{Ballast resistance of electrical circuit to measurement point} \quad [\Omega] \]

Therefore, at the instant the minimum resistance occurs:

\[ R_{sc} = \gamma(T_1) \int_{0}^{l_1} \frac{1}{A_1(x)} \, dx + \frac{1}{\pi \tau_s} \int_{l_1}^{l_1+l_2} \gamma(T(x)) \, dx + R_b \quad [\Omega] \quad (2.5) \]
Where

\[ A_l = \text{Cross-sectional area of liquid phase} \ [\text{mm}^2] \]
\[ L_l = \text{Length of liquid phase} \ [\text{mm}] \]
\[ L_s = \text{Length of solid phase} \ [\text{mm}] \]
\[ r_s = \text{Diameter of electrode (solid phase)} \ [\text{mm}] \]
\[ T(x) = \text{Temperature at position } x \ [\text{K}] \]
\[ T_l = \text{Average liquid phase temperature} \ [\text{K}] \]
\[ \gamma(T) = \text{Electrical resistivity of the electrode at temperature } T \ [\Omega \cdot \text{m}] \]
\[ x = \text{Distance along electrode, starting from workpiece} \ [\text{mm}] \]

The above model for short circuit resistance requires determination of the wire resistivity profile, the temperature profile of the solid wire, the liquid bridge temperature profile and the ballast resistance. From the resistivity profile, an average resistivity of the solid part can be calculated. Equation 2.4 can then be simplified to:

\[ R_s = \frac{1}{\pi r_s^2} \int_{L_l}^{L_s+L_l} \gamma(T(x)) \, dx = \gamma_{\text{ave}} \cdot L_s \]

(2.6)

rearranging,

\[ L_s = \frac{R_s \cdot \gamma_{\text{ave}}}{\gamma_{\text{ave}}} = \frac{R_{\text{SC}} - R_l - R_b}{\gamma_{\text{ave}}} \]

(2.7)

Note that \( R_{\text{SC}} \) can be determined from experimental measurements, \( R_l \) can be calculated from equation (2.3) and \( R_b \) can be experimentally determined on set-up.

The total CTWD can thus be calculated by adding the length assumed for the liquid phase to the length calculated using equation (2.7).
Similar to the estimation method developed from Halmoy's model, this model is also valid for a range of operating conditions and its parameters depend only on consumable properties. It is, however limited in that it is only valid for the short circuit transfer mode.
2.2 Empirical Models

2.2.1 Leneswich’s model

From extensive measurements, Leneswich [37] established a relationship of anode heating from the work-piece, electrical resistive heating from wire extension and melting rate of wire in free-flight transfer mode. Anode heating is generated from the weld-pool where the highest temperature exists in the process. It can be represented mathematically by:

\[ MR_a = K_a \cdot \bar{I} \quad (2.8) \]

Where

- \( MR_a \) = Melting rate of anode heating [mm/s]
- \( K_a \) = Constant related to anode drop [mm/A.s]
- \( \bar{I} \) = Average welding current [A]

The resistive heating is derived from Ohm’s Law:

\[ MR_R = K_R \cdot L_e \cdot (\bar{I})^2 \quad (2.9) \]

Where

- \( MR_R \) = Melting rate of resistive heating from wire extension [mm/s]
- \( K_R \) = Constant related to resistive heating drop in wire extension [1/A².s]
- \( L_e \) = Length of wire extension [mm]

Adding equations (2.8) and (2.9):
\[ \text{MR}_e = \text{MR}_a + \text{MR}_R = K_a \cdot \bar{I} + K_R \cdot L_e \cdot \left(\bar{I}\right)^2 \]  \hspace{1cm} (2.10)

Where

\( \text{MR}_e \) = Melting rate of wire extension [mm/s]

Assuming the melting rate is approximately equal to the wire feed rate and rearranging equation (2.10), a model estimating wire extension is derived,

\[ L_e = \frac{\overline{\text{WFR}} - (K_1 + K_2 \bar{I})}{K_3 \bar{I}^2} \]  \hspace{1cm} (2.11)

Where

\( K_i \) = Constants obtained from experiments (where \( i = 1, 2, 3 \))

\( \overline{\text{WFR}} \) = Average wire feed rate [mm/s]

This model requires establishing the relationship between anode heating and welding current as well as the relationships between resistive heating of the solid wire and welding current. Its parameters depend only on consumable properties and are valid for a range of short circuit and spray operating conditions.
2.2.2 Kim & Na’s model

An empirical model can be derived by applying a least-squares polynomial fit to experimental data. Kim and Na [40] applied such a method to GMAW. They considered the effect of an individual factor and of two factor combinations. The variables chosen to predict welding current (I) response were welding voltage (V), wire feed rate (WFR) and CTWD (standoff). The model was expressed as follows:

\[
I = K_1 + K_2 V + K_3 WFR + K_4 L_{CTWD} + K_5 V \cdot WFR + K_6 WFR \cdot L_{CTWD} + K_7 V \cdot L_{CTWD}^2
\]  

or

\[
[I] = [A] \cdot [K]
\]

Where

\[
[A] = \begin{bmatrix}
1 & V_1 & WFR_1 & L_{CTWD_1} & \overline{V}_1 WFR_1 & WFR_1 L_{CTWD_1} & \overline{V}_1 L_{CTWD_1} \\
1 & V_2 & WFR_2 & L_{CTWD_2} & \overline{V}_2 WFR_2 & WFR_2 L_{CTWD_2} & \overline{V}_2 L_{CTWD_2} \\
1 & V_3 & WFR_3 & L_{CTWD_3} & \overline{V}_3 WFR_3 & WFR_3 L_{CTWD_3} & \overline{V}_3 L_{CTWD_3} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots
\end{bmatrix}
\]

and

\[
K = [K_1 \ K_2 \ K_3 \ K_4 \ K_5 \ K_6 \ K_7]^T
\]

The coefficients K can be determined by measurement:

\[
\]

Where

\[
\bar{I} = \text{Average welding current [A]}
\]
Ki = Empirical constants (where i = 1,2,\ldots)
L = Length [mm]
\overline{V} = Average welding voltage [V]
\overline{WFR} = Average wire feed rate [mm/s]
ctwd = Contact-tip to work-piece distance

After rearranging equation of 2.12, the CTWD can be determined:

\[
L_{ctwd} = \frac{I - (K_1 + K_2 \overline{V} + K_3 \overline{WFR} + K_5 \overline{V} \cdot \overline{WFR})}{(K_4 + K_6 \overline{WFR} + K_7 \overline{V})}
\] (2.16)

It should be noted that the model is only valid for a specific condition of filler material, wire diameter and travel speed.
2.2.3 Carvalho’s model

Carvalho [41] used a similar approach to Kim & Na [40] but estimated the short-circuit resistance (Rsc) instead of average current. He considered the effect of an individual factor and of two factor combinations. The chosen input factors were identical, welding voltage (V), wire feed rate (WFR) and CTWD (standoff), to estimate short-circuit resistance.

\[
\bar{R}_{sc} = K_1 + K_2 \bar{V} + K_3 WFR + K_4 L_{CTWD} + K_5 \bar{V} \cdot WFR + K_6 WFR \cdot L_{CTWD} + K_7 \bar{V} \cdot L_{CTWD}
\]

or

\[
[\bar{R}_{sc}] = [A] \cdot [K]
\]

Where

\[
[A] = 
\begin{bmatrix}
1 & V_1 & WFR_1 & L_{CTWD_1} & V_1 WFR_1 & WFR_1 L_{CTWD_1} & V_1 L_{CTWD_1} \\
1 & V_2 & WFR_2 & L_{CTWD_2} & V_2 WFR_2 & WFR_2 L_{CTWD_2} & V_2 L_{CTWD_2} \\
1 & V_3 & WFR_3 & L_{CTWD_3} & V_3 WFR_3 & WFR_3 L_{CTWD_3} & V_3 L_{CTWD_3} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\end{bmatrix}
\]

and

\[
K = [K_1 \quad K_2 \quad K_3 \quad K_4 \quad K_5 \quad K_6 \quad K_7]^T
\]

The coefficients K can be determined by measurement:

\[
[K] = ([A]^T [A])^{-1} [A]^T [\bar{R}_{sc}]
\]
Where
\[ R_{sc} \] = Average short-circuit resistance [\( \Omega \)]
\[ K_i \] = Empirical constants (where \( i = 1,2,\ldots \))
\[ L \] = Length [mm]
\[ \overline{V} \] = Average welding voltage [V]
\[ \overline{WFR} \] = Average wire feed rate [mm/s]
\[ CTWD \] = Contact-tip to workpiece distance

Upon rearranging,
\[
L_{CTWD} = \frac{R_{sc} - (K_1 + K_2 \overline{V} + K_3 \overline{WFR} + K_5 \overline{V} \cdot \overline{WFR})}{(K_4 + K_6 \overline{WFR} + K_7 \overline{V})} \quad (2.21)
\]

Similar to Kim & Na’s strategy, Carvalho determined the coefficients \( K \) for a range of measured average voltages, currents, wire feed rates and standoffs. This model is also only valid for a specific condition of filler material, wire diameter and travel speed. A change in any of these essential variables necessitates re-calibration.
Chapter 3

Experimental Set-up
In order to evaluate the suitability of standoff estimation for industrial application, the following robotic system was used, see figure 3.1.

Figure 3.1 Robotic welding cell used for the experiments

Figure 3.2 shows a schematic of the set-up used.

Figure 3.2 General layout of the experimental set-up

This system consists of a welding power supply, welding robot, sensors, signal-conditioning unit and monitoring computer. The desired voltage and wire feed rate are
adjusted on the front panel of the power supply. Shielding gas and electrode material are fed directly into the welding torch attached to the robot. The predefined standoff was measured with a vernier caliper to 0.1 mm accuracy during the welding torch path programming stage. Welding voltage, current and wire feed rate are measured using various sensors with the signals fed into a signal-conditioning unit for anti-aliasing filtering. The signals are then processed on the computer using a weld monitoring software package. These items are described in greater detail in the following sections.
A Hitachi M6060II servo controlled industrial robot (as previously shown in figure 3.1) was used for welding trials. This robot has six axes of freedom, enabling it to reach all positions within the working area and to attain the desired angle required of the torch relative to the work-piece. It has a central processing control unit that is used to program its movements. Refer to figure 3.3.

Figure 3.3 Central processing control unit of Hitachi M6060II Robot
Chapter 3

3.2 Welding Equipment

The welding power supply is a Lincoln Idealarc® DC-400, shown in figure 3.4. The DC-400 is NEMA rated 100% duty cycle at 400 A, 36 V for either 60 or 50 Hz supply. It can be used in two operating modes, Constant Voltage (CV) and Constant Voltage/Variable Voltage (CV/VV). The Constant Voltage mode (varying from approximately 12 to 40 V) is commonly used for GMAW processes and was used for this research. The voltage can be adjusted on the front panel of the power supply, along with other variables that affect weld properties. It has a supplementary NA-5R remote control pendant that allows the desired welding voltage and wire feed rate to be set and adjusted during welding.

![Figure 3.4 Lincoln Idealarc® DC-400 and supplementary NA-5R remote controller](image)
3.3 Sensing Devices

Welding voltage is defined as the voltage measured between the work-piece and the contact tip, but physical measurement often occurs further back from the contact tips and thus voltage drops across electrical conductor need to be accounted for. This will directly affect the accuracy of the standoff estimation. Therefore, cable resistances are measured and voltages offset appropriately by the monitoring package.

LEM HA500-SU direct current hall effect transducer was fitted around a power lead to measure welding current, see figure 3.5. The welding current is converted to a voltage signal and sent to a signal-conditioning unit. It is capable of measuring a current range of 0 – 500 A and outputs a 0 – 10 V signal with an accuracy of +/- 1 % of range.

Figure 3.5 LEM HEME hall effect direct current transducer
The wire feed rate sensor consists of two rollers connected to a DC generator, as shown in figure 3.6. The two rollers rotate with the movement of the wire. This rotation generates a voltage signal, which is fed to the signal-conditioning unit.

![Figure 3.6 Wire feed rate sensor](image)

A signal-conditioning unit, (figure 3.7), was used to amplify the measured signals, and filter the data with a 1st order, 2,500 Hz bandwidth anti-aliasing filter.

![Figure 3.7 Signal-conditioning unit](image)
3.4 Consumables

The shielding gas used was BOC “Argoshield 50”. This was chosen instead of Argosheild 51 or 52 because it was more stable for the actual welding process chosen and the standoff estimation. A 0.9 mm diameter type AWS ER70S-4 mild steel filler wire was chosen as it is commonly used in industry. Figure 3.8 shows the shielding gas bottle and corresponding pressure and volumetric sensors. The volumetric sensor can measure a gas flow of 0.5 – 50 l/min; it was adjusted to 15 +/- 0.5 l/min for all experiments.

![Shielding gas bottle with pressure and volumetric sensors](image)

Picture 3.8 Shielding gas bottle with pressure and volumetric sensors
3.5 Data Acquisition and Monitoring Tools

A National Instruments AT-M10-16E-10 12-bit resolution, 100 kS/s sampling rate data acquisition board was used to capture the data at 5 kHz. This board receives the analogue data from the signal-conditioning unit and converts it into digital data.

LabWindows® based monitoring software was used to present and store weld data. As an example, figure 3.9 shows a screen capture of transient data at 2500 samples per channel.

![Figure 3.9 Monitoring software based on LabWindows®](image)
3.6 Calibration of Equipment

To obtain accurate measurements from the welding equipment, a calibration routine must be carried out. Calibration of the data acquisition system requires several measurements taken and compared to predefined values. The sample signals and relative errors are illustrated in table 3.1. The signal and error ranges were determined from 20 data points.

Table 3.1 Signal calibration and error ranges

<table>
<thead>
<tr>
<th></th>
<th>Digital Gain</th>
<th>Range of Sensor</th>
<th>Tolerance</th>
<th>Voltage Offset from absolute zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage [V]</td>
<td>17.241</td>
<td>100</td>
<td>+/- 0.5 %</td>
<td>-0.0053</td>
</tr>
<tr>
<td>Current [A]</td>
<td>131.58</td>
<td>500</td>
<td>+/- 1 %</td>
<td>-0.0068</td>
</tr>
<tr>
<td>Wire feed rate [mm/s]</td>
<td>4.6083</td>
<td>25</td>
<td>+/- 0.7 %</td>
<td>0.0024</td>
</tr>
</tbody>
</table>
3.7 Measurements

In order to evaluate the applicability of standoff estimation for use in industry, commonly used settings for short circuit transfer and spray transfer were adopted. The measurements were taken on a flat plate with constant standoff set at 10, 15 or 20 mm, the actual standoff being measured by vernier calipers to 0.1 mm accuracy. The welding speed was set to 5 mm/s. In table 3.2 and table 3.3, a range of welding conditions were chosen such that stable welds could be produced in both short circuit transfer and spray transfer mode for 0.9 mm diameter wire. The voltage and the wire feed rate were changed in increment of 1 V and 20 in/min respectively. The parameter matrix provides a good indication of how the welding process reacts to parameter changes. The measurements were recorded in two sets with identical welding conditions, with the first set being used to identify the system behaviour and the second set being used to verify the standoff estimation algorithms. The welding conditions used in this thesis are representative of those used in industry. More details of the welding conditions used are attached in appendix (A).

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Voltage range [V]</th>
<th>Wire feed rate range [mm/s]</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>13 – 19</td>
<td>30 - 169</td>
<td>97 * 2</td>
</tr>
<tr>
<td>15</td>
<td>13 – 20</td>
<td>30 - 186</td>
<td>142 * 2</td>
</tr>
<tr>
<td>20</td>
<td>14 – 20</td>
<td>30 - 186</td>
<td>66 * 2</td>
</tr>
</tbody>
</table>
Table 3.3 Welding conditions for spray transfer measurements

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Voltage range [V]</th>
<th>Wire feed rate range [mm/s]</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>27 – 30</td>
<td>150 - 186</td>
<td>12</td>
</tr>
<tr>
<td>20</td>
<td>28 – 32</td>
<td>127 - 220</td>
<td>4</td>
</tr>
</tbody>
</table>
Chapter 4

Experiments and Results
In this chapter, the standoff estimation results are described. Short circuit transfer results are presented first, followed by spray transfer standoff estimates. For each transfer mode, the results of the theoretical models and empirical models are described in detail.

An example of Orszagh’s 10 mm standoff estimation results is shown in figure 4.1. On the y-axis, the estimated standoff is shown in mm. The total number of measurements is shown on the x-axis. The number of measurements obtained and used to estimate the standoff are different for the various standoff experiments because of the different number of experiments carried out for each condition, transfer mode and models. These are discussed in section 3.7. Each data point in figure 4.1 represents the estimated standoff, averaged over 10 seconds of data for that weld.

Figure 4.1 Example of standoff estimation graph
4.1 Theoretical models in short circuit transfer

In this section, theoretical models implemented in short circuit transfer mode are discussed. The conditions and assumptions are stated followed by the results. Halmoy’s and Orszagh’s models are the two theoretical models presented.

4.1.1 Halmoy’s model

As mentioned in chapter 3, Halmoy’s model has an upper heat content ($H_{Le}$) limit of 4 J/mm$^3$. Therefore, only data having a heat content of less than 4 J/mm$^3$ were taken for standoff estimation using Halmoy’s model, as shown in figure 4.2.

![Graph of $H_{Le}$ as a function of $f = \frac{Le \cdot j^2}{WFR}$](image)

Figure 4.2 Graph of $H_{Le}$ as a function of $f = \frac{Le \cdot j^2}{WFR}$ in short circuit transfer mode

This model relates the variable $Le \cdot j$ as a function of $j/WFR$. The results of the measurements are shown in figure 4.3, with the data represented as discrete points and
the fitted line representing the function used for the model. On initial examination, it appears reasonable to use a straight line fit for this model.

Figure 4.3 Graph of Le.j as a function of j/WFR

Figure 4.4 Standoff estimation in short circuit transfer using Halmoy’s model for 10 mm, 15 mm and 20 mm standoff
Since a limit of 4 J/mm\(^3\) exists for Halmoy’s model, the number of measurements used is slightly less than the total number of measurements taken in each standoff dataset (the total number of measurements in each standoff dataset can be found in section 3.7). The straight line fit produced the following coefficients: \(K_1 = 8.8426 \times 10^3\) A/mm and \(K_2 = -2.6519 \times 10^{-3}\) mm\(^2\)/s. Using these coefficients, the resulting standoffs estimated are shown in figure 4.4. The results can be summarised as follows:

10 mm standoff,

\[
\text{Mean of estimation} = 10.23 \text{ [mm]}, \quad \text{Standard deviation} = 1.05 \text{ [mm]}
\]

15 mm standoff,

\[
\text{Mean of estimation} = 14.50 \text{ [mm]}, \quad \text{Standard deviation} = 1.88 \text{ [mm]}
\]

20 mm standoff,

\[
\text{Mean of estimation} = 21.33 \text{ [mm]}, \quad \text{Standard deviation} = 2.38 \text{ [mm]}
\]

The mean of the standoff estimation is within 1.5 mm of the actual standoff for all 3 cases with a standard deviation of up to 2.4 mm. These results show that the model is not very accurate for the 20 mm standoff measurements. The 20 mm standoff measurements have a resistive heat content close to the 4 J/mm\(^3\) threshold, which most likely causes the model to be less accurate at this standoff. If the 20 mm standoff experiments are not taken into account, standoff estimation based on Halmoy’s model results in a mean estimation within 1 mm of the set standoff and a standard deviation of about 2 mm.
The large deviation in results can be explained by the fact that the complete short circuit cycle was captured in the sampled data. A complete short circuit cycle generally includes an arcing period and short circuiting period, see section 1.1.1. In short circuit transfer, standoff is approximately equal to the electrode extension when the electrode is in contact with the base material. During the arcing period, the standoff is actually equal to the length of wire extension, plus the electric arc length between the end of the electrode and weld pool. As stated in section 2.1.1, Halmoy’s model uses average values to estimates the electrode wire extension only. The arcing information in the sampled data, may therefore contribute to the inclusion of deviations found in standoff estimation.
4.1.2 Orszagh’s model

Orszagh’s model requires modelling of both the solid wire and liquid bridge during the minimum short-circuits. Table 4.1 shows data used to develop the model:

Table 4.1 Temperature and Resistivity Data for Solid Wire [39]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temp [°C]</th>
<th>Resistivity [μohm.mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact-tip (solid)</td>
<td>50</td>
<td>179</td>
</tr>
<tr>
<td>Curie point</td>
<td>750</td>
<td>1000</td>
</tr>
<tr>
<td>End of wire (molten)</td>
<td>1500</td>
<td>1180</td>
</tr>
</tbody>
</table>

Furthermore, a straight line interpolation provided the resistivity values in between the given temperatures. It was also assumed that the Curie point is located at approximately 80 % of the wire extension length from the contact-tip, independent of the standoff used for the measurement.

The following data was used to model the temperature and resistivity profile in the liquid bridge:

Table 4.2 Temperature and Resistivity Data for Liquid Bridge [39]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temp [°C]</th>
<th>Resistivity [μohm.mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of wire (Superheat)</td>
<td>2000</td>
<td>1300</td>
</tr>
<tr>
<td>Weld pool (molten)</td>
<td>2500</td>
<td>1400</td>
</tr>
</tbody>
</table>

Again, linear interpolation was applied between the given data points.
To simplify the calculation of the total resistance, it was furthermore assumed that the liquid bridge was cylindrical in shape. The results of the standoff estimation are shown in figure 4.5 and are summarised below:

![Standoff estimation using Orszagh's model](image)

Figure 4.5 Standoff estimation in short circuit transfer using Orszagh’s model for 10 mm, 15 mm and 20 mm standoff

10 mm standoff:

Mean of estimation = 9.79 [mm]  
Standard deviation = 0.77 [mm]

15 mm standoff,

Mean of estimation = 14.55 [mm]  
Standard deviation = 0.75 [mm]
20 mm standoff.

\[
\text{Mean of estimation} = 20.76 \text{ [mm]} \quad \text{Standard deviation} = 0.89 \text{ [mm]}
\]

The data show that the model developed by Orszagh results in a standoff estimation mean less than 1 mm and a standard deviation of also less than 1 mm. It can therefore be concluded that Orszagh's model results in more accurate estimations of standoff than Halmoy's model. An explanation for this is that the Orszagh model uses data that more directly relates to standoff that is the resistance during a short circuit, whilst Halmoy's model uses information on the complete short circuit cycle, thus being influenced by several other factors apart from standoff.
4.2 Experimental models in short circuit transfer

4.2.1 Kim & Na’s model

Kim & Na’s model is based on experimental data collected from measurements. Equation 2.12 is restated below:

\[ I = K_1 + K_2 V + K_3 \text{WFR} + K_4 L_{CTWD} + K_5 \bar{V} \cdot \text{WFR} + K_6 \text{WFR} \cdot L_{CTWD} + K_7 \bar{V} \cdot L_{CTWD} \]  \hspace{1cm} (4.1)

Using a least-square polynomial fit to the measured welding data (i.e. averaged welding voltage, current, wire feed rate and measured standoff); the coefficients \( K_i \) are calculated and summarised in table 4.3 below.

<table>
<thead>
<tr>
<th>Coefficient ( K_i )</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_1 )</td>
<td>-4.4081</td>
</tr>
<tr>
<td>( K_2 )</td>
<td>3.6945</td>
</tr>
<tr>
<td>( K_3 )</td>
<td>1.7922</td>
</tr>
<tr>
<td>( K_4 )</td>
<td>-2.3919</td>
</tr>
<tr>
<td>( K_5 )</td>
<td>-0.0356</td>
</tr>
<tr>
<td>( K_6 )</td>
<td>-0.0221</td>
</tr>
<tr>
<td>( K_7 )</td>
<td>0.1123</td>
</tr>
</tbody>
</table>

Recall from equation 2.16 that standoff can be expressed as:
Standoff estimation using Kim & Na’s model in short circuit transfer mode is illustrated in figure 4.6.

![Kim & Na model](image)

Figure 4.6 Standoff estimation in short circuit transfer mode using Kim & Na’s model for 10 mm, 15 mm and 20 mm standoff

Estimation results are summarised below:

10 mm standoff,

\[
\text{Mean of estimation} = 10.28 \text{ [mm]} \quad \text{Standard deviation} = 2.74 \text{ [mm]}
\]

15 mm standoff,

\[
\text{Mean of estimation} = 15.01 \text{ [mm]} \quad \text{Standard deviation} = 1.78 \text{ [mm]}
\]

20 mm standoff,
Mean of estimation = 20.15 [mm]  Standard deviation = 1.30 [mm]

The mean value of the standoff estimates has accuracy better than +/- 0.5 mm offset from the actual standoff. From the results illustrated, it can be seen that this model is less accurate for the 10 mm standoff measurements due to a standard deviation of 2.74 mm. With higher standoff, this trend seems to reduce magnitude of the peaks.

The inaccuracy of the result may be caused by the use of the complete short circuit cycle during data sampling. Kim & Na’s model predicts the average welding current over the complete short circuit cycle that contains weighted irrelevant information does not directly relate to the standoff during the short circuit. The fluctuation of the result decrease as the standoff increase, it is caused by the noise induced from the measured parameters. The noise is amplified mostly from the denominator and the magnitude is approximately inversely proportional to the standoff. Like Halmoy’s model, Kim & Na’s model utilises average voltage, current and wire feed rate to estimate standoff. These average values consist of both the arcing and short-circuiting information. However, the behaviour of the system varies significantly between these periods, resulting in less accurate estimates.
4.2.2 Carvalho’s model

Carvalho’s model replaces the average current in Kim & Na’s model with the short-circuit resistance. Recalling equation 2.17:

\[
R_{sc} = K_1 + K_2 \bar{V} + K_3 \bar{WFR} + K_4 L_{CTWD} + K_5 \bar{V} \cdot \bar{WFR} + K_6 \bar{WFR} \cdot L_{CTWD} + K_7 \bar{V} \cdot L_{CTWD}
\]

(4.3)

Using collected measurement data and a least-squares polynomial fit, the coefficients \( K_i \) were determined and are listed in table 4.4.

Table 4.4 Coefficients \( K_i \) of Carvalho’s model obtained in short circuit transfer mode

<table>
<thead>
<tr>
<th>Coefficient ( K_i )</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_1 )</td>
<td>(-1.40 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_2 )</td>
<td>(-0.10 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_3 )</td>
<td>(0.04 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_4 )</td>
<td>(0.81 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_5 )</td>
<td>(0.03 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_6 )</td>
<td>(-0.04 \times 10^{-3})</td>
</tr>
<tr>
<td>( K_7 )</td>
<td>(0.12 \times 10^{-3})</td>
</tr>
</tbody>
</table>

Recall from equation 2.21 that standoff can be expressed as:

\[
L_{CTWD} = \frac{R_{sc} - (K_1 + K_2 \bar{V} + K_3 \bar{WFR} + K_5 \bar{V} \cdot \bar{WFR})}{(K_4 + K_6 \bar{WFR} + K_7 \bar{V})}
\]

(4.4)
From which standoff estimates can be calculated and are shown in figure 4.7.

![Figure 4.7 Standoff estimation in short circuit transfer mode using Carvalho’s model](image)

Figure 4.7 Standoff estimation in short circuit transfer mode using Carvalho’s model for 10 mm, 15 mm and 20 mm standoff

Estimation results are summarised below:

10 mm standoff,

Mean of estimation = 10.11 [mm]  Standard deviation = 0.83 [mm]

15 mm standoff,

Mean of estimation = 14.81 [mm]  Standard deviation = 0.60 [mm]

20 mm standoff,

Mean of estimation = 20.12 [mm]  Standard deviation = 0.79 [mm]
Like Kim & Na's model, this model has accuracy better than +/- 0.5 mm and standard deviations within +/- 1 mm tolerance. It can therefore be concluded that Carvalho's model leads to more accurate standoff estimations than Kim & Na's model. This can be explained by the fact that Carvalho's model uses data based on the resistance during a short circuit, which more directly relates to standoff. On the other hand, Kim & Na's model uses information on the complete short circuit cycle (by taking average voltage, current, etc), which is influenced by other factors apart from standoff, such as the duration of short circuits and arcing period.
4.3 Theoretical models in spray transfer

In the following sections, 10 mm standoff measurements are omitted. The reason is that at such short standoffs, stable spray transfer is unsustainable using the existing experimental set-up. The author increased the standoff to 25 mm, but the welds deposited were also unstable. Therefore, 15 and 20 mm standoffs were the only measurements used for standoff estimation in spray transfer.

4.3.1 Halmoy’s model

Halmoy [38] stated that his model is valid only when the resistive heat content in the wire extension \( H_{Le} \) is less than 4 J/mm\(^3\) or for low current processes. The measurements taken during spray transfer are shown in figure 4.8. As can be seen, most of the data points have a heat content \( H_{Le} \) greater than 4 J/mm\(^3\).

![Plot of resistive heat content \( H_{Le} \) as function of \( f = Le j^2/WFR \)](image)

Figure 4.8 Graph of \( H_{Le} \) as a function of \( f = Le j^2/WFR \)
In figure 4.9, the relationship of $\text{Le}_j$ as a function of $j/WFR$ was plotted. The data in this figure was restricted to heat contents ($H_{le}$) less than 4 J/mm$^3$ for observation. A line of best fit was plotted and demonstrated the relationship of $\text{Le}_j$ as a function of $j/WFR$. One would expect to obtain a straight line fit crossing the x-axis, similar to the result obtained in short circuit transfer mode, refer to figure 4.3. Figure 4.9 demonstrates that the relationship is unable to be defined for this transfer mode. It can be concluded that Halmoy's model cannot be implemented in spray transfer mode because the data obtained is inappropriate for the current experimental set-up.
4.4 Experimental models in spray transfer mode

4.4.1 Leneswich’s model

Leneswich’s model requires determination of a resistive heating coefficient and anode heating coefficient prior to implementation. By experiment, Leneswich established the relationships for resistive heating as a function of electrode diameter, and anode heating rate as a function of welding current. These relationships from Leneswich’s measurements are reproduced in figure 4.10 and 4.11, respectively. In figure 4.10, the resistive heating coefficient and electrode diameter are plotted as a linear log-log relationships. This implies that the resistive heating coefficient is constant with electrode diameter of the same material. Leneswich measured anode heating or the melting rate of the anode with a range of welding currents, as shown in figure 4.11. The anode heating rate increases almost proportionally to the increase in welding current. A line of best fit produces a linear relationship; with the anode heating coefficient determined by the line’s gradient.
Figure 4.10 Graph of resistive heating coefficient as a function of electrode diameter in spray transfer mode [36]

Figure 4.11 Graph of anode heating (melting rate of anode) as a function of welding current in spray transfer mode [36]
<table>
<thead>
<tr>
<th>Coefficient $K_i$</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>0.3824</td>
</tr>
<tr>
<td>$K_2$</td>
<td>0.0152</td>
</tr>
<tr>
<td>$K_3$</td>
<td>0.0037</td>
</tr>
</tbody>
</table>

In table 4.5 above, coefficients $K_i$ of equation 2.11 were obtained after interpolation using the experimental values from figure 4.10 and 4.11. Standoff estimation of Leneshwich’s model in spray transfer mode is shown in figure 4.12. The number of measurements obtained is considerably less than those during short circuit transfer, due to the limitations of the equipment used in the experimental set-up.

Figure 4.12 Standoff estimation in spray transfer mode using Leneshwich’s model for 15 mm and 20 mm standoff.
Estimation results are summarised below:

15 mm standoff,

Mean of estimation = 15.00 [mm]  Standard deviation = 0.72 [mm]

20 mm standoff,

Mean of estimation = 20.02 [mm]  Standard deviation = 0.78 [mm]

The mean value of standoff estimates has accuracy less than +/- 0.1 mm from the actual standoff. The standard deviations were less than +/- 0.8 mm.

From the results shown above, it can be concluded that this model has a good accuracy for both the 15 and 20 mm standoff measurements.
4.4.2 Kim & Na's model

As in the short circuit transfer experiments, the coefficient $K_i$ of equation 2.12 were determined using a least-squares polynomial fit. These are summarised in table 4.7 below.

Table 4.7 Coefficients $K_i$ for Kim & Na's model in spray transfer mode

<table>
<thead>
<tr>
<th>Coefficient $K_i$</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>-337.6285</td>
</tr>
<tr>
<td>$K_2$</td>
<td>16.2634</td>
</tr>
<tr>
<td>$K_3$</td>
<td>3.4323</td>
</tr>
<tr>
<td>$K_4$</td>
<td>-4.3534</td>
</tr>
<tr>
<td>$K_5$</td>
<td>-0.0800</td>
</tr>
<tr>
<td>$K_6$</td>
<td>-0.0252</td>
</tr>
<tr>
<td>$K_7$</td>
<td>0.1071</td>
</tr>
</tbody>
</table>

Recall from equation 2.16 that standoff can be expressed as:

$$L_{CTWD} = \frac{L - (K_1 + K_2 \bar{V} + K_3 \bar{WFR} + K_4 \bar{V} \cdot \bar{WFR})}{(K_4 + K_6 \bar{WFR} + K_7 \bar{V})}$$

(4.5)

Substituting the coefficients $K_i$ into equation 4.5, standoff estimations using Kim & Na's model in spray transfer mode are shown in figure 4.13.
Figure 4.13 Standoff estimation in spray transfer mode using Kim & Na’s model for
15 mm and 20 mm standoff

Estimation results are summarised below:

15 mm standoff,
Mean of estimation = 15.00 [mm]  Standard deviation = 0.76 [mm]

20 mm standoff,
Mean of estimation = 20.00 [mm]  Standard deviation = 0.54 [mm]

The mean value of standoff estimates has an accuracy of better than +/- 0.05 mm. The standard deviation was within +/- 0.8 mm error range.

These results illustrate that this model is more accurate for both 15 and 20 mm standoff measurements than Leneswich’s model. A possible explanation is that Kim & Na’s model used a larger number (7 instead of 3) of different relationships/correlation between welding parameters, which more closely relates to standoff estimation.
4.4.3 Carvalho’s model

Similar to short circuit transfer experiments, the coefficients $K_i$ of equation 4.3 can be calculated using a least-squares polynomial fit. These coefficients are summarised in table 4.8.

Table 4.8 Coefficients $K_i$ for Carvalho’s model in spray transfer mode

<table>
<thead>
<tr>
<th>(K) Coefficient</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>$237.10 \times 10^3$</td>
</tr>
<tr>
<td>$K_2$</td>
<td>$-1.23 \times 10^3$</td>
</tr>
<tr>
<td>$K_3$</td>
<td>$-0.71 \times 10^3$</td>
</tr>
<tr>
<td>$K_4$</td>
<td>$-5.82 \times 10^3$</td>
</tr>
<tr>
<td>$K_5$</td>
<td>$-0.04 \times 10^3$</td>
</tr>
<tr>
<td>$K_6$</td>
<td>$0.03 \times 10^3$</td>
</tr>
<tr>
<td>$K_7$</td>
<td>$0.23 \times 10^3$</td>
</tr>
</tbody>
</table>

Recall from equation 2.21 that standoff can be expressed as;

$$L_{CTWD} = \frac{R_{sc} - (K_1 + K_2 \bar{V} + K_3 \bar{WFR} + K_5 \bar{V} \cdot \bar{WFR})}{(K_4 + K_6 \bar{WFR} + K_7 \bar{V})}$$  \hspace{1cm} (4.6)

Substituting the coefficients $K_i$ into equation 4.6, standoff estimation using Carvalho’s model in spray transfer mode can be determined and are illustrated in figure 4.14.
Figure 4.14 Standoff estimation in spray transfer mode using Carvalho’s model for 15 mm and 20 mm standoff

The estimation results are summarised below:

15 mm standoff,

Mean of estimation = 15.00 [mm]    Standard deviation = 0.89 [mm]

20 mm standoff,

Mean of estimation = 19.99 [mm]    Standard deviation = 0.83 [mm]

As with Kim & Na’s model, this model has accuracy better than 0.5 mm from the pre-defined standoff. The standard deviations are within +/- 0.9 mm but are higher than both Leneswich’s and Kim & Na’s model. This can be explained by the fact that Carvalho’s model uses a variable (i.e. minimum resistance), which does not directly relate to standoff in spray transfer mode.
4.5 Conclusion of standoff estimation results

4.5.1 Short circuit transfer mode

Halmoy, Orzsagh, Kim & Na and Carvalho’s methods were implemented and evaluated for short circuit transfer mode standoff estimation. The results are summarised in table 4.9.

Table 4.9 Summary of standoff estimation in short circuit transfer mode

<table>
<thead>
<tr>
<th>Models</th>
<th>Halmoy (Theoretical)</th>
<th>Orzsagh (Theoretical)</th>
<th>Kim &amp; Na (Empirical)</th>
<th>Carvalho (Empirical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>Standoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 [mm]</td>
<td>0.23</td>
<td>1.05</td>
<td>-0.21</td>
<td>0.77</td>
</tr>
<tr>
<td>15 [mm]</td>
<td>-0.50</td>
<td>1.88</td>
<td>-0.45</td>
<td>0.75</td>
</tr>
<tr>
<td>20 [mm]</td>
<td>1.33</td>
<td>2.38</td>
<td>0.76</td>
<td>0.89</td>
</tr>
</tbody>
</table>

As can be seen, the estimation mean errors from empirical models are generally better than those from theoretical models. This was expected as empirical models are derived with measurements from the experimental set-up. The empirical coefficients are determined from measured data, which have been calibrated to the experimental set-up. Another important observation is that Orzsagh’s and Carvalho’s model have better standard deviations. They both have a tolerance well within +/- 1 mm compared to Halmoy’s and Kim & Na’s model. This can be explained by the use of the minimum short circuit resistance during the short-circuiting stage, which is directly related to standoff and is less influenced by the arcing period. This is in contrast to
Halmoy's and Kim & Na's method, which uses average values. Such values include information from the complete short circuit cycle, which may also contain irrelevant information that does not relate directly to standoff.
4.5.2 Spray transfer mode

In spray transfer mode, the theoretical models of Halmoy and Orszagh’s methods could not be evaluated due to their assumptions. Halmoy’s method is limited to a heat content of 4 [J/mm³], whereas most of the spray transfer measurements obtained had heat contents over this limit (refer to chapter 4.3.1). Orszagh’s method is specifically derived for short circuit transfer, so it is obviously not included in the evaluation. The empirical models of Leneswich, Kim & Na and Carvalho, were implemented and evaluated. The results are summarised in the following table.

Table 4.10 Summary of standoff estimation in spray transfer mode

<table>
<thead>
<tr>
<th>Standoff</th>
<th>Leneswich</th>
<th>Kim &amp; Na</th>
<th>Carvalho</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
<td>Mean Error [mm]</td>
</tr>
<tr>
<td>15[mm]</td>
<td>0.00</td>
<td>0.72</td>
<td>0.00</td>
</tr>
<tr>
<td>20[mm]</td>
<td>0.02</td>
<td>0.78</td>
<td>0.00</td>
</tr>
</tbody>
</table>

From the results illustrated in table 4.10, it can be seen that all three methods accurately predict the mean standoff. In terms of standard deviation, Carvalho’s model has greater spread than the others; this can be expected due to the use of the minimum resistance, which does not specifically relate to spray transfer. As there is always an electric arc, the wire electrode never makes contact with the base metal in spray transfer, where as the minimum resistance is determined to be the resistance during short-circuiting in short circuit transfer. Kim & Na’s model demonstrated slightly better results than Leneswich’s model for 20 mm standoff. This was expected.
as Kim & Na's model has accounted for certain, undefined complex relationships between welding parameters. For example, it includes welding voltage and the combination of welding voltage with other parameters, thus resulting in a model that describes the system and the process more accurately.
4.5.3 Discussion

As a result of the preceding investigation, it was suggested by the author that a number of the standoff estimation algorithms could be modified to better reflect the properties of the process. The standoff estimation algorithms for which modification was suggested were Halmoy's [38], Kim & Na's [40] and Carvalho's [41] methods. Orzsagh's [39] method can be omitted as it already reflects the physics of the process to a large degree.

The modification of each method will be discussed in detail in the next chapter. The methods were evaluated in both short-circuit and spray transfer mode and the results are presented.
Chapter 5

*Modified Models*
5.1 Modified models in short circuit transfer

In this chapter, the modification performed with original model to implement in short circuit transfer is presented. As in the previous chapter, a theoretical model will be discussed first followed by empirical models. For the theoretical model, Halmoy's model will be presented, whilst Kim & Na and Carvalho's model will be presented for the empirical models.

5.1.1 Halmoy's model

In the previous chapter, Halmoy's method demonstrated a relationship between $L_e \cdot j$ and $j/v$ with a linear fit. However, improvements over a straight line fit could be made; refer to figure 4.3. It seems to the author that a quadratic polynomial fit would be more appropriate of the form:

$$Le \cdot j = \left( \frac{j}{WFR} + K \right)^2$$

(5.1)

By expanding and rearranging equation 5.1, an expression for standoff can be approximated by the following equation.

$$Le = K_1 \frac{1}{j} + K_2 \frac{1}{WFR} + K_3 \frac{j}{WFR^2} \quad [\text{mm}]$$

(5.2)

Where
K_i = Empirical constants (where i = 1, 2, 3)
Le = Length of wire extension [mm]
\( \bar{j} \) = Average current density [A/mm²]
WFR = Average wire feed rate [mm/s]

The results of this modification are shown in figure 5.1, with the data represented as points and the curved line representing the function used for this model. The linear function from section 4.1.1 is overlaid in the figure for comparison. From this figure, it seems reasonable to use a quadratic function for this model.

**Figure 5.1** Graph of Le \( j \) as a function of \( j/WFR \) with quadratic and linear fit
Figure 5.2 Standoff estimation in short circuit transfer mode using modified Halmoy’s model for 10 mm, 15 mm and 20 mm standoff

The quadratic polynomial fit produced the following coefficients:

\[ K_1 = 13.244 \times 10^3 \, [\text{A/mm}] \]
\[ K_2 = -6.278 \times 10^3 \, [\text{mm}^3/\text{As}] \]
\[ K_3 = 0.738 \times 10^3 \, [(\text{mm}^3/\text{As})^2] \]

Using these coefficients, the resulting estimated standoffs are illustrated in figure 5.2. The results can be summarised as follows:

10 mm standoff,
Mean of estimation = 10.30, Standard deviation = 0.98 [mm]

15 mm standoff,
Mean of estimation = 14.44, Standard deviation = 1.77 [mm]
20 mm standoff,

\[
\text{Mean of estimation} = 21.34, \quad \text{Standard deviation} = 2.23 \text{ [mm]}
\]

The mean of the standoff estimation is within 1.4 mm of the actual standoff and a standard deviation of up to 2.3 mm was obtained.

Table 5.1 Results of original and modified Halmoy’s method

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Halmoy’s original method</th>
<th>Halmoy’s modified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>10</td>
<td>0.23</td>
<td>1.05</td>
</tr>
<tr>
<td>15</td>
<td>-0.50</td>
<td>1.88</td>
</tr>
<tr>
<td>20</td>
<td>1.33</td>
<td>2.38</td>
</tr>
</tbody>
</table>

It can be concluded that the improvements of the modified Halmoy’s model are limited. The above results show that neither Halmoy’s model, nor the modified models are very accurate for the 20 mm standoff measurements. Similar characteristics exist at a resistive heat content close to the 4 [J/mm³] threshold. If the 20 mm standoff experiments are not taken into account, a standoff estimation in short circuit transfer based on the modified Halmoy’s model results in a mean within 1 mm of the set standoff and a standard deviation of approximately 1.8 mm.
5.1.2 Kim & Na’s model

Since Kim & Na’s model is based on the empirical coefficients from measurements and relationships between welding parameters, it can be expected that the more the relationships reflect the structure of the process, the more accurate the standoff estimation will be therefore, the author suggested redeveloping the parameter relationships. The relationships between welding average current and voltage, as well as wire feed rate and current are illustrated in the following figures 5.3, 5.4 and 5.5.

\[
I \propto C_1 + C_2 V
\]  

Figure 5.3 Graph of average voltage vs. average current

Figure 5.3 illustrates the relationships between voltage and current for various standoffs. The voltage shows a decline with an increase in current (the fitted lines have identical voltage settings). It can be observed that the three standoff data sets have similar patterns and overlap each other.

The voltage and current relationships can therefore be expressed as:

\[
I \propto C_1 + C_2 V
\]  

(5.3)
Where

\[ C_i = \text{Constants (for } i = 1, 2) \]

This relationship is included in the modified model.

![Plot of Current vs. WFR](image)

**Figure 5.4 Graph of average wire feed rate vs. average current**

Figure 5.4 shows that relationships between current, wire feed rate and standoff can be established. From the figure, welding current and wire feed rate can be approximated in the following relationship:

\[ \overline{I} \propto \sqrt{\text{WFR}} \]

(5.4)

However, figure 5.5 plots wire feed rate against current² to determine a linear relationship.
The relationship between wire feed rate and current becomes:

$$\overline{WFR} = (c_1 + c_2 L_{CTWD}) I^2$$  \tag{5.5}

Where

$c_i = \text{Constants (for } i = 1, 2)$

Rearranging formula 5.5,

$$\frac{1}{\sqrt{\overline{WFR}}} = \frac{1}{\sqrt{(c_1 + c_2 L_{CTWD})}}$$

or

$$\frac{1}{\sqrt{\overline{WFR}}} = \frac{1}{\sqrt{c_1}} \left( 1 + \frac{c_2 L_{CTWD}}{c_1} \right)^{-\frac{1}{2}}$$  \tag{5.6}

By using the binomial series we now obtain,
\[ f(L_{CTWD}) = \frac{1}{\sqrt{WFR}} = \frac{1}{\sqrt{c_1}} \sum_{n=0}^{\infty} \left( \frac{-1}{2} \right) \binom{2}{2} \left( \frac{c_2}{c_1} L_{CTWD} \right)^n \] \quad (5.7)

Since the binomial coefficient in the series equals:

\[
\frac{(-1/2)(-3/2)(-5/2)\cdots(-1)}{n!} = (-1)^n \left( \frac{2n-1}{2} \right)
\]

Equation 5.7 becomes:

\[
f(L_{CTWD}) = \sum_{n=0}^{\infty} \frac{(-1)^n (2n-1)(c_2)^n}{2n+1} \cdot L^n \]

or

\[
f(L_{CTWD}) = -\frac{1}{2(c_1)^{1/2}} - \frac{c_2}{2(c_1)^{3/2}} L_{CTWD} + \frac{3(c_2)^2}{2(c_1)^{5/2}} L_{CTWD}^2 + \cdots
\]

Rearranging and ignore the higher order terms:

\[
\bar{I} \propto a_0 \sqrt{WFR} + a_0 \sqrt{WFR} \cdot L_{CTWD} \quad (5.9)
\]

Where

\[ a_0 = \text{Constant} \]

Therefore, combining equation 5.3 and 5.9, Kim & Na’s model becomes:

\[ \bar{I} = K_1 + K_2 \bar{V} + K_3 \sqrt{WFR} + K_4 \cdot L_{CTWD} \sqrt{WFR} \quad (5.10) \]

After rearranging the equation becomes:

\[ L_{CTWD} = \frac{\bar{I} - (K_1 + K_2 \bar{V} + K_3 \sqrt{WFR})}{K_4 \sqrt{WFR}} \quad (5.11) \]
Using the measurement data and applying a least-squares polynomial fit to expression 5.10, the coefficients $K_i$ were determined and are summarised in table 5.2.

Table 5.2 Coefficients $K_i$ of Kim & Na’s modified model in spray transfer mode

<table>
<thead>
<tr>
<th>(K) Coefficient</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>-65.3075</td>
</tr>
<tr>
<td>$K_2$</td>
<td>1.0063</td>
</tr>
<tr>
<td>$K_3$</td>
<td>23.3688</td>
</tr>
<tr>
<td>$K_4$</td>
<td>-0.3077</td>
</tr>
</tbody>
</table>

The results of the standoff estimation in short circuit transfer mode are shown in figure 5.6.

Figure 5.6 Standoff estimation in short circuit transfer mode using the modified form of Kim & Na’s model for 10 mm, 15 mm and 20 mm standoff
Estimation results are summarised below:

10 mm standoff,

Mean of estimation = 10.27 [mm]  Standard deviation = 1.27 [mm]

15 mm standoff,

Mean of estimation = 14.91 [mm]  Standard deviation = 0.76 [mm]

20 mm standoff,

Mean of estimation = 19.85 [mm]  Standard deviation = 0.80 [mm]

Table 5.3 Results of original and modified Kim & Na’s method

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Kim &amp; Na’s original method</th>
<th>Kim &amp; Na’s modified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>10</td>
<td>0.28</td>
<td>2.74</td>
</tr>
<tr>
<td>15</td>
<td>0.01</td>
<td>1.78</td>
</tr>
<tr>
<td>20</td>
<td>0.15</td>
<td>1.30</td>
</tr>
</tbody>
</table>

The mean value has an accuracy of better than +/- 0.3 mm from the actual standoff. The standard deviation was within +/- 1.3 mm range.

From the results, it can be concluded that the accuracy of the modified model is similar to the original model (i.e. within +/- 1 mm, which is one of the requirements stipulated for a successful standoff method (see section 1.4)). The standard deviation has dramatically decreased for all three cases namely 10, 15 and 20 mm. The results
also indicate that an improvement is achieved by the modification because it uses fewer coefficients compared to the original model.

These results may also be related to physical theories. Restating the relationship between the welding current and the wire feed rate as a square root in Kim & Na’s modified model gives:

\[ I \propto a_0\sqrt{WFR} + a_0\sqrt{WFR} \cdot L_{CTWD} \]  \quad (5.12)

Similar relationships for the first term in equation 5.12 can be derived from the balance of velocity vectors at the end of the electrode wire. Generally, it can be stated that, when material is constantly transferred from the end of the wire to the base metal with a constant standoff:

\[ MR \propto WFR \]  \quad (5.13)

Considering the melting rate is due to resistive heating,

\[ MR = K \cdot L_e \cdot I^2 \]  \quad (5.14)

Since the wire extension \( L_e \) does not vary significantly and therefore may be assumed to be constant, substituting equation 5.13 into 5.14 and then rearranging, the following equation is obtained:

\[ MR \propto WFR = K \cdot L_e \cdot I^2 \]

\[ WFR = K \cdot I^2 \]

\[ I \propto \sqrt{WFR} \]  \quad (5.15)

Equation 5.15 is identical to the first term in equation 5.12, which is derived from experimental data. However, the second term cannot be directly related to any physical theory.
5.1.3 Carvalho's model

Short circuit resistance is one of the important parameters in Carvalho's method. The relationship between short circuit resistance, standoff and wire feed rate was established and is shown in figures 5.7, 5.8 and 5.9.

![Figure 5.7 Graph of voltage vs. short circuit resistance](image)

Figure 5.7 showed the relationship plot between short circuit resistances and welding voltage. The short circuit resistance increases with an increase of voltage. Therefore, the voltage and short circuit resistance relations can be expressed as:

\[
\overline{R_{sc}} \propto C_1 + C_2 \overline{V} \tag{5.16}
\]

Where

\[C_i = \text{Constants (for } i = 1, 2)\]
In figure 5.8, both a linear and a quadratic polynomial fit were produced. The relationship of minimum short circuit resistance and wire feed rate is better approximated using a square root proportional dependence.
Following the previous discussion in section 5.1.2, we would expect equation 5.17 to relate to physical theory. From equation 5.15, substituting I with V/R from Ohm’s law gives:

\[ I \propto \sqrt{WFR} \]

\[ V \propto \sqrt{WFR} \]

Assuming voltage is constant to demonstrate the relationships:

\[ R \propto \frac{1}{\sqrt{WFR}} \]

(5.18)

As can be seen, equation 5.17 implies resistance increases with wire feed rate. It contradicts 5.18, which implies that resistance decreases with increases in wire feed rate derived from physical theory. An investigation was undertaken regarding power consumed by unit material with wire feed rate, as shown in figure 5.9. The power consumed decreases with increasing wire feed rate, which implies more resistance in the weld pool during material transfer. The possible reason is that when wire feed rate increases, more material builds up. As the heat increases on top of the weld bead, the temperature becomes higher and therefore increases the short circuit resistance.

From figure 5.8 we can derive that the distance between each fitted line is more or less proportional to the difference in standoff:

\[ R_{sc} \propto L_{CTWD} \]

(5.19)
Therefore, combining the relationships of different parameters, the modified Carvalho's model becomes:

\[ \overline{R}_{sc} = K_1 + K_2 \sqrt{WFR} + K_3 L_{CTWD} + K_4 V \]  \hspace{1cm} (5.20)

Rearranging equation 5.20, a standoff expression is obtained:

\[ L_{CTWD} = \frac{\overline{R}_{sc} - (K_1 + K_2 \sqrt{WFR} + K_4 V)}{K_3} \]  \hspace{1cm} (5.21)

The \( K_i \) coefficients of the modified Carvalho model are listed in table 5.4.

Table 5.4 Coefficients \( K_i \) for the modified form of Carvalho's model in short circuit transfer mode

<table>
<thead>
<tr>
<th>( (K) ) Coefficient</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_1 )</td>
<td>-2.5440 \times 10^{-3}</td>
</tr>
<tr>
<td>( K_2 )</td>
<td>-0.0454 \times 10^{-3}</td>
</tr>
<tr>
<td>( K_3 )</td>
<td>0.8682 \times 10^{-3}</td>
</tr>
<tr>
<td>( K_4 )</td>
<td>1.3723 \times 10^{-3}</td>
</tr>
</tbody>
</table>

The results of standoff estimation for the modified Carvalho model in short circuit transfer mode are shown in figure 5.10.
Figure 5.10 Standoff estimation in short circuit transfer mode using the modified form of Carvalho’s model for 10 mm, 15 mm and 20 mm standoff.

Standoff estimation results are summarised below:

10 mm standoff,

Mean of estimation = 10.32 [mm]  Standard deviation = 0.68 [mm]

15 mm standoff,

Mean of estimation = 14.44 [mm]  Standard deviation = 0.61 [mm]

20 mm standoff,

Mean of estimation = 20.32 [mm]  Standard deviation = 0.86 [mm]
Table 5.5 Results of original and modified forms of Carvalho's method

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Carvalho’s original method</th>
<th>Carvalho’s modified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>10</td>
<td>0.11</td>
<td>0.83</td>
</tr>
<tr>
<td>15</td>
<td>-0.19</td>
<td>0.60</td>
</tr>
<tr>
<td>20</td>
<td>0.12</td>
<td>0.79</td>
</tr>
</tbody>
</table>

The modified model has accuracy within +/- 0.6 mm from the predefined standoff, and standard deviations are bounded by +/- 0.9 mm tolerance. Although the improvement is minor, with less than 0.1 mm reduction in standard deviation, the modified model is significantly simpler than the original model, using only 4 instead of 7 coefficients.

A new relationship between short-circuit resistance and wire feed rate was established from the data as shown in equation 5.17, recalling,

\[
\overline{R_{sc}} \propto \sqrt{WFR}
\]  

(5.22)

Equation 5.22 reflects the welding system behaviour better; and as such, it therefore produces better standoff estimation.
5.2 Modified models in spray transfer

5.2.1 Kim & Na’s model

Similar to the strategy employed in short circuit transfer, the structure of the model could be redeveloped to better reflect the process in spray transfer. The relationships between welding parameters in spray transfer mode are illustrated in figures 5.11 and 5.12, showing the dependence of current versus voltage, and wire feed rate versus current respectively.

![Voltage vs. Current](image)

**Figure 5.11 Graph of voltage vs. current in spray transfer mode**

Again, similar relationships between voltage and current can be observed. Welding voltage seems to be more directly related to current than to standoff. Since Kim & Na’s model predicts welding current, coefficients similar to those found during short circuit transfer can be used.

The voltage and current relationships can be expressed as follows:

\[ I \propto V \]  \hspace{1cm} (5.23)
From the plot of figure 5.12 and 5.13, trends similar to short circuit transfer can be observed. Therefore, a similar modified model can be used in spray transfer mode.
implementation. The welding current is approximately proportional to the square root of wire feed rate.

\[
I \propto a_0 \sqrt{\text{WFR}} + a_0 \sqrt{\text{WFR} \cdot L_{\text{CTWD}}}
\]  
(5.24)

Where

\[a_0 = \text{Constant}\]

Therefore, Kim & Na's modified model for spray transfer becomes:

\[
I = K_1 + K_2 \bar{V} + K_3 \sqrt{\text{WFR}} + K_4 \cdot L_{\text{CTWD}} \sqrt{\text{WFR}}
\]  
(5.25)

After rearranging:

\[
L_{\text{CTWD}} = \frac{I - (K_1 + K_2 \bar{V} + K_3 \sqrt{\text{WFR}})}{K_4 \sqrt{\text{WFR}}}
\]  
(5.26)

By fitting a least-squares polynomial to measurement data, \(K_i\) coefficients are determined and are summarised in table 5.6.

Table 5.6 Coefficients \(K_i\) for Kim & Na's model in spray transfer mode

<table>
<thead>
<tr>
<th>(K) Coefficient</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_1)</td>
<td>-184.6493</td>
</tr>
<tr>
<td>(K_2)</td>
<td>4.9101</td>
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<tr>
<td>(K_3)</td>
<td>28.2914</td>
</tr>
<tr>
<td>(K_4)</td>
<td>-0.4386</td>
</tr>
</tbody>
</table>
The standoff estimation of Kim & Na’s modified model in spray transfer mode is shown in figure 5.14.

![Figure 5.14 Standoff estimation in spray transfer mode using Kim & Na’s modified model for 15 mm and 20 mm standoff](image)

The results of standoff estimation are summarised below:

15 mm standoff,

Mean of estimation = 15.01 [mm]  Standard deviation = 0.83 [mm]

20 mm standoff,

Mean of estimation = 20.00 [mm]  Standard deviation = 0.50 [mm]
Table 5.7 Results of Kim & Na’s original and modified methods in spray transfer mode

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Kim &amp; Na’s original method</th>
<th>Kim &amp; Na’s modified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>15</td>
<td>0.00</td>
<td>0.76</td>
</tr>
<tr>
<td>20</td>
<td>0.00</td>
<td>0.54</td>
</tr>
</tbody>
</table>

A standoff estimation with better than +/- 0.1 mm accuracy was obtained. The standard deviation lies within +/- 0.9 mm error range.

These results demonstrated that the Kim & Na’s modified model has minor improvements in standoff estimations in spray transfer mode. Furthermore, it uses fewer coefficients, reducing them from 7 to 4.
5.2.2 Carvalho’s model

Carvalho applied his model to spray transfer with different polynomial coefficients. In spray transfer, it must be noted that there is no short circuit resistance. Carvalho’s model used the minimum resistance in spray transfer. Voltage, minimum resistance, and wire feed rate are related as shown in the following figures 5.15 and 5.16. Figure 5.15 shows an uncertain relationship between voltage and minimum resistance, or with respect to standoff. Therefore, recall the minimum resistance and voltage relationship from section 5.1.3 and rewriting it in the following form:

\[ R_{\text{min}} \propto C_i + C_j \sqrt{V} \]  

(5.27)

where

\[ C_i = \text{Constants (for } i = 1, 2) \]

Figure 5.15 Graph of minimum resistance vs. voltage in spray transfer mode
Chapter 5

Figure 5.16 Graph of minimum resistance vs. wire feed rate in spray transfer mode

In figure 5.16, the minimum resistance is plotted against wire feed rates. Minimum resistance seems to increase with standoff.

\[ R_{\text{min}} \propto L_{\text{CTWD}} \]  \hspace{2cm} (5.28)

The data shows that minimum resistance and wire feed rate can be related in the following form, which is similar to equation 5.17:

\[ R_{\text{min}} \propto \sqrt{\text{WFR}} \]  \hspace{2cm} (5.29)

Therefore, the relationship of the new parameters for Carvalho’s modified model is established below. It is similar to equation 5.20:

\[ R_{\text{min}} = K_1 + K_2 \sqrt{\text{WFR}} + K_3 L_{\text{CTWD}} + K_4 V \]  \hspace{2cm} (5.30)

Rearranging equation 5.30 produces the following standoff expression that follows:
Therefore, a newly developed strategy is implemented for spray transfer mode. Coefficients $K_i$ of this model are listed in Table 5.8.

Table 5.8 Coefficients $K_i$ for Carvalho’s modified model in spray transfer mode

<table>
<thead>
<tr>
<th>$K_i$ Coefficient</th>
<th>Value of polynomial fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>151.6427 * 10^{-3}</td>
</tr>
<tr>
<td>$K_2$</td>
<td>-9.3585 * 10^{-3}</td>
</tr>
<tr>
<td>$K_3$</td>
<td>3.1261 * 10^{-3}</td>
</tr>
<tr>
<td>$K_4$</td>
<td>1.5831 * 10^{-3}</td>
</tr>
</tbody>
</table>

Standoff estimation plots are shown in Figure 5.17.

Figure 5.17 Standoff estimation in spray transfer mode using Carvalho’s modified model for 15 mm and 20 mm standoff
Estimation results are summarised below:

15 mm standoff,

Mean of estimation = 15.00 [mm]  Standard deviation = 1.02 [mm]

20 mm standoff,

Mean of estimation = 20.00 [mm]  Standard deviation = 0.91 [mm]

Table 5.9 Results of Carvalho's original and modified method

<table>
<thead>
<tr>
<th>Standoff [mm]</th>
<th>Carvalho's original method</th>
<th>Carvalho's modified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Error [mm]</td>
<td>Std [mm]</td>
</tr>
<tr>
<td>15</td>
<td>0.00</td>
<td>0.89</td>
</tr>
<tr>
<td>20</td>
<td>-0.01</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Similar to the modification of Kim & Na's model, this model produced an accuracy bounded within +/- 0.01 mm. However, the tolerance slightly increased up to +/- 1.10 mm compared to the original model's +/- 0.9 mm limits. It can be concluded that the modification applied to Carvalho's model made no performance improvement for spray transfer but it was still within the required specification limit and used less coefficients (4 instead of 7) than the original model.
5.3 Conclusions resulting from the modified models

Halmoy’s, Kim & Na’s and Carvalho’s models were modified and evaluated for short circuit transfer of GMAW. In the case of Halmoy’s model, there was an improvement of up to 0.15 mm in standard deviation. However, it exceeded the +/- 1 mm accuracy requirement stated in section 1.4 by up to 1.0 mm. Kim & Na’s new model structure provided an excellent standoff estimation with fewer coefficients (4 instead of 7 coefficients) in both short circuit transfer and spray transfer mode. The results were illustrated in table 5.3 and showed an optimum reduction in standard deviation in short circuit transfer of up to 60%. The modified form of Carvalho’s model achieved a limited 0.1 mm improvement on the standard deviation in short circuit transfer. However, the standard deviation increased 0.1 mm in spray transfer mode, but the results were within the 1 mm requirement. It has similar accuracy to the original model whilst using fewer coefficients, a reduction from 7 to 4. It can therefore be concluded that the modification of Kim & Na’s model has great improvement in short circuit transfer, but no significance for Carvalho’s model in short circuit transfer. Both Kim & Na’s and Carvalho’s modified models showed no significant performance improvements in spray transfer mode. However, similar accuracy was achieved with fewer coefficients in the modified form for both Kim & Na’s and Carvalho’s models. This would significantly reduce the computational effort, important for online estimation of standoff. From Kim & Na’s modified model, it could be concluded that the relationship (equation 5.32) between the welding current and the square root of wire feed rate better reflects the process.

\[ \bar{I} \propto a_0 \sqrt{WFR} + a_0 \sqrt{WFR} \cdot L_{CIWD} \]  

(5.32)
A similar result was derived from the modified form of Carvalho’s model, the data showing that the short-circuit resistance is proportional to the square root of wire feed rate as described by equation 5.33.

\[ R_{sc} \propto \sqrt{WFR} \]  

(5.33)

This new relationship between short-circuit resistance and wire feed rate predicts more accurately the welding system behaviour, both reducing the number of coefficients and producing better standoff estimations.
Conclusion
The focus of this research was on the estimation of standoff in gas metal arc welding. A number of methods often referred to in the literature were implemented and evaluated. These methods were categorised into theoretical and empirical models. Halmoy’s [38] and Orszagh’s [39] models are theoretical models that were derived from the physical and mechanical properties of the welding process. Leneswich’s [37], Kim & Na’s [40] and Carvalho’s [41] model are empirical models that were developed by finding relationships between the process variables based on extensive measurements. These models were implemented and analysed in both short circuiting and spray transfer GMAW. The possibility of improving these by modifying the underlying algorithms was also investigated.

It was concluded that the minimum short circuit resistances of the weld presented more information directly related to the standoff in short circuit transfer. The minimum short circuit resistance occurs during the short-circuiting stage. When the electrode dips into the weld pool, a liquid bridge is formed. The minimum resistance that is measured whilst there is a liquid bridge can be used for standoff estimation.

There are two main advantages to using the minimum short circuit resistance; firstly, the standoff estimations are more stable, which results in a smaller error range, and secondly, it enables the detection of changes in standoff with a relatively high accuracy of less than +/- 1 mm.

It was shown that welding current is more suitable for standoff detection in spray transfer mode than the minimum resistance. This is due to the physics of the process whereby, the current signal produces a relatively stable waveform in spray transfer
mode. Therefore, the average welding current can be used for standoff estimation in spray transfer GMAW.

The advantages and disadvantages of theoretical models and empirical models can be observed by comparing the results of the models of Orszagh and Carvalho. Both models achieved a result of less than 1 mm offset from the actual standoff, and a standard deviation of less than +/- 1 mm. However, Orszagh’s model is suitable for different welding parameter settings (such as travel speed and wire diameter), as opposed to Carvalho’s model, which requires measuring a new data set to determine the coefficients.

From the results, it can be observed that a few models could be modified to better reflect the properties of the process. This could improve the standoff estimation performance in both short circuit and spray transfer mode. Therefore, a number of modifications to theoretical and empirical methods were evaluated. The new models were based on Halmoy’s, Kim & Na’s and Carvalho’s methods. Halmoy’s model produces no improvement with the modified structure. Kim & Na’s modified model showed a significant improvement with a 60 % reduction in standard deviation in short circuit transfer mode. However, the standard deviation of the 10 mm standoff estimation still exceeded the 1 mm requirement for standoff estimation, reaching as high as 1.5 mm. Nevertheless, 15 and 20 mm standoff estimates decreased from 2 mm standard deviation to less than 1 mm, which is within the desired range, whilst reducing the number of coefficients in the new structure from 7 to 4. In spray transfer mode, no significant improvement could be observed but accuracy was retained with fewer coefficients used for the models. The lower number of coefficients results in a
simpler algorithm and reduces the computational effort for a possible on-line system. The modified Carvalho's model showed acceptable performance with less than 1.1 mm standard deviation for both short-circuiting and spray transfer operation. This was again achieved whilst the number of coefficients was reduced from 7 to 4.

In summary, Orszagh's model resulted in the best performance in short circuit transfer mode and Kim & Na's modified model resulted in the best performance in spray transfer mode. However, if it is desired to use only one model for both transfer modes, Carvalho's modified models are suggested. It should be noted however that different coefficients should be used for the two distinct transfer modes.

Recommendations for Future Research

Although the algorithms evaluated in this thesis are suitable for on-line applications, all the analysis was done off-line. The obvious next step for this research would be to test them in process.

For further development of the standoff estimation algorithms, different power supplies could be used. Some characteristics of the welding signals vary according to the power supply employed. Since a variety of power supplies are used in industry, the standoff estimation methods must be tested for robustness and versatility. Different welding parameters and consumables could also be tried, such as using travel speeds other than 5 [mm/s] and materials other than mild steel to verify their effect on the strategies discussed.
The different algorithms should be tested and evaluated in pulse transfer mode, as well as it is another common GMAW process used in industry.
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References


Appendix A

Tables of measurements
Table A-1. Measurements of 10 mm standoff in short circuit transfer mode

<table>
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<td>D16120...D16440</td>
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<td>D17100...D17440</td>
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<td>D18120...D18440</td>
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<td>D19140...D19440</td>
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Table A-2. Measurements of 15 mm standoff in short circuit transfer mode

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Table A-3. Measurements of 15 mm standoff in spray transfer mode

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<td>S28380...S28440</td>
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<td>380 – 440</td>
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<td>380 – 400</td>
<td>S30380...S30400</td>
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Table A-4. Measurements of 20 mm standoff in short circuit transfer mode

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<td>D17120…D17460</td>
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<td>D18140…D18440</td>
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<td>180 – 460</td>
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<td>140 – 460</td>
<td>D20140…D20460</td>
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Table A-5. Measurements of 20 mm standoff in spray transfer mode

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<td>31</td>
<td>460 – 520</td>
<td>S31460…S31520</td>
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</table>
Appendix B

Matlab\textsuperscript{®} Programs on CD
Appendix C

*Measurement Data on CD*
De Boer F.G. and So G.K.

*Novel Standoff Estimation Algorithms for Automation and Robotic Gas Metal Arc Welding*

Paper submitted to be publish

So, G.K. and De Boer F.G.

*Analysis of standoff estimation algorithms in GMAW short-circuit transfer mode*


De Boer F.G. and So G.K.

*Analysis of Theoretical Standoff Estimation Algorithms in GMAW Short-Circuit Transfer Mode*


De Boer F.G. and So G.K.

*Standoff estimation for automated Gas Metal Arc Welding*

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*Estimation of Contact-tip to Workpiece Distance in Gas Metal Arc Welding*