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MODELLING AND REAL-TIME CONTROL OF GAS METAL ARC WELD PROFILE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
The Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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ABSTRACT

The objective of this research is to investigate the use of a unique, hybrid GMAW control system for robustly controlling weld shape of single-pass fillet welds in the presence of common production perturbations and disturbances. The purpose of this is to improve fatigue properties of weldments to increase service life or decrease design requirements. A Design of Experiments (DOE) approach is utilized to develop full quadratic models of weld profile attributes from experimental data with inclusion of fourteen GMAW process parameters. These models are then used in a Response Surface Methodology (RSM) to study the relationship between process inputs and outputs. Results of the statistical studies are used in the development of the control system. The hybrid control system developed integrated multi-input/multi-output (MIMO), feedforward and feedback control loops to perform joint tracking, adaptive fill, contact-tip-to-work (CTWD) regulation, and weld symmetry control. Complex weld profile features such as weld symmetry and weld toe geometry are addressed as reference tracking and disturbance rejection control problems. Robustness to disturbance rejection of common production perturbations such as tack welds, root gaps, variable heat sinking, joint deviations, and changes in CTWD are investigated experimentally. It is demonstrated that a real-time, closed-loop control approach can robustly control the shape of single-pass fillet welds in the presence of common production perturbations and disturbances which affect weld profile.
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CHAPTER 1

INTRODUCTION

Demands for increased productivity while maintaining or improving quality and a desire to reduce supervision of the welding operation have driven developments in automation of welding processes. The basic objectives of automating Gas Metal Arc Welding (GMAW) applications are to maintain a desired weld quality while maximizing productivity without manual supervision. The surface profile of a weld and the presence of discontinuities are weld quality measures that are very influential to the mechanical properties of a weld, such as fatigue performance and strength. Typical robotic GMAW relies on process set points derived from an optimal welding procedure to produce a desired weld profile that is free of discontinuities. This form of open-loop control assumes all the process inputs and disturbances remain fixed and produce a repeatable output in terms of weld quality. Any input error, change in plant dynamics, or disturbance to the process is likely to cause deterioration in the quality of the weld that may require expensive rework or early field failure. Closed-loop control of the weld profile is desired to overcome these limitations and is the subject of this research.

Compared with other manufacturing processes, welding has established a reputation for being difficult to control. This is the result of the multiplicity of interrelated process variables, the complexity of their inter-relationships, the presence of extraneous disturbances, the absence of accurate models, and the difficulty of in-process sensing.

The measurement of weld quality parameters in real-time is one of the major difficulties in the practical application of closed-loop control to arc welding. This is because of the detrimental effects that intense electromagnetic radiation, high magnetic and electric fields, molten metal spatter, and fumes have on delicate sensors and
transducers in the vicinity of the arc. In addition, the interpretation of sensory data to extract meaningful information about the welding process can be difficult.

Arc welding is considered a nonminimum phase system in control engineering terms because of the relatively long transport lags and slow time constants associated with the thermal heat flow as compared with most manufacturing processes. This presents several problems in the design of closed-loop control. This was demonstrated by Christensen, Davies, and Gjermundsen who determined that the arc welding process has slow time constants. A delay in the measurement of process variables is common because of the location or type of sensor being utilized. Therefore, control action will be based on delayed, hence obsolete, process information that may not be representative of the current situation within the process. In addition, arc welding has input delay because of the thermal dynamics and the effect of the control action is not immediately seen in the process outputs. In order to have closed-loop stability, conventional feedback control design requires considerably smaller controller gains that yield sluggish response or time-delay compensation that is sensitive to modeling errors.

Arc welding is a process that is subject to significant disturbances that cannot be effectively handled by conventional feedback control. Some disturbances such as the presence of gaps or tacks, contact-tip wear, and variations in weld torch to joint orientation can be sensed and/or controlled using feedforward control. Other disturbances, such as weldment or electrode contamination, arc blow, wire cast, and part distortion cannot be easily sensed or anticipated before they occur.

Because arc welding is considered a multivariable process with multiple inputs and multiple outputs (MIMO), more complex control problems arise due to input-output pairing, interactions or coupling, and controllability/observability. One of the consequences of having several input and output variables is that a control system can be configured several different ways depending on which input variable is paired with which output variable. The decisions on which variables to pair are not trivial and usually consider which pair will provide the best controller performance. In addition, variable
interactions or coupling must be considered where a particular input variable will
influence several output variables simultaneously.

Many of the relationships between process inputs and outputs of arc welding are
highly non-linear. While their response in the neighborhood of an equilibrium state can
usually be described by a linear system of equations, process dynamics and unmodelled
uncertainties can affect their accuracy.

Accurate mathematical representation of the arc welding process is difficult
because of changes in process set-points, unmodelled dynamics, time delays, non-
linearity, changes in equilibrium point (operating set-point), sensory noise, and unknown
disturbing inputs. Conventional and modern control theory is difficult to utilize because
is assumes that knowledge of the process will produce an accurate system model from
which the controller is designed. When model uncertainty is taken into consideration,
issues of sensitivity and robustness come into play. The attempt to design feedback
control to cope with a wide range of model uncertainty leads to robust, adaptive, or
inverse model control problem formulations. These types of controllers are difficult to
implement for multi-input/multi-output systems.

Previous research efforts have concentrated on conventional or modern control
methodologies to control basic weld geometry features such as weld width or depth of
penetration for simple, autogenous gas tungsten arc welding (GTAW) butt welds. Some
of these efforts have focused on utilizing hybrid control schemes that integrate several
control technologies such as robust, optimal, intelligent, and/or adaptive control
techniques\textsuperscript{23}. By utilizing hybrid controllers, the advantages of several control
technologies can be combined to overcome the difficulties of welding process control.
Few researchers have extended these ideas to complex joint geometries such as fillet
welds, or consumable wire welding processes such as GMAW.

The objective of this research has been to investigate the use of a hybrid GMAW
control system for robustly controlling weld shape of single-pass fillet welds in the
presence of common production perturbations and disturbances. The purpose of this is to
control fatigue properties of weldments to increase service life or decrease design
requirements. It has been shown that fatigue properties are strongly affected by weld geometry and discontinuities\textsuperscript{5,6}. For fillet-welds, this includes all geometrical surface aspects of the weld face and weld root including any discontinuities. This application of a hybrid control system requires integration of multi-input/multi-output, feedforward and feedback control loops to perform joint tracking, adaptive fill, contact-tip-to-work (CTWD) regulation, and weld symmetry control. Complex weld profile features such as weld symmetry and weld toe geometry are addressed as reference tracking and disturbance rejection control problems. Robustness to disturbance rejection of common production perturbations such as tack welds, root gaps, variable heat sinking, joint deviations, and changes in CTWD are investigated. This research promises to lead to control of weld properties what will be beyond what has been previously accomplished.
CHAPTER 2

BACKGROUND

Many welded structures must be designed to withstand dynamic loads due to vibration and cyclical loading. The "weak link" in a dynamically loaded structure is often a welded joint where fatigue cracking of welds is the limiting factor in the design, use, and life of the structure. Prevailing welding operations produce welds with a large variability in strengths and resistance to fatigue. The entire fabrication process presents opportunities for dramatic improvements in fatigue performance and ultimate savings. Welding is however, perhaps the most crucial. Welding is a complex process, and successful welds depend on many factors including the composition of the base metals, the geometry of the weld deposit, the stresses introduced in the parts before, during, and after welding, and of course the welding operation itself. Research have been done on all of these elements, but the interaction and role of all these factors to the strength of the weld is only beginning to be understood and controlled. This chapter defines the various geometrical attributes and discontinuities common to fillet welded T-joints, presents a basic understanding of the influence of weld profile on fatigue performance, and discusses previous research efforts on influencing weld profile through closed-loop control.

2.1 Fillet Weld Profile

Defined by the American Welding Societies' committee on Standard Welding Terms and Definitions, fillet welds are approximately triangular in cross section joining two surfaces that are approximately at right angles to each other in a lap joint, T-joint, or corner joint. The most common T-joint, shown in Figure 1, consists of a continuous (non-butting) member and non-continuous (butting) member. The continuous member is
free to move in any direction perpendicular to its thickness dimension while the non-
continuous member is prevented by the other member from movement in the direction
perpendicular to its thickness dimensions. The joint root is an area where the members
approach the closest to each other and are to be welded. The joint root may contain a
root opening, or gap, between the workpieces.

Figure 1: Schematic of T-joint with definitions.

The general classification of fillet weld surface profiles is shown in Figure 2
where concave or convex profiles are generally associated with welds made in the flat
(1F) position, while S-shaped profiles are generally associated with welds made in the
horizontal (2F) position. The measurement of concavity or convexity is the maximum
development in distance, perpendicular from a line joining the weld toes to the weld surface,
denoted by C in the figures.

For symmetric fillet welds, the weld size is equal to the length of the sides of the
largest isosceles right triangle which can be inscribed within the fillet weld cross-section
bounded by the original edges of the joint members, also shown in Figure 2 by the dashed
lines. For asymmetric fillet welds, the weld size equals the lengths of the sides of the largest right triangle which can be inscribed within the fillet weld cross-section.

![Diagram of various fillet weld profiles](image)

Figure 2: Various fillet weld profiles.

The weld toes are defined as the point where the weld reinforcement and parent materials meet. The weld toe region is most commonly classified as the toe angle or reentry angle, which is the angle formed between the weld face and the parent material. More recently, the radius of curvature of the weld toe region has been used to characterize the fatigue strength of welded joints.\textsuperscript{11,9,10}
Figure 3: Classification of fillet weld toes by radius or angle.

The leg lengths of a fillet weld are defined as the distance from the joint root to the weld toe as shown in Figure 4. If there is a root gap, the leg length measurement includes the gap as part of the dimension. In the presence of undercut at the weld toe, the leg length is measured from the joint root to the point where the undercut starts.

The weld face is the length of a line that connects the weld toes, also shown in Figure 4.
Figure 4: Fillet weld leg lengths and weld face.

The throat of a fillet weld has several classifications (Figure 5). The actual throat is the shortest distance between the weld root and the face of a fillet weld. The effective throat is the minimum distance minus any convexity between the weld root and the face of a fillet weld. For concave fillet welds as shown in Figure 5, the actual and effective weld throats are the same. For convex fillet welds, these measurements will differ. The theoretical throat of a fillet weld is the distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross-section of a fillet weld. The dimension is based on the assumption that the root opening is equal to zero.
2.2 Fatigue in Welded Structures

Fatigue results from cyclic stress that is imposed on a weldment that can produce progressive cracking, and ultimately failure under static loads much less than the ultimate strength of the material. This is different from static failure that results from the instantaneous overload of a structure. Stress cycles can have a wide range of frequencies and patterns, and consist of a combination of tensile and compressive stresses. Fatigue has three phases namely: crack initiation, crack propagation, and fracture (failure). Under cyclic loading, fracture can occur at a stress substantially below a metal's static yield strength and thus its importance to the design of cyclically loaded mechanical components.

The highest cyclic stress that can be resisted by a metal without fracture decreases with the increase in the number of times the stress is repeated. Fatigue resistance is commonly illustrated by plotting applied stress versus the number of cycles to cause failure, commonly called an S-N diagram. An example of an S-N diagram for a fillet welded assembly subject to transverse loading is shown in Figure 6. To create the
curves, specimens of similar weld quality were tested at various cyclic stresses, ranging from 120 to 290 MPa (Mega-Paskals). The applied stress varied from tensile to compressive during each cycle. Because of the large number of stress cycles need to produce fatigue failure, especially at low stresses, the number of cycles is indicated on the abscissa of the S-N diagram using a logarithmic scale. The three S-N curves in Figure 6 represent three series of tests where symmetrical fillet welded weldments where subjected to transverse loading. Weld quality was varied by changing welding procedures, consumables, and welding positions. Each series of tests represented a class of weld quality, with increasing weld quality from series "a" to series "c". The goal of producing a sound weldment to fatigue is to avoid, or at least delay failure. In terms of the S-N diagram, this means shifting the curve for a given weldment to the upper right of the diagram.

![S-N diagram](image)

Figure 6: Fatigue strength of fillet welded assembly subject to transverse loading for various weld quality. (from Janosch, et. al. \textsuperscript{11})

The resistance of a weldment to crack initiation is crucial. Fatigue cracks tend to initiate in a weldment where the applied load produces the highest concentration of stress
or where the weldment is more dependent on stress concentration than the static strength of the metal. Fatigue cracking often initiates at the surface of metal members, where the localized stresses are usually higher. Discontinuities in a weld such as undercut and overlap create stress concentration. Fillet welds are especially susceptible to fatigue cracking because of the high stress concentration present at the weld toes and joint root. These locations are shown in Figure 7. The weld surface profile and the presence of discontinuities strongly influence the fatigue resistance of fillet welds.

![Figure 7: Stress concentration in fillet-welded T-joints.](image)

The influence of weld discontinuities in order of their decreasing effect on fatigue performance has been ranked as follows:\textsuperscript{5,6}:

1. Cracks
2. Weld Surface Profile
3. Lack of Fusion/Lack of Penetration
4. Slag Inclusions
5. Porosity

While cracks are the most influential on fatigue performance as indicated above, it is not normally a problem when welding mild carbon steels such as ASTM A36, commonly used in heavy manufacturing. Hot cracking, also known as hydrogen cracking, is not a problem because of the lower carbon content of the base material, the use of solid wire,
and slower the cooling rates common with heavy pass automated GMAW. Solidification cracking, which is a type of hot cracking, can become a problem only if welding a joint that is thermally or mechanically strained during welding. Large weld pools, created by high heat-input welding procedures, are more susceptible to solidification cracking than low-heat-input procedures. Automated multi-pass GMAW practices such as the use of weld sequencing and intermittent spacing of welds help to reduce residual strain building during the welding of a part and thus cracking.

The weld surface profile is the next most important factor on fatigue performance. For fillet-welds, this includes all geometrical surface aspects of the weld face and weld root including any discontinuities. Geometrical surface aspects include leg lengths, weld throat, convexity/concavity, toe angle and radius, and surface ripples. Surface discontinuities include overlap, undercut, incomplete penetration, drop through, gross porosity, slag, start/stops, and craters. Some examples of fillet weld discontinuities are shown in Figure 8. For a complete description of weld defects and discontinuities, see reference 7. It should also be noted that the position of the weld discontinuity in relation to the weld surface is important. Discontinuities that are located in the proximity of the weld surface are more detrimental than similar discontinuities within the body of the weld. Discontinuities on the weld surface are influential to mechanical properties in that they reduce the cross sectional area of the weld and/or cause stress concentration. A more detailed discussion on weld surface profile will follow.

Lack of fusion (LOF) and lack of penetration (LOP) discontinuities are considered internal discontinuities only. Both have slightly more consequence on fatigue performance than slag inclusions. Most investigators consider that certain levels of LOF, LOP, and slag inclusions can be tolerated depending on their size and location in regard to the applied stress. Assuming an optimized welding procedure is used, lack of fusion and lack of penetration discontinuities are rare. Slag inclusions are typically of concern with multi-pass, multi-layer welds.
Porosity is considered to be the least detrimental discontinuity as long as weld reinforcement is not reduced. For fillet-welds, porosity only influences fatigue performance when extensive, such as gross porosity, or when located near the root of the weld. The effects of porosity can be negated by increasing the size of the fillet-weld for a given volume fraction porosity. Any porosity visible on the surface is considered a surface geometrical discontinuity.

2.3 Control of Weld Profile

The use of an optimal welding procedure for a given weld joint can provide a weld with desired geometrical characteristics without the presence of discontinuities. For a fillet-weld in a T-joint, this would be a large, concave weld with sufficient throat and complete root penetration, and large, smooth reentry angles at the weld toes with no undercut. Reliance on an optimized welding procedure alone assumes all the process inputs remain fixed and a satisfactory, repeatable output in terms of weld quality is obtained. Any input error or disturbance in the process can cause deterioration in the quality and may not be noticed until final inspection.
For most automated welding applications, operating the process open-loop with an optimal welding procedure is not sufficient to overcome the presence of unknown uncertainties due to disturbing inputs. Practical disturbing inputs, that affect geometrical surface characteristics and cause discontinuities include:

- Presence of gaps
- Presence of tacks
- Weldment and electrode contamination
- Poor part edge preparation
- Poor fit-up and fixturing
- Arc blow
- Wire cast and helix
- "Out-of-position" welding
- Contact-tip-wear

While almost all of these process perturbations can, in principle, be mitigated with sound manufacturing practices, it is common in actual production to encounter several on any given weldment. Even with robotic welding applications, there is no sensory feedback to deal with such production perturbations. Therefore, it is not un-common in production to produce weldments with poor geometrical surface characteristics and discontinuities that have less than optimal fatigue performance and strength. This is particularly the case since fatigue strength is a localized characteristic of a weld and even an isolated occurrence will affect fatigue properties.

Several post-welding techniques to modify the surface profile of welds have been developed to improve the fatigue performance of welded structures. The "grinding" technique has been suggested and studied by several researchers where the weld contour and toe region are manually ground after welding to produce a smooth, concave weld less susceptible to stress concentrations\(^{13,14}\). Another technique, known as "TIG Dressing" utilizes the autogenous GTAW (TIG) process to remelt the toe regions of a weld\(^{15,16,17}\). These techniques require additional manufacturing processing at added expense and reduced productivity. Therefore, producing a weld with optimal surface profile and lack of discontinuities is the most efficient technique, requiring no further manufacture processing. The purpose of adding closed-loop control of weld profile is to decrease the
susceptibility of the welding process to common perturbations encountered during manufacturing without the need for additional steps in manufacture.

2.4 Review of Weld Profile Control Efforts

There have been a number of attempts by researchers to regulate through closed-loop control the dimensions of welds made with arc welding processes such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), submerged arc welding (SAW), and flux-cored arc welding (FCAW). The common dimensions that are controlled are weld width, reinforcement, and depth of penetration. These efforts were commonly applied to bead-on-plate welds, less commonly with groove welds, and rarely with fillet welds. Very little attention has been given to the problem of regulation of fillet weld profile in T-joints. This section reviews previous efforts to control aspects of weld shape for GMAW in chronological order.

Bates and Hardt\textsuperscript{18} integrated a heat flow model developed by Eager and Tsai\textsuperscript{19} into a real-time calibrated thermal estimator to be used for model based control of weld geometry. The model assumed a Gaussian distributed heat source moving on a semi-infinite plate with no phase-changes in the material:

\[ \theta = \frac{T - T_0}{T_R - T_0} = \frac{n}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{r^2-2ru+u^2}{2r^2+2u^2}} \frac{\zeta^2}{2r^2} \, d\tau \quad \text{with} \quad \tau = \frac{u - \frac{v\sigma}{2\alpha_d}}{2\alpha_d} \]  \hspace{1cm} (2.1)

where \( \tau \) is dimensionless time, requires solution through a numerical procedure. While the model still required the ambiguous parameters arc efficiency (\( \eta \)) and the arc distribution (\( \sigma \)), the error for predicting weld width and depth was claimed to be less than 30% for GTAW bead-on-plate welds on carbon steel, stainless steel, titanium, and aluminum. The estimator, shown in Figure 9, was developed for closed-loop weld bead geometry control of GTAW or GMAW and could determine weld width and depth based on using known input weld parameters and topside temperature measurement. The single-source pure conduction model of welding was continuously "tuned" to match the
measured temperature gradients by varying a pair of unknown heat source parameters. This adaptive tuning scheme allows for robust model predictions to account for variations in thermal efficiency and distribution associated with welding arcs. This work laid the foundation for later model-based control efforts.

![Diagram of weld pool width and depth estimator](from Bates and Hardt)

Figure 9: Weld pool width and depth estimator. (from Bates and Hardt)

Doumanidis, Hale, and Hardt\textsuperscript{20} developed a more extensive model of the GMAW process, intended for use in a weld geometry control system. They developed analytical and numerical non-linear models by considering both the pool geometry and the "thermally activated properties" such as the heat affected zone width and the centerline cooling rate. Linear first order approximations were used to model the response of the nugget cross-sectional area (NS) to steps in the leading torch's heat input ($Q_l$), torch velocity ($V$), or the ratio of the heat input from a trailing torch to the leading torch ($S=Q_2/Q_1$). The Laplace transform domain transfer functions were:
\[
\frac{NS(s)}{Q(s)} = \frac{K_a}{1 + T_a s}
\]
\[
\frac{NS(s)}{V(s)} = \frac{K'_a}{1 + T'_a s}
\]
\[
\frac{NS(s)}{S(s)} = 0
\]

where \(K_a, K'_a\) are the gains and \(T_a, T'_a\) are the time constants. The heat affected zone was modeled using overdamped second order transfer functions while the cooling rate (CR) step response was modeled as third order with a zero as shown below:

\[
\frac{CR(s)}{Q(s)} = \frac{K_c \omega_n^2 (1 + T_c s)}{(1 + T_c s)(s^2 + 2 \zeta \omega_n s + 1)}
\]
\[
\frac{CR(s)}{V(s)} = \frac{K'_c \omega'_n^2 (1 + T'_c s)}{(1 + T'_c s)(s^2 + 2 \zeta' \omega'_n s + 1)}
\]
\[
\frac{CR(s)}{S(s)} = \frac{K''_c \omega''_n^2 (1 + T''_c s)}{(1 + T''_c s)(s^2 + 2 \zeta'' \omega''_n s + 1)}
\]

where \(K_c, K'_c, K''_c\) are the gains, \(T_c, T'_c, T''_c\) are the time constants, \(\zeta, \zeta', \zeta''\) are the damping coefficients, \(\omega, \omega', \omega''\) are the natural frequencies, \(T_c\) is the centerline cooling rate critical temperature, and \(T_o\) is the initial preheat temperature. The authors did not determine the range with which the linearized model would be acceptable, commenting that this would have to be determined separately. The models were intended for use in a control system.

Smart et al. developed a control methodology to independently control heat and mass input for GMAW (Figure 10) based on the influence of heat input, cooling rate, weld geometry, and presence of discontinuities on the microstructural and mechanical properties of a weldment. A steady state analytical model of the welding process was developed, with travel speed and wire feed speed as the control inputs, and current as the measured process response variable. Experiments showed the controller's ability to maintain the heat input to within one percent of an on-line model and the actual
reinforcement area within five percent of desired area. They concluded that control of mass and heat transfer may be done independently for spray transfer GMAW.

![Diagram](image)

**Figure 10:** Model based control structure developed by Smart et. al.\textsuperscript{21}

Smart and Einerson\textsuperscript{22} later modified the control structure given in Figure 10 by replacing the contact-tip-work-distance (CTWD) model with a PI controller, and replacing the wire feed speed (wfs) and current (I) static models with an adaptive reference model (ARM). This allowed the model to adjust to various metal transfer modes. The controller performed well under steady-state conditions with no error. Three transient conditions were also tested namely weld startup, step change in heat input, and intentional arc instability. If was concluded that the controller was sufficiently robust to overcome these disturbances.

Song and Hardt\textsuperscript{23,24} investigated the adaptive control scheme for weld geometry control to overcome the limitations found in the previous work by Hale and Hardt\textsuperscript{25,26} where they utilized linear control. The linear controller attempted to deal with the nonlineairities of GMAW geometry control by using a scheduled gain approach. This technique quickly showed limited performance when operated outside the baseline weld procedure, and had poor disturbance rejection properties. Song and Hardt developed a
multivariable deadbeat adaptive control system to regulate weld width and depth of penetration for GMAW. They utilized a recursive least-squares model with variable forgetting factors and covariance resetting. The resulting 2-input, 2-output state-space model manipulated travel speed and wire feed speed to control weld width and depth. The model coefficients were continuously updated in real-time to account for the process time variance and non-linearity. While no experimental verification was conducted, simulations showed that the controller had good response, as long as its output was low-pass filtered to slow the controllers response.

![Diagram of multivariable deadbead adaptive controller](image)

**Figure 11:** Multivariable deadbead adaptive controller used by Song and Hardt.  

With the objective of maintaining uniform weld quality, Boo and Cho developed a hybrid PID/fuzzy control scheme for regulation of weld pool size. Infrared temperature measurement of the weld pool surface was fed into the hybrid control structure to regulate wire feed speed, voltage, and travel speed. They found the hybrid control structure performed better than conventional PID control alone. This hybrid control scheme was later modified to utilize a self-organizing fuzzy controller, shown in Figure 12. Experiments showed that the control system yielded uniform weld pool sizes...
for various welding speeds by adapting the rule base to variations of the process dynamics. The implication of their results is that the proposed control is suitable for the control of processes where it is difficult to tune the controller, due to variations of the dynamics or process complexity.

Figure 12: Hybrid Control System to Regulate Weld Pool Size by Boo and Cho\(^{28}\).

Henderson, et. al.\(^{29}\) and Schiano\(^{30}\) also recognized the limitations of conventional linear control algorithms to changing welding process dynamics and operating conditions. They developed a pseudogradient adaptive controller that self-tunes a proportional-integral (PI) control algorithm. The controller system measured weld puddle width using machine vision, and adjusted travel speed for a fixed wire feed speed to regulate width. Through simulation and experimentation, they demonstrated the controllers ability to adapt and converge to changes in current settings and heat sinking.

Based on previous work, Hale and Hardt\(^{31}\) concluded that no numerical model of the process dynamics appropriate to the GMAW control problem existed, therefore an empirically derived transfer function would be required. Their basic control model related wire feed speed and inverse travel speed to weld width and height as second order
system with constant damping but the natural frequency was a function of velocity. A modification to the standard PID algorithm produced a zero tracking control scheme shown in Figure 13. Simulation and control experiments concluded that the bi-valued nature of the process can cause uncertainty in controller performance, and the limited working range precludes effective rejection of all but the smallest disturbances. They concluded that the GMAW process would have to be modified to reduce the output coupling and increase the working range of the process.

Figure 13: Zero tracking controller developed by Hale and Hardt.

In an attempt to overcome the limitations of conventional control, Einerson et al. developed an intelligent control system for regulation of weld reinforcement and cooling rate. The control system, shown in Figure 14, utilized machine vision to measure the weld joint transverse cross-sectional area ahead of the welding torch and the weld bead centerline-cooling rate behind the weld pool. The centerline cooling rate error is fed into a Takagi-Sugeno type fuzzy logic controller to calculate heat transfer rate per unit length as required to obtain the desired weld bead-cooling rate. The values for required reinforcement and weld bead cooling rate are sent to an inverse neural network that maps the wire feed speed, travel speed, for a given power supply open circuit voltage as a function of reinforcement and heat input per unit length. The inverse neural network was a backpropagation type using one hidden layer of 20 nodes with biases and a sigmoid activation function. Few experimental results were presented but it was concluded that a
control strategy for feedback control of weld cooling rate and feedforward control of reinforcement has potential for application to welding fabrication.

![Diagram of intelligent control structure](image)

Figure 14: Intelligent control structure developed by Smart et. al.²¹

The first attempt at multivariable control of GMAW fillet weld dimensions was done by Stefanuk et. al.³³. They developed a multivariable linear controller based on the experimentally derived linear model to overcome common disturbing inputs encountered during manufacturing. The model was developed from data generated by a full factorial experiment on arc voltage, wire feed speed, and travel speed. The response variables measured were weld width the throat thickness. The control equations were developed by multiple linear regression to the coefficients of the linear matrix equations relating changes in inputs to changes in outputs. Their modeling results showed that the equations could account for 72% of the variations of the data for weld width, and 28% for throat thickness. A controller, based on a robust servomechanism structure shown in Figure 15 was designed to regulate weld width by reference tracking. It incorporated both state feedback of wire feed speed, travel speed, and voltage along with output feedback of weld width from a vision system. Experimental results showed that it did provide adequate reference tracking through a limited range of operating setpoints, but that it was limited in its ability to reject root gap disturbances. They also simulated a more complete control scheme based on a 3-input, 2-output, 6-state system using a linear
state-space and optimal control technique designed the regulate fillet weld width and throat thickness. No actual implementation of this controller was tested.

Later, Huissoon et. al.\textsuperscript{34} compared the performance of the previously developed linear control structure with an artificial neural network controller in order to improve robustness to process variations. The linear control structure previously developed was extended from a single output controller to regulate fillet weld width, to a multi-output controller that also regulated weld throat. An estimator was used to provide the linear controller throat thickness feedback based on an open-loop observer based equation. A feed forward neural network using the sigmoid function was developed using the same empirical data that was used to develop the linear model. This network provided a 4-input mapping of voltage, wire feed speed, travel speed, and root gap to two outputs of fillet weld width and throat. They tested a variety of network structures before choosing a 12 node configuration. The neural network control strategy, shown in Figure 16, utilized an inverse model approach. The reference feedforward into the control loop provided a nominal operating point, with the PI controller providing error compensation about the nominal operating point. The inverse model, which is a static neural network,
accepts the modified reference inputs and generates the process setpoints for a given root gap measurement. Through experimentation, it was found that the neural network based controller provided an improvement in performance over the linear controller in maintaining the weld width and throat in the presence of gap disturbances.

![Diagram of neural network control structure](image)

**Figure 16: Neural network control structure studied by Huissoon et. al.**

Moon and Na\textsuperscript{15} recognized the influence of fillet weld geometry on the mechanical integrity of a weld joint and developed a neural-fuzzy open-loop control system to influence the quality of the resulting weld. They performed a fractional factorial experiment design to correlate process parameters with fillet weld shape and used multiple non-linear regression analysis for model development. A neural network was developed to predict the welding conditions appropriate for the desired weld bead geometry, and the fuzzy rule-based method chooses appropriate welding conditions for avoiding weld defects such as undercut and overlap in horizontal fillet welding. Performance of the neuro-fuzzy system was evaluated through experiments, which showed that the system could effectively identify and welding conditions that would produce weld defects.
2.4.1 Summary of Weld Profile Control Efforts

The difficulty of sensing and controlling Gas Metal Arc Weld geometry has long been a research topic of interest. A wide range of sensing and control methods has been applied to the regulation of weld width, height, and penetration. Although minor successes have been achieved, they each have their limitations due to (1) difficulty of in-process sensing, (2) inaccurate models, or (3) limited working range of control. None of these efforts have specifically addressed the regulation of weld profile with the goal of improving the fatigue properties of weldments to increase service life or decrease design requirements. The approach taken in this research extends the basic ideas discussed here in a direction in which further research and development will provide a practical solution to weld profile control for Gas Metal Arc Welding.

2.5 Real-Time Weld Profile Measurement

Real-time process measurement has always been a problem in efforts at real-time control of the arc welding process. Laser-based structured light machine vision technology has developed in the welding industry for automated joint finding, seam tracking, and adaptive welding applications. While the concept of using machine vision for automated weld inspection is not new, only recently has industry begun to realize the potential impact of this technology. This research is based on the real-time measurement of weld profile using this technology.

Laser-based structured light machine vision relies on the principles of triangulation, light projection or scanning, and sensor movement to measure a surface in three dimensions. The first principle, triangulation (Figure 17), allows measurement in the first dimension, height of the detector from the surface. The beam from the laser projects onto the surface of the workpiece to form an illuminated spot. Diffusely reflected radiation from the spot is captured by a lens and projected on a linear detector. The detector consists of a row of separate elements in a CCD camera. The element number on which the peak of the reflected light is projected is mathematically related to the height.
Figure 17: Principle of triangulation.

The second principal, planar light projection or scanning allows measurement in the second dimension, creating a height profile along a line on the surface. In the scanning-spot configuration, a laser beam and the reflected radiation from the weld seam are both deflected by mechanically oscillated mirrors. This causes the laser beam to scan across the seam while the radiation from the reflection remains aligned on a 1-dimensional or linear detector. Each scan gives a line of the surface and is constructed from a number of measuring points. A variation of this principle known as laser-line (or laser-spray) utilizes laser source to project a spray of laser light across the seam while the radiation from the reflection remains aligned on a 2-dimensional detector. This eliminates the need for mechanical motors and mirrors to scan the laser spot.

The third dimension of the surface profile is created through sensor movement. When the camera is moved along a weld seam or other surface, the combination of individual two dimensional height profiles provides the third dimension of the surface. Thus, the topography of the workpiece is reconstructed and the true geometry is known.

For welding applications, the laser light source, filters, lenses, and camera are housed within a protected enclosure that is water cooled, and typically utilize positive air
pressure and protective optics to protect the sensor from spatter and fumes associated with arc welding. A narrow bandpass optical filter is typically used to improve the signal-to-noise ratio of the sensor while rejecting the majority of arc radiation. Scanning-spot laser sensors typically provide better performance such as signal-to-noise ratio in arc welding environments while laser-line sensors have better resolution and are more economical.

2.5.1 Principle of Operation

Using a laser-line sensor as an example, the reflection of the line of laser light from the surface of the weld being inspected is observed by a charge coupled device (CCD) camera at an angle of 20 to 30 deg. The CCD camera is an array of photosensitive devices or picture elements called pixels that stores charge in proportion to the amount of light it receives. This array of pixels typically consists of 480 lines x 512 rows of pixels for a total of 245,760 pixels. The charge of each pixel is quantified into 256 levels of intensity or gray scale with 0 being total darkness and 255 being completely saturated with light. The 256 levels of gray scale corresponds to a resolution of 8 bits ($2^8$). The array is read line by line with the charge of each pixel in a line being summed. This sum of charges is then digitized and transferred to the computer through frame grabbing or digitizing circuitry. A full image from the CCD camera is typically digitized at 30 or 60 times a second. There are newer digital camera formats that allow much higher frame rates such as 120 or 240 hertz. The laser line is then extracted from the image through an image processing routine that finds the brightest pixel in each line of pixels from the camera (see Figure 18).
Arrays of range (Figure 19) and reflectivity (Figure 20) data are generated which correspond to the vertical height (profile) of the laser line and intensity of the reflected laser line. These array's represent the surface of the fillet weld being inspected. Each profile contains 480 data points which corresponds to each vertical line in the CCD camera, with each element containing either a pixel value in camera coordinates or intensity value in gray scale (256 levels). These values can be converted to real world coordinates of inches or millimeters through a transform.
Range and reflectivity profiles are generated for each camera image that is digitized. These profiles, which represent the weld surface, are then made available to the feature detection algorithms to make measurements about the weld geometry and discontinuities.

2.5.2 Range Profile Processing

Using the range profile information, advanced image processing algorithms can then be applied to interpret geometrical information about the weld as well as recognize discontinuities. There are a number of image processing techniques such as edge detection, feature extraction, segmentation, and pattern recognition that can be applied.

An example of segmentation called linear piecewise regression is shown in Figure 21. This linear segmentation algorithm breaks the profile into between 1 and 25 straight line segments defined by starting coordinates, ending coordinates, slopes, and y-intercepts. The criteria used to segment the range profile include amplitude thresholding, region of interest, validation, 1st and 2nd derivatives, local minimums and maximums, and filtering. This technique is useful for identifying flat surfaces such as the adjoining plate surfaces of the weld. A Hough transform, although more computationally intensive, could also be applied to find the target surfaces.
Figure 21: Segmentation of Fillet Weld Range Data

By further processing fillet weld range data, the general shape of the weld can then be inferred as shown in Figure 22. The linear piecewise regression produced two line segments that represent the plate surfaces with a first order equation for each segment. Next a curve is fit to the remaining pixels that represent the weld bead. The intersection of the curve and the line segments representing the plate surfaces indicates the relative positions of the weld toes. From these three curves, leg lengths, face width, convexity/concavity, toe angles, and theoretical throat can all be inferred for a fillet weld.

Figure 22: Line Segmentation and Curve Fitting.

Typically, it is difficult to accurately model welds in the simple geometric terms described above because welds have erratic geometric shapes caused by overlap,
undercut, spatter, porosity, rippling, and complex bead shapes. Therefore advanced geometric modeling techniques are commonly applied.

2.6 Summary

In summary, there have been numerous efforts to control the weld width and/or depth for gas metal arc welding. Many different control techniques such as conventional, modern, and intelligent that use modeling schemes that are analytical and/or empirical have been investigated. The objectives for the majority of this research have been to improve the disturbance rejection properties of the GMAW process. The experimental work in the previous research has been limited to strictly bead-on-plate welds. Little attention has been paid to more common configurations used in manufacturing such as groove or fillet welds. Most of these efforts also fall short in addressing the problems that occur in the manufacturing environment such as variations in fit-up, changes in joint geometry such as gaps and tacks, changes in the welding procedures, and out of position welding. No attempt has been made at real-time control of weld toe geometry with the objective of improving the fatigue life of a weldment.
CHAPTER 3

FILLET WELD PROFILE MODEL IDENTIFICATION

Before design and development of the control system, the process variables under consideration were studied and characterized using statistical techniques. First, a screening experiment was conducted in order to characterize the variables under consideration and determine a working range for each variable. Then an experimental design matrix (DOE) was developed and carried out. The results of this initial DOE were analyzed and then the experimental matrix was augmented with additional welding trials. Next, a regression model was formulated and the results analyzed. The regression models were then embedded into software, allowing analysis of the results using a dynamic response surface methodology. Models developed from this process were used for control system design, outlined in the next chapter. The sponsor of this project conducted all tests discussed in this section for the model identification in the sponsors' laboratory and provided reduced data for this analysis.

3.1 Experimental Conditions

Tests were conducted utilizing a 6-axis articulated arm, welding robot interfaced with a 600 amp DC welding power supply. A welding fixture was utilized to hold the T-joint non-restrained in a flat, 1F or downhand position during welding. Tests were conducted using standard 1.32 cm (0.052 inch) diameter ER70-S3 welding wire and 90% Argon-10% CO2 shielding gas. The base material was standard ASTM A36 steel in various thicknesses with the T-joint configured from 61 cm x 15 cm (24 x 12 inch) pieces.

A data acquisition system was utilized to record voltage, current, and wire feed speed during welding. All welds were scanned with a laser-based machine vision metrology sensor to digitize the solidified weld surface profile. Once the weld surface was
digitized, machine vision algorithms then calculated various geometric features of the weld face along its length. Descriptions of these features were provided in section 2.1.

Because these variables are being used in the development of a weld geometry control system concerned with both optimization and symmetry, the individual leg lengths were added to form an "additive leg length" or ALL, and subtracted to form a difference or "differential leg length" or DLL. In addition, toe radii were added to form the measurements "additive toe radius" or ATR, and subtracted to form a "differential toe radius" or DTR. Finally, the addition of toe angle form a "additive toe angle" or ATA, and subtraction from a "differential toe angle" or DTA. These variables provide a better picture of the symmetry and magnitude of each weld feature to be modelled for the control system development. Weld geometry features such as penetration profile and sidewall fusion were ignored because they could not be directly measured in real-time for use in control. A summary of the response variable nomenclature for the experiments is shown in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Notation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Leg Length</td>
<td>ALL</td>
<td>mm</td>
</tr>
<tr>
<td>Differential Leg Length</td>
<td>DLL</td>
<td>mm</td>
</tr>
<tr>
<td>Additive Toe Radius</td>
<td>ATR</td>
<td>mm</td>
</tr>
<tr>
<td>Differential Toe Radius</td>
<td>DTR</td>
<td>mm</td>
</tr>
<tr>
<td>Additive Toe Angle</td>
<td>ATA</td>
<td>rad.</td>
</tr>
<tr>
<td>Differential Toe Angle</td>
<td>DTA</td>
<td>rad.</td>
</tr>
<tr>
<td>Theoretical Throat</td>
<td>TT</td>
<td>mm</td>
</tr>
<tr>
<td>Convexity/Concavity</td>
<td>CVCC</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 1: Response variables.

### 3.2 Screening Experiments

Before conducting the main experimental design, a screening experiment was initially performed to identify important factors and their operating ranges with a small number of experiments. The D-optimal design criteria was utilized to design the screening experimental matrix because it produces the absolute minimum number of
experiments required to estimate a second order model. D-optimal designs are classified as a resolution V design, where no main effect or two-factor interaction is aliased with any other main effect or two-factor interaction, but two-factor interactions are aliased with three-factor interactions. A D-optimal experimental design is one that maximizes the determinant of Fisher's information matrix, $X^TX$. This matrix is proportional to the inverse of the covariance matrix of the parameters. There maximizing $\text{det}(X^TX)$ is equivalent to minimizing the determinant of the covariance matrix of the parameters. In simpler terms, a D-optimal design minimizes the volume of the confidence ellipsoid of the regression estimates of the linear model parameters. References provide a detailed discussion of D-optimal experimental designs, see references 42, 43, and 44.

The screening experiment matrix contained nine variables whose ranges and factor levels are shown in Table 2. In order to reduce the number of experimental runs to be conducted, Voltage and Wire Feed Speed were treated as covariates, that is they were varied together proportionally, and were combined to form what was called the Power Setting Pair (PSP).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Notation</th>
<th>Range</th>
<th>Units</th>
<th># Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>PSP</td>
<td>27 to 31.5</td>
<td>volts</td>
<td>4</td>
</tr>
<tr>
<td>Wire Feed Speed</td>
<td>PSP</td>
<td>84.6 to 243.2</td>
<td>mm/s</td>
<td>4</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>TS</td>
<td>3.38 to 8.46</td>
<td>mm/s</td>
<td>4</td>
</tr>
<tr>
<td>Torch Offset</td>
<td>TO</td>
<td>-1.3 to 1.3</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Root Gap</td>
<td>GAP</td>
<td>0 to 2.5</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Plate Thickness</td>
<td>PT</td>
<td>6 to 24</td>
<td>mm</td>
<td>4</td>
</tr>
<tr>
<td>CTWD</td>
<td>CTWD</td>
<td>30 to 40</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Travel Angle</td>
<td>TA</td>
<td>-15 to 15</td>
<td>degrees</td>
<td>3</td>
</tr>
<tr>
<td>Work Angle</td>
<td>WA</td>
<td>-15 to 15</td>
<td>degrees</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2: Screening experiment variables, range and number of levels.

3.2.1 Variable Range

A team of welding personnel who had experience in producing single pass fillet welds chose the ranges for the variables shown Figure 2. It was known that certain
combinations of the range extremes would produce welds that were not acceptable, although knowledge of which combinations would produce bad welds was not available a priori. After the screening experiment, approximately 50 of the 120 welds produced were rejected. Examples of such extremes are shown in Figure 23 where welds made with the same welding procedure except a 1.3mm and zero torch offset produced bad (left macro) and good (right macro) welds, respectively.

Figure 23: Welds made with the same welding procedure except for 1.3mm torch offset (left) versus 0mm torch offset (right).

3.2.2 Analysis of Variance

In statistic sciences, a method of statistical inference called hypothesis testing is utilized to determine whether a factor (welding parameter) has a significant effect on a response (weld profile attribute). The null hypothesis, or $H_0$, is the claim that a factor does not significantly affect the response. A test statistic is a function, based on the sampled data, for deciding whether to reject $H_0$. One such test statistic is the $f$-value, where the result of hypothesis testing is to indicate whether $H_0$ was rejected at a specified $\alpha$ of significance. Thus, for level of significance $\alpha$ of 0.01, if the $P$-value is less than $\alpha$, then we are 99% confident that we can reject $H_0$; in other words, we are 99% confident that the factor used in that test did not significantly affect the response. For $\alpha$ of 0.1, we
would only be 90% confident that we can reject $H_0$, etc. Details for the calculation of a $P$-value for a given data-set are quite lengthy and will not be discussed here, but most modern statistical software programs calculate such values.

ANOVA refers broadly to a collection of statistical procedures utilized to compare quantitative data. The simplest form of ANOVA is single-factor or one-way ANOVA which involves the analysis of data from experiments which had two or more levels. Let:

\[ i = \text{the number of levels being compared} \]
\[ \mu_1 = \text{the mean of level 1 or the true average response when level 1 is applied} \]
\[ \vdots \]
\[ \mu_i = \text{the mean of level } i \text{ or the true average response when level } i \text{ is applied} \]

Then the null hypothesis of interest is:

\[ H_0: \mu_1 = \mu_2 = \ldots = \mu_i \]

versus the alternative hypothesis:

\[ H_a: \text{at least two of the } \mu_i\text{'s are different} \]

If the number of levels is three or $i = 3$, the null hypothesis, $H_0$ is true only if all three $\mu_i$'s are identical. The alternative hypothesis, $H_a$ would be true for example if $\mu_1 = \mu_2 \neq \mu_3$, $\mu_1 \neq \mu_2 = \mu_3$, or if all three $\mu_i$'s are different.

The null hypothesis $H_0$ used here, tests whether a variable is significant i.e. the claim that a variable does not significantly affect any weld profile attribute. In other words, $H_0: \mu_1 = \mu_2 = \ldots = \mu_i$. The level of significance $\alpha$ chosen for these tests was 0.05. The test statistics or $P$-values were calculated for all variables tested in the screening experiment and are shown in Figure 3.
Table 3: Significance of the effect of each variable (P-values) on various weld profile measurements.

An example of the interpretation of these results is as follows. Since the P-value for the effect of voltage on additive toe radius (ATR) is 0.00, we are 100% certain that voltage has a significant effect on additive toe radius. With the level of significance (α) at 0.05, the following is an interpretation of the results in Figure 3:

- Significant Factors affecting Additive Toe Radius (ATR) are:
  Voltage, wire feed speed, travel speed, gap, plate thickness, and travel angle.
- Significant Factors affecting Differential Toe Radius (DTR) are:
  Torch offset, and work angle.
- Significant Factors affecting Additive Toe Angle (ATA) are:
  Voltage, wire feed speed, travel speed, torch offset, travel angle, and work angle.
- Significant Factors affecting Differential Toe Angle (DTA) are:
  Voltage, wire feed speed, and torch offset.
- Significant Factors affecting Additive Leg Length (ALL) are:
  Voltage, travel speed, torch offset, gap, plate thickness, and travel angle.
- Significant Factors affecting Differential Leg Length (DLL) are:
  Torch offset, gap, plate thickness, contact-tip-work-distance, and work angle.

The weld profile attributes that contribute to weld shape, such as additive toe radius (ATR) and additive leg length (ALL), both agree in that voltage, wire feed speed, travel speed, and travel angle are significant variables that have an effect. They disagree on several other variables. Given the nature and difficulty of the measurements for toe
radius and toe angle as briefly discussed in section 2.5, these results are not surprising. Since the goal of the control system is to maximize additive toe radius, only the results for ATR were utilized. The variables voltage, wire feed speed, travel speed, gap, plate thickness, and travel angle all contribute to ATR. It is difficult to interpret these results because very little is known about the influence of welding parameters on the toe angles and radii of the weld bead. It is theorized that most of these variables are related to heat flow and weld pool fluid flow phenomena, and that these phenomena are most likely the major factors influencing weld bead toe angles and radii.

The overall volume of the weld is related to the convexity/concavity of the weld along with additive leg length, ALL. While the significance of welding variables on convexity/concavity were not tested, the results of significance testing for ALL indicate that voltage, travel speed, torch offset, gap, plate thickness and travel angle all contribute to overall leg length. It was interesting that voltage was significant while wire feed speed was not since both were treated as covariants. The deposition rate is related to wire feed speed and travel speed as follows:

\[
\text{Deposition Rate} = \frac{\text{Wire Feed Speed} \times \text{Deposition Efficiency} \times \text{Wire Area}}{\text{Travel Speed}}
\]  

(3.1)

The influence of gap on ALL is logical as some of the deposited material may flow into the gap, reducing the overall volume accounted for in the ALL measurement. The influence of plate thickness was unexpected, but may be due to heat flow and its influence on weld shape, such as convexity/concavity, which affects the overall ALL. Finally, the influence of travel angle is significant, which may be due to weld pool fluid flow and its relation to weld shape, such as convexity/concavity, which also affects the overall ALL.

The weld profile attributes that contribute to weld symmetry include differential toe radius (DTR), differential toe angle (DTA), and differential leg length (DLL). The factors that commonly affect these attributes are torch offset and work angle. Results also indicated both DTA and DLL have additional significant factors, but these were
ignored, as the control system was designed to utilize the measurement of DTR for feedback control.

3.3 Design-of-Experiments

After the ranges for the variables were identified, it was necessary to explore the region around the optimal settings to assess sensitivity of the factors and to test for higher order interactions. The Design of Experiments (DOE) approach was chosen because the data involved has experimental error and contains process noise. Therefore, statistical analysis was the only objective approach to the analysis. To use Response Surface Methodology, all factors had to be varied with at least three levels in order to determine higher order terms in the model. Also, to know the main effects and two-factor interactions without aliasing and confounding, the experimental design had to be of resolution V. This allowed construction of a full quadratic model with second order terms and cross terms for each response variable. As with the screening experiment, a D-optimal experimental design was utilized in order to keep the number of experimental runs to a minimum.

Results from the screening experiment were utilized to establish a baseline welding procedure that produced acceptable welds with the desired geometric shape, namely large weld toe radii. In addition to the nine variables tested in the screening experiment, three additional variables for torch weaving were added. The twelve variables, along with the ranges and levels used for the DOE, are shown in Table 4.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Notation</th>
<th>Range</th>
<th>Units</th>
<th># Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>PSP</td>
<td>31.5 to 34.5 volts</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Wire Feed Speed</td>
<td>PSP</td>
<td>375 to 425 inches/minute</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>TS</td>
<td>7 to 12 inches/minute</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Torch Offset</td>
<td>TO</td>
<td>-1.3 to 1.3 mm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Root Gap</td>
<td>GAP</td>
<td>0 to 1.25 mm</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Plate Thickness</td>
<td>PT</td>
<td>6 to 24 mm</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>CTWD</td>
<td>CTWD</td>
<td>25 to 30 mm</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Travel Angle</td>
<td>TA</td>
<td>-15 to 5 degrees</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Work Angle</td>
<td>WA</td>
<td>-5 to 5 degrees</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Part Angle</td>
<td>PA</td>
<td>6 to 10 degrees</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Weave Amplitude</td>
<td>WVA</td>
<td>0 to 8 mm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Weave Frequency</td>
<td>WVF</td>
<td>0 to 1 Hz.</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Weave Dwell</td>
<td>WVD</td>
<td>0 to 0.2 seconds</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4: DOE variables, range and levels.

For the experiments, the twelve factors were varied combinatorially in order to form the full quadratic model. This required that at least 91 \((1+2\times12+12(12-1)/2 = 91)\) distinct tests or runs be conducted. Various experimental designs are compared in Table 5. While it is recommended that a standard design such as the Central Composite (CCD) or Box-Behnken (BBD) be used, this is not usually practical for welding applications because of the large number of experiments required. An alternative is to use a saturated or nearly saturated design that requires near the minimal amount of runs as calculated above. These design types include the small-composite (SCD), Koshal designs, hybrid designs, or optimal designs. The D-optimal design criteria was used here because it produces the absolute minimum number of experiments required to estimate the second order model with a resolution of \(V\). The final experimental matrix consisted of 141 tests as dictated by the D-optimal design criteria augmented with additional tests to expand the experimental region down initially from 10 to 7 inches per minute travel speed.
<table>
<thead>
<tr>
<th>Design</th>
<th>Calculation</th>
<th># Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Factorial Design</td>
<td>$3^{12}$</td>
<td>531,441</td>
</tr>
<tr>
<td>Res.V Central Composite Design</td>
<td>$2^{12}+2*12+5$</td>
<td>4125</td>
</tr>
<tr>
<td>Res.IV Central Composite Design</td>
<td>$2^{12-1}+2*12+5$</td>
<td>2077</td>
</tr>
<tr>
<td>Box-Behnken Design</td>
<td>$2^3*12+5$</td>
<td>101</td>
</tr>
<tr>
<td>D-optimal Design</td>
<td>$D^{12}$</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 5: Experimental designs and their required number of tests.

3.3.1 Analysis of Variance (ANOVA)

Similar to its use in the screening experiments, the $P$-value test statistic was used to determine the significance of each variable and its level on each weld profile attribute. In this case, the null hypothesis is \( H_0: \mu_1 = \mu_2 = \ldots = \mu_i \). The confidence interval was chosen to be 95% ($\alpha=0.05$) in order to indicate 95% or more certainty that a variable significantly affects a response (rejection of $H_0$). A summary of the weld profile attributes and their significant variables are shown in Table 6. The main significance level was 95%, with variables showing at least 90% significant in parenthesis.

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Significant Factors, $\alpha=0.05$ ($\alpha=0.1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR</td>
<td>TS, PT, PA, WEAVE, (TA)</td>
</tr>
<tr>
<td>DTR</td>
<td>TO, (WA)</td>
</tr>
<tr>
<td>ALL</td>
<td>PSP, TS, PT, (GAP, WEAVE)</td>
</tr>
<tr>
<td>DLL</td>
<td>TS, GAP, PT, WA, (PA)</td>
</tr>
<tr>
<td>ATA</td>
<td>TS, PT, PA, (WEAVE, GAP, TA)</td>
</tr>
<tr>
<td>DTA</td>
<td>GAP, (TS, PT, WA)</td>
</tr>
<tr>
<td>TT</td>
<td>PSP, TS, PA, TO, (PT)</td>
</tr>
<tr>
<td>CVCC</td>
<td>TS, PT, TA, PA, (WEAVE, GAP)</td>
</tr>
</tbody>
</table>

Table 6: Significant factors for weld profile attributes ($P$-value test statistic).

The results obtained with the full experimental matrix varied slightly from those obtained with the screening experiment (see Section 3.2.2). This was to be expected due to the fact that the experimental matrix constrained the variable ranges to a much smaller space centered on an optimal region, and the fact that there were more experimental trials.
than in the screening experiment, thus reducing or at least explaining variance within the results.

Variables that affect the weld toe radii size were travel speed, plate thickness, part angle, weave, and less significantly, travel angle. Most of these were in agreement with the screening experiment except part angle. Torch weaving was not considered in the screening experiment and therefore cannot be compared. The power setting pair (PSP) variables, voltage and wire feed speed, appeared significant at first (during the screening experiment), but were later rejected as being significant factors. Results for toe angle were similar, except for gap, which also appeared to be at least 90% significant.

As previously discussed, weld symmetry can be identified by differential toe radius (DTR), differential leg lengths (DLL), and differential toe angles (DTA). Only work angle appeared to significantly affect all three, with other factors varying. This was not the case in the screening experiment where torch offset significantly affected all three. Nonetheless, torch offset appeared 100% significant in explaining the variance in differential toe radius.

Additive leg length (ALL), theoretical throat (TT), and convexity/concavity (CVCC) characterize the overall weld size and volume. The travel speed, power setting pair (voltage and wire feed speed), and gap appeared to significantly affect all three variables. This result is in agreement with the screening experiment.

3.3.2 Model Form

To further study the relationships between factors and response variables, linear-regression was used to develop several models for each response variable. In keeping with our analysis to this point, we choose a linear-in-the parameter model form. Polynomial approximator structures, also known as multiple regression models, are of the form

\[ y_i = \theta_0 + \theta_1 x_{i1} + \theta_2 x_{i2} + \cdots + \theta_k x_{ik} + \epsilon_i, \quad i = 1, \ldots, n \] (3.2)
For the $k$ unknown parameters. The $\theta_i$'s are the unknown parameters (coefficients) and the $e_i$'s are the approximation errors. The exact values of the $\theta_i$'s and $e_i$'s are never known, but are estimated. The principle of least squares is typically used to estimate the regression coefficients in a multiple linear-in-the-parameter regression model. Suppose there are $n > k$ observations or data points available for several response variables $y_1, y_2, \ldots, y_n$. Along with each response $y_i$, there is an observation from each variable $x_i$, therefore $x_{ij}$ denotes the $j$'th observation for the $i$'th response variable. The summarized data appear as in Table 7.

<table>
<thead>
<tr>
<th>$y$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>...</th>
<th>$x_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_1$</td>
<td>$x_{11}$</td>
<td>$x_{12}$</td>
<td>...</td>
<td>$x_{1k}$</td>
</tr>
<tr>
<td>$y_2$</td>
<td>$x_{21}$</td>
<td>$x_{22}$</td>
<td>...</td>
<td>$x_{2k}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$y_n$</td>
<td>$x_{n1}$</td>
<td>$x_{n2}$</td>
<td>...</td>
<td>$x_{nk}$</td>
</tr>
</tbody>
</table>

Table 7: Data for multiple linear regression.

The regression model in equation (3.2) may be rewritten as

$$y_i = \theta_o + \sum_{j=1}^{k} \theta_j x_o + e_i, \quad i = 1, 2, \ldots, n. \quad (3.3)$$

The method of least squares determines the coefficients or $\theta_i$'s in equation (3.3) so that the sum of squares of the errors is minimized. In this setting, the least squares function is

$$f(\theta_i) = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} \left( y_i - \theta_o - \sum_{j=1}^{k} \theta_j x_{ij} \right)^2. \quad (3.4)$$

The goal is to minimize the function $f(\theta)$ with respect to the regression coefficients $\theta_i$'s. The estimated coefficients $\hat{\theta}_i$'s must satisfy
\[
\frac{\partial f(\theta_i)}{\partial \theta_i} \bigg|_{\hat{\theta}_0, \hat{\theta}_1, \ldots, \hat{\theta}_k} = -2 \sum_{i=1}^{n} \left( y_i - \hat{\theta}_0 - \sum_{j=1}^{k} \hat{\theta}_j x_{ij} \right)
\]

and

\[
\frac{\partial f(\theta_i)}{\partial \theta_i} \bigg|_{\hat{\theta}_0, \hat{\theta}_1, \ldots, \hat{\theta}_k} = -2 \sum_{i=1}^{n} \left( y_i - \hat{\theta}_0 - \sum_{j=1}^{k} \hat{\theta}_j x_{ij} \right) x_i = 0, \quad j = 1, 2, \ldots, k .
\]

Simplifying equations (3.5) and (3.6) yields a set of least squares normal equations as follows:

\[
\sum_{i=1}^{n} y_i = n \hat{\theta}_0 + \hat{\theta}_1 \sum_{i=1}^{n} x_{i1} + \hat{\theta}_2 \sum_{i=1}^{n} x_{i2} + \cdots + \hat{\theta}_k \sum_{i=1}^{n} x_{ik}
\]

\[
\sum_{i=1}^{n} x_{i1} y_i = \hat{\theta}_0 \sum_{i=1}^{n} x_{i1} + \hat{\theta}_1 \sum_{i=1}^{n} x_{i1}^2 + \hat{\theta}_2 \sum_{i=1}^{n} x_{i1} x_{i2} + \cdots + \hat{\theta}_k \sum_{i=1}^{n} x_{i1} x_{ik}
\]

\[\vdots \quad \vdots \quad \vdots \]

\[
\sum_{i=1}^{n} x_{ik} y_i = \hat{\theta}_0 \sum_{i=1}^{n} x_{ik} + \hat{\theta}_1 \sum_{i=1}^{n} x_{ik}^2 + \hat{\theta}_2 \sum_{i=1}^{n} x_{ik} x_{i1} + \cdots + \hat{\theta}_k \sum_{i=1}^{n} x_{ik}^2
\]

There are \( p=k-1 \) normal equations, one for each unknown regression coefficient. The solution to the normal equations will be the least squares estimators of the regression coefficients \( \theta_1, \theta_2, \ldots, \theta_k \). To solve the normal equations, it is simpler to convert them to matrix notation as follows:

\[ y = X\theta + \varepsilon \]

where
\begin{equation}
\begin{bmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_n
\end{bmatrix}
= 
\begin{bmatrix}
  1 & x_{11} & x_{12} & \cdots & x_{1k} \\
  1 & x_{21} & x_{22} & \cdots & x_{2k} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  1 & x_{n1} & x_{n2} & \cdots & x_{nk}
\end{bmatrix}
\begin{bmatrix}
  \theta_1 \\
  \theta_2 \\
  \vdots \\
  \theta_p
\end{bmatrix}
+ 
\begin{bmatrix}
  \varepsilon_1 \\
  \varepsilon_2 \\
  \vdots \\
  \varepsilon_n
\end{bmatrix}
\tag{3.8}
\end{equation}

with \( y \) an \((n \times 1)\) vector of the observations, \( X \) an \((n \times p)\) matrix of the levels of the independent variables, \( \theta \) a \((p \times 1)\) vector of the regression coefficients, and \( \varepsilon \) an \((n \times 1)\) vector of errors.

The goal is to find the vector of least squares estimators, \( \hat{\theta} \), that minimizes the least squares function \( f(\theta) \). The least squares function in matrix notation is

\begin{equation}
f(\theta) = \sum_{i=1}^{n} \varepsilon_i^2 = \varepsilon^T \varepsilon = (y - X\theta)^T (y - X\theta)
\tag{3.9}
\end{equation}

which may also be expressed as

\begin{equation}
f(\theta) = y^T y - \theta^T X^T y - y^T X\theta + \theta^T X^T X\theta \\
= y^T y - 2\theta^T X^T y + \theta^T X^T X\theta
\tag{3.10}
\end{equation}

As in equations (3.5) and (3.6), the least squares estimators must satisfy:

\begin{equation}
\frac{\partial f(\theta)}{\partial \theta_i} \bigg|_{\hat{\theta}, \hat{\theta}_2, \ldots, \hat{\theta}_p} = -2X^T y + 2X^T X\dot{\hat{\theta}} = 0
\tag{3.11}
\end{equation}

which simplifies to

\begin{equation}
X^T X\dot{\hat{\theta}} = X^T y \Rightarrow \dot{\hat{\theta}} = (X^T X)^{-1} X^T y
\tag{3.12}
\end{equation}

Therefore, the fitted regression model becomes:
Various forms of polynomial approximator structures were constructed for this study including: linear without the affine term, linear with affine, linear with affine and cross terms, linear with affine and square terms, and finally a full quadratic approximator. These structures were chosen to isolate the linear terms, cross terms, and square terms, in order to determine their overall effect on the models accuracy. The forms of these models using the coded variable names are as follows:

- Linear without affine
  \[ y = \theta_0 + \theta_1 PT + \theta_2 GAP + \theta_3 TS + \theta_4 PSP + \theta_5 PA + \theta_6 CTWD + \theta_7 WVA + \theta_8 WVD + \theta_9 WVF + \theta_{10} TA + \theta_{11} TO + \theta_{12} WA \]

- Linear with affine
  \[ y = \theta_0 + \theta_1 PT + \theta_2 GAP + \theta_3 TS + \theta_4 PSP + \theta_5 PA - \theta_6 CTWD - \theta_7 WVA + \theta_8 WVD + \theta_9 WVF + \theta_{10} TA + \theta_{11} TO + \theta_{12} WA \]

- Linear with affine and square terms
  \[ y = \theta_0 + \theta_1 PT + \theta_2 GAP + \theta_3 TS + \theta_4 PSP + \theta_5 PA + \theta_6 CTWD + \theta_7 WVA + \theta_8 WVD - \theta_9 WVF + \theta_{10} TA + \theta_{11} TO + \theta_{12} WA + \theta_{13} PT^2 + \theta_{14} GAP^2 + \theta_{15} TS^2 + \theta_{16} WFS^2 - \theta_1 \text{volt}^2 + \theta_{17} CTWD^2 + \theta_{18} WVA^2 + \theta_{19} WFS^2 + \theta_{20} WVD^2 + \theta_{21} TA^2 + \theta_{22} TO^2 - \theta_{23} TA^2 + \theta_{24} TO^2 + \theta_{25} WFA^2 \]

- Linear with affine and cross terms
  \[ y = \theta_0 + \theta_1 PT + \theta_2 GAP + \theta_3 TS + \theta_4 PSP + \theta_5 PA + \theta_6 CTWD + \theta_7 WVA + \theta_8 WVD - \theta_9 WVF + \theta_{10} TA + \theta_{11} TO + \theta_{12} WA + \theta_{13} PT \times GAP + \theta_{14} PT \times TS + \theta_{15} PT \times WFS + \theta_{16} PT \times \text{volt} + \theta_{17} PT \times PA + \theta_{18} PT \times WVA + \theta_{19} PT \times WVD + \theta_{20} PT \times WVF + \theta_{21} PT \times TA + \theta_{22} PT \times TO + \theta_{23} PT \times WA + \theta_{24} GAP \times TS + \text{...etc...} \]
• Full Quadratic

\[ y = \theta_0 + \theta_1 PT + \theta_2 GAP + \theta_3 TS + \theta_4 PSP + \theta_5 PA + \theta_6 CTWD + \theta_7 WVA + \theta_8 WVD + \theta_9 WVF + \theta_{10} TA + \theta_{11} TO + \theta_{12} WA + \theta_{13} PT^2 + \theta_{14} GAP^2 + \theta_{15} TS^2 + \theta_{16} WFS^2 + \theta_{17} volt^2 + \theta_{18} CTWD^2 + \theta_{19} WVA^2 + \theta_{20} WFS^2 + \theta_{21} WVD^2 + \theta_{22} TA^2 + \theta_{23} TO^2 + \theta_{24} TA^2 + \theta_{25} TO^2 + \theta_{26} WA^2 + \theta_{27} PT*GAP + \theta_{28} PT*TS + \theta_{29} PT*WFS + \theta_{30} PT*volt + \theta_{31} PT*PA + \theta_{32} PT*WVA + \theta_{33} PT*WVD + \theta_{34} PT*WVF + \theta_{35} PT*TA + \theta_{36} PT*TO + \theta_{37} PT*WA + \theta_{38} GAP*TS + \ldots \text{etc...} \]

It should be reiterated that the WFS and VOLT terms were treated as co-variates and represented in the model as PSP.

3.3.3 Mean Square Error Analysis

The residuals or e_i's are determined by the difference between the observation y_i and the fitted value \( \hat{y}_i \) as follows:

\[ e_i = y_i - \hat{y}_i \quad \text{or in matrix notation: } e = y - \hat{y} \quad (3.14) \]

Residuals can help characterize the fit of a model to the data; that is when the residuals are small, the model is a good fit. A quantitative indicator of model validity is the sum of squares error or sum of squares of residuals. Its derivation in scalar form is

\[ SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{n} e_i^2 \quad (3.15) \]

or in matrix notation

\[ SSE = \sum_{i=1}^{n} e'e \quad (3.16) \]

Substituting

\[ e = y - \hat{y} = y - Xb \quad (3.17) \]

results in

48
\[ SSE = (y - Xb)'(y - Xb) \]  \hspace{1cm} (3.18)

which multiplies out as

\[
SSE = y'y - b'X'y - y'Xb + b'X'Xb
= y'y - 2b'X'y + b'X'Xb
\]  \hspace{1cm} (3.19)

Substituting

\[ X'Xb = X'y \]  \hspace{1cm} (3.20)

results in

\[ SSE = y'y - b'X'y. \]  \hspace{1cm} (3.21)

An equivalent quantitative indicator of fit is the mean square error or mean square of residuals, which simply normalizes the \( SSE \) with respect to sample size or number of experiments as follows:

\[ MSE = \frac{SSE}{n}. \]  \hspace{1cm} (3.22)

Analysis of the mean-square-error (MSE) of residuals for the various model forms applied to the experimental data is given in Table 8. Results indicate that model accuracy increases with the number of terms in the model. The full quadratic model is the most accurate, having the lowest MSE of all models for each response variable. There is a large discrepancy between the "Linear with Square Terms" and "Linear with Cross Terms" models, where it is observed that the cross terms add accuracy. This shows that two-factor interactions have more influence on the response variables than the square terms, indicating curvature in the hyperplane does not account for as much error as does interactions between input variables. It was interesting to note that the affine term has no
effect on linear model accuracy. This must be attributed to the fact that the linear model alone has twelve degrees of freedom that account for the variation in response variables, and that adding one more degree of freedom (the affine term) has no affect.

<table>
<thead>
<tr>
<th>Model</th>
<th>ATR</th>
<th>DTR</th>
<th>ATA</th>
<th>DTA</th>
<th>ALL</th>
<th>DLL</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear without Affine</td>
<td>2.78</td>
<td>2.16</td>
<td>14.23</td>
<td>7.07</td>
<td>2.32</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td>Linear with Affine</td>
<td>2.78</td>
<td>2.16</td>
<td>14.23</td>
<td>7.07</td>
<td>2.32</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td>Linear with Square</td>
<td>2.28</td>
<td>2.08</td>
<td>11.05</td>
<td>6.30</td>
<td>2.18</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>Linear with Cross Terms</td>
<td>1.00</td>
<td>0.74</td>
<td>5.89</td>
<td>3.20</td>
<td>1.07</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>Full Quadratic</td>
<td>0.84</td>
<td>0.61</td>
<td>5.18</td>
<td>2.84</td>
<td>0.94</td>
<td>0.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 8: Mean-Square error of various regression models.

Since we are interested in a model that best fits the data, we chose to utilize the full quadratic model for the rest of this study.

3.3.4 Coefficient of Multiple Determination

The coefficient of multiple determination, or $R^2$, is another measure of the goodness of fit for a model by indicating the percentage of variability explained by the model. The calculation of $R^2$ is as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} e_i^2}{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \quad 0 \leq R^2 \leq 1.$$  (3.23)

The $R^2$ values were calculated for the weld profile attributes by using the full quadratic model developed above with 117 terms. The $R^2$ values indicate that the full quadratic model explains at least 70% of the variability in the data, as in the case for differential toe angle (DTA), and was as high as 90% for additive leg length (ALL). These results are acceptable given the inherent variability of the weld process, the minimal number of experimental runs, and the limited accuracy in the measurement of the weld profile.
attributes. Of particular interest are the results for additive toe radius (ATR) and differential toe radius (DTR), which will later be utilized in the control system.

<table>
<thead>
<tr>
<th></th>
<th>ATR</th>
<th>DTR</th>
<th>ATA</th>
<th>DTA</th>
<th>ALL</th>
<th>DLL</th>
<th>TT</th>
<th>CVCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>84.8%</td>
<td>71.5%</td>
<td>80.1%</td>
<td>69.6%</td>
<td>89.7%</td>
<td>76.7%</td>
<td>86.0%</td>
<td>79.2%</td>
</tr>
</tbody>
</table>

Table 9: Coefficient of multiple determination for full quadratic model of weld profile attributes.

3.3.5 Residual Analysis

In order to further assess the model adequacy, residual analysis can be employed to determine if certain test data qualify as outliers. This is usually done graphically, plotting either the standardized residuals vs. test sequence, standardized residuals vs. fitted values, fitted values vs. actual values, or a normal probability plot of the standardized residuals. Standardized residuals are more commonly utilized because they tend to emphasize outliers better than utilizing the residuals themselves. The standardized residuals are defined as:

$$e_i^* = \frac{e_i}{\hat{\sigma}} = \frac{e_i}{\sqrt{MSE}} \quad (3.24)$$

which produces a mean of zero and approximately unit variance. Therefore, outliers are usually classified as being larger than two standard deviations, with unusually large observations greater than three standard deviations. The outliers can be caused by simple mistakes in recording the data, or serious problems such as indicating that a region of the variable space where the fitted model gives a poor approximation to the true response surface.

The standardized residuals were plotted against their fitted values for additive toe radius, Figure 24, and differential toe radius, Figure 25. The tests which produced outliers larger than two standard deviations (dashed lines) are indicated on each plot. The
outliers (for example dhw125 in Figure 24) appear to be random, with no distinct pattern associated with experimental order (which was determined by plotting the residuals vs. experimental order), or variable level (which was determined by plotting the residuals vs. the levels of each variable). These results indicate that the model may be improved by repeating the test conditions of the outliers.

Figure 24: Standardized residuals versus their fits for additive toe radius (ATR).
3.3.6 Augmented Experimental Matrix

Based on the results of the residual analysis, the original experimental matrix was augmented with additional tests in order to improve the model accuracy. Twenty additional tests were conducted. Tests d2x, d11x, d35x, d80x, d115x, and d121x were repeat tests of outlier data points identified in the previous sub-section. It was not possible to redo all of the outlier data points, so only a select group was repeated. Tests identified as g1x through g10x were added as interpolated test points of regions not included within the main experimental matrix. Finally, the four tests dmx through d073x were developed as repeatability tests to study variance, with all four having the same variable levels, all at the center-point of the entire experimental matrix except for the weave parameters.

After these additional 20 experimental tests were conducted, the data was analyzed with the processes outlined in the previous sections. The coefficient of multiple
determination was calculated as shown in Table 10 for each weld profile attribute model. While the $R^2$ values changed very little for ATR, DTR, and ATA, it dropped as much as 15% for DTA, ALL, DLL, TT, and CVCC. This indicates that previous models were overall more accurate in explaining the variability in the data than the augmented dataset. This unexplained variability is probably due to the combination of measurement error of the weld profiles, unaccounted variables and the random variability of the arc welding process itself.

<table>
<thead>
<tr>
<th></th>
<th>ATR</th>
<th>DTR</th>
<th>ATA</th>
<th>DTA</th>
<th>ALL</th>
<th>DLL</th>
<th>TT</th>
<th>CVCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>83.9%</td>
<td>73.4%</td>
<td>80.0%</td>
<td>69.5%</td>
<td>73.1%</td>
<td>72.2%</td>
<td>63.6%</td>
<td>74.3%</td>
</tr>
</tbody>
</table>

Table 10: Coefficient of multiple determination for full quadratic models of weld profile attributes using augmented experimental matrix.

Based on the results of the main experimental matrix and its augmented runs, it was decided to keep the regression models developed before the matrix was augmented since these models were slightly more accurate.

3.4 Dynamic Response Surface Analysis

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques useful for studying process behavior. RSM shows graphically the relationship between the process inputs and process outputs. Because of its graphical nature, only three dimensions or less can be visualized at one time i.e. the effect of two input variables and their interaction on a single response variable or process output. Higher order relations (i.e. greater than three degrees of freedom) are simplified to three dimensions for visualization. First order models are used for linear approximations while higher order models such as a full quadratic can show curvature. While such models are reasonably accurate for a small experimental region such as this 141 run DOE, they can be quite inaccurate over larger experimental regions as in broader screening experiments.

In order to aid in the visualization of the complex relationships between variables such as in welding, Dynamic Response Surface (DRS) software was developed using
Matlab™. The DRS software contained a graphical user interface that allows the user to generate the 3-D response surface of any two process inputs and process response variables (Figure 26). Then the user can manipulate the other process inputs to see their effect on the chosen relationship. The full quadratic models developed in the previous section were incorporated in the DRS software. Figure 26 shows the relationship between power setting pair (PSP), travel speed (TS), and additive toe radius (ATR). The example response surface indicates that the higher the wire feed speed and voltage, the large the toe radius. Travel speed tends to have an optimal region near its center.

The graphical user interface of the DRS software shows all of the process input variables on the left, the response surface plot in the middle, and the modeled process response variables on the right. The user can choose any variables to plot by choosing its corresponding check box. The controls allow the user to manipulate the other variables in the model to see the effect on the chosen response surface. Another software feature is the optimized search within the model region for the optimized welding procedure based on the constraints chosen by the user. The search method utilized is steepest descent gradient based on the derivative of the variable of interest.
As pointed out in the Analysis of Variance studies in section 3.3.1, the variables that significantly influenced additive toe radius were travel speed, plate thickness, part angle, weave, and travel angle. The response surface for the effect of part angle and travel angle on additive toe radius is shown in Figure 26. The surface is relatively flat, indicating a predominately linear relationship where additive toe radius increases with increasing part angle and travel angle. The effect of disturbing inputs such as gap and plate thickness on additive toe radius is shown in Figure 27. While plate thickness was not considered a disturbing input, it produced variations in heat flow, similar to the effect of other disturbing inputs such as changing part geometry and tacks. The relationship between gap and additive toe radius appears linear with increasing gap causing an
increase in toe radii. The relationship between plate thickness and additive toe radius has curvature with the extremes of plate thickness causing larger toe radii.

Figure 27: Response surface of gap (GAP) and plate thickness (PT) versus additive toe radius (ATR).

The analysis of variance also indicated that torch offset and work angle significantly affects the differential toe radius. A plot of this response surface is shown in Figure 28 where any deviation from the neutral torch position or zero degree torch offset and work angle cause the weld symmetry to skew. This is shown as the saddle point at zero torch offset and zero work angle. The effect of disturbing inputs on differential toe radius is shown in Figure 29. This surface shows that increasing gap or decreasing plate thickness causes the weld to skew.
Figure 28: Response surface of work angle (WA) and torch offset (TO) versus differential toe radius (DTR).
Figure 29: Response surface of gap (GAP) and plate thickness (PT) versus differential toe radius (DTR).

3.5 Summary

The screening experiments allowed the number of experimental levels of each variable to be reduced significantly by identifying an optimal region for maximizing toe radii while minimizing the chance of producing an unacceptable weld. This information was influential in the design of the main experimental matrix determining ranges and number of levels for each factor. In addition, the screening experiment identified important variables that significantly influenced additive toe radius, and differential toe radius.

The experimental matrix based on a D-optimal experimental design allowed reasonably accurate regression models to be constructed with minimal experimental tests.
The analysis of variance on data from these tests verified significant factors initially identified from the screening experiments. Several model forms were investigated and a full quadratic model was chosen based on quantitative analysis of the residuals by mean square error. The coefficient of multiple determination was calculated for each weld profile attribute model in order to determine the goodness of fit. The model for additive toe radius could explain 85% of the variability in the data while the model for differential toe radius explained 72%. Residual analysis based on standardized residuals identified approximately 15 data-points as being outliers based on exceeding two standard deviations. The experimental matrix was then augmented with an additional 20 tests in order to reduce the error in the models. Results indicated that model performance actually degraded, and the original, un-augmented experimental data was utilized in development of the models. It was theorized this degradation was due to the combination of measurement error of the weld profiles, unaccounted variables and the random variability of the arc welding process itself. It should also be noted that the accuracy of the regression models should be independently checked with a dataset other than that used to train the model, which was not possible here.

The regression models were embedded into dynamic response surface software and further studied. Based on the ANOVA study and manipulation of the dynamic response surfaces, it was determined that the welding procedure could be optimized in order to maximize the toe radii. Further, the travel speed, wire feed speed, and arc voltage would have to be manipulated during the adaptive fill control in order to keep the toe radii optimized. Finally, the weld symmetry is influenced by disturbing inputs such as gaps, tacks, change in part geometry, arc blow, and wire cast. Controlling torch offset and work angle can minimize the effect of these disturbing inputs on weld symmetry. These results were then utilized in the design of the weld geometry control system discussed in the next chapter.
CHAPTER 4

WELD PROFILE CONTROL SYSTEM

The results from the weld profile model study outlined in the previous chapter were used in the design and development of a weld profile control system. This control system utilized an articulated arm welding robot interfaced with a laser-based, structured light machine vision sensor. The laser sensor was utilized in both feedforward and feedback control sub-systems. The feedforward control sub-system integrates the tasks of joint finding, joint tracking, and a modified version of adaptive fill called "modified fill". The feedback control sub-system performs the task of weld symmetry control. The feedforward control sub-system utilized simple linear control with heuristics, while the feedback control sub-system utilized fuzzy control. This chapter details the design and development of this weld profile control system.

4.1 Feedforward Control Design

The feedforward control sub-system integrates the tasks of joint finding, joint tracking, and a modified version of adaptive fill called "modified fill", each of which will be discussed separately. The block diagram for the feedforward sub-system is shown in Figure 30. All three of these control tasks rely on sensory feedback from a laser-based, structured light machine vision sensor mounted parallel to the welding torch. Details of this sensor and its integration with the welding system are provided later in section 4.3. The joint finding and joint tracking tasks utilize information about the joint center calculated during pre-weld sensing to adjust the torch offset and contact-tip-to-work distance. The modified fill task utilizes information about the tack area and gap area, along with the required fillet weld leg length to control deposition rate by adjusting travel speed, wire feed speed, and arc voltage.
4.1.1 Joint Finding & Joint Tracking

One problem with automatic and robotic arc welding applications is maintaining the proper alignment of the welding arc (torch) with the weld joint. Dimensional tolerances of component parts, variations in edge preparation and fit-up, distortion during welding, and other dimensional variations can affect the exact position and uniformity of the weld joints from one assembly to the next. Joint finding coupled with joint tracking can overcome these limitations by adjusting the welding torch trajectory relative to the weldment as the welding torch proceeds along the joint.

Tactile sensing, through-arc sensing and machine vision are the most common techniques that can be utilized to find and track a welding joint adaptively. The laser-based, structured-light machine vision technology discussed in section 2.5 was utilized for this approach. This technology can perform the tasks of joint finding, joint tracking, and adaptive fill before welding for measurements used by the feedforward controller as well as conduct weld symmetry measurements in real-time for the feedback controller.
During the joint finding task, the robot scans near the perceived beginning of the weld joint in a pre-programmed pattern to locate the exact beginning of the weld joint. The entire preprogrammed robot path is then globally offset by the difference between the pre-programmed starting point and actual joint location.

Next the robot places the welding torch tool center point at the weld start location and performs a dry-run or no-weld run. The robot then begins to move in the programmed welding direction while the laser sensor scans across the weld joint, gathering imaging information about the joint location. As the torch proceeds along the weld joint, torch offset and contact-tip-to-work distance changes are continuously calculated and updates are sent to the robot controller and saved in a path file for later playback during welding. In addition to joint tracking, information about the weld joint shape is processed and utilized for feedforward adaptive fill as discussed in the next section.

The image processing technique used for the joint finding and joint tracking tasks are diagrammed in Figure 31. The laser sensor scans the T-joint designated by the continuous plate (cp) and the discontinuous plate (dp). The image is processed to find two line segments, namely ls1 and ls2. At the intersection of these line segments is the joint root, which is designated as the tracking point. The tool center point or tcp is then calculated perpendicular to each line segment, and a fixed distance defined as the contact-tip-to-work distance from the tracking point. The TCP is calculated every 2.5mm (0.1 inch) from the weld start point to the weld stop point and is recorded in rectilinear world robot coordinates for later playback during the welding pass.
4.1.2 Modified Fill

Adaptive fill feedforward control can compensate for changes in the required volume of welds due to disturbing process inputs such as variations in part dimensions, edge preparation, fit-up, tacks, and distortion during welding. Adaptive joint fill control can be real-time control, during welding, or can be done by pre-scanning the joint prior to welding. The vision system measures the joint dimensions and volume, then the system determines changes needed in welding variables to compensate for changes in the joint. The control system determines changes in welding process variables, such as travel speed and/or wire feed speed to adjust the volume of deposited weld metal.

The image processing technique utilized in the modified fill algorithm is shown in Figure 32. As the laser sensor scans the T-joint designated by the continuous plate (cp) and the discontinuous plate (dp), it may encounter gaps or tacks. The image processing algorithm detects the presence of gaps and tacks and quantifies their size. The adaptive fill algorithm then calculates the required deposition rate based on the desired fillet weld leg length, and the presence of a gap or tack.

Figure 31: Processed image of T-joint showing joint finding and tracking attributes.
For this project, a modified version of adaptive fill algorithm called "modified fill" was developed. The modified fill algorithm operated similar to a standard adaptive fill algorithm in that travel speed, wire feed speed, and voltage are varied to compensate for disturbing inputs such as gaps and tacks. The difference is that standard adaptive fill is designed to maintain a constant amount of weld reinforcement while maximizing productivity, while modified fill is designed to maintain a minimal amount of weld reinforcement while producing optimal weld toe radii. The required weld deposition area in the presence of gaps and tacks is plotted in Figure 33. A 10mm leg length fillet weld requires 50mm$^2$ deposition area from the relation

$$\text{deposition area} = 0.5 \times \text{leg length}^2. \quad (4.1)$$

Common gap sizes encountered in production range from 0mm to 3mm and cause the required deposition area to increase from 50mm$^2$ to 84.5mm$^2$. Common tack sizes range from no tack i.e. 0mm to 8mm leg lengths which decrease the required deposition area from 50mm$^2$ to 2mm$^2$ in order to maintain a 10mm leg length fillet weld. It should
be noted that these calculations are ideal, made in two dimensions and assumes 100% deposition efficiency. Although the actual deposition is constant, the resulting weld bead will vary along the length of the weld and the deposition efficiency is less than 100%.

![Graph showing the change in required weld deposition area for a 10mm fillet weld from the presence of a gap and tack.]

Figure 33: Change in required weld deposition area for a 10mm fillet weld from the presence of a gap and tack.

The actual deposition area for a standard 1.32 mm (0.052 inch) diameter ER70-S3 wire with 90%Argon-10%CO₂ shielding gas assumes a 95% deposition efficiency and is calculated by

\[
\text{deposition area} = \frac{\text{wire feed speed} \times \text{wire area} \times \text{deposition efficiency}}{\text{travel speed}}
\]  

(4.2)

The standard adaptive fill algorithm was designed to maximize weld productivity, while maintaining a constant level of joint fill for groove welds. The algorithm was
adapted for fillet welds by adjusting the parameter ranges and utilizing a required deposition area for a desired fillet weld size. The characterization of deposition area for the adaptive fill algorithm is shown in Figure 34. The range for wire feed speed is 85 to 254 mm/sec (200 to 600 ipm) and the travel speed range is 3.38 to 6.35 mm/sec (8 to 15 ipm). Arc voltage is varied proportionally to wire feed speed within the range of 28 to 38 volts. Initially, in the low deposition area, the algorithm maximizes travel speed and adjusts wire feed speed. Once wire feed speed is increased to its maximum, then the algorithm begins to lower travel speed. Based on the requirements for a 10mm leg length fillet weld discussed in the previous paragraph, the adaptive fill algorithm will slow wire feed speed in the presence of tacks up to about 4.3 mm in leg length where the limits are reached and minimal deposition occurs. For gaps ranging from 0 to 3mm (required deposition of 50mm$^2$ to ~90mm$^2$), the algorithm increases wire feed speed until its maximum is reached, then starts slowing down the travel speed. While this approach works well for compensating required deposition area while maximizing productivity, it is not conducive to producing optimal weld profiles with large weld toe radii. This is because the welding procedure is not within the range of parameters that produce large weld toe radii.
Figure 34: Characterization of standard adaptive fill algorithm.

The modified fill algorithm was designed to maintain a minimal amount of weld reinforcement while producing optimal weld toe radii in the presence of gaps and tacks. The characterization of deposition area for the modified fill algorithm is shown Figure 35. The range for wire feed speed is 89 to 114 mm/sec (350 to 450 ipm) and the travel speed range is 3.0 to 5.08 mm/sec (7 to 12 ipm). Arc voltage is varied linearly with wire feed speed within the range of 35 to 40 volts. Note that the range for wire feed speed is considerably narrower than that for the standard adaptive fill algorithm, travel speed is slower and narrower, and arc voltage is narrower and higher. Initially, in the low deposition area, the algorithm minimizes wire feed speed and adjusts travel speed. Once travel speed is decreased to its minimum, then the algorithm begins to increase wire feed speed. Based on the requirements for a 10mm leg length fillet weld discussed in the previous paragraph, the adaptive fill algorithm will slow travel speed in the presence of tacks up to about 3.4 mm in leg length where the limits are reached and minimal
deposition occurs. For gaps, the algorithm provides maximum deposition with wire feed speed at its maximum and travel speed at its minimum. While the modified fill algorithm has a smaller deposition range that the standard adaptive fill algorithm, its range and response is conducive to producing welds with desired profiles and optimal weld toe radii.

Figure 35: Characterization of modified fill algorithm.

4.2 Feedback Control Design

4.2.1 Overview

The feedback control sub-system performs the task of weld symmetry control. A diagram of the feedback controller is shown in Figure 36. The weld profile is measured in real-time immediately behind the welding torch using the aforementioned laser-based, structured-light machine vision technology. The inputs to the fuzzy-logic based control
algorithm are error in weld symmetry and rate-of-change of error in weld symmetry. As previously discussed, weld symmetry can be quantified by measurements such as differential toe radius (DTR), differential leg length (DLL), or differential toe angle (DTA). Adjustments to compensate for weld asymmetry are made by the fuzzy controller to the torch offset (TO) and/or work angle (WA).

![Figure 36: Feedback control sub-system block diagram.](image)

### 4.2.2 Structure of Fuzzy Controller

A block diagram of the fuzzy controller, shown in Figure 37, consists of the following four components:

- **Fuzzification Interface** - converts the controller's inputs from engineering units into a format that the inference engine can easily interpret.
- **Rule Base** - a set of heuristic rules which contains a fuzzy quantification of the expert's linguistic description of how to conduct the control.
- **Inference Engine** - algorithm which emulates the expert's decisions process by interpreting and applying knowledge embedded within the rule base.
Defuzzification Interface - converts the outputs from the inference engine into engineering units applicable to the process.

Because the rule base represents the most significant portion of the feedback controller, we describe it separately in the next sub-section. While a basic description of the fuzzy control scheme utilized in this work is provided here, see Passino and Yurkovich\textsuperscript{45} for a complete discussion on fuzzy control.

![Block diagram of fuzzy control system](from Passino and Yurkovich\textsuperscript{45}).

The inputs to the fuzzy controller \((u_i)'s\) are a function of the reference or desired weld symmetry \(r(kT)\) and the output from the welding process or actual weld symmetry \(y(kT)\). The functions utilized here are the error

\[ e(kT) = r(kT) - y(kT) \]  

and the rate of change in error
where $T$ is the sampling interval.

The outputs from the fuzzy controller ($y$'s) are torch offset (TO), and work angle (WA). Since the inputs and outputs are real numbers, not fuzzy sets, they are referred to as "crisp" values. Each input to the fuzzy controller has scaling gains such as $g_t$, and each output has scaling gains $g_o$.

\[
c(kT) = \frac{e(kT) - e(kT - T)}{T}
\]  

Figure 38: Input and output membership functions for fuzzy control system.

The inputs and outputs, represented in Figure 38, utilized triangular membership functions with scaling gains on the universe of discourse as shown ($g_t$, $g_o$), and the same number of rules. The mathematical characterization of triangular membership functions is as follows:
\[
Left: \quad \mu^L = \begin{cases} 
1 & \text{if } u \leq c^L \\
\max \left[ 0,1 + \frac{c^L - u}{0.5w^L} \right] & \text{otherwise}
\end{cases}
\]

\[
Centers: \quad \mu^C = \begin{cases} 
\max \left[ 0,1 + \frac{u - c}{0.5w} \right] & \text{if } u \leq c \\
\max \left[ 0,1 + \frac{c - u}{0.5w} \right] & \text{otherwise}
\end{cases}
\]  \hspace{1cm} (4.5)

\[
Right: \quad \mu^R = \begin{cases} 
\max \left[ 0,1 + \frac{u - c^R}{0.5w^R} \right] & \text{if } u \leq c^R \\
1 & \text{otherwise}
\end{cases}
\]

where \( c^L \) specifies the saturation point and \( w^L \) specifies the slope of the nonunity and nonzero part of \( \mu^L \) or the leftmost triangular membership function. A similar but reversed function exists for \( \mu^R \) or the rightmost triangular membership function. For the central membership functions \( \mu^C \), \( c \) is the center of the triangle and \( w \) is the base-width.

Singleton fuzzification was utilized on the inputs where a function \( f \) transforms any crisp input \( u \) to a fuzzy set denoted by \( \tilde{A}_n^{\mu u} \). The singleton membership function is defined by

\[
\mu_{\tilde{A}_n^{\mu u}}(x) = \begin{cases} 
1 & x = u, \\
0 & \text{otherwise}
\end{cases}
\]  \hspace{1cm} (4.6)

The inference engine determines the extent to which each rule is relevant to the current situation characterized by the inputs \( u_i \)'s and draws conclusions using the rule base. There are \( u_i \), with \( i = 1,2,\ldots,n \) inputs to the fuzzy controller at any given time. The fuzzification process produces the fuzzy set

\[
\tilde{A}_1^{\mu u}, \tilde{A}_2^{\mu u}, \ldots, \tilde{A}_n^{\mu u}
\]  \hspace{1cm} (4.7)
which represents the inputs. Next the inference engine combines the fuzzified inputs with the rule base premises i.e. each of the fuzzy sets is a singleton that is scaled by the premise membership function for all \( i = 1,2,\ldots,n \) for the given \( u_i \) inputs so that

\[
\mu_{\tilde{A}_i}(u_i) = \mu_{A_i}(u_i) \\
\mu_{\tilde{A}_j}(u_j) = \mu_{A_j}(u_j) \\
\vdots \\
\mu_{\tilde{A}_n}(u_n) = \mu_{A_n}(u_n)
\]  

(4.8)

Next the inference engine determines which rules are on by forming membership values \( \mu_i(u_1,u_2,\ldots,u_n) \) for the \( i^{th} \) rule's premise that represent the certainty that each rule premise holds for the given inputs. This produces

\[
\mu_i(u_1,u_2,\ldots,u_n) = \mu_{A_1}(u_1) \cdot \mu_{A_2}(u_2) \cdot \cdots \cdot \mu_{A_n}(u_n)
\]

(4.9)

where \( \mu_i(u_1,u_2,\ldots,u_n) \) is used to represent the certainty that the premise of rule \( i \) matches the input information i.e. the degree to which a particular rule holds for a given set of inputs. Finally, the inference engine determines the implied fuzzy sets by computing, for the \( i^{th} \) rule \( (j,k,\ldots,l;p,q) \), the implied fuzzy set \( \tilde{B}_q^i \) with the membership function

\[
\mu_{\tilde{B}_q^i}(y_q) = \mu_{i}(u_1,u_2,\ldots,u_n) \cdot \mu_{B_q^i}(y_q).
\]

(4.10)

The implied fuzzy set \( \tilde{B}_q^i \) specifies the certainty level that the output should be a specific crisp output \( y_q \) within the universe of discourse, taking into consideration only rule \( i \).

Finally, the defuzzification process produces an output \( y_q^{\text{crisp}} \) based on the implied fuzzy set \( \tilde{B}_q^i \). The center of gravity (COG) defuzzification technique was utilized here where a crisp output \( y_q^{\text{crisp}} \) is chosen using the center of area and area of each implied fuzzy set, given by

74
where $R$ is the number of rules, $b_i^q$ is the center of area of the membership function of $B_q^p$ associated with the implied fuzzy set $\tilde{B}_q^i$ for the $i^{th}$ rule $(j,k,...,l;p,q)_i$ and

\[
\int y_q \mu_{\tilde{B}_q^i}(y_q) dy_q
\]

(4.12)

denotes the area under $\mu_{\tilde{B}_q^i}(y_q)$.

4.2.3 Rule Base

The expert knowledge for the dynamic behavior of the controlled system is described using linguistic rules of the modus ponens or "If-Then" form as follows:

"If (process state linguistic variable) is (linguistic value), then (control variable linguistic variable) is (linguistic value)"

where the premise is "If (process state linguistic variable) is (linguistic value)" and the consequent is "(control variable linguistic variable) is (linguistic value)". This conditional statement is defined as a fuzzy control rule, which relates the process state in the premise with the control action in the consequent. An implicit sentence connectively links the rules into a rule set, known as the fuzzy rule base.

The process state linguistic variable can be any single or combination of system outputs or states that are inputs to the fuzzy controller denoted as $\tilde{u}_i's$. The control variable linguistic variable can be any single or combination of system inputs that our output from the fuzzy controller denoted as $\tilde{y}_i's$. The proper choice of process states and control variables is essential in the operation of the controller. Engineering knowledge plays an important role in the selection of the linguistic variables, which has a
substantial effect on the performance of the fuzzy controller. In this research, the *process state linguistic variable* are the error and rate of change in error.

The linguistic variables $\tilde{u}_i$'s and $\tilde{y}_i$'s take on *linguistic values* that are used to describe characteristics of the variables. *Linguistic values* are generally descriptive terms such as "positive large", "zero", and "negative small". In this research, the *linguistic values* where quantified as scalar numbers. Let $\tilde{A}_i^j$ denote the $j^{th}$ linguistic value of the linguistic variable $\tilde{u}_i$ define over the universe of discourse $U_i$. Then, the linguistic variable $\tilde{u}_i$ takes on the elements from the set of *linguistic values* denoted by:

$$\tilde{A}_i = \{\tilde{A}_i^j : j = 1,2,...,n_i\}.$$  

Similarly, let $\tilde{B}_i^j$ denote the $j^{th}$ linguistic value of the linguistic variable $\tilde{y}_i$, define over the universe of discourse $Y_i$. The linguistic variable $\tilde{y}_i$ takes on the elements from the set of *linguistic values* denoted by:

$$\tilde{B}_i = \{\tilde{B}_i^j : j = 1,2,...,m_i\}.$$  

We can now illustrate an example of a single-input/single-output (SISO) fuzzy system, which would have the following form:

$$R_1: \text{if } \tilde{u}_i \text{ is } \tilde{A}_i^j \text{ then } \tilde{y}_i \text{ is } \tilde{B}_i^p$$

$$R_2: \text{if } \tilde{u}_i \text{ is } \tilde{A}_i^j \text{ then } \tilde{y}_i \text{ is } \tilde{B}_i^p$$

$$..............$$

$$R_n: \text{if } \tilde{u}_i \text{ is } \tilde{A}_i^j \text{ then } \tilde{y}_i \text{ is } \tilde{B}_i^p$$

where $\tilde{u}_i$ and $\tilde{y}_i$ are the linguistic variables representing the input process state variable and control variable respectively; $\tilde{A}_i^j$ and $\tilde{B}_i^p$ are linguistic values of $u_i$ and $y_i$ in the universes of discourse; and the rule numbers $r = 1, 2, ..., n$.

Several properties must hold in order to have a robust rule-base. The property of *completeness* states that the fuzzy controller must always be able to produce an appropriate control action for every state of the process. The property of *consistency* states that the number of contractions between rules must be minimized.
The development of the rule base for this research relied on the evaluation of the data from the modeling effort described in the previous chapter. From this work, it was determined that torch offset and work angle were to be the control variables, whose physical limits were determined to be +/-2.5 mm and +/-5 degrees respectively before hitting the part. The state variables were determined to be differential toe radius (DTR), rate of change in differential toe radius (DDTR), and differential leg length (DLL). These state and control variables were to be tested in various configurations of single-input/single-output (SISO) and multi-input/single-output (MISO) controllers.

An example of a SISO control system tested utilized DTR as the input and TO as the control variable. By studying the dynamic response surface produced under varying conditions such as the one shown in Figure 28, it was determined that the general relationship of DTR with respect to the two control variables TO and WA was the linear surface shown in Figure 39. In order to construct a rule-base for control, this relationship was simply inverted.
Figure 39: Generic response surface for the effect of work angle and torch offset on the differential toe radius (DTR).

Using five input and output membership functions for the SISO controller discussed here, the membership functions for the differential toe radius (DTR) input with a scaling gain of 5 are:

Skewed Left Large:  
\[ \mu_{u_1}(u) = \begin{cases} 
1, & \text{if } u \leq -5 \\
\max \left[ 0, 1 + \frac{-5 - u}{2.5} \right], & \text{otherwise}
\end{cases} \]

Skewed Left Small:  
\[ \mu_{u_2}(u) = \begin{cases} 
\max \left[ 0, 1 + \frac{u + 2.5}{2.5} \right], & \text{if } u \leq -2.5 \\
\max \left[ 0, 1 + \frac{-2.5 - u}{2.5} \right], & \text{otherwise}
\end{cases} \]
Symmetric: \[ \mu_{u3}(u) = \begin{cases} \max \left[ 0, 1 + \frac{u}{2.5} \right] & \text{if } u \leq 0 \\ \max \left[ 0, 1 - \frac{u}{2.5} \right] & \text{otherwise} \end{cases} \]

Skewed Right Small: \[ \mu_{u4}(u) = \begin{cases} \max \left[ 0, 1 + \frac{u - 2.5}{2.5} \right] & \text{if } u \leq 2.5 \\ \max \left[ 0, 1 + \frac{2.5 - u}{2.5} \right] & \text{otherwise} \end{cases} \]

Skewed Right Large: \[ \mu_{u5}(u) = \begin{cases} \max \left[ 0, 1 + \frac{u - 5}{2.5} \right] & \text{if } u \leq 5 \\ 1 & \text{otherwise} \end{cases} \]

The membership functions for torch offset (TO) control with a scaling gain of 2 are:

Move Left Large: \[ \mu_{y1}(u) = \begin{cases} \max \left[ 0, 3 + u \right] & \text{if } u \leq -2 \\ \max \left[ 0, -1 + u \right] & \text{otherwise} \end{cases} \]

Move Left Small: \[ \mu_{y2}(u) = \begin{cases} \max \left[ 0, 2 + u \right] & \text{if } u \leq -1 \\ \max \left[ 0, -u \right] & \text{otherwise} \end{cases} \]

Don't Move: \[ \mu_{y3}(u) = \begin{cases} \max \left[ 0, 1 + u \right] & \text{if } u \leq 0 \\ \max \left[ 0, 1 - u \right] & \text{otherwise} \end{cases} \]

Move Right Small: \[ \mu_{y4}(u) = \begin{cases} \max \left[ 0, u \right] & \text{if } u \leq 1 \\ \max \left[ 0, 2 - u \right] & \text{otherwise} \end{cases} \]

Move Right Large: \[ \mu_{y5}(u) = \begin{cases} \max \left[ 0, u - 1 \right] & \text{if } u \leq 2 \\ \max \left[ 0, 3 - u \right] & \text{otherwise} \end{cases} \]

The graphical representation of the above membership functions for the input of differential toe radius (DTR) and the output of torch offset (TO) is shown in Figure 40. Note that the outermost membership functions "saturate" for the controllers input (DTR), but are limited on the controllers output (TO). This structure essentially bounds the controllers action for a given limit on the input.
The set of linguistic rules for this controller are as follows:

1. If DTR is Skewed Left Large then TO is Move Right Large.
2. If DTR is Skewed Left Small then TO is Move Right Small.
3. If DTR is Symmetric then TO is Don't Move.
4. If DTR is Skewed Right Small then TO is Move Left Small.
5. If DTR is Skewed Right Large then TO is Move Left Large.

Various combinations in the number of membership functions, scaling gains, and input and output variables were tested with the results discussed in the next chapter.

4.3 Experimental System Hardware

The experimental weld profile control system consisted of a welding robot with controller, welding power supply, laser-sensor, and PC-based weld geometry controller (Figure 41). The welding robot was a standard ABB IRB2400 6-axis articulated arm.
robot with S4 controller interfaced to a Lincoln DC600 power supply. A Servo-Robot M-Spot 90 laser sensor with CAMI II controller was utilized for process sensing. The M-Spot 90 laser sensor was modified to output 100mW visible laser power over its usual 40mW rating in order to increase image processing robustness during welding. The CAMI II sensor controller utilized a TI DSP based computer residing on an ISA bus for image process tasks. A Pentium based PC was added to the ISA bus to house the weld profile controller.

![Diagram of components](image)

**Figure 41: Components of the weld profile control system.**

The distance between the laser line sensed on the plate surface and the welding electrode tip was 54 mm with the torch perpendicular to the plate, or 60 mm with the torch tilted at 8 degrees. This distance is calibrated in the software, and does not affect the feedforward portion of the controller. It does represent a considerable time lag between the welding arc and when the resulting weld that is measured, which in turn
affects the performance of the feedback controller. At a typical welding travel speed of 4.2 mm/sec (10 ipm), this measurement delay is fourteen seconds.

Communication between the weld profile controller (pentium PC) and the laser sensor (DSP) was performed by DMA (direct memory access) through the ISA bus. The WEGE controller also communicated with the S4 robot controller through ethernet. All other communication i.e. S4 robot controller to robot arm, and S4 robot controller to DC600 power supply is performed through proprietary links.

4.4 Experimental System Software

Three separate software programs were developed to run simultaneously on the three separate computers to comprise the Weld Geometry (WEGE) control system. The adaptive fill algorithm, which runs in the feedforward loop, was written in the ADAPT language developed by Servo-Robot and runs on the DSP. The robot program was written in the RAPID language and runs on the robot controller. And the WEGE control program, written in C++, runs on the PC residing on the CAMI II ISA bus.

The RAPID program controls the overall sequence of the welding operation and communicates with the ADAPT program and WEGE program at the appropriate times. The following steps are an outline to the RAPID program flow:

1. Move to approximate end of weld seam.
2. Search for exact end of weld seam.
3. Track the weld joint backwards to the start of the weld seam.
4. Record joint deviations from taught path plan.
5. Record weld seam features such as gaps and tacks.
6. Position torch at start of weld.
7. Start welding.
8. Follow recorded joint path.
9. Perform adaptive fill from recorded joint preview information.
10. Perform WEGE control from real-time sensor feedback.
11. End welding at end of joint.

During the joint finding routine, the RAPID program communicates with the ADAPT program to first find the joint, then search in a given direction for the end of the
joint. The weld joint has to initially be within the sensor field of view for the algorithm to work. The ADAPT program recognizes the T-joint and joint root.

Once the end of the joint has been found, the RAPID program moves the torch and sensor in the perceived joint direction. The RAPID program continuously communicates with the ADAPT program about the location of the joint. If the joint deviates from the pre-programmed starting and stopping trajectories, then corrections are made to the robot path plan to follow the actual joint location. The joint deviation information, along with information about the T-joint itself such as gap area and tack area are stored in a file for every 0.1 inch of weld joint. This information will be replayed during welding in order to perform adaptive fill and joint tracking in a feed-forward manner.

Next the RAPID program positions the weld torch at the start of the weld and begins the welding operation. During welding, the RAPID program reads the feedforward data file every 2.5mm (0.1 inch) and performs joint tracking and adaptive fill operations based on the information saved in the pre-scan. The WEGE program reads in a scan of the weld profile from the laser-sensor, then a fuzzy control loop determines what torch offset and/or work angle should be. Every 2.5mm, the RAPID program polls the WEGE control program for corrective measures to the torch offset and work angle. The average overall control rate is 1.4 hertz.

4.5 Summary

In this chapter we have explained in detail the design of the weld profile control system. This control system utilized an articulated arm welding robot interfaced with a laser-based, structured light machine vision sensor. The laser sensor was utilized in both feedforward and feedback control sub-systems. The feedforward control sub-system integrates the tasks of joint finding, joint tracking, and a modified version of adaptive fill called "modified fill". The feedforward loop controls travel speed, wire feed speed, arc voltage, torch offset, and contact-tip-work-distance. The feedback control sub-system performs the task of weld symmetry control. The feedback loop controls torch offset
and/or work angle. Linear control with heuristics was utilized in the feedforward sub-system while fuzzy control was utilized in the feedback sub-system. In the next chapter, we discuss the performance of this control system through a series of tests and compare the results.
CHAPTER 5

PROFILE CONTROL EXPERIMENTATION

In this chapter, real-time closed-loop control of weld profile is described for the robotic GMAW process. The chapter starts with an overview of the experimental procedure and data formats used during the control experiments. Then, an overview of the performance of the feedforward portion of the control system is given where the control tasks of joint finding, joint tracking, and adaptive fill are analyzed. Finally, the performance of the feedback portion of the control system is analyzed in various configurations of single-input/single-output, and multi-input/single-output control schemes. This symmetry feedback control task is critiqued for reference tracking and disturbance rejection performance under various controller configurations and gains. This portion of the research was conducted in the sponsors' laboratory by the author.

5.1 Experimental Procedure

A non-restrained welding fixture was utilized to hold a T-joint in an 8 to 10 degree downhill flat (1F) position during welding as shown in Figure 42.
All control tests were conducted with the same welding specimens consisting of a T-joint made from two 45.7cm x 6.35cm x 12.7mm (18" x 2.5" x 0.5") A36 grade steel plates. In order to simulate common perturbations encountered during production, two tacks and a gap were placed on each specimen as shown in Figure 43. A 2.5cm long, 5mm leg length tack (1" x 1/5") was used to represent a new standard by which tacking was not to exceed. A 5cm long, 8mm leg length tack (2" x 1/3") represented a common size as seen in production. A 2mm (0.08") tapered gap was placed towards the end of the joint by using an ordinary washer for spacing in order to duplicate a common gap size encountered in production. All welding specimens were prepared with the robotic welding cell, so the size and placement of the tacks and gap were highly repeatable.
All tests were conducted with a standard 1.32mm (0.052") diameter ER70-S3 wire with 90%Argon-10%CO₂ shielding gas. The baseline welding procedure is shown in Table 11, where ranges are given for the wire feed speed, voltage, and travel speed that can vary due to the feedforward modified fill algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Feed Speed</td>
<td>159 to 180 mm/s (375 to 425 ipm)</td>
</tr>
<tr>
<td>Voltage</td>
<td>33 to 36 volts</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>3 to 5.08 mm/s (7 to 12 ipm)</td>
</tr>
<tr>
<td>CTWD</td>
<td>30 mm (1.2 inch)</td>
</tr>
<tr>
<td>Travel Angle</td>
<td>-0.175 rad. (-10 deg.)</td>
</tr>
<tr>
<td>Part Angle</td>
<td>0.14 rad. (8 deg.)</td>
</tr>
</tbody>
</table>

Table 11: Baseline welding procedure used for all control experiments.

Before each test, the standardized welding specimen was placed in the fixture. The robot was then initiated to run the program. The robot would then perform the pre-scan, welding, and post-scan tasks discussed in the previous chapter, while recording various data as described in the following section.
5.2 Experimental Data Format

Three types of data were recorded for each welding test: A pre-scan or "mod" data file format, a control or "dat" file format, and a post-scan or "bin" file format. The "mod" and "dat" files were in standard ASCII format while the "bin" files were encoded binary files.

5.2.1 Pre-scan File Format

The pre-scan or "mod" file was used to store information from the joint tracking and modified fill feedforward control tasks described in the last chapter, at intervals of 2.5mm (0.1 inch) along the weld joint from the start to finish. An example "mod" file is shown in Figure 44 with comments in italic to the right of the percent (%) symbols. The "mod" file is a text file that contains the trajectory coordinates for the welding torch tool center point (TCP) for every point along the weld joint from its start position to the stop position. In addition, for every TCP coordinate, there is a corresponding wire feed speed and travel speed command value for the modified fill program.

```plaintext
%%
VERSION:1
LANGUAGE:ENGLISH
%%
MODULE Path 99
num nSavedStatus=7;
adapt param SavedSettings:=[1.32,95,9.54,10.8,36,19,3,5,0.08]; % modified fill parameters
pose peSavedDisp:=[[-1.3213,-4.24004,-7.13235],[1,0,0,0]];
robot target SavedPath{381}:=
	 [[420.68,1406.29,493.38]]; % starting position of weld in robot coordinates
	 % positional data points between weld start & stop
	 % ending position of weld in robot coordinates
adapt data SavedData{381}:=
	 [[25,0.5,9.3,0,0]] % modified fill parameters for start of weld
	 % modified fill parameters between weld start & stop
	 % modified fill parameters for end of weld
PROC CopyDataPath 99()
nPathStatus:=nSavedStatus;
AdaptSettings:=SavedSettings;
peSavedDisp:=peSavedDisp;
FOR i FROM 1 TO Dim(SavedPath,1)DO
    StoredPath[i]:=SavedPath[i];
    StoredData[i]:=SavedData[i];
ENDFOR
nPthIndex:=Dim(SavedPath,1);
ENDPROC
ENDMODULE
```
5.2.2 Control File Format

The actual weld profile attributes and controller values are recorded in real-time during the feedback weld symmetry control task by the control program into a "dat" file format. An example of the "dat" file format is shown in Figure 45. The first line of the data file contains the type of control, number of membership functions, and gains used in the controller. Then there is a header line that describes the data in each column. Finally, for every control cycle of 0.7 hertz, a line is appended to the data file summarizing:

- inputs to the fuzzy feedback controller - differential toe radius (DTR) and rate-of-change in differential toe radius (DDTR).
- outputs of the fuzzy controller - torch offset (TO) and work angle (WA).
- general weld profile attributes - toe radius A (TRA), toe radius B (TRB), toe angle A (TAA), toe angle B (TAB), leg length A (LLA), leg length B (LLB), convexity or concavity (CVCC), theoretical throat (TT), plate angle (PA), and work angle (WA).

![Figure 45: Example "dat" data file format during welding control.](image)

5.2.3 Post-scan File Format

The surface profiles of each weld were recorded after welding by conducting a post-scan into a binary or "bin" file. This file was created by positioning the laser scanning sensor at the beginning of the weld, and appending the raw surface profile for each scan while moving along the weld to the end. By coordinating the sensor travel speed with the scanning rate, the weld surface was digitized by scans spaced 0.5 mm...
(0.020") apart. For the 0.457 m (18") long plates, this corresponded to approximately 900 scans.

5.3 Weld Profile with No Control

Tests were conducted on the standard T-joint specimen in order to characterize the resulting profile of fillet welds made with the baseline welding procedure used throughout the control experiments. This welding procedure, shown in Table 12, utilized the middle of the ranges indicated for the baseline welding procedure shown in Table 11.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Thickness</td>
<td>12 mm (0.5 inch)</td>
</tr>
<tr>
<td>Wire Feed Speed</td>
<td>169.3 mm/s (400 ipm)</td>
</tr>
<tr>
<td>Voltage</td>
<td>31.5 volts</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>4.2 mm/s (10 ipm)</td>
</tr>
<tr>
<td>CTWD</td>
<td>30 mm (1.2 inch)</td>
</tr>
<tr>
<td>Travel Angle</td>
<td>-0.175 rad. (-10 deg.)</td>
</tr>
<tr>
<td>Part Angle</td>
<td>0.14 rad. (8 deg.)</td>
</tr>
<tr>
<td>Torch Offset</td>
<td>0 mm</td>
</tr>
<tr>
<td>Work Angle</td>
<td>0.785 rad. (45 deg.)</td>
</tr>
</tbody>
</table>

Table 12: Welding procedure used for no-control test.

An example of the resulting weld profile made with only joint finding and joint tracking feedforward control is shown in Figure 46. No modified fill feedforward control or weld symmetry feedback control was utilized during these tests. The disturbing inputs of a 5mm tack, 8mm tack and 2mm gap are also indicated on each plot.

The impact of both tacks can be seen in the plot of additive toe radius (ATR) where the mean toe radii decrease near the tacks. The additive leg lengths (ALL) also increase as well as the throat of the weld (TT) because of the tacks. The modified fill feedforward control should increase the overall mean toe radii while minimizing the effects from tacks.

The resulting weld symmetry can be determined by the plots of differential toe radius (DTR) and differential leg lengths (DLL). Both are consistently negative indicating the weld is skewed to one side. The sum-of-square error for DTR is 49.4 mm².
The designed weld symmetry feedback control should minimize any differences in weld symmetry, causing the DTR and DLL to average around zero.

5.4 Joint Finding and Joint Tracking Feedforward Control

While it was difficult to quantify the feedforward controller's performance for joint finding and joint tracking, the effects of torch to joint misalignment on the resulting weld symmetry were demonstrated in order to illustrate the effect of the misalignment in the absence of feedforward control. An example of the magnitude of deviation of the weld joint root is shown in Figure 47. This information is contained within the "mod" file that is recorded during the weld pre-scan. The robot trajectories of the welding torch tool center point (TCP) for two successive welds in the experimental fixture used in this research are shown. The plots show the TCP in world coordinates, in units of millimeters. While the weld start region was essentially the same for both welds, the
joint root and weld stop points were not the same, with a maximum difference of 5mm. Successive experimentation determined that 5 mm was the maximum path deviation encountered, with deviations on the order of 1 to 2 mm most common. This deviation most commonly occurred near the weld stop region. It was concluded that these deviations occur because of distortion caused by the tacking sequence of the T-joints prior to welding.

![Figure 47: Deviation of weld joint root for two successive welds in the same fixture.](image)

A step test was designed in order to demonstrate the effect of misalignment between the weld joint and welding torch on the resulting weld profile. Here, a baseline welding procedure, shown in Table 13, was utilized to weld on a standard T-Joint with no gaps or tacks.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Thickness</td>
<td>12 mm (0.5 inch)</td>
</tr>
<tr>
<td>Wire Feed Speed</td>
<td>169.3 mm/s (400 ipm)</td>
</tr>
<tr>
<td>Voltage</td>
<td>31.5 volts</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>4.2 mm/s (10 ipm)</td>
</tr>
<tr>
<td>CTWD</td>
<td>30 mm (1.2 inch)</td>
</tr>
<tr>
<td>Travel Angle</td>
<td>-0.175 rad. (-10 deg.)</td>
</tr>
<tr>
<td>Part Angle</td>
<td>0.14 rad. (8 deg.)</td>
</tr>
</tbody>
</table>

Table 13: Welding procedure used for torch offset step test.

During the test, initially the torch offset was 0, then after 0.025 meters of travel, the torch offset was instantaneously changed to +1.5 mm. After another 0.25 meters of travel, the offset was changed back to zero. Then torch offset was moved in the opposite direction to -1.5 mm, then back to zero. This cycle was repeated for torch offset increments of +/- 3 mm, and finally, +/- 4.5 mm. The results, shown in Figure 48, demonstrate the effect of torch offset on the weld symmetry in terms of the differential leg length (DLL) and differential toe radius (DTR) that are plotted versus torch offset along the weld joint.
Figure 48: Difference in leg lengths (DLL) and toe radii (DTR) for various torch offsets (TO).

It can be seen in Figure 48 that at 0 mm offset, the weld is somewhat asymmetric as previously discussed. Also, the 0.025 meter distance for each step change is just long enough to allow the weld pool to become stable, i.e. the resulting weld shape seems to achieve steady-state. The first 0.1 meters of weld where the torch offset was oscillated to +/- 1.5 mm should be ignored. The test weld symmetry started positive, then at +1.5 mm offset the differential leg length and differential toe radius went in opposite directions, followed by a 0 mm offset where the symmetry was negative. These discrepancies are probably due to the initial startup conditions of the weld test where the balance between heat input and cooling rate of the weld had not reached a steady-state.

The effect of torch offsets of +/- 3 mm and +/- 4.5 mm on the weld symmetry is dramatic. The effect of misalignment of the welding torch with the weld joint is that the weld symmetry changes accordingly. Therefore, a misalignment on the order of the diameter of the welding electrode, 1.32 mm in this case, causes a change in weld
symmetry. The feedforward control functions of joint finding and joint tracking are important to minimize the effect of production disturbances such as joint fit-up and fixturing on weld symmetry. Because this function is performed in the feedforward portion of the control, other production disturbances such as arc blow, contact-tip wear, and wire cast and helix cannot be compensated. Feedback control of weld symmetry allows for compensation of these disturbances.

5.5 Modified Fill Feedforward Control

The effects of the modified fill feedforward control on the fillet weld with disturbing inputs is demonstrated next. The standardized T-joint containing a 5mm tack, 8mm tack, and 2mm gap were utilized for this experiment along with the baseline welding procedure outlined in Table II. Comparisons for each weld profile attribute are shown for welds made with no adaptive fill, standard adaptive fill, and modified fill. The effect of feedforward fill control is discussed for toe radius, leg length, theoretical throat, and convexity/concavity.

5.5.1 Effect on Toe Radius

The effect of feedforward fill control on the weld toe radius is shown in Figure 49 (ATR) and Figure 50 (DTR). Both the adaptive fill and modified fill tend to reduce the effect of the 5mm and 8mm tacks on reducing additive toe radius. This can be seen in Figure 49 where the top plot shows a definite reduction in additive toe radius as the weld goes over the tacks. The effect of a gap on the additive toe radius is negligible. This figure also shows an improvement in the modified fill algorithm over the adaptive fill algorithm in maximizing the toe radii. While the mean additive toe radius with adaptive fill was slightly less than 5mm, the modified fill algorithm averaged 7.5mm. The feedforward fill control appears to have no effect on differential toe radius as shown in Figure 50. While the tacks appear to definitely skew the weld symmetry with no fill control, the effect of fill control is negligible. In addition, tacks sometimes skew the weld asymmetry from one side to the other as seen in the modified fill plot for DTR in Figure
50 (bottom plot). Here, as the weld goes over the 5mm tack, the weld shifts from one dominant or larger toe to the other.

Figure 49: Effect of feedforward fill control on additive toe radius (ATR).
Figure 50: Effect of feedforward fill control on differential toe radius (DTR).

5.5.2 Effect on Leg Length

The effect of feedforward fill control on the leg lengths is shown in Figure 51 and Figure 52. With no feedforward fill control, the top plot of Figure 51 shows the additive leg length increases over tacks and decreases slightly over the gap. This is because no adjustments in weld reinforcement are made as the weld goes over these disturbances, which effectively decrease and increase required deposition. The standard adaptive fill algorithm does well at regulating the weld leg lengths over the disturbances. The modified fill algorithm, whose primary goal is to maximize additive toe radii, does not regulate the leg lengths as well as the adaptive fill algorithm. This tradeoff was acceptable because the primary goal of the control system is to maximize the additive toe radius.
Figure 51: Effect of feedforward fill control on additive leg length (ALL).

The effects of fill control on weld symmetry with respect to the leg lengths is shown in Figure 52 where differential leg lengths are plotted. There appears to be no significant effect of utilizing feedforward fill control on weld symmetry. This result was expected as the modified fill feedforward control was designed to maximize toe radii only, and not effect weld symmetry. The task of weld symmetry control was designed into the feedback control scheme.
Figure 52: Effect of feedforward fill control on differential leg length (DLL).

5.5.3 Effect on Theoretical Throat

The effect of feedforward fill control on the weld theoretical throat is shown in Figure 53. Intuitively, the weld theoretical throat should behave similarly to the leg lengths with respect to changing joint volumes and deposition areas. With no fill control, the weld throat increases in size over the tacks due to the constant rate of deposition, and reduces in size slightly over the gap. With adaptive fill, a relatively constant throat is achieved despite the disturbances. Again, the modified fill algorithm does not regulate deposition; its effect on the theoretical throat is similar to that on the additive leg lengths.
Figure 53: Effect of feedforward fill control on theoretical throat (TT).

5.5.4 Effect on Concavity/Convexity

Finally, the effect of feedforward fill control on the weld concavity or convexity is shown in Figure 54. Here, negative numbers reflect the amount of reinforcement in the convexity and positive numbers reflect the amount of concavity. With no fill control, the tacks clearly make the weld convex where the weld is otherwise flat. The adaptive fill feedforward control is consistent, in that it makes the entire weld convex. Unfortunately, a convex weld is less conducive to having large weld toe radii. The modified fill control produces a weld that is slightly concave, which is more conducive to large weld toe radii as shown above in section 5.5.1.
Figure 54: Effect of feedforward fill control on concavity/convexity (CVCC).

5.6 Differential Toe Radius Feedback Control using Torch Offset

Tests were conducted on the standard T-joint specimens in order to determine the ability of the controller to compensate for fluctuations in differential toe radius via control of torch offset as a single-input, single-output controller configuration. During all tests with the weld symmetry feedback controller, the feedforward controller with modified fill was also enabled. Twenty-four tests were conducted varying the torch-offset gain, differential toe radius gain, and number of membership functions of the fuzzy controller. The test matrix, along with the mean-square error of differential toe radius, is shown in Table 14. Note that the "#MF" refers to the number of membership functions (fuzzy rules) used on both the inputs and outputs.

Initially, the control gains were set heuristically, with the torch offset gain set equal to the torch offsets' physical limit of -1.3 mm, the differential toe radius gain set at
1, and the number of membership functions set at 15 for both inputs and outputs. Control tuning experimentation was then carried out varying each gain to determine the gain that minimized the sum-of-square-error of the differential toe radius. After the first seven tests, it was determined the torch offset gain had to be reversed so a gain of 1.3 was used. After further experimentation, a torch offset gain of 0.4 was found to best minimize the sum-of-square error.

<table>
<thead>
<tr>
<th>Test ID#</th>
<th>TO Gain</th>
<th>DTR Gain</th>
<th>#MF</th>
<th>DTR SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>dtr_to1</td>
<td>-1.3</td>
<td>1</td>
<td>15</td>
<td>64.7</td>
</tr>
<tr>
<td>dtr_to3</td>
<td>-1.3</td>
<td>1</td>
<td>15</td>
<td>67.9</td>
</tr>
<tr>
<td>dtr_to4</td>
<td>-0.3</td>
<td>1</td>
<td>15</td>
<td>64.5</td>
</tr>
<tr>
<td>dtr_to5</td>
<td>-0.5</td>
<td>4.5</td>
<td>15</td>
<td>65.6</td>
</tr>
<tr>
<td>dtr_to6</td>
<td>-0.5</td>
<td>4.5</td>
<td>15</td>
<td>61.7</td>
</tr>
<tr>
<td>dtr_to7</td>
<td>-0.5</td>
<td>4.5</td>
<td>15</td>
<td>89.2</td>
</tr>
<tr>
<td>dtr_to8</td>
<td>0.5</td>
<td>4.5</td>
<td>15</td>
<td>55.7</td>
</tr>
<tr>
<td>dtr_to9</td>
<td>1.3</td>
<td>4.5</td>
<td>15</td>
<td>48.7</td>
</tr>
<tr>
<td>dtr_to10</td>
<td>0.5</td>
<td>4.5</td>
<td>25</td>
<td>34.2</td>
</tr>
<tr>
<td>dtr_to11</td>
<td>0.3</td>
<td>3</td>
<td>25</td>
<td>21.1</td>
</tr>
<tr>
<td>dtr_to12</td>
<td>0.3</td>
<td>3.5</td>
<td>25</td>
<td>20.9</td>
</tr>
<tr>
<td>dtr_to13</td>
<td>0.5</td>
<td>3.5</td>
<td>25</td>
<td>17.3</td>
</tr>
<tr>
<td>dtr_to14</td>
<td>0.3</td>
<td>3.5</td>
<td>15</td>
<td>25.7</td>
</tr>
<tr>
<td>dtr_to15</td>
<td>0.4</td>
<td>3</td>
<td>15</td>
<td>28.7</td>
</tr>
<tr>
<td>dtr_to16</td>
<td>0.4</td>
<td>3</td>
<td>15</td>
<td>43.0</td>
</tr>
<tr>
<td>dtr_to17</td>
<td>0.2</td>
<td>1.5</td>
<td>5</td>
<td>26.2</td>
</tr>
<tr>
<td>dtr_to18</td>
<td>0.6</td>
<td>4.5</td>
<td>25</td>
<td>35.9</td>
</tr>
<tr>
<td>dtr_to19</td>
<td>0.2</td>
<td>3</td>
<td>15</td>
<td>32.2</td>
</tr>
<tr>
<td>dtr_to20</td>
<td>0.6</td>
<td>3</td>
<td>15</td>
<td>31.7</td>
</tr>
<tr>
<td>dtr_to21</td>
<td>0.4</td>
<td>3</td>
<td>25</td>
<td>41.8</td>
</tr>
<tr>
<td>dtr_to22</td>
<td>0.4</td>
<td>3</td>
<td>5</td>
<td>36.2</td>
</tr>
<tr>
<td>dtr_to23</td>
<td>0.4</td>
<td>1.5</td>
<td>15</td>
<td>26.1</td>
</tr>
<tr>
<td>dtr_to24</td>
<td>0.4</td>
<td>4.5</td>
<td>15</td>
<td>17.7</td>
</tr>
</tbody>
</table>

Table 14: Test matrix for feedback symmetry control using DTR and TO.

Examples of the experimental results for differential toe radius control using torch offset are shown in Figure 55 (test dtr_to19), Figure 56 (test dtr_to11), and Figure 57 (test dtr_to24). These figures show the effects of different gains on the sum-of-square
error in differential toe radius. The top plot in each figure shows the differential toe radius as measured from the start of the weld with the actual measurement shown as a data points, and a moving average shown as the line. The location of the tacks and gap are also indicated. The sum-of-square error in differential toe radius is calculated from the actual data points and is indicated in each figures' caption. The bottom plot of each figure shows the torch offset command signal generated from the feedback controller.

Figure 55: Differential toe radius feedback control using torch offset with a DTR gain of 3 and TO gain of 0.2, showing a high DTR SSE of 32.2 mm² (test dtr_to19).
Figure 56: Differential toe radius feedback control using torch offset with a DTR gain of 3 and TO gain of 0.3, showing a lower DTR SSE of 21.1 mm$^2$ (test dtr_to11).
Figure 57: Differential toe radius feedback control using torch offset with a DTR gain of 4.5 and TO gain of 0.4, showing minimal DTR SSE of 17.7 mm² (test dtr_to24).

Experimentation on the differential toe radius gain found that a value of 4.5 worked well. Finally, it was determined that 15 membership functions on both the input and output were appropriate. With a torch offset gain of 0.4, differential toe radius gain of 4.5, and 15 membership functions, a minimal sum-of-square error value of 17.7 mm² was achieved (test dtr_to24).

5.7 Differential Toe Radius Feedback Control using Work Angle

Tests were conducted on the standard T-joint specimen in order to determine the controller's ability to compensate for fluctuations in differential toe radius via work angle. A total of four tests were conducted varying the Work Angle gain, with all other fuzzy controller parameters set at a nominal levels that gave acceptable performance from the initial tuning tests. The test matrix, shown in Table 15, emphasized tuning the work angle gain. The best work angle gain of 2 was found to minimize the differential toe
radius sum-of-square error to 7.6 mm², roughly half that of the best control found for torch offset control. The resulting experimental plot for this setting is shown in Figure 58.

<table>
<thead>
<tr>
<th>Test ID#</th>
<th>WA Gain</th>
<th>DTR Gain</th>
<th>#MF</th>
<th>DTR SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>dtr_wa1</td>
<td>-0.5</td>
<td>3</td>
<td>15</td>
<td>81.8</td>
</tr>
<tr>
<td>dtr_wa2</td>
<td>0.5</td>
<td>3</td>
<td>15</td>
<td>14.9</td>
</tr>
<tr>
<td>dtr_wa3</td>
<td>3</td>
<td>15</td>
<td></td>
<td>10.1</td>
</tr>
<tr>
<td>dtr_wa4</td>
<td>2</td>
<td>3</td>
<td>15</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Table 15: Test matrix for feedback symmetry control using DTR and WA.

Figure 58: Differential toe radius control using work angle with a DTR gain of 3 and WA gain of 2 (test dtr_wa4).
5.8 Rate of Change in Differential Toe Radius Feedback Control using Torch Offset

Tests were conducted on the standard T-joint specimen in order to determine the controller's ability to compensate for fluctuations in differential toe radius and rate-of-change of differential toe radius, via torch offset. Nine tests were conducted varying the gains for DTR, DDTR, and TO as shown in Table 16. This test matrix of gains was determined by centering the matrix around the best baseline gains determined in previous experiments for differential toe radius and torch offset.

<table>
<thead>
<tr>
<th>Test ID#</th>
<th>TO Gain</th>
<th>DTR Gain</th>
<th>DDTR Gain</th>
<th>#MF</th>
<th>DTR SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ddtr_t01</td>
<td>0.2</td>
<td>0.5</td>
<td>0.05</td>
<td>15</td>
<td>39.5</td>
</tr>
<tr>
<td>ddtr_t02</td>
<td>0.6</td>
<td>0.5</td>
<td>0.05</td>
<td>15</td>
<td>32.66</td>
</tr>
<tr>
<td>ddtr_t03</td>
<td>0.2</td>
<td>0.5</td>
<td>0.1</td>
<td>15</td>
<td>10.1</td>
</tr>
<tr>
<td>ddtr_t04</td>
<td>0.6</td>
<td>0.5</td>
<td>0.1</td>
<td>15</td>
<td>30.8</td>
</tr>
<tr>
<td>ddtr_t05</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>15</td>
<td>17.9</td>
</tr>
<tr>
<td>ddtr_t06</td>
<td>0.6</td>
<td>0.5</td>
<td>0.2</td>
<td>15</td>
<td>44.6</td>
</tr>
<tr>
<td>ddtr_t07</td>
<td>0.2</td>
<td>1</td>
<td>0.05</td>
<td>15</td>
<td>35.7</td>
</tr>
<tr>
<td>ddtr_t08</td>
<td>0.2</td>
<td>1</td>
<td>0.1</td>
<td>15</td>
<td>14.6</td>
</tr>
<tr>
<td>ddtr_t09</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>15</td>
<td>35.3</td>
</tr>
</tbody>
</table>

Table 16: Test matrix for feedback symmetry control using DTR, DDTR, and TO.

Experimental results show that the sum-of-square error for differential toe radius was minimal with a TO gain of 0.2, DTR gain of 0.5, and a DDTR gain of 0.1. The resulting DTR SSE was 10.1 mm² with the control plots shown in Figure 59. The plot shows more oscillations and variance in the DDTR measurement over the DTR measurement, resulting in use of a control gain lower than that for DTR.
Figure 59: Differential toe radius and rate of change feedback control using torch offset with a DTR gain of 0.5, DDTR gain of 0.1, and TO gain of 0.2 (test ddtr_to3).

5.9 Differential Leg Length Feedback Control using Torch Offset

Tests were conducted on the standard T-joint specimen in order to determine the controller's ability to compensate for fluctuations in differential leg length while welding in the flat (1F) position, via torch offset. This configuration is still essentially a weld symmetry control problem, utilizing differential leg length instead of differential toe radius as the feedback variable. Five tests were conducted, shown in Table 17, varying the work angle and torch offset gains, with all other fuzzy controller settings set at a nominal level that gave acceptable performance. The torch-offset gains were based on best results from previous experimentation.
The results show that similar performance was achieved for all gains tested in the experimental matrix. The lowest sum-of-square error for differential leg length achieved was 21.0 mm². These results cannot be compared with the sum-of-square errors achieved with differential toe radius control because of the difference in magnitude of the measurement variable. An example of the results obtained for differential leg length feedback control is shown in Figure 60 where a differential leg length gain of 0.4 and torch offset gain of 4.5 was utilized.

Table 17: Test matrix for feedback symmetry control using DTR and TO.

<table>
<thead>
<tr>
<th>Test ID#</th>
<th>TO Gain</th>
<th>DLL Gain</th>
<th>#MF</th>
<th>DLL SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>dll_to1</td>
<td>0.2</td>
<td>3</td>
<td>15</td>
<td>36.2</td>
</tr>
<tr>
<td>dll_to2</td>
<td>0.4</td>
<td>3</td>
<td>15</td>
<td>25.1</td>
</tr>
<tr>
<td>dll_to3</td>
<td>0.6</td>
<td>3</td>
<td>15</td>
<td>28.3</td>
</tr>
<tr>
<td>dll_to4</td>
<td>0.4</td>
<td>1.5</td>
<td>15</td>
<td>32.0</td>
</tr>
<tr>
<td>dll_to5</td>
<td>0.4</td>
<td>4.5</td>
<td>15</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Figure 60: Differential leg length feedback control using torch offset and a DLL gain of 4.5 and TO gain of 0.4 (test dll_to5).

5.10 Differential Leg Length Feedback Control in the Horizontal (2F) Position using Torch Offset

Tests were conducted on the standard T-joint specimen put into the horizontal or 2F position as shown in Figure 61. The controller was set up to monitor differential leg length and control torch offset. Three tests were conducted, utilizing a set of gains determined from previous experimentation in the flat (1F) position. The same gains, namely a torch offset gain of 0.6, and a differential leg length gain of 4.5, were utilized for all three experiments to test repeatability (shown in Table 18).
Figure 61: Welding test conducted in the 2F position.

<table>
<thead>
<tr>
<th>Test ID#</th>
<th>TO Gain</th>
<th>DLL Gain</th>
<th>#MF</th>
<th>DLL SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>hdll_to1</td>
<td>0.6</td>
<td>4.5</td>
<td>15</td>
<td>26.7</td>
</tr>
<tr>
<td>hdll_to2</td>
<td>0.6</td>
<td>4.5</td>
<td>15</td>
<td>44.0</td>
</tr>
<tr>
<td>hdll_to3</td>
<td>0.6</td>
<td>4.5</td>
<td>15</td>
<td>43.9</td>
</tr>
</tbody>
</table>

Table 18: Test matrix for feedback symmetry control in the horizontal (2F) position using DLL and TO.

The results for the sum-of-square error for differential leg length were similar for two of the three experiments, averaging around 44. The initial test had a significantly lower sum-of-square error at 26.7 mm². An example of the control experiment result is shown in Figure 62 where the plot of differential leg length shows the horizontal leg is always slightly larger than the vertical leg. This is evident from the positive differential leg length which is calculated as the horizontal leg minus the vertical leg. This result was expected, even with control, because welds made in the horizontal position tend to sag due to gravity, causing the horizontal leg to lengthen and the vertical leg to shrink. The measurement of differential leg length also appeared to have more outliers than in the previous tests.
5.11 Differential Leg Length Feedback Control in the Horizontal (2F) Position using Work Angle

Similar tests were conducted on the standard T-joint specimen put into the horizontal or 2F position, except the controller was set up to monitor differential leg length and control work angle. After some initial experimentation, two tests were conducted with the same gains, namely a work angle gain of 5, and a differential leg length gain of 4.5. The resulting sum-of-square error for differential leg length, shown in Table 19, is higher than similar tests conducted controlling torch offset.
<table>
<thead>
<tr>
<th>Test ID#</th>
<th>WA Gain</th>
<th>DLL Gain</th>
<th>#MF</th>
<th>DLL SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>hdll wa1</td>
<td>5</td>
<td>4.5</td>
<td>15</td>
<td>63.0</td>
</tr>
<tr>
<td>hdll wa2</td>
<td>5</td>
<td>4.5</td>
<td>15</td>
<td>48.3</td>
</tr>
</tbody>
</table>

Table 19: Test matrix for feedback symmetry control in the horizontal (2F) position using DLL and WA.

Review of the control data, shown in Figure 63, reveals that the controller quickly saturated the work angle to its limit. Therefore, for work angle to have similar effectiveness as torch offset as a control variable, a larger degree of freedom would be required in order for work angle to compensate for fluctuations in the differential leg length.

![Graph showing differential leg length feedback control in the horizontal (2F) position using work angle with a DLL gain of 4.5 and WA gain of 5 (test hdll_wa2).](image)

Figure 63: Differential leg length feedback control in the horizontal (2F) position using work angle with a DLL gain of 4.5 and WA gain of 5 (test hdll_wa2).
5.12 No Control in the Horizontal (2F) Position

For comparison with the previous two tests, welds were made on the standard T-joint specimen in the Horizontal 2F position order to characterize the resulting profile of fillet weld. An example of the resulting weld profile made with only joint finding and joint tracking feed-forward control in the 2F position shown in Figure 64. No modified fill feedforward control or weld symmetry feedback control was utilized during these tests.

Because 2F welds are made in the horizontal position, the liquid weld pool tends to sag during solidification towards the horizontal plate. This causes the resulting weld profile to skew asymmetric as seen in Figure 64. This is indicated in the plots of differential toe radius and differential leg length. The sum-of-square error for DLL is 133 mm² and DTR is 124.8 mm². In addition, the weld is highly convex as seen in the plot of convexity/concavity (CVCC) as a negative number.
5.13 Discussion

Tests were conducted in order to characterize the resulting profile of fillet welds made with the baseline welding procedure on the standard T-joint specimen used throughout the control experiments. These tests demonstrated the effect of tacks and gaps as disturbing inputs on the resulting weld profile and symmetry. With no modified fill control, the mean additive toe radius is small (~5 mm) while tacks cause a large decrease. This decrease can also be seen in additive leg length and weld throat. These tests also demonstrated that the weld symmetry typically skews to one side as seen in the differential toe radius and differential leg length.

While it is difficult to quantify the performance of the joint finding and joint tracking feedforward control, the effect of no control was demonstrated on the resulting weld profile. Joint finding and tracking compensate for changes in joint location due to
fixturing or distortion by adjusting the torch trajectory via torch offset and contact-tip-work-distance. Without this compensation, any variation in fixturing or part distortion will cause weld asymmetry as demonstrated in plots of differential toe radius and differential leg lengths.

The performance of the modified fill feedforward control algorithm was demonstrated by comparing its effect on the resulting weld symmetry with no adaptive fill control, and standard adaptive fill control. It was shown that modified fill has advantages over standard adaptive fill when the objective is to maintain a minimal amount of weld reinforcement while producing optimal weld toe radii in the presence of gaps and tacks.

The performance of various weld symmetry feedback control schemes was quantified and demonstrated. Different combinations of measuring differential toe radius and rate-of-change in differential toe radius while controlling torch offset and/or work angle were tested. No single combination appeared to be advantageous over the others, with the best results from each combination providing similar performance. A comparison of results for various control schemes of differential toe radius is shown in Table 20. There are advantages to using some form of weld symmetry feedback control over conventional open-loop control in that the resulting weld profile is symmetric and consistent.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Controlled Variable</th>
<th>DTR SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTR</td>
<td>None</td>
<td>49.4 mm²</td>
</tr>
<tr>
<td>DTR</td>
<td>TO</td>
<td>17.3 mm²</td>
</tr>
<tr>
<td>DTR</td>
<td>WA</td>
<td>7.6 mm²</td>
</tr>
<tr>
<td>DDTR/DTR</td>
<td>TO</td>
<td>10.1 mm²</td>
</tr>
</tbody>
</table>

Table 20: Comparison of sum-of-square error (SSE) for differential toe radius (DTR) under several control schemes.

Finally, tests were also conducting controlling differential leg length (DLL) in the flat (1F) position, and horizontal (2F) position with no part angle. Using the feedback
variable of DLL appears to perform acceptable as a means of controlling weld symmetry. Trying to control DLL in the horizontal 2F position was more challenging than controlling DTR in the 1F position due to the tendency of the weld pool to sag. The performance of controlling symmetry in the 2F position was limited because of the limited range of the control variables torch offset and work angle. Results from several control schemes are shown in Table 21.

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Controlled Variable</th>
<th>DLL SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLL</td>
<td>None</td>
<td>133 mm^2</td>
</tr>
<tr>
<td>DLL</td>
<td>TO</td>
<td>26.7 mm^2</td>
</tr>
<tr>
<td>DLL</td>
<td>WA</td>
<td>48.3 mm^2</td>
</tr>
</tbody>
</table>

Table 21: Comparison of sum-of-square error (SSE) for differential leg length (DLL) in the horizontal 2F position under several control schemes.

The majority of these tests were conducted with simple SISO (single-input/single-output) controllers. One case of a MISO (multi-input/single-output) controller was tested using rate of change of differential toe radius as the additional input. Further experiments utilizing various MISO and MIMO (multi-input/multi-output) configurations should be examined in order to increase the robustness of the control.
CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Summary of Contributions

A real-time, closed-loop control approach can improve the fatigue properties of weldments, increase service life, and decrease design requirements by robustly controlling the shape of single-pass fillet welds. No previous attempt has been reported for real-time control of weld profile with the objective of improving the fatigue life of a weldment. Common production perturbations and disturbances which affect weld profile such as gaps, tacks, joint-to-torch alignment, joint-to-torch distance, and torch orientation can be compensated for by incorporating feedforward and feedback closed-loop control.

The contributions from this work can be logically broken down into three categories: modeling and system identification, control system development, and control system performance. Briefly, contributions are summarized as follows:

- An accurate mathematical representation of the influence of key welding parameters on the weld profile has been developed for a limited experimental region.
- A unique hybrid, robotic GMAW control system integrated with laser-based machine vision technology has been developed and demonstrated.
- Experimentation with the weld profile control system determined that robust control of weld shape for single-pass fillet welds can be achieved in the presence of common production perturbations and disturbances.
6.1.1 Modeling and System Identification

The following conclusions can be drawn from the research on experimental modeling of weld profile:

- Screening experiments allowed the range of each variable to be reduced significantly by identifying an optimal region for maximizing weld toe radii while minimizing the chance of producing an unacceptable weld.
- The experimental matrix based on a D-optimal experimental design allowed reasonably accurate regression models to be constructed with minimal experimental tests.
- Analysis of variance techniques identified key variables that affect the weld profile. Specifically, factors that significantly affect the toe magnitude of the weld toe radius include voltage, wire feed speed, travel speed, gap, plate thickness, and travel angle. Factors that significantly affect the symmetry of the weld toe geometry are torch offset and work angle.
- A full quadratic model developed for additive toe radius based on twelve welding parameters could explain 85% of the variability in the test data. A full quadratic model based on twelve welding parameters developed for differential toe radius explained 72% of the variability in the test data.
- Simulation of weld profile through dynamic response surfaces derived from the full quadratic models indicated that the welding procedures could be further optimized to maximize weld toe radii.

6.1.2 Control System Development

The following conclusions can be drawn from the development of an experimental weld profile control system:

- This application of a hybrid control system required integration of multi-input/multi-output, feedforward and feedback control loops to perform joint tracking, adaptive fill, torch height regulation, and weld symmetry control.
• A modified version of adaptive fill called "modified fill" was developed in order to minimize interference between simultaneous feedforward and feedback control loops.

• Complex weld profile features such as weld symmetry and weld toe geometry were addressed as reference tracking and disturbance rejection control problems.

6.1.3 Control System Performance

The following conclusions can be drawn from the experimentation of the weld profile control systems performance:

• The toe radii of welds produced with only joint finding and tracking feedforward control and no modified fill or weld symmetry feedback control are consistently skewed with the larger toe radius on the continuous plate side. The presence of disturbing inputs such as gaps and tacks either magnify or reverse the weld asymmetry. It is theorized that this phenomena is due to heat flow from the weldment into the workpiece.

• Welds produced with nominal welding procedures and no modified fill feedforward control exhibit small mean additive toe radius (~ 5 mm) while the presences of tacks cause a large decrease. This decrease can also be seen in additive leg length and weld throat.

• Modified fill outperforms standard adaptive fill when the objective is to maintain a required amount of weld reinforcement while producing optimal weld toe radii in the presence of disturbances such as gaps and tacks. This is because modified fill was designed to maximize weld toe radius while maintaining weld reinforcement while adaptive fill maximizes productivity while maintaining weld reinforcement.

• Joint finding and tracking compensate for changes in joint location due to fixturing or distortion by adjusting the torch trajectory via torch offset and contact-tip-work-distance. Without this compensation, any variation in fixturing
or part distortion will cause weld asymmetry through differential toe radius and differential leg lengths.

- Once optimized, all forms of weld symmetry feedback control investigated here proved advantageous over conventional open-loop control. While all combinations of control inputs and outputs performed well at regulating weld symmetry, the combination of measuring differential toe radius (DTR) and controlling work angle (WA) performed the best with a DTR SSE of 7.6mm². This results was six times better than the uncontrolled case whose DTR SSE was 49.4mm².

- Feedback control in the horizontal 2F position measuring differential leg length (DLL) proved advantageous over no control at minimizing weld asymmetry. Feedback control systems based on regulating work angle (WA) or torch offset (TO) had a DLL SSE of 48.3mm² and 26.7mm² respectively. This was a two to four times improvement over the non-controlled case where the DLL SSE was 133mm².

6.2 Suggestions for Future Work

Improvements in process sensing and integration of control system technologies are necessary in order to evolve weld profile control into an industrially robust system. These developments are needed in machine vision, control system integration, and the control algorithms, each of which will be addressed separately in the following sections. Once these developments are achieved, this overall control approach could be extended to more welding applications such as multi-pass welds and out-of-position welds.

6.2.1 Machine Vision

While laser-based, structured light machine vision technology is well developed for robotic welding applications, further improvements in processing speed, resolution, image quality and feature detection should be made. Improvements in processing speed are straightforward and come naturally with innovations in computer hardware.
Increased efficiency of image processing algorithms also enhances processing speed. Resolution was limited because of the large field of view required to measure large fillet welds. This system was rated 90mm field of view providing 0.7mm resolution. Higher resolutions could enhance the robustness of the image processing algorithms. Because of the nature of the gas metal arc welding process, which characteristically emits smoke and spatter, image quality will always be poor and thus improvements in the robustness of the image processing algorithms must be made. Improvement in the robustness of feature detections, such as in the measurement of weld toe radius, would greatly enhance the robustness of the control system by providing stable real-time measurements.

6.2.2 Integration of Control Technologies

The experimental system integrated the machine vision processor, weld geometry control system, robotic control system, and welding power supply through existing communication interfaces and protocols. This proved detrimental to the overall control rate (several hertz) and limited real-time access to the controlled variables. By modifying and further developing the communication interfaces and protocols, higher control rates could be achieved which would improve overall control system performance. The ideal scenario would embed the vision system and weld geometry controller processors on the same computer bus as the robot manipulator. While this approach would reduce system hardware and overall complexity, it would require a large amount of software development.

6.2.3 Control Algorithms

Finally, improvements in the weld symmetry feedback control algorithms should be investigated to improve the robustness of the control system. This includes investigation of a SIMO control system that senses differential toe radius and controls both torch offset and work angle simultaneously and a MIMO control system that adds rate of change in differential toe radius to the SIMO system mentions above. Also, the investigation of utilizing supervised learning such as a fuzzy model reference learning control algorithm (FMRLC) or adaptive fuzzy control could improve the systems ability
to adapt to time varying parameters such as welding wires with different casts or changes in part fitup.
REFERENCES


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