DEVELOPMENT OF A SYNCHRONIZED, HIGH-SPEED, STEREOVISION SYSTEM FOR IN SITU WELD POOL MEASUREMENT

by

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ABSTRACT

Many different types of systems have been developed to measure the geometry of the weld pool in Gas Metal Arc Welding. Stereovision has yet to make a significant impact as a sensor for measuring three-dimensional pool geometry. Currently, most systems rely on two-dimensional information for controlling the shape of the weld. Existing systems that can measure the three-dimensional structure of the pool are slow. The research presented in this thesis outlines the development of a stereovision system for measuring three-dimensional pool geometry. This system consisted of two major components, the stereovision system itself and a synchronized triggering system for the cameras. A basic system was developed to show the feasibility of this approach and to provide a basis for future development. Results from this basic system were evaluated to determine improvements for each system component. Images were collected of 19 welds with varying torch speed, standoff distance, and torch angle. Each weld was cut, encapsulated in epoxy, polished, and etched to measure the cross-sectional properties of the bead. Images from each weld were used to obtain the three-dimensional characteristics of the pool. The pool geometry was then related to the bead geometry. Both the pool geometry and bead geometry were related to the weld parameters to provide a basic knowledgebase for a control scheme to be developed in the future. The measured pool width and height correspond directly to the bead width and height. The system is not effective at estimating bead toe-angle, although an inverse relationship was found. The width to length ratio of the pool has a linear correlation to penetration depth, and the width to height ratio of the pool has a parabolic association to penetration width. Width is determined by the torch speed. Height is influenced by torch speed and torch angle. Toe-angle is affected by torch angle. Penetration depth is dependent on torch angle and torch speed.
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CHAPTER 1
INTRODUCTION

1.1 Thesis Motivation

The automation of welding processes allows manufacturers to produce higher quality parts in less time than if they use a human welder. In some applications, such as submerged welding of pipes for oil rigs in the ocean, it is impossible to have a human present to produce the needed weld. Robotics has provided a much greater ability to manipulate manufacturing processes. However, robots are designed to receive specific commands from an operator, and do not automatically adapt to the varying conditions of different applications. To achieve such adaptability, sensor and control systems are needed to close the loop on process control. Several such systems have been developed for automating the weld process (discussed in the next section). However, the rate of development of sensor systems to provide control systems with adequate process measurements necessary for such adaptability has been much slower. For human welders, vision is the dominant sensor for assessing welding performance. Machine stereovision has yet to make a significant impact as a sensor for welding automation and process control. The main objective of this research is to show the utility of stereovision as a sensor for welding automation.

This research aims to address two specific problems related to automated welding. Currently, no system exists that can measure the entire three-dimensional surface of the weld pool at a particular instant in time. This is a critical component for automating the welding process since this is the primary information that a human welder uses to control the quality of the weld. Additionally, the three-dimensional structure of the weld pool directly determines the three-dimensional structure of the weld bead, which is the core
factor in determining the physical quality of the weld. The second problem related to automated welding systems is that they typically rely on the weld line being flat (in-position) in order to remove the effect of gravity on the weld pool. Welding in-position is not always possible in industrial applications as some parts must be kept in place (in situ) due to other manufacturing constraints. In general, out-of-position welding processes have not been sufficiently studied to provide the characterization data necessary in order to automate the out-of-position welding process. This research concentrates on discovering features of the weld pool (generated as part of an out-of-position weld) that can be measured via a stereovision system and characterizing those features versus adjustable weld process parameters.

To approach these problems, this research is divided into three primary categories. The first is the development of the stereovision system, which entails developing software that can compute the three-dimensional structure of the weld pool. A first-pass stereovision system was developed and initial results were obtained. These results were analyzed to determine necessary improvements for the system. The development of the stereovision system addresses the problem of being able to obtain the full three-dimensional structure of the weld pool at a particular instant in time. The second category is the development of a synchronized triggering system for the cameras. This system is needed to synchronize the cameras with one another and with the current pulses of the welder to capture images at the times when the lighting from the arc is optimal. Again initial results were obtained and analyzed to determine how to optimize the triggering scheme. The final category involves the characterization of weld pool and bead parameters as related to the welding parameters. Once the system was fully optimized, data was collected for varying welding parameters. Relationships were then obtained between the welding parameters and the pool and bead shape. The bead characteristics were determined using another measurement system that is known to produce accurate results, thus providing a basis for comparison. This characterization addresses the need for a study of out-of-position welding parameters as they pertain to the
structure of the weld pool and bead. Specific objectives and approaches for each subsystem are detailed in the subsequent chapters of this document.

The motivation of this research is to develop the backbone for a real-time, out-of-position, weld pool measurement system. In this case, real-time means that the weld pool can be measured while a weld is being generated and information from the measurement system can be used to adjust parameters of the weld process. The system developed through this research is for non-real-time weld pool measurement, meaning that image data is collected for a given weld process and then processed after the weld has been generated. This allows for the optimization of the stereovision system as a useful tool for in situ weld pool measurement and will provide a proven starting point for the future development of out-of-position, real-time, in-process weld control.

1.2 Background Information

This section describes the work of other persons or organizations in developing sensors for weld pool monitoring. There are four primary types of sensors that monitor similar characteristics as the system presented in this document. All of these categories are defined as non-destructive measurement techniques since the sensors do not alter the physical structure of the weld pool. Radiographic, ultrasonic, infrared, and vision sensors are discussed in this chapter. Vision and infrared sensors are the most commonly used sensors today, taking the place of the older radiographic and ultrasonic sensors. Radiographic sensors use gamma-rays or X-rays to detect defects in the microstructure of the solidified weld bead. Ultrasonic sensors use acoustic waves to detect defects forming in the weld pool, which become trapped in the weld bead. Defects in the weld bead are defined as small, unintentional inclusions in the weld material that can alter the structural quality of the weld. Too many defects can reduce the yield strength, ultimate tensile strength, and fatigue life of a part. Therefore, it is advantageous for a system to be capable of detecting defects in-process and then change welding parameters to reduce the
amount of defects. Infrared sensors can be used to measure base metal temperature and to obtain a thermal profile of the weld pool. The base metal temperature is related to the depth of penetration of the weld, which is another major factor in determining the structural properties of the welded specimen [1]. A thermal profile of the weld is useful for studying phase transformation phenomena in the weld pool [2]. The microstructure (and thus the material properties) of the weld bead is determined by the how the deposited weld material is heated and cooled [3]. Thus a direct measurement of the weld pool’s thermal profile can be used to predict and control the microstructure of the weld bead. Additionally, the temperature gradient across the weld pool can be used to determine the length and width of the weld pool [2]. Vision sensors can be used to directly obtain geometric information about the weld pool [4]. Simple systems are able to measure the length and the width of the weld pool while more advanced sensors can reconstruct the third dimension (height) of the weld pool geometry. Three-dimensional measurement systems are less-common since they are often more difficult to implement; however, the variation of the height of the weld pool in time can be used to estimate physical properties about the weld such as the penetration depth [5]. Geometrical measurements of the weld pool provide information about the shape of the solidified weld bead, which also contributes to the strength and quality of the welded part. In general, the shape of the solidified weld bead, the thermal properties of the deposited material, and the amount of defects in the weld bead will determine the residual stress concentrations present in the weld bead. If these stress concentrations are not controlled properly, the welded specimen will experience a reduction in performance with respect to material failure, which reduces the overall safety of the manufactured part. Therefore, by predicting and controlling properties of the weld pool, the quality of the part being manufactured can be controlled. Out-of-position welding is characterized by the non-flat orientation (with respect to the ground) of the welding specimen. This orientation allows gravity to affect the properties of the weld pool, whereas an in-position system simplifies the role of gravity. As previously mentioned, out-of-position welding process properties
have not been adequately studied. As a result, sensor systems for monitoring out-of-position welding processes have not been explored. It is conceivable that the current sensor systems could be adapted to explore out-of-position welding properties, but conversely some complications could arise. The best example of this is submerged arc welding (SAW) for pipelines on deep sea oil rigs. The main complication is that the part is oriented vertically and the weld line could be at nearly any imaginable orientation. This means that the measurement system must be able to adapt to the position of the weld and be capable of retaining its ability to measure features in the weld.

1.2.1 Radiographic Sensors

Radiographic sensing of the weld involves detecting changes in gamma-ray or X-ray beam absorption to detect defects in a weld. The defects are detected due to the fact that the absorption coefficient (the fraction of energy absorbed per unit distance the energy passes through in a medium) for a defect is different from the surrounding metal. Although radiographic sensors were only widely used for weld inspection prior to the 1960’s, there are still some applications where radiographic methods are used, e.g. they are still widely used for pipeline weld validation. The original radiographic process involved taking images on film, which prevented the use of these sensors in real-time [2]. The film in conventional radiography is highly susceptible to noise, and many times the contrast in the image was too low to detect defects. Recent advances in information technology have led to the digitization of radiographic film through the use of scanners in order to process the images to improve the ability to detect defects in welds [6]. Additionally, developments in the last decade have replaced the film with an electronic sensor, which makes radiography a more viable alternative for real-time weld pool measurement [7]. The main disadvantage of radiographic sensing is the cost of the required equipment. Additionally, since these sensors use X-rays, there are health and safety risks that must be taken into consideration, e.g. exposure to radiation [2].
Furthermore, real-time applications of radiography are constrained by the slow feedback to the control architecture since defects can only be detected in the solidified weld bead.

1.2.2 Ultrasonic Sensors

The next generation of sensors used the ultrasonic response of the weld pool to determine the characteristics of welds. Conventional ultrasonic sensors require a point of contact with the test material, which is not suitable for real-time weld monitoring. However, early work in contact ultrasonic sensors demonstrated the feasibility measuring features in molten material using ultrasonics. There are two primary methods for removing the need to have the sensor in contact with the weld pool by using a laser ultrasonic sensor. In both methods, a laser is pulsed on the specimen, which causes ultrasonic waves to propagate through the weld pool. The two methods differ in how these waves are detected [2].

The first technique is to use a laser interferometer to receive the photo-acoustic signals in the weld pool. The time between the impingement of the pulse and the collection of the ultrasonic waves is measured. The velocity of sound in the material depends on the distribution of temperature. By scanning the input laser across the surface, a profile of the weld pool can be obtained [8]. One hindrance to this method is that laser interferometers require a smooth, shiny surface in order to function properly. Such a surface is not common in arc welding [2].

The second technique used to receive the ultrasonic signals that have propagated through the weld pool was developed to eliminate the need for a smooth and shiny surface. This method uses an electromagnetic-acoustic transducer (EMAT) to detect the ultrasonic vibrations in the electromagnetic field caused by the incident laser. Again, the profile of the weld pool is obtained by moving the input laser position over the surface [9]. This method of receiving the ultrasonic signals is much more reliable, but it still has limitations. There are two disadvantages of the EMAT system. The first is that it needs
to be close to the surface of the weld pool, which means that it must be capable of operating in elevated temperatures. Furthermore, the ultrasonic wave generated by the laser travels in every direction, which results in a low signal to noise ratio [2].

One method to improve the signal to noise ratio in the detected ultrasonic waves is to use a laser phased array. A phased array consists of multiple input laser sources that are delayed in time. This allows the ultrasound field to be amplified in a particular direction. The interference pattern from the multiple inputs is measured to determine the characteristics of the weld pool geometry [2].

1.2.3 Infrared Sensors

There are two types of infrared sensing that have been explored in the past few years. The first type is a point infrared sensor that measures the broadband infrared emissions from the weld material. The second kind of infrared instrumentation system consists of an infrared camera that can observe the heat distribution of the weld pool [2].

Several studies have shown that a front-side, point infrared sensor can be used to detect the status of penetration in the weld. The point sensor is used to detect the base metal temperature, which is affected by the weld pool penetration depth. Therefore, associations between the base metal temperature and the penetration depth have been made [1]. One complicating factor of a point infrared sensor is that the radiation from the arc and from the hot electrode makes it difficult to measure the base metal temperature accurately [10]. Another issue with point infrared sensors is that they cannot be used to measure the weld pool geometry since they only detect broadband infrared emissions.

Infrared vision systems have been used for weld pool analysis since the early 1980’s. Since the sensor is a camera, a three-dimensional thermal profile of the weld pool can be obtained (two-dimensional in space, one-dimensional in temperature). Typical systems use an edge-detection image processing algorithm to find the length and the width of the weld pool based on the temperature gradient present in the acquired images. In early
implementations, penetration was estimated from the width of the weld pool. This assumes that there is a constant proportion between the pool width and the penetration, which may not be true for a particular weld process [2]. Further research using thermal imaging has shown that the entire thermal profile of the weld pool changes based on the thickness of the plate and the penetration depth. However, the complex nature of the coupled thermal and geometrical attributes of the system makes accurate relationships between thermal image results and bead quality more difficult to model [3].

1.2.4 Vision Sensors

CMOS and CCD vision sensors are widely regarded as the best sensors for automated welding. The principle behind this statement is that skilled human welders are able to control weld bead quality by observing the shape of the weld pool and the dynamics of the welding process. This indicates that there must be a direct relationship between the three-dimensional shape of the weld pool and the quality of the finished bead. The two broad categories of vision systems are two-dimensional and three-dimensional weld pool sensing systems. These categories can also be subdivided by the method with which the images are acquired.

The first category of two-dimensional vision-based weld pool sensing systems is characterized by the presence of a pulsed illumination source (typically a laser). The camera is synchronized with the pulses from the illumination unit, which is much brighter than the arc light. Several independent research efforts have shown that the reflection from the weld pool is significantly less than that of the solidified bead, thus the high contrast allows for the two-dimensional weld pool geometry to be observed. Saima Maqbool, et al. [11], studied the relationship between the weld pool width and the torch speed, arc current, and plate thickness. Jing Zhao, et al., used a closed-loop control system based on the detection of edge points in the weld pool image to control the width of the weld pool [12]. Y. M. Zhang, et al., demonstrated the ability to estimate the weld
penetration by creating a two-dimensional model of the weld pool from extracted image data [4]. Hong, et al., showed that a neurofuzzy control logic scheme could be used to achieve desired two-dimensional weld pool geometry [13]. Saeed, et al., illustrated how to configure the laser and camera system for obtaining optimal images [14]. Hu, et al., exhibited the ability to use computer vision to analyze laser surface modifications (changing the physical properties of the surface material while leaving the bulk material unchanged) on solidified weld beads [15].

In the second category of two-dimensional vision-based weld pool sensing systems, the laser illumination unit is replaced by an optical band-pass filter in front of the camera. The filter blocks out wavelengths of light associated with the arc and allows wavelengths associated with the thermal radiance of the weld pool to pass through the filter to the camera. These systems are somewhat less common than the laser illuminated systems, but they have provided insight into the relationship between the weave position and the presence of arc in the image [16].

All of these systems characterize penetration depth information from the two-dimensional shape of the weld pool, which has been extensively studied by Y. M. Zhang at the University of Kentucky [4]. However, there is still a need for the development of three-dimensional measurement systems in order to fully classify weld processes since the height of the weld pool determines properties such as toe-angle. Additionally, in mass production applications, the height of the weld pool might need to be controlled to reduce the amount of material that is deposited in order to help reduce costs associated with material waste. Other aspects of interest in the welding process include the tie-in to the base-metal, complete fusion, no slag entrapment, and prevention of porosity.

Most three-dimensional vision-based weld pool sensing systems use structured light to illuminate the weld pool surface. Structured light is defined as a light source that produces a particular pattern of lines, triangles, or grids. Based on the known structure of the incident light, three-dimensional information can be triangulated to determine the weld pool geometry. This is much like removing a camera from a stereo vision system
and replacing it with a specific light source [5]. Two different forms of structured light are used in weld pool sensing systems. The first is a projected sheet of light, where the light illuminates a stripe of the area-of-interest. To obtain the full structure of the surface the stripe is scanned across the entire area-of-interest. The second is a scanned point beam, where a small point of light is scanned over the area-of-interest in multiple sweeps. The sheet of light approach is the most common due to its low cost and ease of implementation even though the results are inferior to the scanned point beam approach. The projected sheet of light is more susceptible to noise from the arc than the scanned point beam and the preprocessing time of the projected sheet of light is larger than that of the scanned point beam method (more area means more processing time) [17].

The other form of three-dimensional weld pool sensing involves stereovision. This research demonstrates the ability to use stereovision for three-dimensional weld pool measurement. At this time, only one other such system is known to exist. This system uses a single CCD camera and a biprism to generate a stereo pair from which three-dimensional information can be reconstructed [18]. This work appears to be very preliminary as no journal or conference proceedings on this work have been found. The hardware system used in this approach seems to be slow as the results obtained do not show the entire three-dimensional surface of the weld pool, but only cross-sections of the weld pool with respect to width and height. The biprism method is also less accurate since there is potential for distortions in the biprism.

1.3 Thesis Organization

This document is arranged to show the development process for a synchronized, high-speed, stereovision system for in situ weld pool measurement. It is organized to show the development of each subsystem separately and then discusses the integration of the subsystems to obtain the complete sensor system. Each chapter is introduced by describing the requirements and objectives for the design of each particular subsystem.
The introduction also describes how the remainder of the chapter is structured. An explanation of the methodologies used to design and test the system are included within every chapter. Each chapter contains a discussion of intermediate results for the system at that particular stage of development. This entails describing the specific needs for the improvement of the system based on the intermediate results analyzed within the chapter. The chapter concludes by specifying and analyzing the improvements made to the system. A discussion of characterization results for the stereovision system as a weld pool measurement sensor is provided in the final chapter along with recommendations for future research in this area. Figure 1.1 shows a flowchart of the thesis organization.

A compact-disc is included with this thesis, which contains all image processing code, referenced movies, instructions for setting up the system, explanations of the nuances of the system, this document, and any other files needed to use the system.
CHAPTER 2

EXPERIMENTAL SETUP

2.1 Introduction

This chapter outlines the experimental setup for the system by discussing the equipment used in this research and how the system was configured. Specifically, explanations are included of how the welding apparatus, cameras, frame-grabbing boards, and the triggering application are set up. The physical and electrical structure used in the characterization experiments (Chapter 5) will not deviate greatly from the arrangement described within this chapter. Explanations of the experimental setup later in this document will focus only on modifications to this setup.

2.2 Welding Apparatus

Welds are produced using a Fanuc ArcMate 100iB, six degrees of freedom, robotic welder with a Lincoln Power Wave 455 power source, a Tregaskiss torch, 0.035 ER70S-6 Lincoln Electric SuperArc wire, and a Fanuc ArcMate 100iB System R-J3 control unit. The ArcMate control unit is used to control the motion of the Fanuc robot and the torch speed during welding. The Lincoln power source provides the current and voltage for the welding process. The Tregaskiss torch controls the wire feed speed and gas flow. The initial setup uses a shielding gas that is 75 percent Argon and 25 percent Carbon Dioxide, which is a typical configuration used in many welding processes. The welding process of the system is classified as the Gas Metal Arc Weld pulsed (GMAW-p) process since the current used to generate the arc is pulsed rather than being constant. The frequency of these pulses is around 120 Hz. The power supply provides a constant-voltage and pulses
the current delivered to the arc. The welds generated by the system are bead-on-plate
welds with the plate mounted in a vertical (downhill) position (out-of-position). Figure
2.1 shows the Fanuc ArcMate 100iB Robotic Welder used throughout this research. The
Fanuc ArcMate 100iB System R-J3 control unit is shown in Figure 2.2. Figure 2.3 is a
picture of the Lincoln Power Wave 455 power supply and Figure 2.4 shows the spool of
0.035 ER70S-6 Lincoln Electric, SuperArc wire.

Figure 2.1 Fanuc ArcMate 100iB Robotic Welder

Figure 2.2 Fanuc ArcMate 100iB System R-J3 Control Unit
2.3 High-Speed Cameras

The camera system is at the heart of this research. The stereo cameras are the sensors used to study the weld pool shapes as a function of time and to analyze the independently controllable weld parameters (e.g. arc current, torch speed, etc.) and dependent (uncontrollable) weld parameters (e.g. ambient temperature, humidity, etc.). By using a high-speed (500 frames per second at 1024 by 1280 pixels), stereovision system, three-dimensional weld pool morphology can be obtained at a data rate that allows direct
measurements of shape, oscillations, and potentially the convective surface flow of material in the weld pool. Image pairs are collected using two, Basler Vision Technologies, A504k, high-speed, digital cameras. These cameras use a CMOS sensor to acquire grayscale images. Basler also provides a camera customization utility (CamReg) that can be used to set the exposure mode, exposure time, and the area-of-interest. Each camera is powered by a 12 volt, DC power supply. Two Camera Link cables connect each camera to a frame-grabber board, which is described below. Due to the signal drive strength of the cameras, the length of these cables must not exceed 5 meters. The cameras have several modes of operation. The only mode used in this research was the “ExSync, Programmable” mode. In this mode, the camera begins to acquire an image as soon as the external trigger is detected. Exposure time is determined by a programmable timer. Figure 2.5 is a timing diagram for the ExSync, Programmable mode.

![ExSync Timing Diagram](http://www.baslerweb.com/popups/396/A500k_Users_Manual.pdf)

**2.4 Camera Mounting and Shielding**

In future research, the cameras will be mounted on a second robot arm for experimental purposes. Ideally, the cameras (or fiberoptics running to the cameras) would be mounted at the end of the robotic welder’s arm. However, in order to avoid additional variations in the setup during the development of this system, the cameras are mounted on a tripod that stands next to the bench where the welds are generated. It is
important to design the mounting structure such that it keeps the alignment between the cameras constant to reduce the chance that the cameras would need to be re-calibrated between experiments. The mounting structure consists of three rectangular aluminum plates. There are two small plates for providing a center-mount for each camera and a long plate, which mounts to the tripod and to which the cameras are mounted.

Due to the volatile nature of the GMAW-p process, it is important to protect any sensor close to welding apparatus. A simple cover was designed to prevent spatters and sparks from damaging the lenses of the cameras. This cover fits onto the mounting structure for the cameras (Figure 2.6, bottom half). The cover is comprised of a piece of aluminum bent into an “open-box” shape (Figure 2.6, 2nd from top) and a rectangular piece of acrylic (Figure 2.6, top) that is used for the front end. The acrylic provides a clear medium for the cameras to look through and is close enough to the camera lenses that it is not in the focal range of the camera.

Figure 2.6 Camera Mounting and Shielding System
A photograph of the actual camera mounting equipment is displayed in Figure 2.7. Figure 2.8 is a photograph of the camera shield. Two thin glass plates are attached to the acrylic using paperclips. This provides a low-cost, replaceable barrier that prevents spatters from the welder from damaging the acrylic.
2.5 Frame-Grabbing Boards

Each camera is connected to a DataCube MaxRevolution board via two Camera Link cables. Each MaxRevolution board is installed in a PCI slot on a host computer running the Microsoft’s Windows 2000 Professional operating system. Due to limitations of the acquisition software provided by DataCube, only one board is allowed in each host computer. The DataCube boards have 256 MB of onboard Double-Data Rate (DDR) memory for image storage and each also includes a Xilinx Virtex II field-programmable gate array (FPGA), which can be used for future real-time image processing. DataCube also provides a configuration package called VLL Toolbox that controls how the boards function. VLL Toolbox can be used to display the current image from the camera in order to simplify the setup process. Through trial and error, it was determined that the hardware configuration for the PC’s required version 3.0.0.2 of the driver and version 1.0 of the VLL Toolbox application. Finally, the MaxRevolution boards have a set of input/output pins that are used to trigger the camera attached to each board.

2.6 Triggering to Synchronize Cameras

An external triggering signal must be used in order for the cameras to acquire images at the same moment in time. Synchronization between the cameras is essential for accurate stereo matching. A computer running MATLAB’s xPC Target application is used to generate a square wave at CMOS voltage levels. This computer contains a PCI-DAS1602/12 (Measurement Computing Corporation) analog to digital card, which connects to two input/output boards. In the initial setup, two twisted-pair wires run from the output terminal of the output board to “Auxiliary One” input of each MaxRevolution board. The triggering signal arrives at both DataCube boards simultaneously, and is immediately passed on to the cameras, thereby synchronizing the cameras with one another.
2.7 Physical Layout of System

All equipment should be placed out of the reach of the robotic welder. The Fanuc 100iB has a maximum reach of about 1.4 meters and can rotate six joints at a minimum of 250 degrees. Therefore, there is a circular region in which users should avoid placing unnecessary items or themselves. There is a steel bench next to the welder that holds the plate in place. The tripod is placed such that the view direction is nearly orthogonal to the plate being welded. The System R-J3 control unit, Lincoln Power Wave 455 power source, and the shielding gas bottle are placed well outside the reach of the robot. The xPC Target computer sits on a table between the robotic welder and the camera host computers. Figure 2.9 shows an overhead view of the physical setup described above. This figure is not drawn to scale.

Figure 2.9 Physical Layout
2.8 Electrical Layout of System

The system requires several electrical connections in order to function properly. Figure 2.10 is a diagram of the electrical layout of the system. Both Camera Link cables must be connected correctly to establish communication between the host computer and the camera. The Camera Link connections are denoted as CL1 and CL2 for the two ports on the cameras and the boards. Each camera is powered by a 12 volt, DC power supply that is connected to a standard electrical outlet. The xPC Target computer’s PCI-DAS1602/12 board is connected to the input and output boards via a 100-pin ribbon cable. In the initial setup, only the output board is used. Channels one and two (pins one and two) from the output board are used to send a CMOS level square wave to each of the MaxRevolution boards. Two channels were used in order to provide a strong enough signal to each of the MaxRevolution boards. The MaxRevolution boards also require a neutral connection from the output board, which is provided by pin 50.
2.9 Summary

This chapter has outlined the hardware components used throughout this research. Descriptions of the functions and setup of each device were provided. An explanation of the physical setup of the system showed how the cameras were mounted, protected, and oriented with respect to the other system equipment. Additionally, the electrical layout of the system was described to show the connections necessary for system operation. This chapter provided the information needed for future researchers to set up a system of their own.
CHAPTER 3
STEREOVISION SYSTEM

3.1 Introduction

This chapter is focused on describing the development of the stereovision system. A preliminary system was developed to obtain initial results, which could be used to develop requirements for improving system performance. Background information about the fundamentals of stereo computer vision is also provided. The main objective for this stage of the research was to demonstrate that stereovision could be used to measure three-dimensional weld pool characteristics. Secondary objectives included finding the best exposure time, determining what could and could not be seen well by the cameras, and examining the accuracy of the stereo matching results. The methods used to acquire and process the images are detailed in this chapter and an assessment of the system’s performance at this stage of development is included. Improvements to the stereovision system are described and analyzed. The first improvement was to change the stereo matching algorithm to provide a more reliable match score and to reduce the image processing time needed to compute the disparity map. This routine was then optimized by varying the size of the match window and the disparity range. Sub-pixel disparity interpolation was added to smooth the computed three-dimensional structure of the weld pool. Interpolation and outlier removal functions were added to the stereo matching program as well. To improve the visualization of the weld pool in three-dimensions, a more sophisticated rendering method was used. Additionally, the three-dimensional coordinates returned by the stereo triangulation program were transformed to the coordinate space of the plate in order to simplify length, width, and height measurements.
3.2 Fundamentals of Stereo Computer Vision

The fundamental idea behind stereo computer vision is that depth information can be computed when two points of reference are given for a single three-dimensional point. The method used to compute the depth of a point is called triangulation. Figure 3.1 shows a simple illustration of how triangulation works.

To understand triangulation, a physical relationship is derived between the camera positions ($C_1$ and $C_2$), the point $P$ in three-dimensional space, the length $b$ of the baseline (the vector connecting the two cameras), the perpendicular distance ($D$) from the point $P$ to the baseline, and the angles ($\Theta_1$ and $\Theta_2$) formed by the vectors pointing from $C_1$ and $C_2$ to the point $P$ intersecting with the baseline vector. The baseline distance and the angles $\Theta_1$ and $\Theta_2$ are known and the vector $a$ and perpendicular distance $D$ are unknown. Two independent equations are required to solve for these two unknowns. These
equations are provided by Pythagorean geometry which states that the tangent of the angle between the hypotenuse and one of the legs of a right triangle is equal to the ratio between the leg of the triangle opposite to the angle and the leg of the triangle adjacent to the angle. The system of equations needed to solve for the depth ($D$) is given by Equation 3.1. The solution to this system of equations is shown in Equation 3.2.

$$a \cdot \tan \theta_1 = D = (b-a) \cdot \tan \theta_2$$

(3.1)

$$D = \frac{b \cdot \tan \theta_1 \cdot \tan \theta_2}{\tan \theta_1 + \tan \theta_2}$$

(3.2)

The stereo computer vision process is slightly more complicated than this model since the images contain a two-dimensional array of points instead of a single point of reference. However, the depth computation is much simpler.

The epipolar plane contains the three-dimensional point of interest, the two optical centers of the cameras, and the image points of the point of interest in the left and right images. An epipolar line is defined by the intersection of the epipolar plane with image planes of the left and right cameras. The epipole of the image is the point where all the epipolar lines intersect [19]. Figure 3.2 shows a diagram of epipolar geometry for image planes contained in a common plane parallel to the baseline.

Figure 3.2 Epipolar Geometry [19]
To derive the relationship between the image points and the perpendicular depth from the baseline to the three-dimensional point \( P \), one must revisit the triangulation diagram from Figure 3.1 (shown again in Figure 3.3). The focal length of the cameras \( f \), the angles \( \Theta_1 \) and \( \Theta_2 \), the camera center points \( (c_1 \) and \( c_2) \) in the image planes \((IP_1 \) and \( IP_2) \), the image points \( p_1 \) and \( p_2 \), and the horizontal distance \((v_1 \) and \( v_2) \) between the image points and the camera center image point for each image are known. This leaves the perpendicular distance \( D \) from the baseline to the point \( P \) as the only unknown.

The disparity \( d \) between the left and right image points is defined as the difference between \( v_2 \) and \( v_1 \). In stereovision systems, the disparity is not directly known, but can be found through the process of stereo matching (discussed later in this chapter). Using the law of similar triangles (based on the angles of two triangles being the same and the sides of the two triangles are scalar multiples of each other), a simple relationship between the disparity and the perpendicular depth \( D \) can be obtained (Equation 3.3). In
this equation, $D$ is the depth, $b$ is the baseline distance, $f$ is the focal length, and $d$ is the disparity.

$$D = \frac{b f}{d}$$  \hspace{1cm} (3.3)

### 3.2.1 Rectification

Stereo rectification is a warping of the images to remove the effects of differing internal and external camera geometries before sending the images to the stereo matching routine. Figure 3.4 shows the epipolar geometry for a stereovision system prior to image rectification. After rectification, the epipolar lines are parallel to the image rows and the epipoles are on the line at infinity (Figure 3.5) [20].

![Figure 3.4 Epipolar Geometry prior to Rectification](image)
The rectification algorithm used in this research was provided in the Camera Calibration Toolbox discussed earlier [21]. The rectification code was modified to properly rectify narrow field of view images as are used in this research. Rectified images are then sent to the stereo processing routine.

3.2.2 Stereo Matching

Stereo matching is the process by which a match score is computed for a given pixel location in either the right or left image coordinate frame. There are several methods for how the match score is computed. In area-based stereo matching methods such as the one used in this research, small image regions (or pixel neighborhoods) are matched between the two images. In left-to-right matching, one region is held fixed in the left image, and the other is shifted to positions along the epipolar line (a shift along the x direction in rectified image pairs). The disparity is defined as the shift in x from the left to the right image. In right-to-left matching the roles of the left and right image are
reversed. The stereo matching algorithm outputs a disparity map, which contains the two-dimensional image location of each pixel and the disparity where the stereo matching score was best. The match score used in the initial system computes the sum of squared differences between the left and right images (with the mean of the images subtracted out) across the match window and normalizes this sum by the variance of the window. This match score is commonly known as the Zero mean Sum of Squared Differences method (ZSSD). The subtraction of the mean pixel intensity from the images compensates for radiometric distortion (where the intensities for the same points in the left and right images are offset from one another by a constant and/or a gain factor). In the preliminary stereo matching system used for this research, the ZSSD score is also normalized by the variance of the window, which is more characteristic of a normalized cross-correlation match metric. This normalization further compensates for a gain offset between the two images of the stereo pair [22]. In this type of stereo matching scheme, the minimum match score indicates the best match. Therefore, the disparity map contains the disparity number that corresponds to the minimum match score at each pixel location [19]. To provide a way to detect invalid disparity numbers, disparity maps are computed both left-to-right and right-to-left. The disparity values of the area outside the valid stereo matching region are set to have a value of infinity. If the stereo matching algorithm fails to find a minimum match score less than infinity, the disparity is set to infinity to indicate an invalid match. Additionally, a pixel location might also have a disparity of infinity if the variance in the match window for that pixel is too small, or if the disparities from left and right disparity maps do not agree. The final disparity map is sent to a stereo triangulation routine provided in the Camera Calibration Toolbox, which computes the depth of each pixel in the map. In the disparity map for the right-to-left match, a larger disparity indicates a greater depth from the camera. All image processing was programmed and executed in MATLAB using the Image Processing Toolbox.
3.2.3 Auto-Cropping Algorithm

One way to reduce image processing time in stereo matching algorithms is to reduce the image area over which the algorithm must be applied. An auto-cropping algorithm was developed to automatically select a region of interest for the stereo matching code to process. This routine converts the rectified stereo image pair into black and white images using a threshold value. Since the weld pool is much larger and brighter than anything else in the image, a connected-component labeling system is used to find the object in the image that has the largest area. The bounding box for this object gives the image region that should be sent to through the stereo matching algorithm. Additionally, a cross-correlation function is applied to the cropped stereo image pair to find the best alignment between the two images. This alignment determines the starting disparity for the stereo matching algorithm.

3.2.4 Individual Camera Calibration

In order to obtain accurate results from image processing, the cameras must be calibrated. The first step for calibrating the cameras is to find the intrinsic parameters of each camera individually. Intrinsic parameters are properties that are unique to each camera mostly due to small variations in manufacturing. The intrinsic parameters include the principle point, scale factors, focal length, and lens distortion factor. The principal point is defined as the “intersection of the optical axis with the image plane” [19]. There are two scale factors which give the physical dimensions of the horizontal and vertical pixels. Focal length is defined as the “distance from the optical center to the image plane” [19]. Finally, the lens distortion factor accounts for radial and tangential imperfections in the lens.

The next step for the individual camera calibration is to compute the extrinsic properties of the camera. Extrinsic parameters specify the position and orientation of the camera in the world coordinate frame. The extrinsic parameters include a translation
vector and a rotation matrix. The translation vector gives the position of the camera in three-dimensional space and the rotation matrix gives the orientation of the camera [19].

Typical calibration software uses a three-dimensional model-to-image matching algorithm where the three-dimensional model is a planar checkerboard pattern of known dimensions. The horizontal and vertical dimensions of each square on the calibration target are known, which allows the computation of the intrinsic and extrinsic parameters for the individual cameras. In order to prevent inaccuracies between calibrations, the cameras should be placed where they will be for taking measurements and the calibration target should be as close to the measurement target as possible. Additionally, the calibration target should be oriented in multiple positions that span the three-dimensional space that the objects of interest will occupy.

The Camera Calibration Toolbox for MATLAB, developed by Jean-Yves Bouguet at CalTech [21], was used to calibrate the cameras for this research. The calibration target used was a black and white checkerboard pattern where each square was 4.5mm by 4.5mm. The calibration target was then taped to a compact-disc to provide a surface that would not distort the dimensions of the checkerboard pattern (Figure 3.6). 15 images were taken at a variety of orientations and input into the Camera Calibration Toolbox, which returns the intrinsic and extrinsic parameters.

The final step for calibrating the cameras is to find the relationship between the locations of the cameras in the three-dimensional world. Since each camera has been calibrated, its location in the world coordinate frame is known. Therefore, the Camera Calibration Toolbox combines the results from the individual calibrations to determine the rotation and translation between the two cameras [21]. These dimensions are necessary to triangulate depth information from stereo image pairs.
3.3 Methodology

The cameras remained in their position after the calibration. The baseline distance between the cameras was approximately 10cm and the distance from the cameras to the plate was about 58cm. To retain a constant distance from the cameras to the location of the weld on the plate, the plate is shifted between each weld instead of changing the coordinates of where robotic welder will weld. This means that in three-dimensional space, the welder always welds at the same location, but the placement of the plate on the welding bench is varied so that sequential welds do not overlap.

The camera acquisition software provided by DataCube (provided on CD) simply captures images until the onboard memory is filled. The board acquires an image each time the external trigger signal is detected since the cameras had been configured to wait for a triggering signal. Therefore, the camera acquisition program was executed on each camera host computer and then the triggering signal was generated from the xPC Target computer. The triggering signal for these experiments was a zero to five volt square wave with a frequency of 250Hz. This synchronized the left and right cameras.

The image size for these experiments was 1280 pixels by 1024 pixels, the maximum image size for these cameras. The image size determines how many images can be stored
in the MaxRevolution board’s onboard memory. The equation for calculating how many frames the system will acquire is given by Equation 3.4.

\[
\text{Frames} = \text{Floor}\left(\frac{268435456}{H \times V}\right)
\]  

(3.4)

H is the horizontal image size and V is the vertical image size. There are 268,435,456 bytes available in the MaxRevolution board’s onboard memory. One byte (eight bits) is used for each pixel, and every intersection of a row and column in the image defines a pixel. For the image size given above, there is room for 204 frames in the MaxRevolution’s onboard memory.

Since the frame rate is 250 frames per second and there can be only 204 frames taken, the entire data set will comprise less than a second of the actual weld process. The field of view for the cameras is small, so it is necessary to know when the weld pool will be in the image. This was achieved by monitoring the display screen of the VLL Toolbox while a weld was running. The best time to begin triggering the cameras with this setup was about two seconds after the weld had been started.

To find the best exposure time, images of the welding process were taken at a variety of exposure times (set using the CamReg utility). The exposure times should be small since the arc is exceptionally bright. However, the exposure time must be long enough to allow the weld pool signal to exceed the background noise in the frame. The tested exposure times were kept between 50µs and 500µs and varied in increments of 75µs.

Stereo matching was performed using the ZSSD technique described previously. This version of the image processing code is provided on the included compact disc for reference (dispfor3dv2.m). The match window was set to be a 17 by 17 pixel square and the disparity range was -15 to +15.
3.4 Initial Results

This section discusses the results from the exposure time optimization experiment and describes the area of the weld pool that is visible in the stereo pairs. An analysis of the stereo matching algorithm is also provided. The results from the initial stereovision system configuration were promising.

3.4.1 Exposure Time Optimization

Seven welds were produced on the same plate and the exposure time for the cameras was varied from 50µs to 500µs in 75µs increments. Both cameras were set to have the same exposure time for each weld so that images collected from the weld could be processed accurately. The exposure time of 50µs was found to be too short since the image signal produced by the weld pool was in the same range as the background noise. Exposure times greater than 200µs were found to be too long because the bright emissions from the arc would make the images almost completely white, destroying any information from the weld pool signal. The optimal exposure time was thus determined to be 125µs, which allowed the weld pool image signal to be present in image intensities between the dark background noise and the bright image noise from the arc emissions.

3.4.2 Weld Pool Visibility

The CMOS image sensors used in the Basler A504k cameras are able to pick up infrared spectra, allowing the weld pool to be visible in the images due to its high temperature radiance. Due to the near orthogonal viewing angle of the cameras, almost the entire weld pool is visible. The images of the weld pool have a significant amount of detail due to the fine resolution of the cameras. The movie file “weldmovie1.avi” on the included CD shows the sequence of images captured from one of the exposure time optimization welds (125µs exp, 250fps). Approximately every other frame shows the
weld pool without a significant presence of the arc, while the frames in between show the exact opposite. Figure 3.7 shows an example image taken from the movie where the arc was nearly nonexistent and Figure 3.8 shows an example of when the arc was the dominating feature in the image; both images are from the right camera.

Figure 3.7 Image of Weld Pool without Arc

Figure 3.8 Image of Weld Pool with Arc
An interesting feature of Figure 3.8 is the circular dark spot in the center of the arc. This is believed to be the wire, which has not had the chance to heat up, entering the arc. Figure 3.7 shows that it is possible to obtain a highly detailed image of the weld pool without using any type of illumination unit or optical filtering.

3.4.3 Stereo Matching Analysis

The ability to reconstruct depth information from a stereo image pair of the weld pool is at the heart of this research. Therefore, several stereo image pairs were taken from the captured sequence during times when the arc emissions present in the images were minimal. These pairs of images were processed using the sum of squared differences minimization algorithm described in the previous chapter. Figure 3.9 shows an example of a stereo pair from this data set. The left image is from the left camera and the right image is from the right camera.

![Figure 3.9 Cropped Stereo Image Pair](image)

The stereo pairs are rectified using the rectification program from the Camera Calibration Toolbox and then they are sent through the stereo matching algorithm. The auto-cropping code aligns the left and right images and the disparities for each pixel
location are computed. The stereo matching routine relies on the presence of slag in the weld pool to provide unique detail in each region. The resulting disparity map (holding the right image fixed and shifting the left image) is shown in Figure 3.10.

![Figure 3.10 Disparity Map](image)

The light areas correspond to greater depths from the camera while dark shades indicate less depth from the camera. The areas of pure white are regions where the match score could not be computed or is invalid. A point can be determined to be invalid for three different reasons. The first is if the disparities between the left and right disparity maps do not agree. The second is if the matched region did not come from an area where the match window was fully contained in the left and right weld pool images (as determined in Section 3.2.3). The third invalid score criteria occurs if the variance in the match window does not exceed the noise variance threshold. The noise variance threshold was determined by examining the correlation function outside the region-of-interest. Stereo image pairs often have too few pixels available for matching due to the
different camera views. Thus, the area where matching is valid is limited by the smaller area of the weld pool between the left and right images. To prove that depth information can be obtained from the disparity map, the stereo triangulation algorithm is performed on the disparity map. The algorithm returns the horizontal, vertical, and depth dimensions in millimeters. Figure 3.11 demonstrates the results of the stereo triangulation in a three-dimensional plot. Warm and dark colors indicate greater depths from the cameras while “cool” colors indicate less depth.

![Figure 3.11 Three-Dimensional Plot of Weld Pool](image)

The results from the stereo triangulation demonstrate that a three-dimensional reconstruction of the weld pool is possible. The range of depths computed falls between 580 and 600mm, which is reasonable since the cameras were placed about 580mm from the weld. However, the stereo matching algorithm has a few problems, first of which is the fact that it uses the global minimum match score instead of a local minimum. An ideal match function is characterized by one definitive minimum match score, which
gives the plot a “V” shape. A poor match score curve has several localized minimums, but the stereo matching routine only focuses on the global minimum. An example of a match score curve with a clear and unique minimum is shown in Figure 3.12. In these plots, the sum of squared differences normalized by the variance is shown on the vertical axis and the disparity index is shown on the horizontal axis. The true disparity numbers range from -15 to +15 in increments of one and the corresponding disparity indices vary from one to 31 in the plots. The ZSSD match function causes a superimposed trend that distorts the true minimum score as shown in Figure 3.13. In this figure, the correct disparity index is 14, but this is not the global minimum due to the trend in the data. This problem arises because the ZSSD method subtracts from each pixel in the match score window the mean of the values in the window centered around that pixel instead of subtracting the mean of the values in the window from every pixel in the window. If the mean of the values in a match score window does not change quickly as the window is moved one window-width, the ZSSD method provides a good approximation. However, for weld pool images, the mean changes quickly, causing the trend shown in Figure 3.13.

Figure 3.12 Ideal Match Score versus Disparity Index
Another problem with the stereo matching algorithm is the presence of holes and outliers. The holes represent match scores rejected in the stereo matching process, while the outliers are seemingly correct match scores that do not reflect the true weld pool surface. Additionally, the three-dimensional representation needs a plane of reference (the orientation of the plate) in order for the visualization to be meaningful. The most substantial problem with the ZSSD method is the processing time required to obtain the disparity map. Since the match is computed at each point in the left and right images for each possible disparity, there is a great deal of repeated calculation.

3.5 Stereo Matching Improvements

As discussed earlier, there are several stereo matching routines that have been developed. The first-pass system used the ZSSD minimization technique. Another kind of stereo matching routine involves the computation of the cross-correlation between two images. Each method has advantages in terms of theoretical complexity and computation time [22]. Another way to find the best match between a pair of images is to find a linear
transformation of the intensities of one image that minimizes the intensity deviations between two images. The deviation is still measured as a sum of squared differences; however, the match score is also dependent on the linear transformation. The first step in deriving this matching metric is to write the error between the pixels of the original left image and the linearly-transformed pixels of the right image (Equation 3.5).

\[ \varepsilon_k = \sum_{i=1}^{N} (L_i - a^* R_i - b)^2 \] (3.5)

In this equation, \( L_i \) is the image intensity of the left image at location \( i \), \( R_i \) is the image intensity of the right image at location \( i \), the parameter \( N \) is the number of pixels being matched (in the match score window), and parameters \( a \) and \( b \) specify the linear transformation. For each match score window, the routine seeks the \( a \) and \( b \) that minimize the sum of squared differences, \( \varepsilon_k \). The minimal \( \varepsilon_k \) is then the match score.

Equation 3.5 can be expanded into Equation 3.6 to simplify further algebra.

\[ \varepsilon_k = b^2 N - 2b \sum_{i=1}^{N} L_i - 2a \sum_{i=1}^{N} R_i L_i + \sum_{i=1}^{N} L_i^2 + 2ab \sum_{i=1}^{N} R_i + a^2 \sum_{i=1}^{N} R_i^2 \] (3.6)

The \( a \) and \( b \) that minimize the error \( \varepsilon_k \) can be computed by taking the derivative of Equation 3.6 with respect to each parameter, \( a \) and \( b \), and setting these derivatives equal to zero. This gives a system of two equations with two unknowns. Solving for the parameters \( a \) and \( b \) (Equations 3.7 and 3.8, respectively) and substituting into Equation 3.6 provides the result shown in Equation 3.9.

\[
a = \frac{\sum_{i=1}^{N} R_i L_i}{\sum_{i=1}^{N} R_i^2} + \frac{\sum_{i=1}^{N} R_i \left( 4 \sum_{i=1}^{N} R_i L_i - 4 \sum_{i=1}^{N} R_i^2 \sum_{i=1}^{N} L_i \right)}{\sum_{i=1}^{N} R_i^2 \left( 4N \sum_{i=1}^{N} R_i^2 - 4 \left( \sum_{i=1}^{N} R_i \right)^2 \right)} \] (3.7)

\[
b = \frac{-\left( 4 \sum_{i=1}^{N} R_i \sum_{i=1}^{N} R_i L_i - 4 \sum_{i=1}^{N} R_i^2 \sum_{i=1}^{N} L_i \right)}{\left( 4N \sum_{i=1}^{N} R_i^2 - 4 \left( \sum_{i=1}^{N} R_i \right)^2 \right)} \] (3.8)
In order to normalize this error over linear transformations of the left image, one can examine the behavior of these equations under such a transformation. If a constant $b'$ is added to the left image $(L)$ intensities, the parameter $a$ is unchanged, the parameter $b$ is increased by $b'$, and the expression for the error in Equation 3.5 is unchanged. If the left image is scaled by a factor of $a'$, $a$ and $b$ are both scaled by $a'$ and the error $\varepsilon_k$ of Equation 3.5 is scaled by $a'^2$. This suggests that $\varepsilon_k$ should be divided by the sum of squared deviations from the mean in the left image in order to normalize the error. A reduced expression for sum of squared deviations from the mean in the left image is given by Equation 3.10.

\[
\sum_{i=1}^{N} L_i^2 - \left( \frac{\sum_{i=1}^{N} L_i}{N} \right)^2
\]  

(3.10)

Dividing $\varepsilon_k$ by $N$ times this quantity results in the match score given in Equation 3.11.

\[
\text{score}_k = 1 + \frac{-N^2 \left( \sum_{i=1}^{N} R_i L_i \right)^2 - \left( \sum_{i=1}^{N} L_i \right)^2 \left( \sum_{i=1}^{N} R_i \right)^2 + 2N \sum_{i=1}^{N} R_i \sum_{i=1}^{N} R_i \sum_{i=1}^{N} L_i \sum_{i=1}^{N} L_i}{\left( \sum_{i=1}^{N} L_i \right)^2 - N \sum_{i=1}^{N} L_i^2 \left( \sum_{i=1}^{N} R_i \right)^2 - N \sum_{i=1}^{N} R_i^2}
\]  

(3.11)

This result is symmetric between the left image and the right image (i.e., the equation is the same if you exchange $R$ and $L$). Equation 3.11 also shows that only the cross match terms (where $R$ is multiplied by $L$) are dependent on the disparity. This allows several terms to be pre-computed only once instead of once per disparity. The result is a much faster and more reliable match algorithm [23].
Another modification to the stereo matching algorithm was the addition of a masking system that guarantees that each pixel to be matched is valid in both the left and right images. This forces the maximum size of the weld pool disparity map to be the minimum size of the weld pool area present in the left and right images.

A variance threshold was used to determine where disparities are invalid. This threshold was found by examining the range of variances present across the images. Finally, the redundant computation of the left-to-right and the right-to-left matches was also removed.

3.5.1 Algorithm Testing

The new stereo matching routine was tested by computing the disparity maps for the same images used in the initial verification of the system. This provided a basis for comparing the two methods of stereo matching. The first test was to confirm that a similar disparity map could be obtained using the new algorithm. Figure 3.14 shows the disparity map computed from the stereo image pair displayed in Figure 3.9.

Figure 3.14 New Disparity Map
This disparity map is similar, but superior, to the original map and was computed in about half the time. The next test was to determine if the trend in the match score versus disparity curve had truly been removed and to compare the steepness in the unique minimum to the previous method. Figure 3.15 shows the match score versus disparity curve for the same point as in Figure 3.13. The minimum in the match score in Figure 3.15 is much better defined than in Figure 3.13 and is also in the correct location. Although there are still local minima present in the match score function, there is no trend that biases the match score function as shown in Figure 3.13. This suggests that the new stereo matching algorithm is a more accurate method for matching regions in stereo image pairs.

![Figure 3.15 New Match Score](image)

3.5.2 Sub-pixel Disparity Computations

Since the cameras are set up to have a narrow field of view and the weld pool is only a small portion of the image, a change of one in the disparity index indicates a substantial change in the height of the weld pool. This results in a staircase effect in the three-
dimensional reconstruction (as shown later in Figure 3.18). In order to smooth out the reconstructed shape of the weld pool, a sub-pixel disparity algorithm was developed. Since the shape of the match score function around a minimum is approximately parabolic (see Figure 3.15 above), it is simple to develop an interpolation function to find the true best match between the left and right images based on a parabolic fit. The general equation for a parabola is given in Equation 3.12, where $d$ is the disparity index.

$$f(d) = ad^2 + bd + c$$  \hspace{1cm} (3.12)

To compute the sub-pixel disparity index, the parameters $a$, $b$, and $c$ must be found at each location $i$ on the disparity curve by least squares fitting. In general, let $M$ be a $p$ by three matrix, where $p$ is the number of points that will be used for the fit. Let $P$ be a vector containing the parameters $a$, $b$, and $c$. Let $\text{MatchScore}$ be a vector of length $p$ containing the match score values that are to be fit. The middle row of the $\text{MatchScore}$ vector should correspond to the location $i$ on the disparity curve where the parabola is to be fit. The sub-pixel algorithm developed in this research uses a three point fit; therefore, the parameter $p$ is three. This gives the following relationship between the parameters $a$, $b$, and $c$, the matrix $M$, and the match score values (Equation 3.13). To solve for the vector $P$, multiply both sides of the equation by the pseudo-inverse of $M$ (Equation 3.14).

$$
\begin{bmatrix}
1 & -1 & 1 \\
0 & 0 & 1 \\
1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
=
\begin{bmatrix}
\text{MatchScore}(d-1) \\
\text{MatchScore}(d) \\
\text{MatchScore}(d+1)
\end{bmatrix}
\hspace{1cm} (3.13)
$$

$$
M \ast P = \text{MatchScore}
$$

$$
P = (M^TM)^{-1}M^T \text{MatchScore}
$$

(3.14)

In order to simplify the implementation of the sup-pixel disparity algorithm, three filters (one for each parameter) can be made from the matrix $M$. Each row of the matrix $F$ (given by Equation 3.15) is a filter for the corresponding parameter (i.e. the first row of $F$ is the filter for parameter $a$, the second row for parameter $b$, etc.).

$$
F = (M^TM)^{-1}M^T
$$

(3.15)
Therefore, the match score matrix is reorganized into a two-dimensional matrix and the MATLAB command “imfilter” is used to compute the parameters a, b, and c for each point in the match score matrix. The sub-pixel shift in the disparity is given by taking the derivative of Equation 3.12 with respect to the disparity index and setting it to zero to solve for the disparity shift. The solution, $\Delta d$, for the offset from the disparity index $i$ of the minimum of the parabola is given in Equation 3.16.

$$\Delta d = \frac{-b}{2a}$$

(3.16)

The final step in the sub-pixel disparity computation is to find the best match score and determine whether that match is valid. To find the best match score, several criteria are examined. The first check guarantees that the minimum match score is below 0.2. The second check makes sure that the linear shift (parameter b) is between -0.1 and +0.1 to ensure that the value of the best match score does not deviate significantly from the minimum value of the parabola. The third check discards all points where the sub-pixel shift ($\Delta d$) is not between -0.5 and +0.5 (a disparity index range of one). The remaining points are analyzed by finding the disparity index where the parameter $a$ is the largest (indicating the most amount of curvature). The sub-pixel shift is then added to the disparity index where the parameter $a$ is maximized to produce the sub-pixel accurate disparity. The resulting disparity map (and thus three-dimensional reconstruction) is much smoother (as can be seen in modelmovie.avi on the included CD). A match is deemed invalid if the checks described above eliminate all possible disparities for a given point in the match score matrix.

### 3.5.3 Interpolation of Invalid Interior Regions

The algorithm still produces invalid regions within the valid regions of the disparity map. One method for dealing with these regions is to fill them with interpolated values from the surrounding areas. To find the regions that need to be interpolated, a mask is
created based on the regions where the disparity map is infinite (the disparities identified as invalid by the stereo matching algorithm) within the boundaries of the weld pool. This mask is sent to the “roifill” function in MATLAB, which fills in the invalid regions with interpolated values. The interpolated disparity map computed from the disparity map in Figure 3.14 is shown in Figure 3.16. There are still several outliers remaining in the interpolated disparity map, but overall the region filling process has provided a disparity map without the interior regions of invalid disparities.

![Figure 3.16 Interpolated Disparity Map](image)

### 3.5.4 Outlier Removal

The disparity gradient constraint gives the criteria for determining outliers in disparity maps. The constraint states that the gradient of disparities in a local area cannot exceed a certain threshold [20]. The outlier removal algorithm must employed after the first interpolation due to how the regions are filled in. If the outliers were removed first, large holes (indicating invalid matches) would form in the disparity map. For the stereo matching routine, two different gradient methods are used to find regions where the
gradient in disparities exceeds a low and high threshold. The first check uses a Prewitt edge detector with a threshold of 0.6 and the second check uses a Roberts edge detector with a threshold of 0.9. Each of the results of the edge detections provides a binary mask of regions where the gradient exceeds the given threshold. This mask is used to fill in the region with new interpolated data. Figure 3.17 shows the disparity map from Figure 3.16 with the outliers removed. This new disparity map shows that changes are only made to the regions where outliers are present and the regions without outliers are preserved.

![Figure 3.17 Disparity Map with Outliers Removed](image)

### 3.5.5 Three-Dimensional Rendering and Reference Plane

To provide a clearer visualization of the reconstructed three-dimensional shape of the weld pool, the coordinates returned from the stereo triangulation were transformed to a coordinate system based on the plate geometry. Shading and lighting were applied to the three-dimensional plot to remove confusing lines caused by the wireframe generated by the “trimesh” function in MATLAB. Figure 3.18 shows the result of the applied shading and lighting before the reference plane was added. At this stage, the axes are the horizontal, vertical, and depth dimensions in the world coordinate frame as viewed by the
cameras. Therefore, the axes are not aligned in a way that makes length, width, and height measurements simple. Note that sub-pixel interpolation was not used on this plot.

![Figure 3.18 Rendered Three-Dimensional Plot](image)

To transform the computed three-dimensional points into a coordinate system based on plate orientation, a stereo pair of an x-y axis was collected (Figure 3.19, left image on top). Note that at this stage of development, the cameras had been rotated (as described later in chapter 4); therefore, the y-direction of the plate is in the horizontal image direction. By finding the pixel locations of the points “X”, “Y”, and “O” in both the left and right images and applying the stereo triangulation algorithm to these points, the three-dimensional location of the points X, Y, and O are known. To transform the points in all three-dimensions, one more piece of information is needed. The triangulation of points X, Y, and O allow for two vectors to be drawn (one between X and O, the other between Y and O). These vectors define the X-Y components of the reference plane. In
order to capture the third (Z) component of the reference plane, the cross product
operator is applied to the vectors from X to O and Y to O to provide a vector that is
perpendicular to both of the original vectors. Some additional considerations are
necessary since the reference plane images are not rectified. This allows for a skew
between the X to O vector and Y to O vector, meaning that even though they are
perpendicular in three-dimensional space, the three-dimensional reconstruction may not
return vectors that are perpendicular. This effect is shown in Figure 3.20. In Figure 3.20,
\(x\) is the vector that points from \(O\) to point \(X\); \(y\) is the vector (original y-direction) that
points from \(O\) to point \(Y\). To force the \(x\) and \(y\) vectors to be perpendicular, the projection
of \(y\) onto \(x\) (\(y_{\text{proj}}\)) is subtracted from the vector \(y\) as shown in Equation 3.17.

\[
y' = y - \frac{x^T y}{x^T x} x \tag{3.17}
\]
Taking the cross product of \( y' \) and \( x \) yields the final vector \( z \) needed to transform the coordinate space. The three vectors \( (x, y, \text{ and } z) \) are normalized by their magnitudes to produce unit vectors that the transformation between coordinate spaces does not scale the points, but simply rotates them. The rotation matrix \( (T) \) is constructed by using the three unit vectors as the columns of the matrix. A second matrix \( (P) \) is constructed whose columns contain the vectors pointing from the origin to each three-dimensional point returned by the stereo triangulation. This matrix is a three by \( N \) matrix, where \( N \) is the number of triangulated points. Every column of the matrix is comprised of an \( X, Y, \text{ and } Z \) coordinate in thee-dimensional space. Multiplying the transpose of the rotation matrix by the matrix containing the original three-dimensional vectors provides the new three-dimensional points \( (P') \) that are aligned with the plate orientation. This multiplication is shown in Equation 3.18.

\[
P' = T^T P
\] (3.18)

An example of the result of this transformation is shown in Figure 3.21. In order to display this information in an intelligible way in this document, two views are provided
in Figure 3.21. The left view is the X-Y plane view where it is as if the camera is looking at the weld pool in the negative Z direction. The right view is the X-Z plane view where it is as if the camera is looking in the negative Y direction. These views together allow for a quick observation of the three-dimensions of the weld pool (width, length, and height). In both views, the units of the axes are in millimeters.

3.6 Summary

This chapter has explained the methodologies used to compute the three-dimensional structure of the weld pool. A discussion of the fundamentals behind stereovision was provided. The first-pass system was analyzed to determine improvements that could be made. The final stereovision system demonstrated that the three-dimensional structure of the weld pool could be measured directly from the stereo image pair. Future improvements to the system can focus on automatically measuring certain properties of the weld pool. In general, these results show a great deal of promise for making stereovision a useful tool for weld pool measurement.
4.1 Introduction

This chapter describes the triggering systems used to synchronize the cameras with one another. In addition, a synchronization scheme was developed to reduce the number of frames where the light from the arc made it impossible to capture data from the weld pool in the images. This chapter begins by analyzing the constant frame rate triggering system used during the development of the stereovision system. A summary of the methodology involved in developing a synchronized triggering scheme is provided. This chapter also includes a description of the modeling used to design the inductive sensor used for synchronization. Since the robotic arc welding environment is noisy (with respect to electromagnetic fields), a filtering system was designed to improve the accuracy of the inductive sensor measurements. A custom-made triggering application was designed using MATLAB’s Simulink program. The arc intensity as a function of time was studied (in relation to the pickup signal) to determine the optimal time to acquire images. In order to demonstrate that time behavior of the weld pool could be analyzed, the frame rate was increased to 1,666 frames per second using the area-of-interest capabilities of the cameras.

4.2 Triggering Method Analysis

The simple square wave triggering technique is not an effective way to acquire images of the weld pool due to the high percentage of frames that contain a significant
amount arc emission. Additionally, for the GMAW-p process used, the weld pool oscillations are expected to be between 200 and 500Hz. In order to accurately capture the frequency behavior of a system, the sampling frequency must be at least twice the maximum frequency of the system (Nyquist Theorem) [24]. However, this triggering method did establish that there are times when the presence of the arc is minimized. Therefore, a new triggering system would need to be developed based on this result.

4.3 Methodology

The first step in developing the inductive pickup for synchronizing the system was to model the electrical dynamics of the pickup itself. This involved modeling the current provided to the welder and the physical location of the pickup with respect to the ground return wire. The pickup was designed to produce a large magnitude signal to guarantee that subsequent filtering would not degrade the signal below a useable level. A model of the induced Electro-Motive Force (EMF) was developed based on the shape of the coil, the number of turns in the coil, and the model of the arc current. Measurements of the actual response of the pickup were acquired using an oscilloscope while the weld process was running. These measurements were compared to the modeled waveforms to verify the predicted behavior of the system.

Both hardware and digital filters were designed to reduce the noise in the system. The hardware filter was developed using the inductance and resistance of the coil and added capacitors. This filter was designed to be a second order low-pass filter. This filter also uses a high-impedance voltage divider to reduce the voltage sent to the data acquisition system. The digital filter was implemented in the xPC triggering system. This filter was designed to be a 2nd order Chebyshev low pass filter.

The improved triggering system employed a variety of methodologies to obtain reliable operating behavior. The incoming signal from the pickup is converted to a square wave by clipping at a threshold value. The triggering of the cameras occurs at a
programmed delay after the positive-to-negative zero-crossing of the square wave and consists of a one-sample duration pulse. A delayed version of the one-sample long pulse is used to set the pulse width of the output wave. This portion of the triggering code functions like a one-shot. To create multiple pulses, delayed versions of the one-shot output are added together to produce a chain of pulses that have the same pulse width and the delays in the one-shot signal determine the frequency of the triggering signal.

In order to characterize the arc intensity with respect to time in as few welds as possible, the cameras were set to have two different delays, where the right camera was always triggered one millisecond after the left camera. This allows two delays to be tested for every weld produced. The tested delays ranged from half a millisecond to eight milliseconds, in half millisecond increments.

Finally, the area-of-interest feature of the cameras was used to increase the maximum possible frame rate of the cameras. There are two main factors that influenced the methodology used to explore higher frame rates. The first factor is that the maximum possible frame rate of the cameras is determined by the height of the image, due to the manner in which the information is shifted out of the camera. Secondly, the weld pool takes up a large vertical area in the image and a small horizontal area (the exact opposite of idea from the standpoint of increasing the frame rate). Thus, the camera mounting on the tripod was rotated by 90 degrees, allowing the vertical image direction to correspond to the horizontal dimension (width) of the weld pool. The change in orientation of the cameras in three-dimensional space makes a new calibration necessary since the extrinsic parameters of the stereo setup are different.

4.4 Synchronization

The initial verification of the system showed that there were times during the welding process where the arc emissions were significantly reduced. To avoid capturing frames with a high presence of arc, which wastes the available onboard memory of the
MaxRevolution boards, a synchronization scheme was developed. This system consists of an inductive pickup and a much more sophisticated triggering algorithm. The pickup is placed next to the ground return of the welder and a voltage is induced in the loop of wire based on the rate change of the magnetic flux through the pickup. The new triggering program measures the voltage of the pickup to determine the status of the welder. This configuration was used to find the optimal image acquisition times.

4.4.1 Inductive Pickup Modeling and Design

The magnetic field produced by a straight, current-carrying conductor is described by Equation 4.1. This magnetic field is oriented circularly around the wire, where the direction is determined by the right hand rule. In this equation, $\beta$ is the magnetic field, $i(t)$ is the current in the wire, $\mu_0$ is the permeability of free space constant, and $R$ is the distance from the center of the wire to the loop of wire.

$$\beta = \frac{i(t)\mu_0}{2\pi R}$$  \hspace{1cm} (4.1)

The flux of the magnetic field is equal to the integral of the magnetic field over the closed area through which the field passes (Equation 4.2).

$$\Phi = \oint \beta \cdot dA$$  \hspace{1cm} (4.2)

The voltage induced in a loop of wire is proportional to the rate change of the flux of the magnetic field times the number of turns in the loop (Equation 4.3) [25].

$$EMF = -N \frac{d\Phi}{dt}$$  \hspace{1cm} (4.3)

The inductive pickup was designed to have 400 turns around a one foot long, 2.5 inch wide square piece of wood. This pickup is placed up against the ground return for the welder as shown in Figure 4.1.
The current through the ground wire was modeled by a 120Hz sine wave to the 20\textsuperscript{th} power plus a DC component of 50 Amps. The total peak amperage was set to be 350 Amps. These numbers were determined from the wave builder program for the ArcMate system. The 20\textsuperscript{th} power of the sine wave (Equation 4.9) provides a steep rise in the current as shown in the wave builder program. A graph of the modeled current is shown in Figure 4.2.

\[ i(t) = 50 + 300(\sin(120 \times 2\pi t))^2 \]  \hspace{1cm} (4.4)
The induced voltage, caused by the modeled current, in the inductive pickup is displayed in Figure 4.3. This model was remarkably accurate to the true performance of the system. The pickup was first connected to an oscilloscope while the welding process was executed. The peak voltage measured on the scope was about 40 volts instead of the modeled 30 volts. A significant amount of noise was present in the actual system and the input/output boards can only measure from -10 to +10 volts. Therefore, a filtering system with attenuation was needed.

![Figure 4.3 Modeled EMF versus Time](image)

### 4.4.2 Signal Filtering

Two types of signal filtering were employed to remove the high frequency noise caused by the motors and other electrical components present in the room. The first filter is a hardware filter using discrete components. Since the pickup consists of a long piece of wire wrapped around in a loop, it can be modeled as an inductor and resistor in series. The values of the inductance and resistor were measured using an RLC meter. The inductance of the pickup was 59.3mH and the resistance was 153Ω. By placing a capacitor between the two ends of the pickup, a series RLC filter is produced. A voltage
divider was connected in parallel with this capacitor to attenuate the signal by a factor of 10. To produce a cutoff frequency of around 300Hz, the capacitor value was found to be about 4.3\( \mu \)F. The cutoff frequency was set to 300Hz to keep the capacitance at a value that can be made from ceramic and tantalum type capacitors since electrolytic capacitors are often noisy. An additional 10nF capacitor was connected at the output to help smooth the waveform. A circuit diagram for the filter is shown in Figure 4.4.

![Figure 4.4 Hardware Filter Schematic](image)

A Bode plot of the output was produced using PSPICE to verify that the filter was behaving properly (Figure 4.5). The cutoff frequency was found to be about 308Hz from PSPICE, which is close enough to the desired value. The Bode plot also demonstrates that the output is now reduced by a factor of ten so that it can be input into the analog to digital card. Since this is a second order, low-pass filter, every decade of frequency beyond the cutoff frequency the magnitude is reduced by a factor of 100 (-40dB/decade). The output of the pickup was then connected to the filter, whose output was sent to the
data acquisition system. A weld was performed while the output of the filtered signal was monitored. The result showed a vast improvement in the signal, but there was still a substantial amount of noise present. Therefore, a second-order Chebyshev digital filter was implemented at the input of the pickup signal.

![Figure 4.5 Bode Plot of Hardware Filter](image)

The triggering program is set to have a sample time of 0.1 milliseconds. This sampling time determines how to design a digital filter with a specific cutoff frequency. For the digital filter, a cutoff of around 200Hz was used. This results in the discrete time transfer function given by Equation 4.5.

$$
\frac{0.002073z^2 + 0.004146z + 0.002073}{z^2 - 1.892z + 0.9018}
$$  \hspace{1cm} (4.5)

The Bode plot for this transfer function is shown in Figure 4.6 (note that the frequency is in radians per second in this plot). The Bode plot shows that the cutoff of
the system is at about 180Hz and that each decade the magnitude is reduced by a factor of 100. Thus the overall filtering reduces the magnitude by a factor of 10000 for every decade beyond 300Hz.

To test the performance of the filtering, a weld was produced and a measurement of the filtered signal was acquired over several cycles. These measurements were averaged over one hundred cycles to see how well the results compared to the expectations provided by the model. The standard deviation was also added and subtracted from the mean values to provide an estimation for the variation in the cycle duration. The graph in Figure 4.7 shows the average signal (solid) for one cycle and one standard deviation above and below the average (dashed).
Note that the signal is delayed from the actual status of the pickup due to two filtering techniques used. However, this delay does not affect the synchronization since the triggering pulses will be delayed with respect to the filtered signal.

4.4.3 Synchronized Triggering

A new triggering program was developed (using MATLAB’s Simulink program for compilation to xPC) based on the input from the pickup. The block diagram in Figure 4.8 shows the new triggering logic. The pickup input is measured and sent through the digital filter. Next, the waveform is transformed from a sinusoid to a square wave. A threshold of 0.005 is applied to eliminate false triggers caused by the small amount of noise still present in the signal. The output of the transformation is a square wave that has values of positive one where the pickup voltage is positive and negative one where the pickup voltage is negative. If the value of the input signal is between -0.005 and
+0.005, the previous state is retained until the signal breaks one of these thresholds.

Figure 4.9 shows the block diagram of the logic behind the transformation function.
The output of the transform function is sent to a falling-edge detector, which creates a one-sample long (one-shot) pulse every time the square wave makes a transition between a positive and negative value. This logic is shown in Figure 4.10.

Due to limitations in the MATLAB xPC Target program, a unique pulse generator had to be created. The cameras require that the triggering pulse remain high for a certain duration. Equation 4.6 gives the relationship between the frame rate and the minimum high time for the triggering pulse. In Equation 4.6, \( f \) is the frequency of the triggering signal (the frame rate).

\[
T_{\text{high time}} = \frac{1}{f} - 4 \mu s
\]

(4.6)

Figure 4.11 shows the block diagram of the logic behind the pulse generator.
The output from the falling-edge detector is used to generate a pulse with a guaranteed pulse width. The start of the pulse occurs when the one-shot has a value of one. A delay is added to the one-shot to provide a signal for when the pulse should be terminated. This delay sets the pulse-width of the pulse. A combinational logic routine is used to determine whether the pulse should be on, off, or retain its current value. The pulse generator also includes a method for eliminating false triggers by setting a minimum time between pulse generations. The minimum time used is 7.5ms since the welding process has a frequency around 8ms (120Hz). The output of the pulse generator is sent to the output board and then to the cameras.

4.4.4 Timing Optimization

The next step in creating a synchronized system was to find the relationship between the arc intensity and the pickup signal at different points in time. There is no need to process stereo information to determine the arc presence, so the cameras do not need to be synchronized with one another. Therefore, to reduce the number of welds needed to classify the arc intensity versus trigger delay time, the right camera was given an additional 1ms delay from the left camera. This means that two delays could be checked simultaneously, thus halving the number of welds that need to be produced. The range of delays used was from 0.5ms to 8ms, in 0.5ms increments.

An algorithm in MATLAB was developed to automatically detect the presence of arc in the image (autoarcdetect_v1). This program counts the number of pixels that have intensities greater than 75 and divides by the number of pixels that have intensities greater than 175 (out of 255 since there are eight bits per pixel). The score for the image is computed by subtracting this ratio from one. A good frame is defined has having a score greater than or equal to 0.75, an “OK” frame has a score between 0.5 and 0.75, and a bad frame has a score less than 0.5. These classification boundaries were found by
computing the score for 25 non-sequential images and manually examining the images to
determine what classification each should be given.

The cameras were configured to have an area of interest that was only 512 pixels
wide so that the total number of samples (frames) could be increased from 204 to 512
images. Increasing the number of samples decreases the chance that the results from the
testing will only show random behavior. The results were placed into a table and then
made into a graph. Table 4.1 shows the percentage of good, ok, and bad frames versus
delay time while Figure 4.12 shows these results in a graphical format. The average
pickup signal is also superimposed on Figure 4.12 to show the relationship between the
arc intensity and the pickup signal.

<table>
<thead>
<tr>
<th>Delay(ms)</th>
<th>%Good Frames</th>
<th>%OK Frames</th>
<th>%Bad Frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>12.89%</td>
<td>44.14%</td>
<td>42.97%</td>
</tr>
<tr>
<td>1</td>
<td>16.80%</td>
<td>60.16%</td>
<td>23.05%</td>
</tr>
<tr>
<td>1.5</td>
<td>9.18%</td>
<td>68.75%</td>
<td>22.07%</td>
</tr>
<tr>
<td>2</td>
<td>8.01%</td>
<td>82.23%</td>
<td>9.77%</td>
</tr>
<tr>
<td>2.5</td>
<td>4.30%</td>
<td>52.73%</td>
<td>42.97%</td>
</tr>
<tr>
<td>3</td>
<td>3.91%</td>
<td>84.18%</td>
<td>11.91%</td>
</tr>
<tr>
<td>3.5</td>
<td>4.30%</td>
<td>80.86%</td>
<td>14.84%</td>
</tr>
<tr>
<td>4</td>
<td>2.93%</td>
<td>89.26%</td>
<td>7.81%</td>
</tr>
<tr>
<td>4.5</td>
<td>3.13%</td>
<td>25.78%</td>
<td>71.09%</td>
</tr>
<tr>
<td>5</td>
<td>2.34%</td>
<td>20.70%</td>
<td>76.95%</td>
</tr>
<tr>
<td>5.5</td>
<td>1.56%</td>
<td>36.52%</td>
<td>61.91%</td>
</tr>
<tr>
<td>6</td>
<td>2.34%</td>
<td>56.64%</td>
<td>41.02%</td>
</tr>
<tr>
<td>6.5</td>
<td>6.45%</td>
<td>45.51%</td>
<td>48.05%</td>
</tr>
<tr>
<td>7</td>
<td>10.55%</td>
<td>59.18%</td>
<td>30.27%</td>
</tr>
<tr>
<td>7.5</td>
<td>10.55%</td>
<td>48.63%</td>
<td>40.82%</td>
</tr>
<tr>
<td>8</td>
<td>12.30%</td>
<td>57.62%</td>
<td>30.08%</td>
</tr>
</tbody>
</table>
The pickup signal, plus and minus one standard deviation, are the smoothed lines on the plot while the percentage of frames lines are represented as discrete points connected by straight lines. One way to analyze Figure 4.12 is to consider the percentage bad frames (red) to be the intensity of the arc versus time. The increase in bad frames at a delay of 2.5 milliseconds is due to the adaptive frequency change present in the Fanuc ArcMate system. If the system detects that the arc has been extinguished during a time period when the welder expects the arc to be on, the welder will create a secondary pulse to generate a new arc.

4.5 Increasing the Frame Rate

As mentioned earlier, the maximum frame rate of the cameras is determined by the height of the images to be acquired due to the way the camera outputs data to the image acquisition boards. The maximum frame rate is given by Equation 4.7, where F is the
frame rate (frames per second) and \( L \) is the number of lines in the image (image height of the area-of-interest in pixels).

\[
F = \frac{10^6}{2L}
\]  

(4.7)

To reduce the number of lines in the image, the camera mounting was rotated 90 degrees using the tripod so that the vertical image direction corresponded to the horizontal dimension (width) of the weld pool. This allowed the height of the area-of-interest to be reduced to 200 pixels (from 1024). For a 200 line image, the maximum frame rate is 2500 frames per second (Equation 4.7). Using the timing optimization information discussed earlier in this chapter, delay times were chosen to match periods of low arc-presence. These delays were 1.0, 1.6, 2.2, 2.8, 3.4, and 4.0 milliseconds, which corresponds to a frame rate of 1,666 frames per second. It should be noted that this triggering system does not use a constant sampling rate, which can complicate frequency calculations. However, this method performed satisfactorily (weldmovie2.avi on included CD). In watching this video, one can see that the majority of the weld pool is observable in a large percentage of the frames since the arc is confined to a fairly small area. On the other hand, there are still times when the arc is the only feature present in the image due to the somewhat random behavior (due to material spatter, etc.) of the welding system and also the adaptive frequency change of the welding system.

4.6 Summary

A synchronization system to reduce the number of captured frames that contain a large presence of arc was described in this chapter. An analysis of the initial (constant sampling time) triggering system was provided. The electromagnetic field theory behind the development of the current sensor was discussed. A model of the arc current was used to determine the behavior of the sensor. The sensor signal filtering methods were also described. Details about the logic that drives the optimized synchronization system
were provided. A characterization of arc presence to pickup signal was performed to find the triggering delay times that minimized the overall amount of arc in a sequence of images. Finally, the frame rate of the cameras was increased to approximately 1,666 frames per second using the area-of-interest feature of the cameras. The increase in frame rate is crucial to determining whether a stereovision system can directly measure the oscillation frequency of the weld pool. Overall, the system performs well. However, the computations of the oscillation frequency could become more complex since the system no longer samples at a constant rate.
CHAPTER 5

CHARACTERIZATION OF WELD POOL AND BEAD GEOMETRIES OVER SEVERAL WELD PARAMETERS

5.1 Introduction

This chapter presents the three-dimensional geometry results obtained from the stereovision system described in the previous chapters. The main objective of this chapter is to demonstrate the utility of stereovision as a sensor in welding processes. This chapter includes an explanation of the methodologies used to obtain the metallurgical measurements and the measurements from the stereovision system. A discussion is provided of the relationship between the weld pool geometry and the weld bead geometry. Additionally, an analysis is presented of the relationships between varied weld parameters and the pool and bead geometries. These relationships can be used as the basis for a control system to be designed in the future. Note that these relationships are preliminary and by no means do they provide definitive correspondences between the welding parameters and the bead properties. This chapter is concluded by discussing the recommendations for future research in this area.

5.2 Methodology

The first step in characterizing the weld pool and bead geometries over several weld parameters was to set bounds for each parameter. Wide bounds were set in order to gain a basic understanding of the relationships of the pool and bead geometries to each other
and to the welding parameters. The welding parameters selected for these experiments were torch speed, standoff distance, and torch angle. The torch speed is defined as the rate of travel of the torch head along the length of the weld. Standoff distance was measured as the perpendicular distance between the plate and the center of the front of the torch cup. The torch angle is defined as the angle between the principal axis of the torch cup and the vector normal to the plate. Torch speed was varied between five and nine millimeters per second, standoff distance ranged from 14 to 18 millimeters, and the torch angle was varied from 11 to 23 degrees. The nominal test condition consisted of a torch speed of seven millimeters per second, a standoff distance of 16 millimeters, and a torch angle of 17 degrees. A total of 19 welds were generated using various combinations of these parameters. Table 5.1 shows the combination of parameters used for each weld.

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<th>Weld #</th>
<th>Torch Angle (degrees)</th>
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The welds were generated on three different plates. Once the welds were completed, these plates were cut using a band-saw so that the cross-sectional properties of the weld bead could be measured. The weld beads were cut in the location as close as possible to the region where imagery was acquired. The welds were then encapsulated in epoxy to provide a better means for handling the specimens during metallurgical processing. Each weld was polished using the same sequence in grit number (60, 120, 220, 320, 400, and 600 grit). The grit number refers to the relative size of the particles on the grit paper, where smaller grit numbers indicate larger particle size. The samples were then etched using a mixture of nitric acid and ethanol. The etching solution allows the heat affected zone and penetration to be more visible. Each sample was then scanned at 1200 dots-per-inch using an off-the-shelf computer scanner (a resolution of about 21µm per pixel). These scans are available on the included compact disc. The physical geometry of each sample was obtained by measuring the geometry of the scanned image in pixels and scaling by the resolution of the image (millimeters per pixel). The measured parameters were the maximum width, height (also called reinforcement), penetration depth, penetration width, and also the toe-angle. These properties are shown in Figure 5.1.

Figure 5.1 Metallurgical Weld Bead Measurements
The cameras were re-calibrated using the methods discussed previously (additionally, a new reference plane was obtained). The cameras remained in the high-frame rate setup discussed earlier. 699 images were acquired at 1,666 frames per second for each weld. 60 consecutive images were used to represent the weld pool geometry for the given parameters. The reduction in the number of processed images was to help reduce the time needed to reconstruct the three-dimensional structure of the weld pool since this system is not setup to do these measurements in real-time. A timestamp for each image is recorded by the triggering system in order to provide a means for studying the temporal behavior of the weld pool. The length and width of the weld pool were measured by taking the average maximum length and width across the images. The height of the weld pool was measured by averaging the maximum height in each cross-sectional slice of the weld pool and then averaging these values across the sequence of images. The toe angle was estimated by averaging the slope of the last two points in each slice and averaging the computed toe angle across the image sequence.

5.3 Relating Weld Pool Geometry to Weld Bead Geometry

To show the usefulness of determining the three-dimensional structure of the weld pool, relationships between the pool and bead geometries were examined. Width, height, and toe-angle measurements from the stereovision system were directly compared to the same measurements from the bead. The weld pool length measurement provided by the stereovision system is used to form ratios between the width and length and the height and length. These two ratios along with the ratio between the width and height were compared to the penetration depth and width. The best fit was found by maximizing the linear correlation coefficient (R), which indicates a minimization in the probability that two sets of data are uncorrelated. Since this data set consists of 19 measurements, the value of the R squared should be greater than 0.208 to show that the probability of uncorrelated data is less than five percent [26].
5.3.1 Pool and Bead Width

The first comparison made was the relationship between the weld pool width and weld bead width. Figure 5.2 shows a strong linear relationship between the pool and bead width. However, there are some explainable inaccuracies in the pool measurement system. One of these inaccuracies stems from the fact that the cameras are not positioned to be perpendicular to the weld pool due to interference with the welder. Although almost the entire weld pool is visible in the images, the far side of the pool contains fewer pixels than the near side of the pool, which translates into a steeper slope than is present in the pool, thus cutting off a small portion of the pool width. A second error source is caused by slight variations in where imagery was collected versus where metallurgical measurements were made. Finally, some reconstructions contain a few outliers that can artificially increase the observed pool width. Despite these inaccuracies, the relationship between the bead and pool width is strong and demonstrates that the stereovision system can estimate bead width from pool width. The remaining differences between the bead and pool widths can be explained by the shrinkage of the weld pool as it cools.

Figure 5.2 Bead Width versus Pool Width
5.3.2 Pool and Bead Height

The next relationship to examine was that between the bead height and the pool height. Figure 5.3 shows a linear relationship between the two measured heights. The reconstruction of the height does not suffer as much from inaccuracies as the width. There are only a couple of sources of error in the weld pool height measurements. The first is the inherent error in the triangulation itself, which is caused by small errors present in the calibration of the stereovision system. Plate warping/shape is the other main source of error in the height reconstruction. Small variations in the distance from the cameras to the plate will cause inaccuracies in the calculation of depth from the vision system. Although the value of the linear correlation coefficient in the depth comparison is smaller than that of the pool and bead width comparison, the fit shows more of a direct scaling between the bead and pool heights (i.e. less of a constant offset). A direct scaling between the weld pool height and bead height can be expected from the contraction (caused by cooling) of the pool height to the bead height. Figure 5.3 shows that bead height can be reasonably predicted from pool height.

Figure 5.3 Bead Height versus Pool Height
5.3.3 Pool and Bead Toe-Angle

The final direct relationship examined was that between the predicted toe-angle from the weld pool to the measured toe-angle of the weld bead. Figure 5.4 is a graph of the weld pool toe-angle versus the weld bead toe-angle. The relationship between the predicted toe-angle and the actual toe-angle shows that the stereovision system cannot estimate the bead toe-angle. One reason that there might not be a good relationship between the two is that the image filtering used to remove outliers and fill in holes erodes a small amount of the outside of the weld pool disparity map, which means that these points are not a part of the three-dimensional reconstruction. Another reason that a relationship is difficult to obtain is that the weld pool contracts into the solidified weld bead. Fluid mechanical constraints make the weld pool have asymptotic tails that attach the pool to the plate but the contraction of the pool material can increase the slope of these tails by sucking in the material towards the center of the weld bead. Finally, small ripples that form at the interface between the plate and the weld pool have a significant impact on the toe-angle measurement from the three-dimensional reconstruction.

\[
y = -0.2792x + 133.01 \\
R^2 = 0.1051
\]

![Figure 5.4 Bead Toe Angle versus Pool Toe Angle](image-url)

Figure 5.4 Bead Toe Angle versus Pool Toe Angle
5.3.4 Pool Ratios and Bead Penetration Depth

Since the bead geometry is characterized in cross-sections and the bead length is only determined by how far the torch travels, there is no relationship between the length of the weld pool and the length of the weld bead. However, the ratios (of the pool) between the width and length, width and height, and height and length could be used to estimate bead properties that cannot be measured directly by the stereovision system such as penetration depth and width. Figure 5.5 shows linear relationships between these ratios and the penetration depth. The best correlation is between the ratio of width to length and the bead penetration depth, which is consistent with the research performed by Y. M. Zhang at the University of Kentucky [4]. However, there is some error in the measurement of the length of the weld pool. For small torch angles, the weld pool is partially occluded by the torch cup, which reduces the measurement of the length of the weld pool. Additionally, the small amount of arc present in the images also can obscure a little area of the weld pool, which reduces the measured length. Methods for how to alleviate these errors are explained in the recommendations for future research.

![Figure 5.5 Pool Geometry Ratios versus Penetration Depth](image)
5.3.5 Pool Ratios and Bead Penetration Width

The final comparison between bead and pool geometry involved trying to relate the bead penetration width to the ratios of width to height, width to length, and height to length. Figure 5.6 illustrates parabolic fits for these relationships. The best measurable parameter for estimating the bead penetration width is the ratio between the width and the height of the weld pool. The fit for the ratio between the width and the length also shows a useful relationship for the bead penetration width, which has not been as widely researched as penetration depth. Once again, there are still errors present in the measurement of this ratio due to the errors in the measurement of the width and height, as discussed previously.

Figure 5.6 Pool Geometry Ratios versus Bead Penetration Width

5.4 Relating Weld Pool and Bead Geometries to Weld Parameters

In order to control the properties of the weld bead geometry, relationships must be obtained between the controllable (varied) weld parameters and the bead morphology.
There must also be a middle step that relates the observable parameters of the weld (from the stereovision system) to the final geometry of the bead. This section discusses the associations between each of the weld parameters, observed weld pool parameters, and the final bead parameters. This section presents results where strong correlations are present between the observed pool dimensions and the measured bead dimensions or where strong correlations are present between the bead properties and welding parameters. Other plots are available on the included compact disc. Results are presented in three-dimensional plots where the x-axis represents one weld parameter (torch angle or standoff distance), the y-axis represents the torch speed (since this was the only parameter that was varied at the same time as other parameters in the experiments), and the z-axis represents the weld pool and bead parameters. The surfaces are shaded based on the values along the z-axis. Each weld parameter name is abbreviated on the axes of the graphs for simplicity: torch angle is TA, standoff distance is SD, and torch speed is TS. Again, note that these findings are preliminary and do not necessarily reflect the true relationships between the varied weld parameters and the bead properties. Further testing is needed to determine these relationships in greater detail. The results in this thesis are meant to show the utility of the stereovision system in relation to the features of the weld pool the system is capable of measuring.

5.4.1 Torch Angle and Torch Speed

This section discusses the relationships between the pool and bead properties across the variations of torch angle and torch speed. The pool and bead widths across the torch angle and torch speed variations are displayed in Figure 5.7. This plot demonstrates that there is a linear association between bead and pool widths and the torch speed. The torch angle does not make a significant impact on the weld width. However, the torch speed does cause small variations in the width, which might be desired effect in a controlled system and thus torch angle would provide a means for making minor modifications to
the width. The relationship between the torch angle and the widths of the weld pool and bead is mostly linear.

Figure 5.7 Pool and Bead Width

Figure 5.8 shows the weld pool and bead height measurements in relation to the torch speed and torch angle. One can see that there is a strong correlation between the height of the pool and the height of the bead as the shape of these two plots are very similar. Both the pool and bead height show a parabolic dependence on the torch speed. It is interesting how the torch angle affects the relationship between the torch speed and the heights. For high and nominal torch speed, the maximum height corresponds to the nominal torch speed. For low torch speed, this relationship is reversed where the minimum height corresponds to the nominal torch speed. This is probably due to the increase in arc force normal to the weld pool. At smaller torch angles (closer to normal to the plate), the arc force will be more normal to the weld pool, causing the height to be
depressed. This depression is less affected at high torch speeds since the arc does not have as much time push the weld pool down and the amount of material in the weld pool directly in the arc is less. Additionally, the depression might also be less affected at low torch speed because the increase in weld material would make the arc force less significant.

Figure 5.8 Pool and Bead Height

Figure 5.9 shows the toe-angle associations with respect to the torch angle. The pool toe-angle shows a somewhat inverted behavior with respect to the bead toe-angle. There is a direct relationship between the torch angle and the bead toe angle where as torch angle increases, so does the toe angle. There also seems to be a parabolic dependency of the toe-angle to the torch speed, particularly at increasing torch angles. At low torch angles, the torch speed appears to have only a minor effect on the weld bead toe-angle.
Figure 5.9 shows that the bead toe-angle is largely determined by the torch angle, and that this relationship could be used for control purposes.

The relationship between the penetration depth, weld pool width to length ratio, and the torch angle is rather complex (Figure 5.10). For large torch angles, the penetration depth and width to length ratio display only small changes across the range of torch speeds. However, at the low torch angle, the penetration depth varies greatly with changing torch speed. The relationship also becomes inverted at low torch angles. The width to length ratio shows similar characteristics, except for the fact that low torch angles do not affect this ratio as much. The relationship between the torch angle and the penetration depth is logical since the more normal the torch is to the plate, the more
difficult it will be to melt the plate material and thus place the weld material. At less normal torch angles, the material can be much more easily melted.

![Figure 5.10 Pool W/L Ratio and Bead Penetration Depth](image)

### 5.4.2 Standoff Distance and Torch Speed

This section analyzes the variations of stand off distance and torch speed and their affiliation with the weld pool and weld bead geometries. The first discussion is based on the weld pool and bead widths as shown in Figure 5.11. This plot shows that both the pool and bead widths are almost completely independent of the standoff distance and rely solely on the torch speed. Once again, the relationships between the bead and pool widths and the torch speed are linear. The standoff distance effectively changes the welding voltage. This is due to the fact that the arc represents a large potential difference (an electric field) and the voltage varies by the inverse of the distance from the electric
field to the specimen. This implies that there should not be a significant change in horizontal geometry based on the standoff distance alone.

Figure 5.11 Pool and Bead Width

Figure 5.12 presents the relationships between the pool and bead heights across the variation in standoff distance. This plot suggests a slightly different interpretation of the relationship between the height of the weld and the torch speed. In the previous section, a parabolic relationship was found where in this case, the association seems much more linear. The standoff distance shows a small linear relationship with respect to the height of the weld pool. This is probably due to a small change in the amount of arc force that is pushing on the surface of the weld pool. Therefore, a smaller standoff distance will depress the weld pool surface more, causing the height to be smaller than at larger standoff distances. This plot also shows a strong connection between the pool and bead
heights with a single major variation between the two at low torch speed and large standoff distance.

Figure 5.12 Pool and Bead Height

5.5 Recommendations for Future Research and Improvements

This section discusses the recommendations for future research with this system. These recommendations are based on the future advancement of overall project goals as well as general recommendations for improving the system.

5.5.1 Full Characterization

Several combinations of the weld parameters were analyzed in this research in terms of their relationship to pool and bead geometries. However, for a robust control system to be implemented, further work is needed to determine the best parameters for
controlling a particular aspect of the weld bead geometry. By analyzing the effects of more welding parameters, the relationships between the geometry and the parameters might be shown to be less coupled, allowing for a greater flexibility of how the shape of the weld bead can be controlled. Additionally, testing different combinations of weld parameters could provide more insight into these relationships. Taking more samples within the parameter ranges could supply a clearer understanding of how small changes in the weld parameters change the weld pool and bead morphologies. Finally, since gravity is allowed to affect the weld pool in out-of-position welds, the force from the arc plays a significant role in how the bead forms and stays on the plate. It is conceivable that the temporal variations of the three-dimensional shape of the weld pool could provide a means for measuring the arc force directly. In addition, the depth information could be used to measure pool oscillations, which earlier researchers have related to penetration depth [12].

5.5.2 Improved Camera Mounting System

As discussed earlier, the ideal mounting position for the cameras (or fiber-optic cables running to the cameras) would be at the end of the torch. Such a system would have many benefits including a greater resolution in the three-dimensional shape, a constant position of the weld pool within the image, and a clear view of the weld pool (unobstructed from the torch cup). The greater resolution would allow for more accurate measurements of the weld pool shape in general as well as potentially providing a better system for measuring small fluctuations in the weld pool surface (particularly for measuring weld pool oscillation). Having the weld pool at a constant location in the image is advantageous for the implementation of seam-tracking and could be used to monitor how well the robotic welder is being controlled. Finally, having the cameras mounted on the end of the torch would eliminate the occlusion of the weld pool in the
images at shallow torch angles. These occlusions can cause inaccuracies particularly in measuring the length of the weld pool.

5.5.3 Optical Band-Pass Filtering

Although the synchronized triggering system greatly reduces the number of frames where the arc eliminates all useable information in the image, most of the frames still have some amount of arc in them, which usually blocks out the bottom-most portion of the weld pool. This makes length measurements of the weld pool more inaccurate. By optically filtering out wavelengths associated with the arc, it could be possible to obtain clear images of the entire weld pool in every triggering sequence. This work could be fairly in-depth since spectroscopic measurements of the arc emissions might be needed to identify wavelengths that should be filtered out. On the other hand, it is possible that a simple weld hood filter could be used to achieve similar results.

5.5.4 Real-Time Image Processing

In order to be capable of controlling the weld pool shape in real-time, the system must be adapted to process images in real-time. This task could be fairly daunting as a great deal of code (image rectification, stereo matching, etc.) might need to be re-written in a different language such as C. Additionally, programming the Xilinx FPGA onboard the MaxRevolution boards to perform all necessary image processing tasks could take some time. There will most probably be three limiting factors in how fast the system is able to compute the weld pool geometry. The first of these is that time it takes to rectify the image. The second main limiting factor is the size of the weld pool in the image (the more points to match, the longer it takes). Finally, the sub-pixel disparity algorithm takes much longer than the basic stereo matching. However, the FPGA can process the information several orders of magnitude faster than the PC using MATLAB. Another
complication is how to match the left and right images since the boards do not currently communicate with each other. The boards might need to be in the same PC in order to communicate, which could make it hard to get started since in the early stages of this research it was difficult to get one board to work in a given computer. One benefit to a real-time system would be that only a list of the triangulated three-dimensional points would need to be stored in the onboard memory instead of an entire image. This could lead to an increase in the number of samples that the system can take. A final improvement that would be useful in a real-time system would be the addition of a temporal interpolation scheme for invalid stereo matches instead of the spatial interpolation the system currently uses.

5.5.5 Real-Time Weld Control

Once a real-time, stereovision image processing system has been developed, the final stage of this research is to develop a control system that will rely on stereovision feedback to make decisions about how to change the weld parameters. The control system will probably be a neurofuzzy type control logic, where the image processing system outputs data corresponding to the geometry of the weld pool, which are input to a trained model that will figure out what the geometry means in terms of the welding parameters. This research will probably require a more detailed characterization (as discussed before) to be completed before beginning the neurofuzzy control logic implementation. Additionally, this stage of development will require knowledge of how to modify the weld parameters of the robotic welder during the weld process.

5.6 Summary

This chapter has discussed the methodologies used to obtain the results presented in this thesis. Relationships between the weld pool and weld bead geometries were obtained
to show how the stereovision system can be used to predict weld bead properties. Additionally, the pool and bead geometries were characterized over the varied weld parameters. Width is determined by torch speed. Height is influenced by the torch speed and torch angle. Toe-angle is affected by torch angle. Penetration depth is dependent on torch angle and torch speed. The stereovision system is an excellent sensor for acquiring weld pool width and height information and thus estimating the bead width and height. Since a pulsed GMAW process is used, the motion in the weld pool is mostly driven by the deposition of new welding material, and thus pool oscillations were unobservable. However, the three-dimensional reconstructions show that other time varying behavior is observable by the stereovision system (modelmovie.avi on included CD). The ripples shown in this movie could provide information regarding the arc force and the convective flow in the weld pool. Additionally, the motion at the boundary between the weld bead and pool (left side in modelmovie.avi) could potentially provide greater information about the properties of the bead.
6.1 Introduction

The purpose of this chapter is to summarize the research documented in this thesis. The summaries in this chapter are discussed in the context of the project goals as described in the thesis motivation section of this thesis (Section 1.1). The main goal of this research is to show the utility of stereovision as a sensor for welding automation. Two problems in current automated welding systems are addressed in this research. The first objective is to develop a stereovision system that can reconstruct the entire three-dimensional shape of the weld pool at a particular instant in time. The second objective is to research the relationships between the welding parameters, weld pool shape, and weld bead properties for an out-of-position welding system. Combining these two objectives leads to the third goal of this research, which is to develop a sensor system that can predict weld bead properties from measurements of the weld pool. The motivation for this research is to provide the backbone for the future development of a real-time, out-of-position, weld pool measurement. This chapter discusses how the goals mentioned above are met by the system developed in this research.

6.2 Summary of Work

This section summarizes the work performed in the development of the stereovision and triggering systems. This section also contains a discussion on the major findings of this research.
6.2.1 Stereovision System

A stereovision system was developed to reconstruct the instantaneous three-dimensional shape of the weld pool in a non-real-time environment. An automatic alignment algorithm was developed to reduce the computation time for the stereo matching algorithm. The exposure time that optimized the signal to noise ratio in the images was found to be 125 microseconds. A stereo matching method was developed to prevent the biasing of the match score that is present in more typical stereo matching algorithms. A sub-pixel disparity algorithm was implemented using a parabolic least squares fit to the match score versus disparity index function. This allows for greater detail in the three-dimensional reconstruction of the weld pool. An interpolation function was created to fill in regions of the disparity map containing invalid match scores as well as to remove outliers found by the stereo matching algorithm. A method for obtaining the orientation of the plate in three-dimensional space was developed in order to align the reconstructed three-dimensional points to the orientation of the plate. This allows for much simpler computations of the weld pool geometry.

6.2.2 Triggering System

A sophisticated triggering system was developed using xPC Target from MATLAB. This system is used to synchronize the cameras with one another and to minimize the amount of arc that is present in the images. If the arc is bright (or large), it will prevent the weld pool from being visible in the images, making it impossible to measure the properties of the weld pool in the locations containing the arc. The triggering system is based on the input from an inductive pickup placed on the ground next to the ground return for the power supplied to the welder. A second-order, low-pass hardware filter was developed to reduce the noise in the signal caused by the electromagnetic fields created by the arc and the motors of the robotic welder. The signal from the hardware filter is used as the input to an analog-to-digital PCI card. A second-order, low-pass,
Chebyshev digital filter is implemented on the front end of the xPC program to further reduce the noise in the signal from the inductive pickup. The filtered signal is the basis for the synchronization of the cameras to the times of minimal arc presence. The signal from the pickup is clipped using a threshold to produce a square wave. The positive to negative zero-crossing of this square wave is used to signify the start of a triggering cycle. This zero-crossing is detected using a falling edge detector. This zero-crossing generates a one-sample duration pulse that is used to create the pulses for triggering the cameras. The one-sample duration pulse is delayed by a specified amount of time that determines the pulse width of the triggering signal, much like a one-shot integrated circuit. The output of this one-shot is delayed to generate the chain of pulses used to trigger the cameras. By changing the area-of-interest of the cameras, the frequency of these pulses could be increased to 1,666 frames per second. The intensity of the arc was studied as a function of delay times from the zero-crossing of the clipped pickup signal. It was found that the optimal times to take images at a frame rate of 1,666 frames per second were 1.0, 1.6, 2.2, 2.8, 3.4, and 4.0 milliseconds delay from the zero-crossing.

The high frame rate of the cameras and the synchronization to the welder allows the motion of the weld pool to be visible between the pulses of the welder. This permits the study of the time-varying behavior of the weld pool on a small time scale.

6.2.3 Major Findings

The first major finding of this research is that a stereovision system is an ideal sensor for obtaining the three-dimensional geometry of the weld pool at a particular instant in time. The system is fully capable of measuring the length, width, and height of the weld pool at the same moment in time. Another major finding of this research is that the measurements of the pool width and height provided by the stereovision system allow for the prediction of the bead width and height. Thirdly, this research discovered that it is difficult to predict the bead toe-angle by trying to compute the toe-angle of the weld pool.
due to the volumetric shrinkage of the weld pool as it cools and solidifies into the weld bead. Additionally, the bead penetration depth and width are difficult to predict from the morphology of the weld pool. This is partly due to the non-constant relationship between the geometry of the weld pool (particularly the width) and the penetration. Furthermore, this research found that the motion of the weld pool at the interface of the pool and bead is easily observable with the stereovision system. Further research of this behavior could provide deeper insight into how the weld bead will form. This research also shows that ripples in the weld pool can be observed in the three-dimensional reconstruction, which could allow for future measurements of the arc force on the weld pool and the convective flow of the surface of the pool. The characterization performed during this research has provided a preliminary look at how the pool and bead properties are affected by the welding parameters. It was found that the width of the pool (and thus the bead) was mostly affected by the torch speed. Additionally, the heights of the pool and bead were found to be largely determined by the torch speed and the torch angle. The toe-angle of the bead is mainly influenced by the torch angle. Both penetration depth and width are dependent on torch angle and torch speed. Though these results are preliminary, they demonstrate that the stereovision is capable of observing changes in the weld pool (and thus predicting these changes in the bead) caused by the variation of the welding parameters. The overall results from this research have shown that a stereovision system can be used as an accurate weld pool measurement sensor and that it is possible to observe (and measure) the weld pool without using an illumination unit or optical filter.
REFERENCES


