

CHARACTERIZATION OF LARGE SCALE  
GAS METAL ARC WELDING SYSTEMS

by

Andrew Michael Neill

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in Partial fulfillment of the requirements for the degree of Master of Science (Mechanical Engineering)

Golden, Colorado

Date: \_\_\_\_\_

Signed: \_\_\_\_\_  
Andrew M. Neill

Signed: \_\_\_\_\_  
Dr. John P.H. Steele  
Thesis Advisor

Golden, Colorado

Date: \_\_\_\_\_

Signed: \_\_\_\_\_  
Dr. Greg Jackson  
Professor and Head  
Department of Mechanical Engineering

## **ABSTRACT**

It is often the case that newly assembled robotic welding systems that use gas metal arc welding do not perform as expected. This is often due to a lack of knowledge about the intrinsic characteristics of the welding system. The objective of this project is to provide an understanding and a methodology of characterizing large-scale arc welding systems and to provide a way to improve calibration of these systems. The results from this project demonstrate that most welding work cell calibration error is due to incorrect feedback in the welding power supply's sensing system, usually caused by unaccounted for voltage drops in the welding loop. The problem can be resolved by following special work cell design criteria, altering the voltage feedback, or recalibrating the power supply with the entire system. The findings presented here will give manufacturers the ability to standardize their work cells which will provide more consistent welding and reduced programming time because welding parameters will not have to be adjusted due to poor calibration.

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“If I have seen further than others, it is by standing upon the shoulders of giants.”

- Sir Isaac Newton

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## **DEDICATION**

I would like to dedicate this work to my late friend, companion and pet Sandy Neill. Sandy was the best dog any boy could ask for and the best friend any man could dream of. She will forever be one of the great memories of my lifetime and I will cherish the time I spent with her forever. She was a source of great patience and understanding on some of my most stressful days of this project and many projects before, but left my side before I could finish. She was a pillar of strength and for 12 short years, my dearest friend.

# **CHAPTER 1 : INTRODUCTION AND MOTIVATION**

## **1.1 Introduction**

Any manufacturing process requires that the tooling be standardized. All units of measure must match up so that the produced parts can be properly created and assembled. If 5 machinists are building the same part, but using 5 different measurement tools their parts can all be different. The parts will not match up and may even cause the system to fail. An automated welding system must be able to follow this same fundamental principle.

Since the invention of welding we have been able to join two pieces of metal together into one solid component with relative ease. Welding is one of the most effective methods for joining metals together and is therefore used in nearly every manufacturing process from shipbuilding and erection of skyscrapers down to electronics and fan blades. However, welding has been a skilled craft more than a science, leaving the quality of the weld as much in the hands of the welding professional as in the machines he is using.

According to an AWS study, 50,000 welding professionals are leaving the industry every year, but only 25,000 are replacing them (Miller & Crawford, 2001). Automated welding processes are filling many of these jobs. With the advent of large scale automated welding processes comes new challenges to ensure quality welds are made. Skilled welders must set the proper weld settings, often by trial and error. If the weld does not work as it should the operator must adjust the settings as he sees fit. Knowledge of welding parameters has come a long way though, and most weld parameters can be selected from trusted databases. Welding engineers specify welding procedure specifications (WPS) with a procedure qualification record (PQR) for the welds they have called out. This is the industry standard for welding and many parts are fed through several different work cells and it is assumed that the WPS will be followed. It is essential that different systems be standardized so that they are capable of supplying the same weld inputs as defined by the engineer's WPS.

In the past few decades many manufacturers have been moving towards automated welding systems as automated processes become more capable. Using a mechanical welding

operation leads to increased precision, speed, productivity, and safety. There are many types of systems that can be used, from a simple track system using a gravity fed shielded metal arc welding (SMAW) process to a full industrial robot and gantry system equipped with tandem gas metal arc welding (GMAW) heads. All of these different systems are designed to have very high precision. This precision drastically improves the repeatability of the process because each weld will be nearly identical.

Automated work cells do not always have the same outputs, however, which means this precision and repeatability between work cells is imprecise. This is because many manufacturers do not fully understand how these work cells operate and the control architecture is more complicated than they realize. This study will demonstrate a better understanding of the welding work cell to provide better knowledge of the relationship between inputs and outputs. This will give manufacturers the ability to better control the output of their systems by providing guidance for better system design and calibration.

## **1.2 Background**

Welding is a very complicated process with multiple inputs and multiple outputs. In order to understand how to standardize the robotic welding we must first look at the fundamentals of welding and how welding applies to automation.

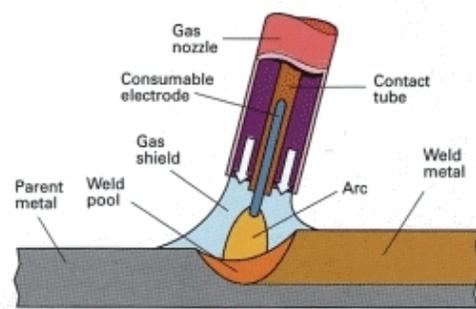
### **1.2.1 Welding Basics**

Welding is the joining of two materials by melting them together. There are many different techniques for accomplishing this, from using a gas combustion heat source to electricity to friction. The main focus of this research is using electrical power sources. As welding systems become more advanced the weld is most easily controlled and powered by an electrical arc welding machine.

Arc welding is composed of many different processes, but they all involve an electric arc generated by a power supply and controlled by input power and torch location. The main focus of this research will be on Gas Metal Arc Welding, but will be applicable to other type of welding as well.

Arc welding originated with simple batteries, cables, and a “stick electrode.” The first record of a commercial welding shop was in La Chappelle, France 1887. This stick electrode was simply a small length of wire without any coating. The user would strike the electrode against a piece of metal as one would strike a match to begin the arc. Once the arc is established the weld metal melts and begins to form a molten pool of metal. This molten pool can be controlled by the user to join pieces of metal together. It was soon learned that types of oxidation coating produced better welds, which then lead to the knowledge of shielding gasses. Electrodes were then made with a flux coating to produce the shielding gas during welding, which significantly improved arc stability. The idea was patented around 1907 but became commercially available in 1929 (Pierre, 1968).

Welding progressed from using batteries to motor-generator systems and finally up to the current high-power electrical transformer and rectifier systems. Weldments, the pieces being welded on, became larger and more versatile. Additionally, manufacturers wanted a process that was more versatile and productive. Once such process that helped increase productivity is gas metal arc welding, or GMAW, also known as MIG welding. GMAW was patented in 1950 along with the development of constant voltage machines (Pierre, 1968). GMAW uses a consumable electrode that is constantly fed off of a spool into the welding arc. Shielding gas is delivered by an external gas supply rather than an oxide in the electrode, which minimizes slag build up. Current is passed through a contact tube into the electrode and the power supply maintains a constant voltage rather than current. The constant voltage power supply maintains a steady arc length, which is often referred to as a “self-regulating” arc. Figure 1.1 shows a cutaway of the GMAW process.



*Figure 1.1: Gas Metal Arc Welding Process*

The current is determined by a complicated interaction between the voltage and wire feed speed, but to maintain a constant voltage the power supply delivers a current until the voltage setting is met. The original constant voltage power supply used a component called a saturable reactor for AC welding, or a stabilizer for DC welding. This component used a coil of wire and block of iron to regulate current flow by increasing or decreasing magnetic saturation, thereby controlling the impedance of the reactor. Modern power supplies use higher fidelity circuitry though, and the coils of wire and high-impedance reactors are often counterproductive. Therefore, the modern power supplies use a much more efficient transformer and a device called an Insulated Gate Bipolar Transistor, or IGBT. These IGBTs allow the power supply to regulate the current thousands of times per second and provide much more advanced control over the welding arc such as waveform shaping. These advance control systems make up the foundation of how the GMAW power supplies operate but if the architecture is not adequately understood then the power supply may not function as expected. Therefore, these power supply control features are often the underlying cause for much of the problems seen in the large scale welding work cells.

### **1.2.2 Automated Welding Processes**

Over the last few years more welding professionals have been leaving the industry than entering it (Miller & Crawford, 2001). This means that manufacturers are starting to see a shortage of welders. To combat this many of them are turning to automated welding processes. As demands for higher standards of accuracy and productivity increase, it is also compelling to move towards automated processes for increased repeatability, precision, and throughput. Many automated welding processes are done with the use of an industrial robot arm. An industrial robot arm can maintain movement repeatability on the order of 0.5mm or better, depending on the robot. This is a substantial improvement from nearly any human welder. This increase in precision leads to improved weld quality and a higher quality final part. This also helps in performing complex interactions in the part. For instance if the part is on a positioner or conveyor, or the robot is on a movable pedestal known in the industry as a gantry system, the robot is capable of following a path without difficulty even if the part or robot base is in motion. A human welder would have a very difficult time performing such an action.

The use of robots also allows for increased speed during manufacturing. Industrial robots are capable of working continuously for days at a time without requiring breaks, except for occasional maintenance every few months. They are also capable of moving as fast as 2 meters per second, or even more, depending on the manufacturer and specifications of the arm. Such high speeds are not usually used while making an arc weld, but they do allow the robot to get into position to begin the weld much faster. These higher speeds, continuous work hours, and higher amounts of precision greatly increase the productivity of the assembly line.

The final, but perhaps most important advantage of using an automated welding process is worker safety. Welding employs incredibly high amounts of electrical energy and the welders are usually only inches away from the main current paths. Protective gear usually protects from electric shock, but there is still imminent danger if care is not taken while operating these machines. Additionally, after welding, the materials are very hot and can easily burn anything it touches. Weldments are usually large heavy pieces of metal, which opens an additional opportunity for danger from dropping pieces of metal on toes or other appendages. As workers spend years working they inhale fumes from welding and are exposed to dangerous light emissions, known as arc flash. Over many years these fumes can cause buildup in the lungs and both arc flash and fumes can lead to the development of cancers. Overall, welding is usually a dirty and dangerous environment where it is much safer for robots to work rather than humans.

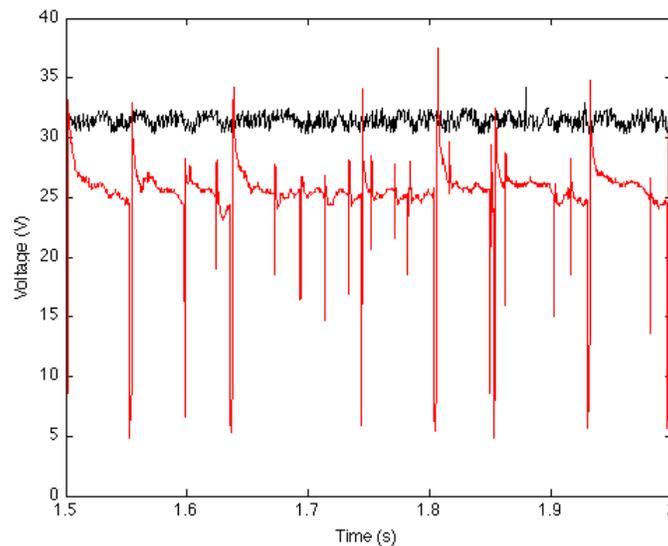
### **1.3 Motivation**

Just as all the machinists in an assembly factory must have tools calibrated together for the same output, sets of arc welding machines must also be calibrated to produce the same outputs for welding. The welding machines are calibrated when they are manufactured, but very often they are then placed into a much more elaborate welding work cell with extensive welding leads allowing the work to be distanced from the power source. This often causes issues with the final output because of the impedances and other electrical phenomena in the cabling.

In order to reliably control the welding process the output of the system must be carefully understood. In a small welding work cell with only a few feet of cabling the difference between the output of the power supply and the output at the arc will be negligible. But when the power supply is placed into a very large system with hundreds of feet of cabling as well as multiple

other systems involved in the welding and positioning of the weld and weldments, the output at the arc cannot be assumed to be the same as the output of the power supply. This means that although the power supply is set to deliver a certain output, that output may be different from the parameter delivered to the arc. The bulk of this project will be focused on large work cells with multiple grounding points and sections of cabling, weld sense leads, and long lengths of cabling but it is also worth noting that the concepts also apply to precision welding where very precise parameters must be maintained, such as those used in sheet metal welding and alloys that require tightly controlled heat inputs.

It has also been observed that two identical systems can have two separate outputs. For instance, Wolf Robotics has built 3 separate work cells but each cell produces a slightly different output, in spite of identical designs (Personal Communication, January 2011). Ultimately the customer would like to use the same program on all 3 work cells but different parameters must be selected for each system so that they all produce the same welding output. Knowledge of each system's input to output relationship would allow the user to know exactly what values will be coming out of the system depending on the inputs. Additionally, if the effect of all system components is known, the problem may be avoided or even resolved.



*Figure 1.2: Effect of voltage difference on power input*

There are many reasons for keeping the parameters as close to the set point as possible, but the top three are: control heat input, maintain arc stability, and provide quality control across different systems. It should be noted that a slight difference in voltage can have a large effect on the current input, which thereby causes a large change in the heat input. Figure 1.2 demonstrates this effect. The red waveform has a power input of 5850 watts while the black waveform has a power input of 8800 watts, yet the set voltage difference is 6 volts. The arc power also has a substantial effect on the arc stability. Arc parameters are often on the edge of changing transfer modes and if the power is not correct the arc may be less stable than desired. If the heat input varies too much, the arc can even fluctuate between transfer modes.

Customers often have very precise weld specifications and they need to be confident that their systems will deliver the weld parameters as specified. If a work cell is not properly calibrated this can be very difficult to achieve and the quality of the manufactured part can suffer. Additionally, calibration is essential in situations where multiple work cells are building the same part. If different work cells produce different welds then there will be inconsistencies in the products. It also makes it very difficult to migrate programs across the systems because each system may have different outputs so the operators must spend time to dial in the weld parameters on a system-by-system basis.

The ultimate goal of welding control is to control the direct weld parameters such as the bead dimensions, flaws, etc. This cannot be accomplished unless the relationship between the input parameters and the welding process parameters are known. Figure 1.3 shows the relationship between the input parameters, welding process parameters, and the ultimate goal of welding process control: the direct welding parameters (Naidu, Ozcelik, & Moore, 2003).

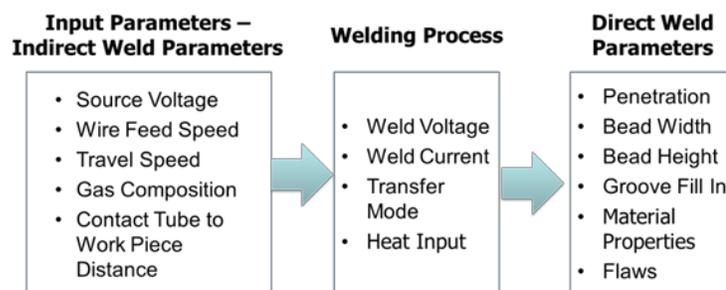


Figure 1.3: Relation of input parameters to weld (Naidu, Ozcelik, & Moore, 2003)

This project will develop a better understanding of the relationship between the input parameters and the welding process parameters to lay a foundation for future work in controlling the direct weld parameters. For instance, if the relationship between the source voltage and weld voltage is known, then it gives the foundation to truly understand and characterize the relationship between the source voltage and the direct weld parameters. This task will be accomplished by understanding how the welding work cell affects the relationship between the power supply's inputs and the welding process parameters.

## **1.4 Objective**

The purpose of this project is to first, better characterize how these welding system work, and second to provide guidance on how to correct the variation between system set points and their corresponding actual performance, thereby providing better calibration of these robotic welding systems. This calibration information will lead to improvements in repeatability and reproducibility across work cells.

To better understand the system, the project started with system characterization. Characterization of a system is to establish and understand all the system components and the control architecture. For these work cells this starts with the welding circuitry. There is a multitude of welding cables, support circuitry, sensing systems, and external controls. Part of this characterization is a better understanding of the power supply control architecture and the welding system control architecture.

Once the system has been characterized and the components are understood then the system can be identified. System identification means developing mathematical models of the input-output relationships of the system and providing numerical values for the system model parameters. This involves establishing values for resistances and other pertinent system components. The key problem area is then isolated from finding which components have the largest effect. These components depend on factors such as sense lead configuration and operations as well as the power supply output.

The end goal of the project is to find the root cause of the variation in welding parameters. A more complete understanding of the system is developed from the characterization

and identification. This knowledge will be used to find methods to correct the problem. Techniques for correcting the problem can include work cell design considerations and recalibration. The findings led to several methods for accounting for problems in design considerations as well as techniques for recalibrating the system.

## **CHAPTER 2 : LITERATURE REVIEW AND SIMILAR WORK**

The work presented in this thesis is a fundamental look at the electrical characteristics of a welding system. In spite of thorough searching for similar work, little was found. The main focus of the literature review will therefore be performed on individual system components and how they operate.

### **2.1 Welding Power Supplies**

The welding process is heavily controlled by the power input. The operator, or robot, defines the work and lead or drag angle, the contact tube to work distance, and the travel speed. The power supply delivers voltage and current, but modern power supplies carefully monitor these values. The voltage and current is used to control the heat input, transfer mode, and depending on the power supply, the wire feed speed can be regulated based on the feedback information. The power supply controls the power inputs and is therefore a major point of interest for this project.

#### **2.1.1 Basics of Welding Power Supplies**

In electric arc welding the electricity must be carefully modified and controlled to provide favorable electrical signals to create a weld. Standard electrical power from the utility company is AC power but most types of arc welding work best with DC power or a modified AC power. The power must also be transformed to high current instead of high voltage. High current and low voltage produces a smaller, more controllable arc but with the same power input. The only drawback is that lower voltages and higher currents require much larger cables to conduct the current. Therefore, welding power supplies use very large cables and connectors and require very high power controls that can handle power usually in the tens of kilowatts range. Additionally, these cables and connectors are a known cause of problems in welding power supplies because the system is so susceptible to resistance. When welding at 400 amps a resistance of 0.005 ohms will cause a voltage drop of 2 volts. Therefore cables are kept as short and thick as possible and power supplies often use voltage sensing to help see past the resistances in the welding circuit.

### **2.1.2 Transformers and Rectifiers**

Usually several hundred volts at tens of amps are supplied to the power supply and the power supply converts this power to tens of volts at several hundred amps. This is done because a welding arc needs to be in the range of tens of volts to be stable and controllable. In order to obtain the required power to heat the metal, a high current must then be passed through the arc. Therefore the high voltage low current input power must be transformed to low voltage high current power. This is most easily accomplished by the use of a transformer. A transformer uses a large coil of wire with many turns to induce a magnetic field in a core, usually made of iron. This magnetic field then induces a current in another coil of wire with fewer turns. This steps down the voltage but proportionally increases the current, thereby enabling the power supply to have a more manageable weld voltage with a high current.

The power that comes into the power supply and then out of the transformer is AC power. Some welding processes use AC such as TIG on aluminum but for GMAW it is most common to use DC or at least a pulsed DC. In order to supply this DC power the power supply must then convert tens of volts at hundreds of amps from AC to DC. It accomplishes this with a rectifier circuit. The rectifier circuit varies across different power supplies and the architecture is either patented or closely guarded but there are a few patents that explain some of the architecture of a few types of rectifier circuits (United States of America Patent No. 4897522, 1990), (United States of America Patent No. 005351175A, 1994), (United States of America Patent No. 006995337B2, 2006), (United States of America Patent No. 4876433, 1989), (United States of America Patent No. 20110000900A1, 2011), (United States of America Patent No. 20120120687A1, 2012). There are dozens of circuits to accomplish the rectifier function in a welding power supply, but the fundamental principle of a rectifier circuit is to only allow current to flow in one direction.

This high power rectification used to be done by the use of selenium and silicon rectifiers but modern power supplies use high power digital controls such as metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs). The modern digital controls have very complicated inputs that open and close current paths. They act as gates to allow current to flow when the controller enables the flow. These devices can handle hundreds

of amps and can control the amount of current that flows out. They can also adjust the current flow very quickly, at tens of kilohertz. These systems rely on the controls though, which rely on the feedback information of the voltage sensing.

### 2.1.3 Welding Power Control

One of the most prominent sources for power supply design is Pan Jiluan's book, Arc Welding Control (Jiluan, 2003). In this book he gives a general explanation for how power supplies function. A great deal of work can be done to model the output from the power supply but the main piece of knowledge is the concept that the power supply adjusts the current based on the voltages. This subject will be discussed in greater detail from the results of this thesis, but Jiluan gives a basic control equation for how a DC, dynamic response power supply functions.

$$\Delta I = \frac{\Delta U}{R} (1 - e^{-\frac{Rt}{L}}) \quad (2.1)$$

Equation 2.1 gives the general equation for how a power supply changes current ( $\Delta I$ ) based on a change in voltage ( $\Delta U$ ). R and L denote the internal resistance and inductance. On a fundamental level, this is the main essence of how a GMAW power supply functions. With the advent of microcontrollers and high fidelity high power electronics the power supplies used for welding began to become increasingly complex, but the concept of how the power supplies function is still the same. Old power supplies use to solely rely on analog controls using magnetic coils and large toggle switches to control the output. In the past few decades these methods have become far outdone by digital controls. These digital controls allow for integration with other digital systems such as robots and computers, as well as increased fidelity in the welding waveforms.

Modern power supplies use very high precision electronic systems, including but not limited to the IGBT's discussed earlier, to control the welding. These systems allow the designers to create customized waveforms that precisely control the arc and therefore make a much smoother weld. The welding machine can limit the current and thereby limit the explosion caused by short circuit transfer mode, which reduces spatter and makes a much smoother and more desirable weld. As we will see though, this control system is dependent on the feedback information made available to it, which can cause erroneous welds.

## 2.2 Cabling System Configurations

There is a very limited amount of literature available on the topic of optimal cabling and noise avoidance for welding systems and specifically GMAW systems. For example, Lincoln Electric publishes just one page on proper cabling practices in their welding manuals as shown in Figure 2.1 (Lincoln Electric Company, 2004).

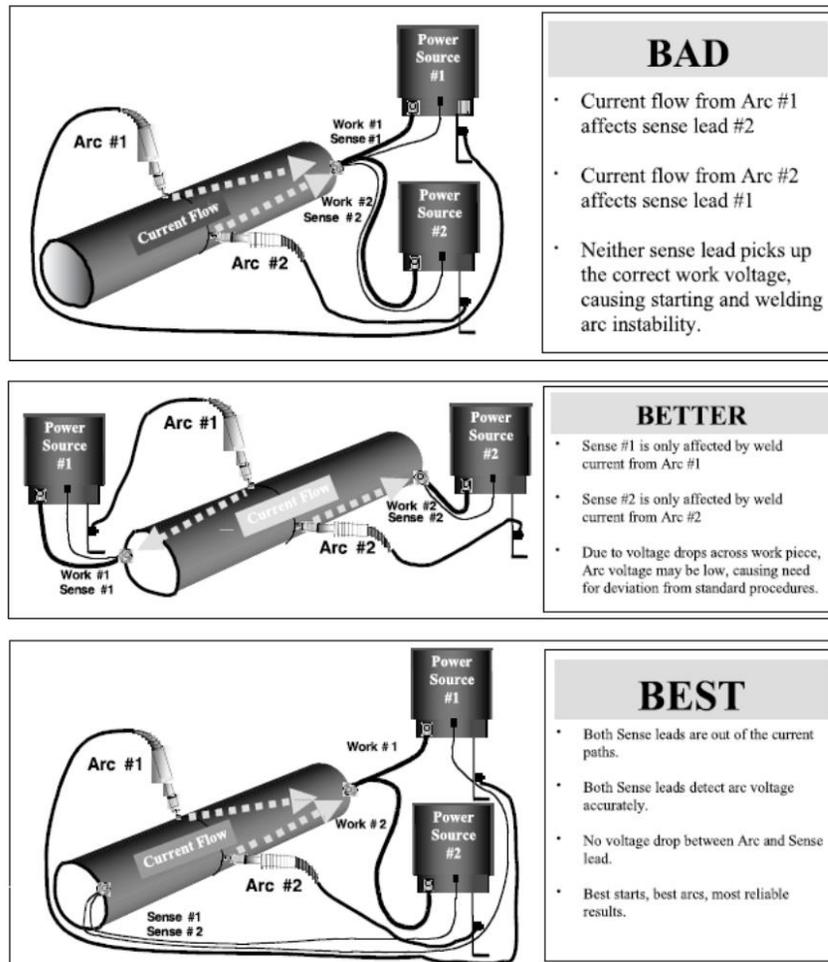


Figure 2.1: Lincoln's optimal cabling configurations

This configuration is vague at best though. It outlines proper cabling for two different power supplies but doesn't explain how to properly cable one power supply or why. There is a general understanding that the work sense lead should be attached to the weldment but in a large work cell there is no definition of where the best places to attach are or if the sense lead should be attached near or away from the ground.

Another resource for high-energy cabling is in the power distribution industry. One patent that gives a way of characterizing these power systems and identifying problems is given by Hochwald (United States of America Patent No. US 20120068718 A1, 2012). In this patent he outlines proper techniques for identifying problem areas in power distribution systems. His method involves supplying a test signal and reading the response. This is a way of troubleshooting rather than defining proper practices, but it can lead to better understanding of the system. In this patent Hochwald suggests using a test input and measuring the response at multiple locations. His systems have multiple inputs and outputs and by applying a test input and measuring the response. When multiple paths are present the patent uses a series of shunt resistors to measure the differences in paths. A similar method can be used to characterize these systems but since all measurements were taken with only one power supply active this thesis uses a single input and single output test input and response but does not require the complicated procedure outlined in this patent.

For a basic understanding of the cabling systems and to model the circuits there are a few sources of resistances for cabling. Some basic numbers for cabling are available from Manz's article (Manz A. , 2009). The article outlines the resistances and their effects on the system. Some of these resistances are given in Table 2.1.

*Table 2.1: Cable Sizes and Resistances*

<b>AWG Size</b>	<b>Resistance (mΩ/foot)</b>
6	0.394
5	0.313
4	0.249
3	0.197
2	0.156
1	0.124
1/0	0.0983
2/0	0.0779
3/0	0.0618
4/0	0.049

Table 2.1 describes the effects of the different in welding cable sizes. The voltage drops that these cause can then be calculated based on current. For instance, if 100A is passed through

50 feet of 1/0 cable, it will have a voltage drop of 0.49V. Clearly this can cause problems in the system but this project will seek to better understand how significant these problem can be as well as why this happens and how to correct these issues.

When it comes to modeling these cable resistances in the work cell most people look to the common weld model of a simple resistance and inductance. One such model is shown in Figure 2.2 (Thomsen, 2004). This model is usually accurate, or at least adequate, because usually the greatest resistance by a large margin is in the arc. Most research is concerned with modeling the arc physics and droplet transfer in small work cells and thus the circuit resistance is not a large concern.

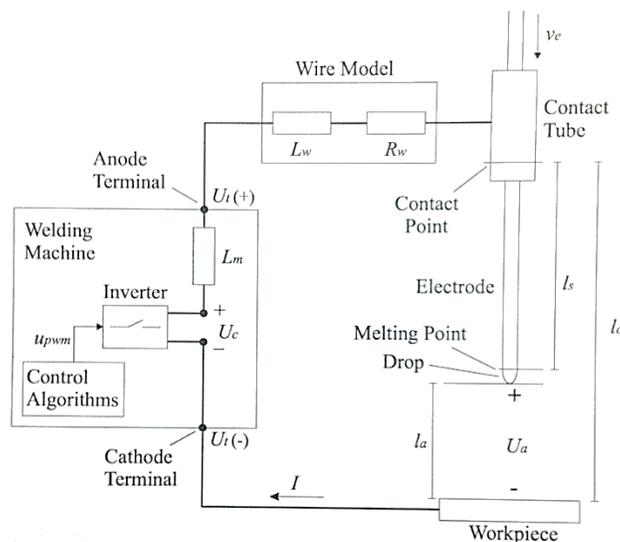


Figure 2.2: Common Welding Circuit Model (Thomsen, 2004)

The welding cables are thought of as negligible compared to the arc, but when large lengths of cables are involved this is not a safe assumption. This model fails to take into account large circuit resistances that may be in parallel and provide multiple paths for current. It also does not include the power supply voltage sensing. The differences in resistances of a large work cell can lead to subtle differences in arc voltage which, when the resistances are large, can become much more influential.

## **CHAPTER 3 : APPROACH/PROCEDURE/EXPERIMENTS**

### **3.1 Approach**

The best way to understand a complex system like a welding power supply is to first explore how it responds to inputs and differences in control parameters. This is commonly done in two processes: characterization and identification. Characterization is the process of understanding the “black box” functionality and identification is the process of then mathematically representing the system’s functions.

#### **3.1.1 System Characterization**

To better understand the system, the project started with system characterization. Characterization of a system is to establish and understand all the system components and the control architecture. For these work cells this starts with the welding circuitry. There is a multitude of welding cables, support circuitry, sensing equipment, and external controls. Part of this characterization is a better understanding of the power supply control architecture and the welding system control architecture.

To characterize these systems a general model with simplified components was developed to use as a foundation for understanding welding circuitry in general. This model was as basic as possible so that it could be applied to any welding circuit. It contained only resistances, inductances, and a general layout with no values. This model was then explored in greater detail to narrow down the problem area. It established how the circuitry works and provided a starting point for analyzing pieces of the system.

#### **3.1.2 System Identification**

Once the system has been characterized and the components are understood then the system can be identified. System identification means developing mathematical models of the input-output relationships of the system and providing numerical values for the system model parameters. This involved establishing values for resistances and other pertinent system components. The key problem areas were then isolated from finding which components have the largest effect. These components depend on factors such as sense lead configuration and operations as well as the power supply output.

To begin, the resistance and inductances of the full system was measured. In these circuits the cabling and connections are the only resistances and are very large in diameter, so the resistance is negligible in most cases. Very specialized meters have to be used to measure such small resistances, so rather than measure it directly a current was applied to the circuit and the resulting voltage was measured. The voltage and current measurements could then be used to calculate the resistance. The resistances can also be partitioned by measuring the voltage across the section of interest.

Once the system model has values for the components the effect of each component can be better understood. The difference in values between systems can also lead to an understanding of why the systems exhibit different outputs by looking at trends in values between systems. For example, if a set of circuits show a correlation between a particular resistance and a voltage offset, particularly a linear one, then this may be the cause of the problem and should be further explored.

### **3.1.3 Attempt to Fix Problem Area**

The end goal of the project is to find the root cause of the variation in welding parameters. A more complete understanding of the system is developed from the characterization and identification. This knowledge will be used to find methods to correct the problem. In this case it was found that resistances in the welding circuit caused voltage drops which interfered in the power supply's voltage sensing. From this knowledge, a few methods for correcting the problem were explored. Techniques for correcting the problem can include work cell design considerations and recalibration. The findings led to several methods for accounting for problems in design considerations as well as techniques for recalibrating the system.

Since the problem is in the voltage sensing, the first attempt to fix the problem was to explore alternative sensing techniques. It might be possible to improve on the current voltage sensing location or at least give directions such as measuring the voltage away from the flow of current. Currently most systems have a voltage sense lead permanently attached to the wire feeder, as part of the power supply manufacturer's cabling, and another attached to the work piece. The work sense lead placement is designed by the work cell manufacturer and therefore does not have a standardized mounting location, making it an area of interest.

Before the project began, Wolf Robotics informed us of a technique they had been using involving a potentiometer in the positive voltage sensing. They found that this effectively brought the voltage up to within an acceptable range but couldn't explain why this was the case and were suspicious that this negatively affected the welding current. This also led them to believe that the power supply was the main cause of issue. The technique seemed effective on the voltage but may have caused unseen problems in other areas of the welding so further exploration was required to understand why this works and what other effects it may cause. Also, they had been connecting a multimeter across the welding and dialing the potentiometer until the welding set point matched the welding process voltage. This was imprecise and therefore it would be beneficial to have an equation for setting the potentiometer.

The final approach for fixing the problem is to recalibrate the system. This could involve simply adding an "error factor" to the process parameters or recalibrating the power supply. Adding an error factor could be as simple as adding a volt or two if the welding is consistently a volt or two low. This could be done behind the scenes in the welding work cell software. The other factors must be taken into consideration too though, so this theory was explored to ensure that it would not have a negative effect on the overall process. It might be necessary, to ensure that the overall process is still within the recommended parameters, to recalibrate the power supply. The power supply is the main control unit of the welding process and if the user were to try to "trick" the power supply it could have an adverse effect and thus it may be that the power supply must be recalibrated to maintain the same level of control. However, if the power supply is not calibrated correctly it can cause damage within the system and can produce even worse issues in the future. If the power supply must be recalibrated then, it must be done by a trained professional.

## **3.2 Equipment**

The equipment used for testing in this project is all readily available. Some of the most notable items used are the data acquisition system, load bank, and welding systems. Anyone wanting to repeat the work done here should be able to find equivalent equipment that will serve the same purpose.

### 3.2.1 Data Acquisition Systems

The main data acquisition system employed in this project is an ArcTracker self-contained data acquisition (DAQ) system made by Lincoln Electric. This DAQ is specially made for obtaining data during welding and can be connected to a computer for analysis. The software used with this system is proprietary and closely guarded by Lincoln under a non-disclosure agreement and will therefore not be discussed in this thesis.



*Figure 3.1: Arc Tracker System*

The ArcTracker system acquires voltage and current data at a rate of 120 kHz. The update rate of the controller in Lincoln Electric Power Waves, which is the main power supply model studied in this project, is 10 kHz. This ensures that the data capture is well over the Nyquist sampling rate and therefore any state change of the power supply will be observed by the DAQ system.

This research also used Lincoln Electric's Power Wave Manager software. This software enables the user to connect a computer directly to a Lincoln Power Wave power supply and observe the power supply's operations. It can be used to graph the output of the power supply and any state change that the power supply performs. The software can also be used to send a pulse of current into the system and change the power supply's calibration set points. This may be useful to provide a false voltage offset for exploring parameter settings and for troubleshooting systems. Additionally the Power Wave manager software can be used to induce a step input and turn the output on for desired current settings.

### 3.2.2 Load Bank

A load bank is an electrically resistive component that is used to simulate an electrical load. In the case of welding systems it can be used to simulate a welding arc, but provides a much more stable and controllable load. The load bank can handle high currents but has similar resistance to an electrical arc so that it can produce similar voltages. There are many commercially available load banks for industrial power applications, but only a few are specifically made for welding systems. The load bank used for this project is the Miller LBP-350.



*Figure 3.2: Miller LBP-350 Load Bank*

This load bank was generously lent to the project by General Air, Denver. It was only available on scheduled and short time intervals but proved to be very useful in qualifying the system. If more time was allowed for this project more work would have been done with the load bank.

### 3.2.3 Colorado School of Mines Automated Welding Laboratory System

One of the main systems used for basic testing is the Automated Welding Laboratory System in the Robotics and Automation lab in the Brown Building, room W325, on the Colorado School of Mines campus. This lab has a Fanuc ArcMate 100iB industrial robot. This robot is controlled by a R-J3i controller and is connected to one of two Lincoln Electric Power Waves via DeviceNet.

The welding work area is on a specially built table directly in front of and level with the base of the Fanuc Robot. The table is a solid steel table with a slotted surface to prevent over penetration from welding plates to the table. To ensure solid grounding a bolt connection rather than a clamp grounds the table. The table has a ventilation system attached to the side to draw out the welding fumes. For arc flash safety, a red flash curtain encloses the entire welding area.

The first welding power supply is a Lincoln Electric Power Wave 455R. This is a very modern, highly industrial, and commonly used power supply. This power supply is capable of supplying up to 400 amps at 36 volts in a 100% duty cycle. Other versions of the same power supply can supply higher amounts of current and all models are very customizable in connections with other systems and creation of welding waveforms. This makes these power supplies one of the most versatile and superior power supplies on the market. The second power supply is a Lincoln Electric Power Wave i400. This is a newer version of the 455R with built in communication interface and much more functionality through the Ethernet interface.

The power supply is connected to the torch through electrical cabling and a Lincoln Electric PF10R wire feeder. This wire feeder is mounted on the elbow of the robot and connects the weld power and feeds welding electrode wire and gas to the weld torch. The welding torch is air cooled with a standard GMAW contact tube and gas nozzle.



*Figure 3.3: CSM Robotic Welding Lab*

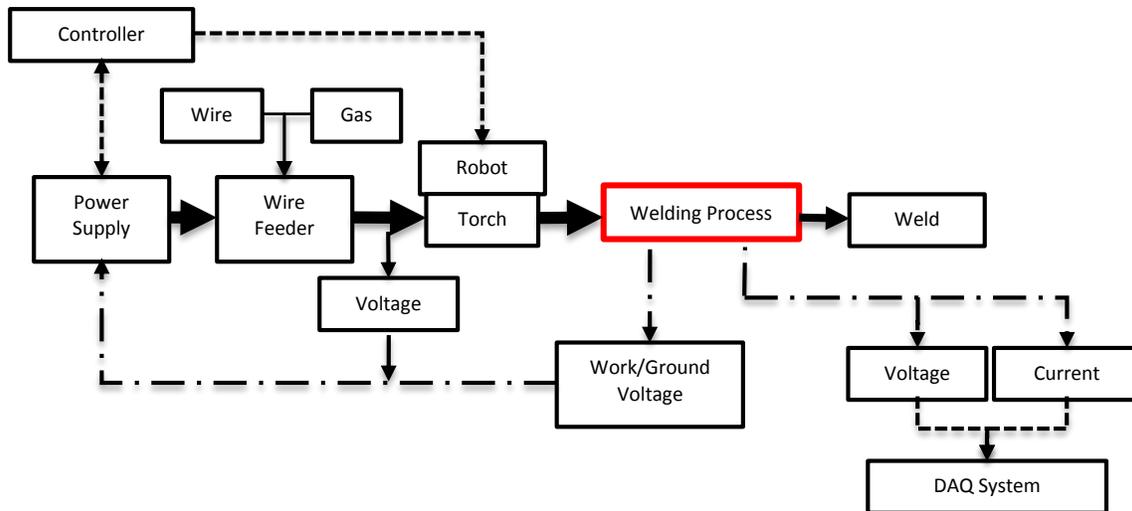


Figure 3.4: System Block Diagram

The consumables for this system are only gas and wire. The gas is a 90% Argon, 10% CO<sub>2</sub> mixture. This promotes a spray transfer mode and is a widely used gas in industry. Promoting the spray transfer mode helps to maintain a stable arc. A stable arc is much easier to monitor for electrical properties such as voltage and current because there is significantly fewer oscillations caused by droplet transfers while welding. The consumable wire is a standard GMAW wire produced by Lincoln Electric. It is 0.035 inches in diameter and is the L-56 composition wire. All weld base material is standard A-36 structural steel.

### 3.2.4 Wolf Robotics Work Cell Welding Systems

The bulk of data was collected at Wolf Robotics on an array of their systems as they became available. Because of this each system was slightly different, but for the most part they shared main components. The power supplies used in Wolf's systems was the Power Wave 655R. This is the same power supply at the 455R in the CSM lab, but with the capability of providing greater power, up to 44 volts at 600 amps in a 100% duty cycle.

Different systems were composed of different robots, but the robots were not an integral part of the welding circuit. The robots were ABB industrial robots, usually mounted on a gantry system allowing them to move around the work cell to get in position to weld very large parts. One of these work cells is shown in Figure 3.5. All electrical systems were carefully planned and built by Wolf Robotics for an end user to install on an industrial assembly line.



*Figure 3.5: Wolf Welding Work Cell*

The difference between these systems and the work cell in the CSM lab is the lengths of cables and overall capabilities of the system. The welding systems are practically identical, but with several hundred feet of additional cabling both in sensing cabling as well as welding cable.

### **3.3 Procedures**

Several techniques were developed to explore these welding systems. These techniques are discussed here. The welding procedures were chosen based on the cell. The load bank and data acquisition procedures were standardized for all systems to maintain consistent results.

#### **3.3.1 Welding Procedures**

Since the main goal of the project is to determine the differences in welding parameters across systems, the welding setup was kept as simple as possible. To accomplish this all welds were done as simple bead-on-plate welds with the plate on a horizontal table and the torch at a perfectly upright position. In other words, a zero degree work angle and no drag or push. Using bead-on-plate welds also enabled multiple welds to be done on a single plate, thereby saving a significant amount of material.

The parameters were held as constant as possible. The purpose of the testing was to find intrinsic differences in the systems, so it was imperative that all the welding was done with identical parameters for comparison. The welds performed at Wolf Robotics had a significantly higher heat input than those at the Colorado School of Mines research lab, so parameters varied by location, but comparisons were not made between these locations.

*Table 3.1: Table of Welding Parameters*

	CSM Lab		Wolf Robotics		Units
	Nominal	Test Range Min/Max	Nominal	Test Range Min/Max	
Voltage	29	27/31	28-29	26/32	v
Wire Feed Speed	400	350/450	375	350/400	in/min
Contact Tube to Work Distance	0.5		20mm		in
Travel Speed	25	25/35	8-10	13-Aug	in/min
Wire	0.035		0.052		in
Gas Composition	90/10		90/10		Ar/CO2

Preliminary welding data showed differences in the systems. One of the most notable findings was in a graph of the relationship between wire feed speed and current. In this graph it was apparent that something was very different between the systems under investigation. After some exploration into the differences it was quickly found that the CSM lab welder was operating in a “Synergic” mode in which the power supply controls the voltage and current based on the user’s wire feed speed setting. It essentially infers what it believes to be the correct parameters based on the wire feed speed setting thereby taking the system out of a constant voltage mode. After learning of this, all subsequent welding was carefully set to “Mode 5”, a simple and straight forward constant voltage mode available in all the Lincoln power supplies.

Another observation during preliminary exploration was the difference in transfer modes with very minor differences in voltage. In only a few volts difference, the transfer mode changed from globular transfer to spray transfer modes. This was intriguing because it shows how easily the minor differences in voltage can cause such large differences in the welding parameters.

### 3.3.2 Load Bank Procedures

A load bank was used to give a stable, precise, and controllable load for testing eccentricities of individual power supply systems. The load bank was first used to ensure that all the power supplies were giving the same outputs. The most logical approach to finding the source of differences in the systems was to begin at the source and look through the system out to the arc. The configuration shown in Figure 3.6 was used to check the calibration of each power supply. All cable lengths were kept as short as possible, nominally around 3 feet.

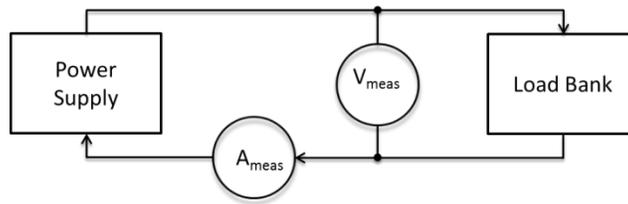


Figure 3.6: Load bank connection diagram

Two voltage meters were used in testing the power supply with the load bank, a digital multimeter and the Arc Tracker. The Arc Tracker was also used to monitor the current. The Power Wave Manager software was then used to turn the power supply on to a specific current and the corresponding voltage was measured. The load was varied by increasing the load bank resistance to thereby plot a nominal voltage based on the current and resistance settings as related to the actual voltage as determined by the power supply. The load bank had 7 intervals of  $0.7\Omega$  in parallel but each reduction in parallel resistance legs also required a decrease in the maximum current by 50A.

During testing the load bank resistance had a settling time, most likely due to heating of the resistive coils. All measurements were therefore taken at approximately 15 seconds after the load was changed. This appeared to be past the 5% settling time of the exponential rise.

### 3.3.3 Data Acquisition Procedures

All data was taken with the Arc Tracker and corresponding software at 120 kHz sampling rate. Voltage, current, power, and filtered voltage and current were recorded. The acquisition was triggered by a 10 V trigger on the raw voltage channel, meaning as soon as the raw voltage passed 10 V the acquisition began but then was manually stopped.

Once the data was recorded and stored the signals were examined for irregularities such as unusually high or low voltage, poor starts, or power drops or spikes. When such an event occurred it was noted and usually re-run if it was caused by a wire feed error or improper setup etc. The qualified data was then windowed to approximately one second after the weld start to just before the welding end. Voltage and current averages and standard deviations were then recorded as well as any notes regarding arc stability and process or plate changes.

## CHAPTER 4 : RESULTS

### 4.1 Welding Input to Output Relations

The goal of the project is to develop an understanding of how to standardize welding systems. The first step was to characterize the system which entailed understanding the differences between systems and the relationship between input and output parameters. Testing includes simple voltage measurements based on different voltage and wire feed speed inputs, as well as exploration of current from the same variations. The load bank was also used to explore the differences between individual power supplies without their system's involved.

#### 4.1.1 Voltage Differences Between Systems

Before setting out on any project it is imperative to first gain a complete understanding of the problem. After speaking with a handful of manufacturers it became apparent that the issue between set weld parameters and actual weld parameters is widespread but first a baseline of the problem must be established. Data was taken on three identical work cells to gain a fundamental understanding of the problem. Each work cell had two power supplies, two robots, and circuits that were mirror images of each other. They shared only grounding circuitry. Figure 4.1 shows a graph of voltages recorded from six different power supplies in three different systems and shows that some parameters do not come out of the work cell as they are prescribed. The graph shows the set voltage vs. measured voltage, that is, the voltage that the power supply should be delivering as compared to what it is actually delivering.

Figure 4.1 shows that the power supply output does not match the set point. Ideally, all the data points should be in a straight line with no variation in the vertical axis. The graph shows that the voltages have errors on the order of 1V above or below the set voltage and the error appears to be linear. Figure 4.2 shows the same data but as error in the set voltage. The error is calculated as  $V_{\text{error}} = V_{\text{set}} - V_{\text{weld}}$  meaning that a negative error is caused by the weld voltage being above the set voltage and a positive error is caused by the weld voltage being below the set voltage. This is the convention for control systems and will be the convention used through this thesis.

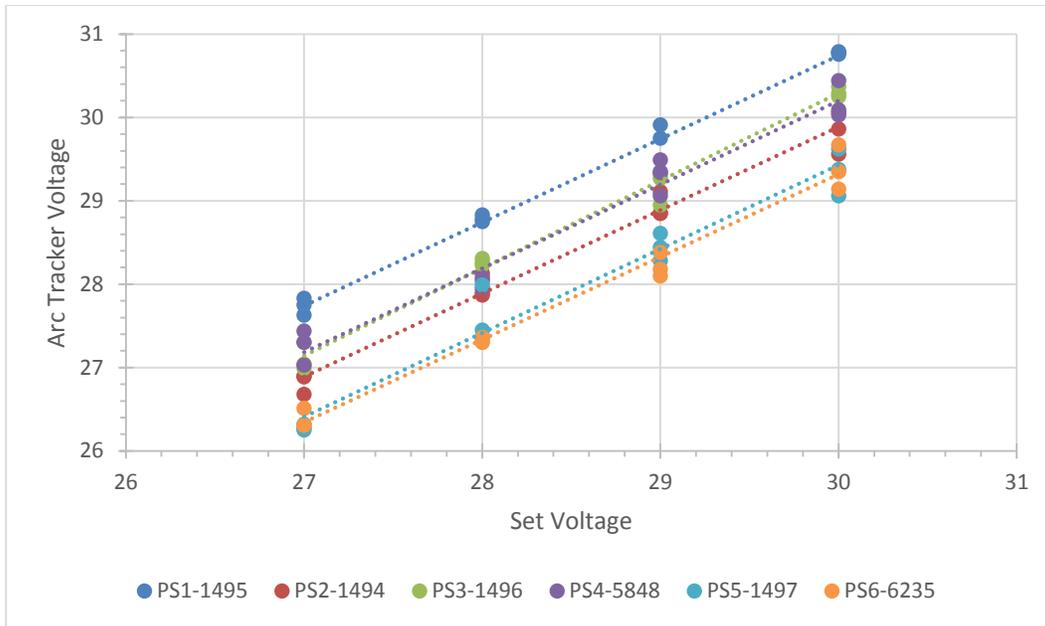


Figure 4.1: Set Voltage vs. Measured Voltage

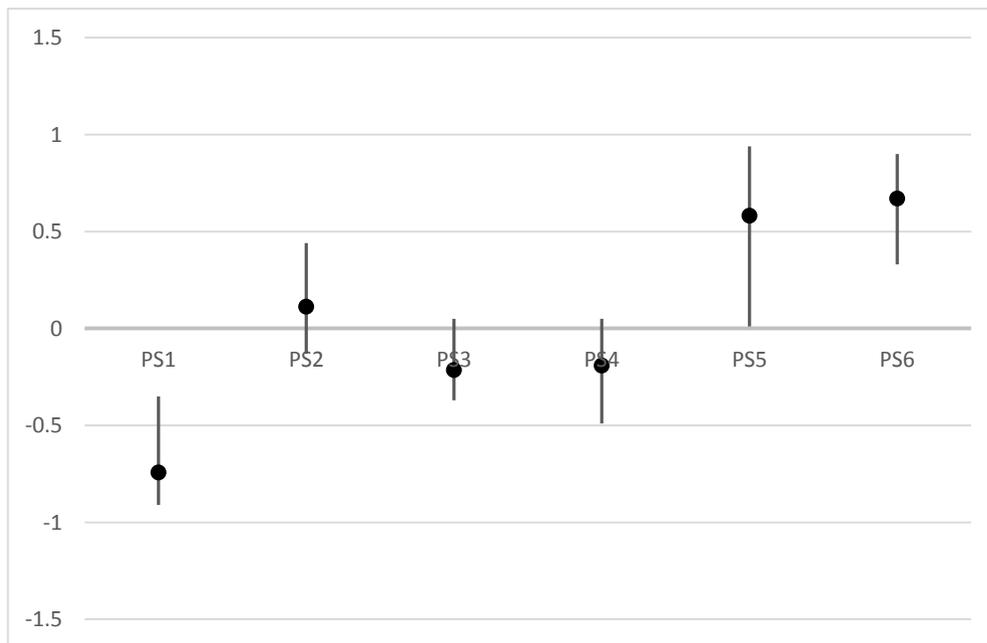


Figure 4.2: Error in Voltage for 6 Power Supplies

The error in the voltage clearly shows the differences in error across power supplies. It is also notable that the power supplies 5 and 6 are on the same system and both appear to have similar errors. This is not the case, however, for power supplies 1 and 2. This is because when

this data was collected the voltage sensing was not understood and the potentiometer was left at its initial setting, causing this error. This phenomenon will be explained in further detail in the discussion.

#### 4.1.2 Voltage Different Between Array of Power Supplies

All the previous figures were observing identical systems that incorporated identical Lincoln Electric 655R power supplies. To ensure that other systems saw the same issues a test was conducted to observe the error in other power supplies and in other shielding gasses. Data was compared from a Miller Axxess 450 with 75/25 Ar/CO<sub>2</sub> gas, the Wolf Robotics Lincoln Electric 655R with 90/10, and a Power Wave 455R with 75/25. All the systems demonstrated a similar error. Curiously though, the error in the 455R was drastic, as high as 6 volts. Figure 4.3 shows the results of this test, but graphed relative to the wire feed speed. All the process nominal voltages are 32 volts.

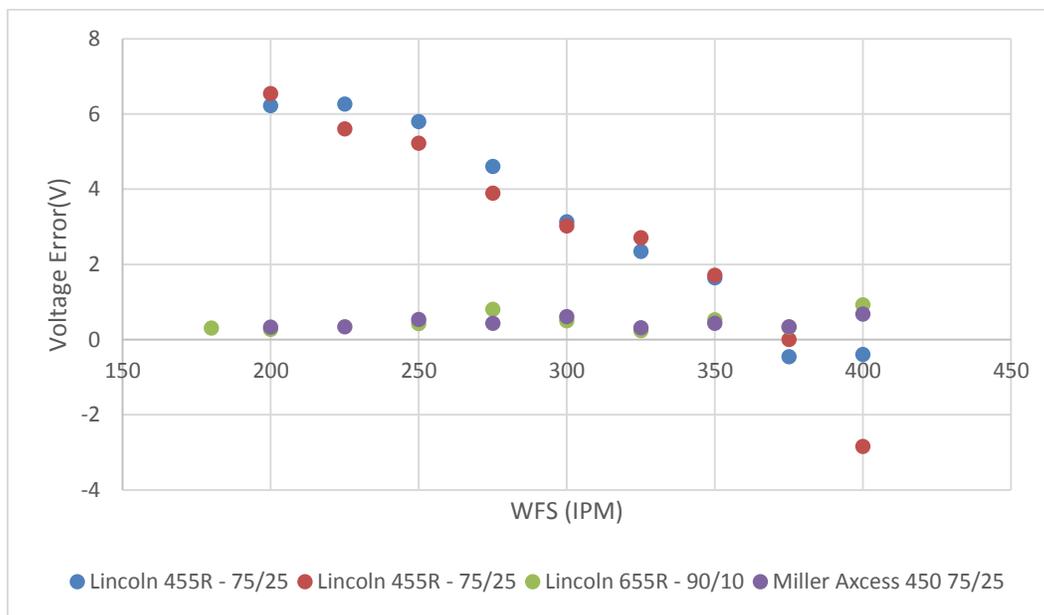


Figure 4.3: Effect of “Synergic” Weld Mode

This graph clearly shows that there is a trending error with the 455R power supply that follows the wire feed speed. After some exploration into the power supply’s settings it became apparent that the power supply was in a “Synergic” weld mode. In this weld mode the controller in the power supply adjusts the output voltage based on the wire feed speed setting. Since this

project is concerned with the error in set voltage as compared to actual voltage this process is counterproductive because the power supply is causing a voltage error based on the wire feed speed. Therefore, from this point forward, it was determined that all welding would be done in a constant voltage, “non-synergic” weld mode.

The purpose of this test was to explore the error in voltage across multiple power supplies. The different power supplies, including the Miller and, when the synergic mode was corrected, the Lincoln 455R demonstrated the same error first observed in the 655R. This test conclusively demonstrates that the error is widespread across different power supplies and different manufacturers.

### 4.1.3 Current Differences Between Systems

The same trends seen in the voltage are also apparent in the current. This is very interesting to note because, based on this graph, the current error seems to follow the voltage error. Figure 4.4 shows the same power supplies from Figure 4.1 and their current error as related to the voltage setting. The power supplies that had a higher voltage output than the others also have a higher current output in this graph, and vice versa for the power supplies with lower voltages. This is interesting to note because the current errors seem to follow the voltage error proportionally.

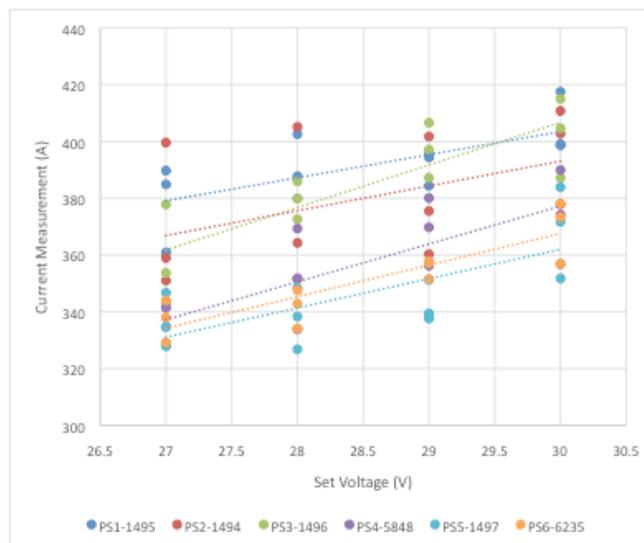


Figure 4.4: Trend in current readings vs. voltage

The current errors follow the voltage errors because of the power supply design. The power supply delivers and adjusts current until the set voltage is reached (or at least what the power supply measures as the set voltage). If the voltage is erroneous, then the current will have a similar error. The current drives the voltage so the same error trends in voltage should exist in the current because the voltage is used to control the current output. Therefore, if the error in the voltage can be understood and corrected, the error in the current should also be corrected.

## 4.2 Power Supply Output Testing via Load Bank

After establishing the fact that the issue is widespread and not localized to a particular power supply the next course of action was to identify where the problem existed, whether in the power supply, a particular part of the weld circuit, or somewhere else. To move top down through the circuit though, it was necessary to start with the power supply. The power supply is the head of the system and if there is any problem in the power supply it will be present throughout the rest of the system. A load bank can be used to provide a controlled load to test the output of the power supply. Using short lengths of cable the load bank was connected directly to the power supply.

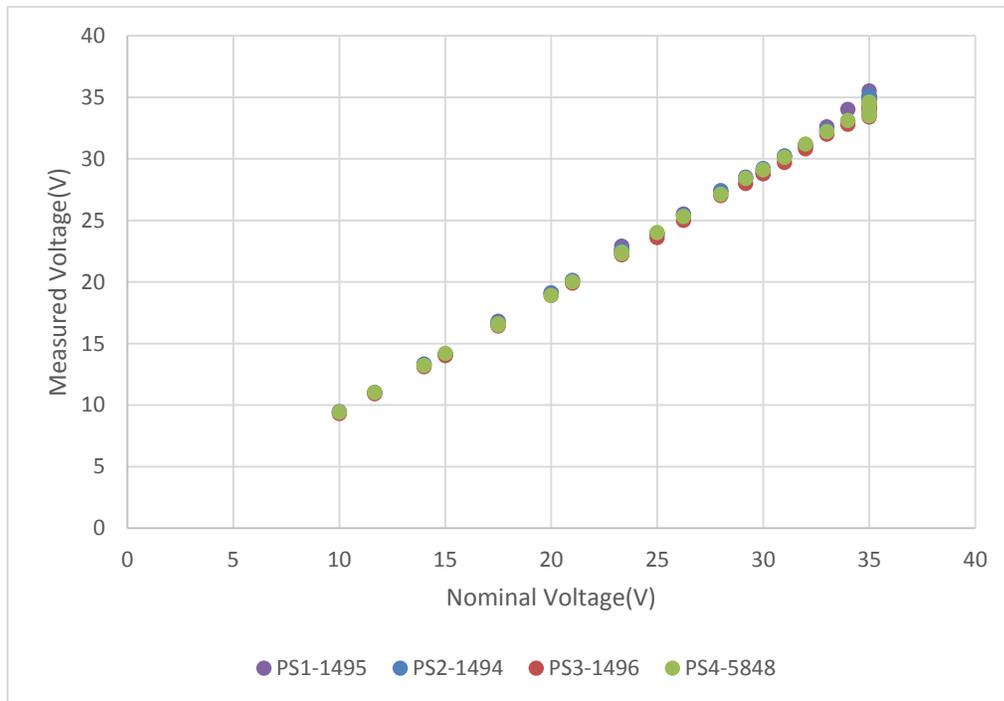


Figure 4.5: Load Bank Test Results – Voltage

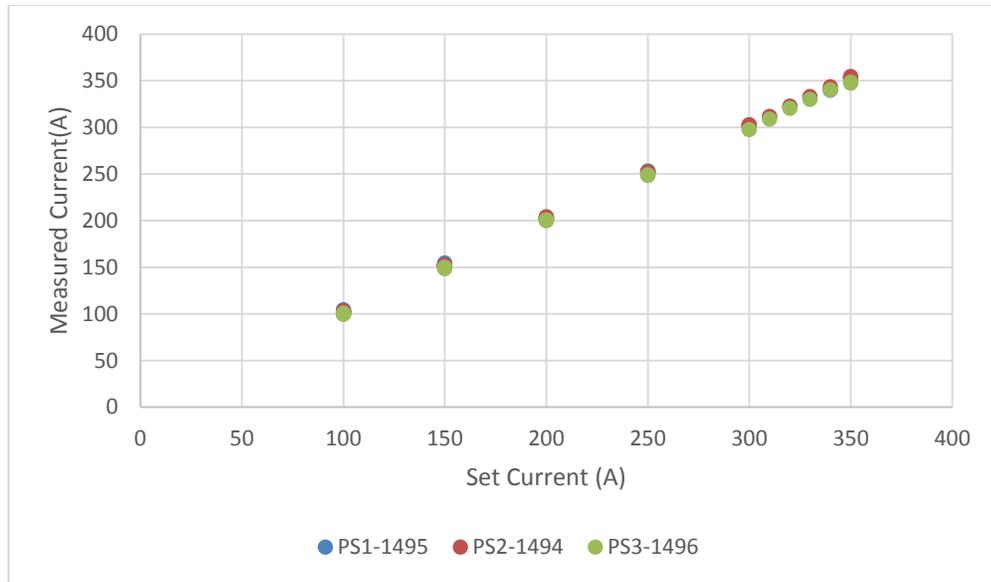


Figure 4.6: Load Bank Test Results - Current

The graphs show that regardless of the power supply, the output is consistently on target. The measurements here are slightly imprecise because the load bank has a rise time, but each measurement was taken as close to 15 seconds after the test at a specific step began as was possible. It is clear that in spite of this error, each power supply has the same response and they are all linear. Therefore, the issue does not lie in the output of the power supply.

### 4.3 Resistances and Inductances of Electrical Circuit

The results from the power supply comparison test show that the power supplies are producing reasonably identical outputs. The error most likely comes from the system beyond the power supply. This section explains the differences observed in systems due to different resistance and inductance.

#### 4.3.1 Overall Circuit Resistance

The next step forward in the system is the cabling and connectors between the power supply and the weld. These cables are usually very large to minimize resistance while carrying very high currents but the resistance of the cables is often not precisely known. Theoretically the cable resistances are negligible compared to the resistance in the welding arc. Depending on the cable length, the resistance is usually less than 5 mΩ while the arc is usually in the range of 500 to 1000 mΩ based on test results in this project. So the first test was to verify the resistance range

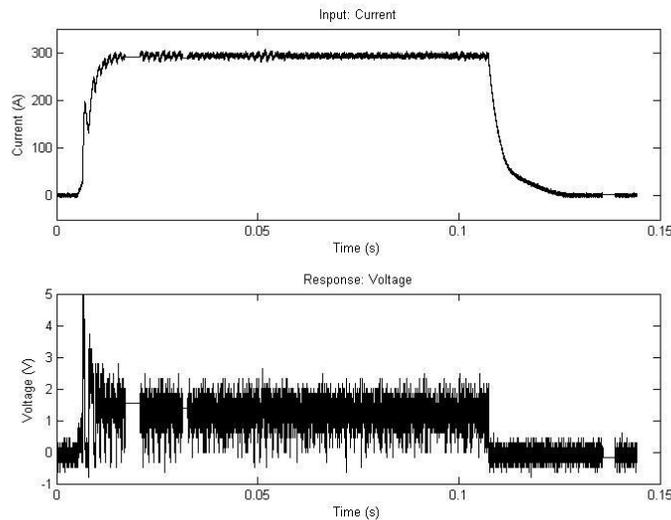
of the systems. However, since the resistances are so low it was not possible to connect a standard ohmmeter. These values were therefore measured by sending a square wave current burst at 300 amps and measuring the resulting voltage. A response of one of these step signals is shown in Figure 4.7. The step response can then be used to measure the inductance and resistance by ohms law and the time constant equations given in Equation 4.1 and 4.2.

$$V_t = V_0 e^{-\frac{t}{\tau}}$$

$$\tau = -t \ln\left(\frac{V_t}{V_0}\right) \quad (4.1)$$

$$L = R\tau \quad (4.2)$$

The results of these tests and measurements across the six identical systems are given in Table 4.1. Each system tested is an identical circuit, but there are clearly very different values between the systems and between circuits. The circuits are paired together within single work cells, i.e., 1 and 2, 3 and 4, and 5 and 6 are welding power supplies that shared the same physical infrastructure. Circuits 3 and 4 have lower resistances, which implies that this welding work cell system has a lower resistance than the other systems. However, even in the same work cell, the individual circuits have some small differences.



*Figure 4.7: Step Response of Welding Circuit*

Table 4.1: Circuit Resistance Values

System Number	Resistance(mΩ)	Inductance(μH)
1-1495	8.31	48.07
2-1494	8.07	48.78
3-1496	1.73	10.89
4-5848	1.0	4.80
5-1497	7.7	45.17
6-6235	9.25	56.73

The inductance of the systems also appears to be inconsistent. The differences are small, however, and a simple test of just the power supply showed that most of the inductance comes from inside the power supply itself. The time constants are only different by a few milliseconds, and for the purposes of this project it was determined that the inductance differences are negligible. All welding done for this testing was in a constant voltage mode so the rise and settling time was ignored and measurements were taken at steady state.

#### 4.3.2 Circuit Resistance by Components

Since such large variances were found in the different systems, it was necessary to break the system down further to see if there was a particular problem area. The circuit model in Figure 4.8 shows a breakdown of all the different system components. The components shown are present in nearly all welding systems but in a more specific work cell the circuitry can be broken down even further. Other systems may have slightly different fixturing and associated resistances, but the overall model can be translated across every welding system.

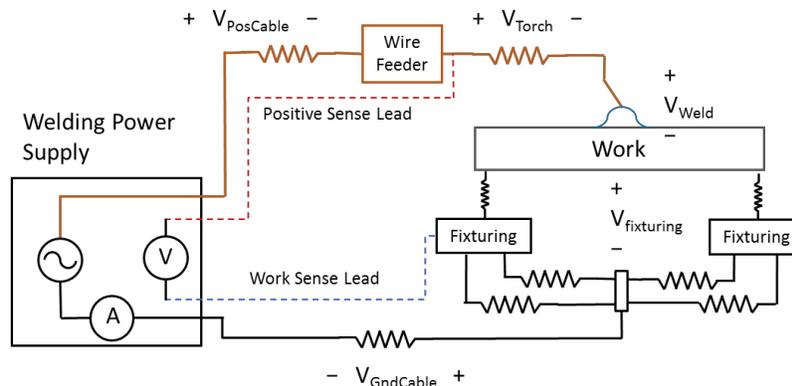


Figure 4.8: Simple Welding Circuit Model

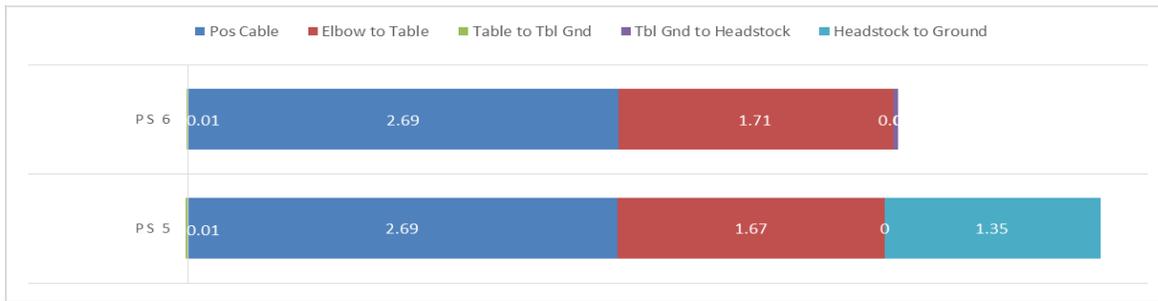


Figure 4.9: Makeup of Resistances around Systems 5 and 6

Based on this graph there are definitely small differences in each system and each system has unique resistances in different parts of the circuit. The difference in resistances between the headstock and ground connection is very large here. It would also appear that since each system is identical in cable lengths, construction and other respects, the differences are not something that can be fixed, but only minimized or simply accounted for. The system can be better realized with the use of a circuit model, such as the one shown in Figure 4.10. This demonstrates how each section of the circuit can be different and each part causes a slightly different voltage drop.

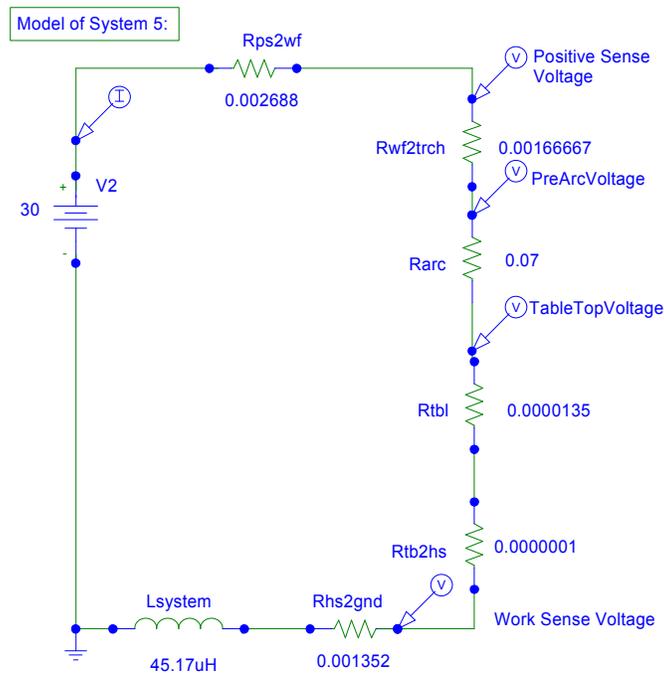


Figure 4.10: Full Circuit Schematic of System 5

These different voltage drops are the fundamental principle of the problem with system's bad calibration. When the circuit has resistances between the power supply and the welding, these resistances cause a voltage drop. This voltage drop causes the voltage across the weld to be less than the voltage across the power supply.

### 4.3.3 Cable Connections Resistance

One place that is always suspected as a problem area for experienced welders is the ground connection and cable connections. A series of currents were sent through the circuit with a tight and loose cable connection and the voltage was measured. The currents ranged from 100 to 400 amps and the resulting voltage across the bolt connection was measured and the resistance calculated using Ohms law.

*Table 4.2: Cable Connection Resistances*

<b>Torque</b>	<b>Average Resistance(mΩ)</b>	<b>Maximum Resistance(mΩ)</b>
<b>Tight</b>	0.04	0.07
<b>Finger Tight</b>	0.19	0.19
<b>Loose</b>	0.55	0.67

It is apparent by these numbers that there is a difference between torqued, finger tight, and loose cable connections, but at most the difference is only 0.67 mΩ when the connections are barely hanging on the bolt. When the connection is at least finger tight, the maximum is only 0.19 mΩ. This is such a small value relative to the overall system resistance that as long as the connections are finger tight, the connections do not appear to cause any large differences in circuit resistances.

## 4.4 Voltage Sensing and Controls

Based on the results from the resistance testing it is clear that the resistance of the system has an effect on the welding system. However the voltage sensing was observed to have an effect as well. Additionally, the Power Wave manual discusses the importance of proper sense lead placement over system resistance (Lincoln Electric Company, 2004).

#### 4.4.1 Testing With and Without Ground Sense Leads

The sense leads are a relatively new development in welding systems and most modern power supplies use them because it gives the power supply the ability to measure the arc voltage closer to the arc and better control the arc. However, the voltage sensing can also be a source of error. To demonstrate this, a test was run with and without the voltage sense leads. To start, the work sense, or ground sense, lead was attached to the plate being welded on, then it was removed so the power supply was sensing at the ground connector of the power supply. The results of this test are shown in Figure 4.11.

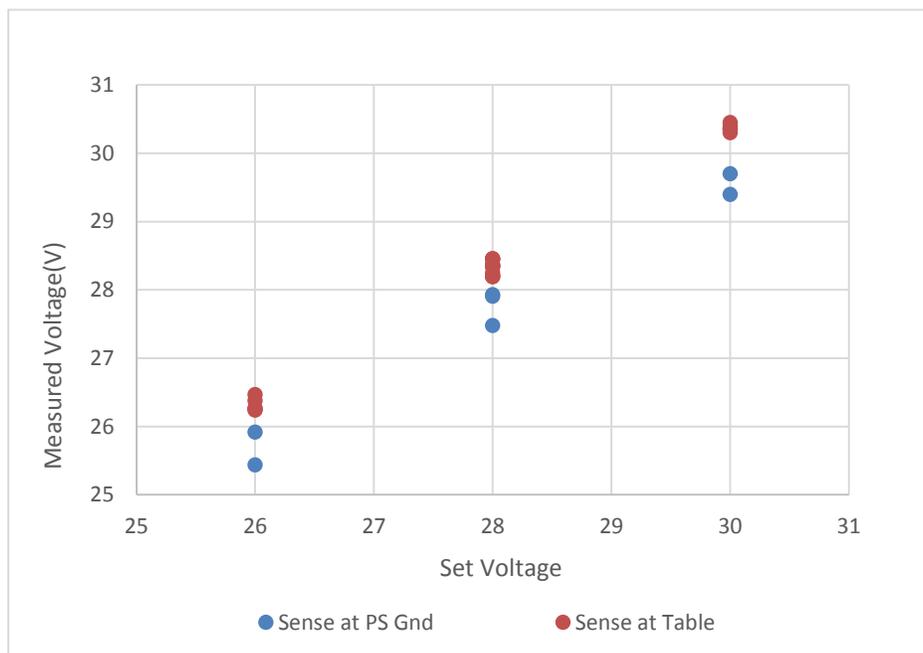


Figure 4.11: Ground Sense Placement Test

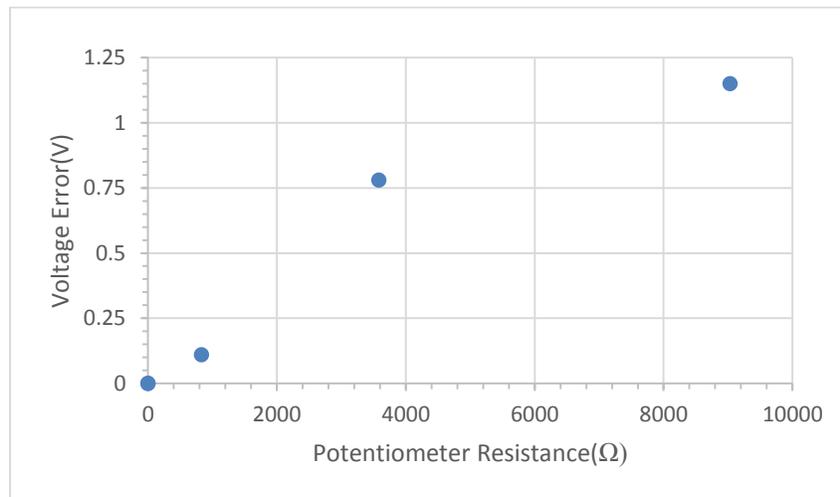
It is clear from this test that the location of the work sense lead has a noticeable effect on the weld voltage. When the work sense lead is closer to the welding arc the weld voltage is much closer to the set voltage. Having the work sense lead farther away at the power supply means that the voltage drops across the welding circuit are measured as part of the weld voltage. This causes the voltage to be lower and less accurate.

After testing the work sense lead the positive sense lead was tested, but in removing the sense lead the power supply overcompensated and ran the weld at such high voltages and

currents that it destroyed the contact tube and nozzle. Because of this destructive response a different way of testing the positive sensing was developed.

#### 4.4.2 Testing the Positive Sense Lead

To better understand the positive sensing but still remain in control of the welding without letting the power supply overcompensate, a potentiometer was added to the positive sensing lead. Adding this in caused the weld voltage to increase but at a more controlled level.



*Figure 4.12: Voltage Change due to Potentiometer*

This graph shows that as the potentiometer value increases the voltage increases. The potentiometer causes a voltage drop between the arc voltage and the power supply, meaning that the power supply senses less voltage than is actually at the welding arc. This causes the power supply to compensate and deliver a higher voltage. The potentiometer clearly has an effect on how the power supply manages the weld and the weld voltage is clearly controlled by the voltage sensing.

#### 4.4.3 Voltage Measurement Locations

The voltage sensing is clearly an important part of the system and can account for the errors in voltage in the system. These voltage errors are caused by the differences in resistances in the circuit, which thereby cause differences in voltage. So, to further explore the sensing, welds were done with and without the ground sense active and the voltage was measured at the sense location and at the arc.

The voltage error between the set voltage and measured voltage is clearly much larger at the weld than it is at the sensing location. In fact, the error is negative in the sensing location meaning that the power supply is actually delivering a higher voltage than it believes it should. This leads to two main findings. First the power supply is delivering a more than adequate voltage based on the sensed voltage. The weld voltage is lower than the sensed voltage because of the many voltage drops in the system, but the sensed voltage is the voltage that the power supply uses to control the weld and therefore this is the voltage it tries to maintain at the setpoint value.

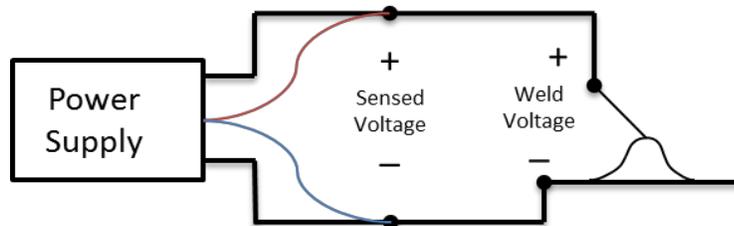
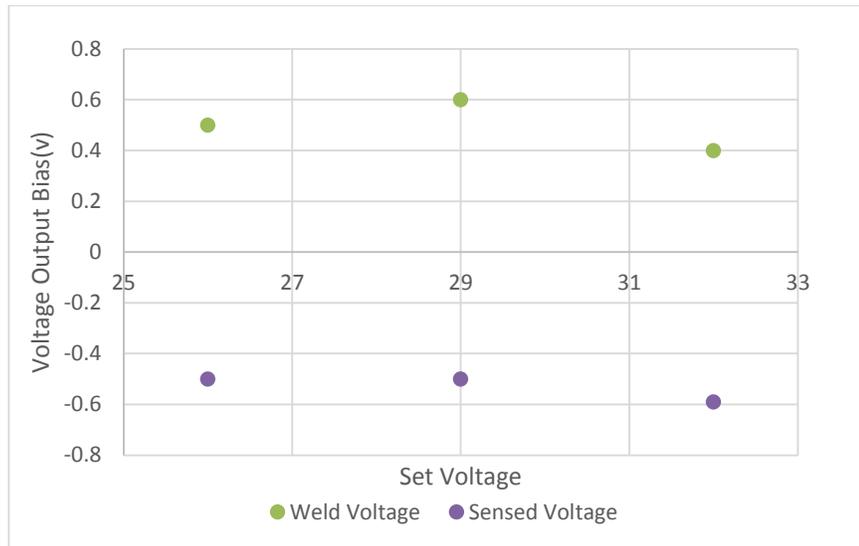


Figure 4.13: Voltage Sensing at Different Locations

The second observation is that the error for the sensed voltage is negative, meaning that the voltage at the sensing location is slightly higher than the setpoint value. This negative error is caused by a calibration factor that is inherent to almost all power supplies and can be adjusted. This calibration, or bias voltage, can be used to account for voltage errors in the overall system and thereby compensate for the errors observed that are due to the system resistances. The power

supply simply needs to be calibrated with the entire system instead of isolated and separate from the system.

### 4.5 System Layout Configurations

Since the systems are relying on the voltage sensing to monitor and control the welding process it is essential to better understand the effect of different configurations of the system. It is possible that a correct layout of the system could correct the error. In Lincoln Electric’s publication (Lincoln Electric Company, 2004) there are many different configurations that they suggest. From a fundamental electrical standpoint, if the problem seems to be voltage drops caused by system resistances then, by Ohm’s law, if the measurement is taken away from all current flow then there will be no voltage drop. In other words, if the error is in the voltage sensing and the sensing is done near any current flow, then since  $V = IR$ , if current, “I”, is zero, there will be no voltage. The table below shows a test done with voltage sensing in and away from current flow.

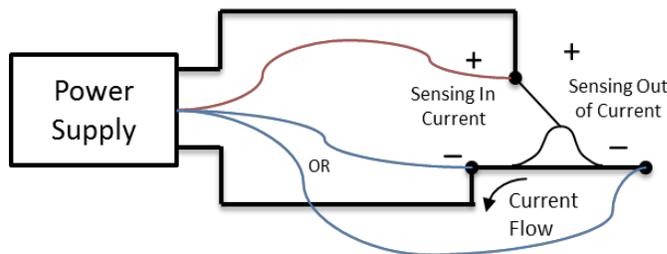
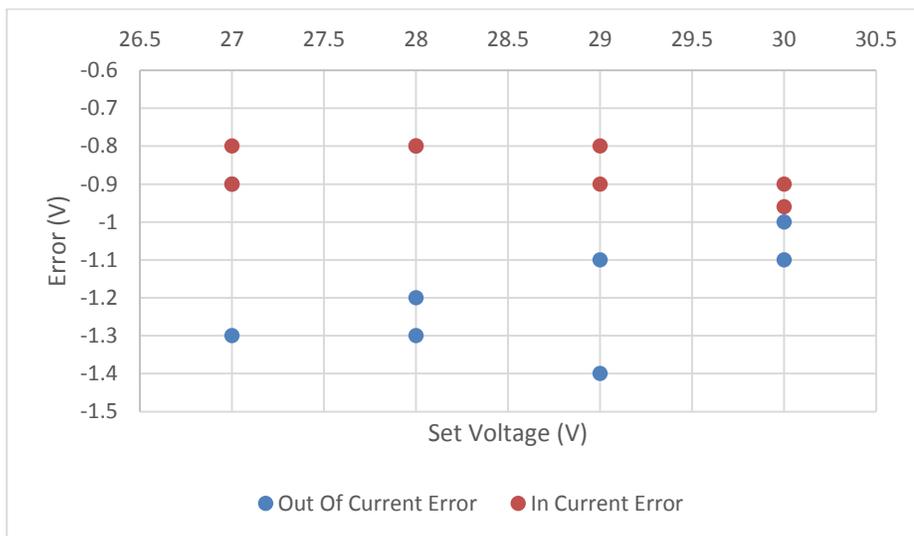


Figure 4.14: Effect of voltage measurement in and out of current flow

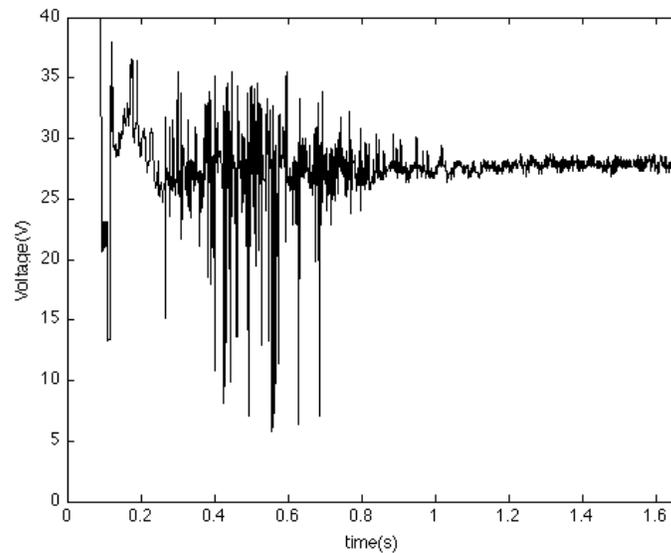
The measurements were all taken at similar locations on the weld table in the, but some were taken at the ground connection and others on the far side of the table outside of welding current flow. This data was collected at the CSM robotics lab and thus does not correspond to the previous power supplies. The data shows that when the sensing is done properly the error can be well below the desired level. The negative error means that the output voltage is actually higher than the set voltage, which in this case means that the welding power supply has been calibrated to output higher voltage than is necessary in this work cell. When sensing is connected outside of the current flow, however, the error can be further reduced. The negative error shows that by sensing outside of the flow of current the error is even more negative, or the output voltage is even higher than the set voltage. This is because the power supply's calibration is accounting for error that is no longer present. In a large welding work cell sensing outside of the flow of current can reduce the welding error even more substantially because the resistances are generally much higher.

## **4.6 Arc Stability**

While running the many test welds some very interesting characteristics relating to arc stability arose. All welds were run in a constant voltage mode, but in varying the parameters it often occurred that the weld would start in a globular transfer mode then transition into a spray transfer mode. The time required before this transition varied but usually was faster with higher heat inputs and slower with lower heat inputs. The waveforms during this transformation began with volatile changes, often referred to as high kurtosis, but then would settle out into more stable, consistent variations. A waveform demonstrating this is given in Figure 4.15.

Most commonly the transfer mode is defined by the shape and frequency of the electrode melt off as it transfers to the weld pool. Globular transfer modes occur when a ball of molten metal forms that grows to be larger than the diameter of the electrode and then falls off. Spray transfer occurs when droplets smaller than the diameter of the electrode melt and fall off into the weld pool. While welding, the globular transfer mode usually causes a more volatile, harsh, and crackly sound, whereas the spray transfer mode sounds more like a crisp smooth humming sound. Most welders use this sound to identify the quality of the weld. If a welder hears the

smooth humming sound they attribute it to a good weld while the harsh sound of globular transfer usually indicates a rougher weld bead and more spatter.



*Figure 4.15: Arc Stability Transition*

On many occasions in the experiments for this project the weld would be harsh at first and then become smooth after a second or so. During this harsh time the weld would have a rough bead, poor penetration and the waveforms would indicate a globular transfer mode. Additionally, the standard deviation would be high. Correspondingly, when the weld would settle into a gentle humming sound the weld would be very smooth, have good penetration and the waveform would indicate a spray transfer mode. The standard deviation of the voltage and current would also be very low. Note, all of these welds were performed in the flat position.

## **CHAPTER 5 : DISCUSSION**

### **5.1 Welding System Issues**

The results show several key problem areas. The differences in the systems are caused by resistances and manifest themselves in voltage error. The errors in voltage readings cause differences in the current as well though. It is therefore very important to understand this relationship to ensure that the voltage and current can be correct.

#### **5.1.1 Voltage Error Observations**

The voltage error in these systems is a result of the resistances between the power supply and the welding. The voltage sensing leads help the power supply to more accurately measure the weld voltage closer to the arc, but there is still many areas for problems to arise. The positive voltage sensing's standard mounting location is on the wire feeder but the ground sensing lead can be almost anywhere depending on how the manufacturer sets up the work cell. This leaves many sources of error in the sensed voltage that then cause errors in other weld parameters.

The voltage error is always linear, indicative of a linear relationship between the error and voltage. This is because the error is caused by resistance. The error also tends to be positive, meaning the actual weld voltage is lower than it should be. This happens because resistances in the system create voltage drops between the welding arc and the power supply voltage sensing. The sensed voltage is therefore higher than the actual arc voltage because of these resistances and thus the weld voltage is lower than it should be because the power supply controls the weld based on the sensed voltage which is inflated by these additional voltage drops within the sensed portion of the circuit. The sensed voltage is, however, higher than the set voltage due to calibration in the power supply. This shows that the power supply does account for some resistance between the voltage sensing and the arc. These trends imply that the voltage error can be corrected by minimizing system resistances, proper voltage sensing, and power supply recalibration.

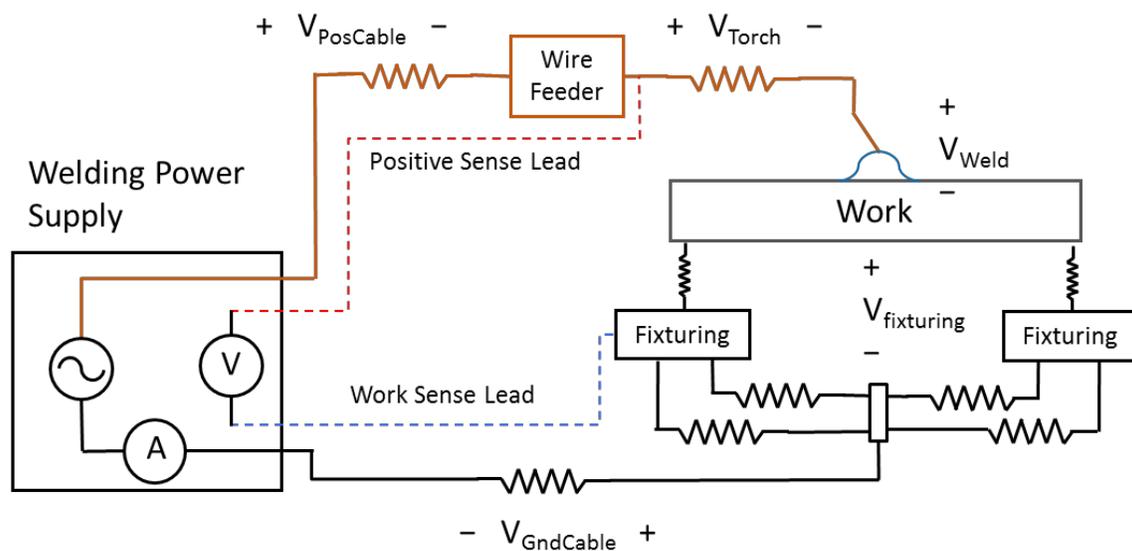
#### **5.1.2 Voltage and Current Control Relationship**

Voltage has been the main study of this research but imprecision in current is also a concern for many manufacturers. Figure 4.1 and Figure 4.4 show that the current error follows

the voltage error. This is because of the design of the feedback control loop of the power supply. If the voltage reading is higher than it should be because of a voltage drop between the weld and the voltage sensing, then the power supply will deliver less current because it senses that the desired voltage has been met. The weld voltage and current will therefore be lower than they should be. Conversely, if a potentiometer is in the circuit, the power supply will sense a lower voltage and provide more current to increase its perceived voltage. This will cause the weld voltage and current to increase.

## 5.2 System Characterization

The main findings of this project are in the system characterization, or how the system functions. Before this project much of the control architectures and effects of system circuitry were relatively unexplored. The project therefore started with a system model. The diagram in Figure 5.1 shows a simplified view of a common welding circuit.

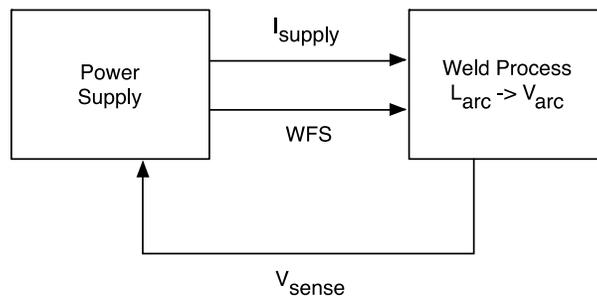


*Figure 5.1: Welding System Circuit Diagram*

This model presents the main components of the system. The primary points to note are the many resistances around the circuit as well as the voltage sensing cables. The resistances of the circuit affect the energy flow between the power supply and the welding arc, but the true source of the welding power is in the power supply, so it is essential to have a comprehensive understanding of how these power supplies function. The power supplies work by adjusting the

current until a designated voltage is reached. This process is made possible by devices such as the Insulated Gate Bipolar Transistor, or IGBT for short. The IGBT is a high-power device that allows current to flow based on input commands. It opens and closes an electronic “gate” allowing more or less current to flow as called for by the control. The IGBTs in welding power supplies are able to do this very quickly, at around 10 kHz, and with very high currents, i.e., in the hundreds of amps.

The power supply controls the amount of current the IGBT will supply by monitoring the welding process voltage and controlling the current flow until it measures the voltage it wants. The welding process is given a wire feed speed and current by the power supply and the robot program defines a contact tube to work distance. For the purposes of this project, in addition to using the constant voltage mode, we will assume that the wire feed speed is held constant and is properly calibrated. Variations in wire feed speed could also cause problems though. The current, wire feed speed, and contact tube translate into an arc length, which is responsible for arc voltage. This voltage, or some derivative of it, is then read back into the power supply. The power supply then adjusts the current until the desired voltage, as given to it in the weld process parameters, is measured. The block diagram in Figure 5.2 demonstrates this process.



*Figure 5.2: Block Diagram of Power Supply Control*

Thus the power supply relies heavily on the sensed voltage to maintain proper control. This voltage feedback is how the power supply monitors the process and controls the inputs. This sensing is often done by measuring the voltage at the power supply’s weld lead connections, but in large work cells the voltage sensing is usually done with sense leads that are external to the power supply. The positive voltage sensing is attached to the wire feeder and the negative voltage sensing is attached at some point that the work cell designer prescribes. This work sense

lead is therefore a very important part of the system design because the voltage it senses controls the output of the power supply.

The system voltage is a principle controlling aspect of GMAW welding, and if the system senses the correct voltage, then the system should be calibrated correctly. In other words, the power supply gauges the amount of current flow by the voltage reading and voltage is the main feedback variable. If the sensed voltage is correct and the system adjusts the voltage according to that sensed voltage, then the system should produce the desired weld parameters. So if the voltage sensing and control are good, then the system should be calibrated. Based on the many individual resistances throughout the system though, there are many places where voltage drops exist and therefore cause differences in sensed voltage.

### **5.3 System Identification**

In order to truly understand how much each part affects the system, it was essential to establish values for each component. These resistances are far too small to simply measure with an ohmmeter, inductance meters are not readily available and measuring sections of the circuit would be difficult. It was therefore necessary to use another approach to determine the resistances and inductances around the welding loop. After some initial testing, it was determined that the resistances and inductances could be measured by sending a high current through the system and measuring the resulting voltage. The circuit could be completed by either short circuiting the contact tube to the work piece or connecting a load bank in the loop. To measure the inductance, a step function was used to induce an exponential decay. This exponential decay can then be used to calculate the time constant by Equation 4.1 and system inductance can then be found by Equation 4.2.

In addition, the voltage drops across certain segments of the circuit could be used to determine the resistance in that segment, such as the resistance in a particular weld cable. Inductance would be a little more difficult to measure in sections like this, but after measuring the entire system it was determined that the inductances were relatively negligible. The results of measuring the step response through the entire system are shown in Figure 4.1. The table shows each power supply and the power supply's corresponding circuit resistance and inductance. The

power supply internal resistance is a design characteristic of the power supply and was determined to have very little effect on the calibration of the system.

Based on these tests each system has very different resistances. The power supplies are grouped in pairs of two for each system since the welding work cells tested each had two robot welders, so PS1 and PS2 are on the same work cell, etc. With this in mind, it appears that each system has unique resistances, but each circuit has different resistance as well. That is, the circuits associated with power supplies 1 and 2 and 5 and 6 are in the 8m $\Omega$  range while the circuit in power supplies 3 and 4 are in the 1-2m $\Omega$  range. To delve deeper into the issue resistances were measured at different points around the loop. The graph in Figure 4.9 shows the resistances around the welding loop in two power supply circuits in the same system.

This shows that the same segment in different welding circuits can have different resistances, and different components in seemingly identical systems can have different resistances. These differences manifest themselves in the welding process as a voltage drop, which causes the difference in voltages in the systems.

The resistances in the welding circuit are most often caused by the welding cable. A 4/0 weld cable has about 0.05 m $\Omega$  per foot (Manz A. , 2009). This means that 100 feet of cable would have about 5 m $\Omega$  of resistance. At 400 amps this would cause a 2-volt drop. Another point of concern for many people is cable connection tightness. However, based on our testing, the difference between a torqued cable and a finger tight cable is only about 0.5m $\Omega$ . This is not completely negligible, but it is more important to minimize weld cable lengths than to have perfectly and identically torqued connections throughout the welding loop.

## **5.4 System Design Considerations**

Modern power supplies already have the voltage sensing in place to account for voltage errors caused by resistances, but in spite of this many systems are still not providing the correct weld parameters. These errors still exist because there are some design principles that must be considered when designing these work cells. With the more complete understanding of how the system's controls work, some of these design considerations are now more evident.

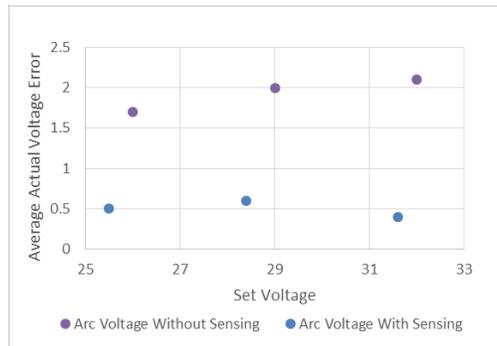
#### **5.4.1 Design Considerations: Cabling**

The main issue with the systems is the inherent resistances that cause voltage drops. These voltage problems can be avoided or accounted for in several ways. First and foremost is to minimize the cable lengths. This ensures that there is only a minimal amount of resistance between the power supply and the welding process. In the instance where the work cell is very large, large cables, and even cables in parallel should be used. If more than 100 feet of cable is required or high current is being used, e.g. more than 300 amps, then large diameter cables should be used. If high currents and long cable runs are required, it is recommended that large cables be used in parallel. Having the cables in parallel will significantly reduce the overall circuit resistance (think a factor of two resistance reduction for each cable added). This is commonly known among most system designers, but hopefully this paper will help convey the reasoning behind this practice.

#### **5.4.2 Design Considerations: Voltage Sensing**

Voltage sensing is usually available in modern, high-tech power supplies. If it is available, then it should be used. The voltage sensing gives the feedback for the power supply to use for control, and thus the voltage that the power supply is sensing is critical for proper operation. If the sensing is done close to the arc, then the weld circuit outside of the voltage sensing will be ignored. If the sensing is on the wire feeder and the headstock (normal voltage sensing location), then the voltage control will be based on the circuit between these two points. The power supply will produce enough current to ensure that the voltage between these two points is the desired voltage. This means that any voltage drops before or after this section of the circuit will be ignored. The cable resistance between the power supply's positive connection and the wire feeder and on the other side of the circuit between the headstock and the power supply negative connection will be ignored. This means that the voltage potential across the power supply connection lugs will be greater than the voltage measured closer to the welding process, and the welding process voltage will be much closer to what is prescribed via the power supply's welding voltage set point. Figure 5.3 shows a graph of the welding process with and without the voltage sensing active. This graph clearly shows that the error is much higher, as much as 1.5 volts or more, without the use of voltage sensing. This data was collected from a equivalent welding system to the previous ones shown, but did not have voltage sensing active during the

welding process. These results clearly show the large difference between welding with and without voltage sensing.



*Figure 5.3: Weld Process Voltage Error With and Without Voltage Sensing for Different Welding Set Point Voltages*

The Lincoln Electric Power Wave series power supplies have voltage sensing using connection terminals 67 and 21, which are most commonly internal to the machine. To ensure that the sensing is active, one of the dip switches, usually dip 8 on the Power Wave series, must be on. The positive voltage sense lead is part of the wire feeder cable bundle and is attached to the front of the wire feeder block where the torch cable connects. The work sense lead is its own cable connection on the front of the power supply. More information about the Lincoln Electric power supplies is available in the power supply's manual and further detail on the subject depends on the type of power supply.

With regard to voltage sensing there are a few techniques for minimizing the sensing error. If the voltage sensing is able to exactly measure the weld arc voltage then the power supply will be able to maintain a weld voltage that is what the process parameters specify. To ensure that the voltage sensing can sense the correct voltage, the sense leads should be attached as close to the arc as possible. Since every component has some resistance associated with it, if the voltage sensing is too far away from the arc then there will be several voltage drops in addition to the true weld arc voltage, thus causing an erroneous reading. In most cases the positive voltage sensing is done at the wire feeder. This is usually a prescribed configuration by the power supply manufacturer and thus should be accounted for in the weld process specification. The work sense lead (ground sense lead) is therefore the major source of error as

its location varies between system designer and work cells. The work sense lead should be attached right on the work piece itself, or as close to it as possible.

Another technique to consider is measuring the voltage away from the current flow. If possible, the current should flow to one side of the work piece and the voltage reading should be made on another side. If there is no current flow then there will be no voltage drop, and thus the voltage at the base of the arc will be approximately the same voltage that is measured by the work sense lead. By Ohm's law,  $V=IR$ , if  $I=0$  then  $V=0$  even in the presence of resistance.

Wolf Robotics engineers also mentioned that the current was not following the desired value. But by the architecture of the power supply control, if the voltage sensing is correct then the current output should be exactly what the power supply needs to deliver in order to achieve that set voltage. So if the voltage error is corrected, then the current should also be brought back to the correct value.

## **5.5 Methods for Correcting Error**

Sometimes it is not possible to follow these design considerations because of the size of the part, limitations in fixturing, etc. In large systems it is often necessary to ground to several points to minimize arc blow and maintain a good ground throughout the work. Some parts also must be fixtured repeatedly and so it is undesirable to constantly reattach the sense lead. In these cases sometimes the ground sense lead must be attached at a point that is within the current flow and cannot be as close to the weld as possible. In these cases it may be necessary to find another way to account for the error. This can be accomplished by adding in a programmed voltage offset, by (1) using a potentiometer in the voltage feedback, or (2) recalibrating the power supply.

### **5.5.1 Correcting Voltage: Offset**

The root cause for the variation in system characterization is in the resistance, which has a linear relationship with voltage. By ohms law,  $V = IR$ , thus any  $\Delta R = \Delta V/I$  because voltage is the control parameter. Therefore, the issue can be corrected by adjusting the voltage set point with an error factor to account for the difference in welding voltage and set point voltage. This

linear error relationship can be seen in Figure 5.4. The diagram in Figure 5.5 shows where these readings were taken.

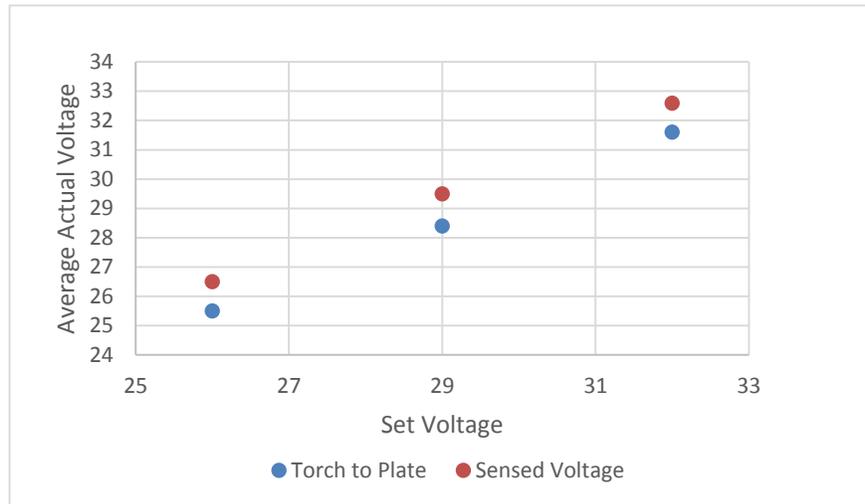


Figure 5.4: Set Voltage vs. Actual Voltage Close and Far from Arc

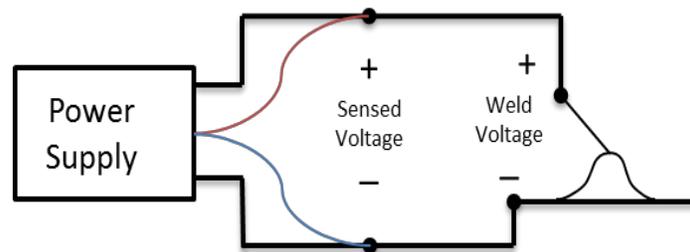


Figure 5.5: Locations of Voltage Sensing vs. Welding Voltage

### 5.5.2 Correcting Voltage Error: Tricking Voltage Sensing

Adding in this error factor is imprecise and is not always optimal. In many instances there are several identical work cells and when the manufacturer changes a process they much prefer to write a single program and upload it to each one. In this case it is much better to calibrate each individual work cell without having to use a voltage adjustment in the welding program. Wolf Robotics has come up with a system of doing this by using a potentiometer in the voltage sensing. By putting a resistor in the positive voltage sensing, by the wire feeder, they are able to adjust the voltage reading enough to adjust for the error and thereby calibrate the system. This

effectually tricks the voltage sensing into seeing a different voltage than what is really there, which makes the power supply adjust the output voltage accordingly. A block diagram of the process is shown in Figure 5.6.

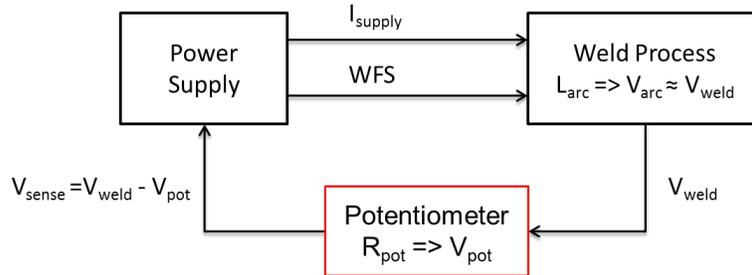


Figure 5.6: Adding a potentiometer into the voltage sensing

This potentiometer can be adjusted for each individual system that will then allow the operators to install one program into multiple work cells. Currently though, Wolf dials in the potentiometer by reading the output voltage and adjusting the potentiometer until the weld voltage meets the desired voltage. Based on the circuit resistances and operation though, if the voltage error is known then the resistor value can be calculated by Equation 5.3.

$$R_{pot} = \frac{R_{sense} V_{error}}{V_{set} + V_{error}} \quad \begin{array}{l} R_{sense} \approx 150k\Omega \\ V_{error} = V_{set} - V_{weld} \end{array} \quad (5.1)$$

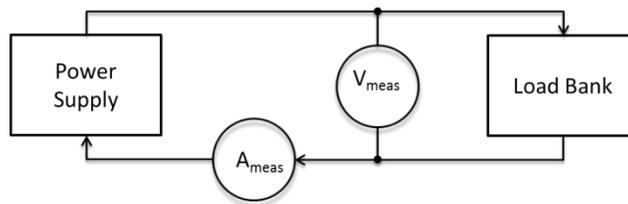
This equation treats the circuit as a simple voltage divider where the desired value is the resistance, given a voltage error. So, if the user has a voltage error, which should be constant across all voltages, then this equation can be used to calculate an approximate potentiometer value from that voltage error and the nominal weld voltage for the system. The sensing resistance is the resistance of the power supply's voltage sensing system and the voltage error is the average difference between the set voltage and the weld voltage.

### 5.5.3 Correcting Voltage Error: Recalibrating Power Supply

Using this resistor in the sensing is an added hardware piece that can be used to correct the voltage error, but it would be ideal to correct the sensing error by recalibrating the power supply. Power supplies have their own calibration in them and are calibrated when they ship from the factory. The calibration voltage is a small error factor that is programmed in to power

supply to account for any difference in the power supply's perceived voltage and actual voltage during factory calibration. The problem is though, that the calibration is done with short cables and the voltage sensing is done at the power supply's weld cable connection lugs. Then when the power supply is inserted into a large welding system, the sensing is different, there are several new resistances in the circuit, and the power characteristics of the whole circuit change. Therefore, to really calibrate the power supply, it needs to be calibrated using the entire system.

To calibrate the power supply with the entire system a load bank must be used. A load bank is a very high capacity resistor that has a very low resistance, but can dissipate large amounts of energy. In this case, the load bank can be used to simulate the weld. It provides the system with a very stable, controllable load that can be used to generate a voltage from a given current. The load bank can be connected into the welding circuit, as close to the arc as possible, to generate a voltage from the power supply's current input that is in the range of a weld voltage.



*Figure 5.7: Load Bank Connection Diagram*

The power supply can then be recalibrated by an experienced professional. The calibration software has the option of calibrating based on the power supply sense leads. During this project, we did not have access to a load bank for sufficient time to try this approach but the methods are in place to do so. The calibration must be done with the calibration software using the voltage sensing at the sense leads rather than the weld lead connection lugs, as is the default. With this in place, the power supply can be calibrated as part of the entire system. The process will be to simply adjust the power supply calibration until the measured voltage across the load bank is equal to the voltage that the power supply thinks it is delivering.

## 5.6 Arc Stability

In running many of the tests, it was found that the arc stability was a strong indicator of the welding process's quality. An unstable arc would produce a more volatile weld pool, which

would in turn cool into a very sharply textured weld pool. The weld penetration appeared to be significantly less as well. It is interesting to note that the weld would often start off in this unstable, globular transfer mode, but then as the weld progressed it would transition into a spray transfer mode. The time before the transition varied and seemed to be longer with lower heat inputs. Interestingly as well, the transition would occur later when using high strength steel.

The arc stability and corresponding transfer mode could be used to determine if a welding process is not functioning normally. It could be used to easily determine when the weld is no longer in a spray transfer mode when it should be, and thereby alert the operator when something is not occurring as planned. The transition time between globular and spray modes could also be used to determine irregularities in the process. Further exploration into this area could prove to be very beneficial.

## CHAPTER 6 : SUMMARY AND CONCLUSIONS

### 6.1 Summary

Gas metal arc welding systems are one of the most common types of welding and account for a large portion of automated welding processes. Manufacturers demand very high precision in these automated welding systems but the work cells often do not supply the welding parameters that are required. This project sought to better understand how these systems operate and developed techniques to correct these issues.

Robotic welding work cells are a very high-precision tooling system that needs better standardization. Many manufacturers have multiple *identical* work cells but each system can produce different welds. This makes quality control and standardization of parts very difficult. The manufacturer usually has to have different program parameters for each work cell and all the parameters have to be checked and validated to make sure that the weld is being produced is in fact what is desired.

Although many manufacturers are experiencing this problem, there has been little work done in developing a better way to standardize these work cells. Either the manufacturers (1) program all the weld settings by hand, (2) add in error factors into all the welding parameters, or (3) they find rudimentary ways of calibrating their systems. Much of the architecture of the welding power supplies is proprietary and closely guarded, which makes it difficult for the operators to truly know how the power supplies operate.

The objective of this project was, therefore, to develop a way to better standardize and calibrate these welding systems. The final goal was to ensure that system's parameters are properly calibrated and that identical work cells can have the same program and welding parameters and give identical results. This was accomplished by developing a better understanding of the welding power supply's operation and isolating the problem area. From this, design criteria were laid out that can be used to properly calibrate these work cells.

The findings in this project show that the welding output can be erroneous because of poor voltage sensing feedback. GMAW power supplies use voltage sensing to control the

welding output. The power supply provides current into the welding process until the voltage is met. The voltage is therefore the control feedback that, if it is incorrect, will cause the welding process to not be working at the correct set points.

Proper work cell design, “tricking” the voltage feedback, or recalibrating the welding power supply can correct problems with this feedback. The best practice is to properly design the welding work cell so that the voltage sensing is as close to the weld as possible and outside of the current flow. If the work cell cannot be redesigned or the fixturing cannot be made to ensure the voltage sensing is close and out of current flow, then other techniques can help to correct the issue. The voltage set point can be increased slightly to account for the voltage drop, or adding a resistor to increase the voltage that the power supply senses can alter the feedback and bring the voltage up to the desired set point. It is possible to have a trained professional recalibrate the power supply as well. The recalibration, to be effective, should be done with the full system and should be done using the voltage sensing leads, not the voltage sensing at the power supply lugs as is normally done. This must be done by a trained professional otherwise the power supply can be damaged or the problem can be made worse.

## **6.2 Conclusions**

- Each welding work cell has inherent differences due to resistances, voltage sensing and cabling configurations, which cause different responses between systems.
- In most GMAW power supplies, the power supply delivers current to the weld until a voltage is met. The voltage is therefore the feedback to the control architecture and is the main source of error.
- Large scale industrial welding work cells are very complex systems but the voltage sensing in the power supply helps the welding power supply to have better information of what is happening in the welding process and thereby tighter control of the welding process.
- Errors in the voltage can be solved by following special work cell design criteria, altering the voltage feedback, or recalibrating the power supply with the entire system.
- Arc stability appears to play an important role in determining how a welding process is performing.

### **6.3 Suggestions for Future Work**

Power supply manufacturers tightly guard their control architecture, but it would be useful to further explore the voltage sensing control architecture to develop a system model for the power supply for specific power supplies. This could be added to the knowledge developed in this thesis to give a full system model. This model could be used to better understand and control the welding output, not just the relation between the power supply output and the full system output. This would also require further analysis of the system inductance and wire feed speed. Future work should include an analysis of the inductance and wire feed speed as they relate to the power supply output.

Further work could also be done to examine resistance in the contact tube. The true welding voltage is between the electrode and the plate, but the closest that the data acquisition system in this project could get to the welding voltage is between the contact tube and the plate. Incorporating the resistance in the contact tube would give an even more precise welding voltage.

The arc stability was only briefly noted in this study, but the correlation to weld quality was definitely observed. Further work would be especially beneficial if a pass fail criteria could be determined based on arc stability. Based on the observations thus far, it appears that it might be possible to develop thresholds that relate to the arc stability to determine when a welding process is performing properly or not.

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