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Automated Welding System

CONCEPTUAL STUDY

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TERMS, DEFINITIONS, AND ACRONYMS

QPS	Quasi-Poloidal Stellarator
MDL	Magnet Development Lab
MABE	Mechanical, Aerospace and Biomedical Engineering
Ar	Argon
TIG	Tungsten Inert Gas
GTAW	Gas Tungsten Arc Welding



Introduction:

In support of the Quasi-Poloidal Stellarator (QPS) effort at the Magnet Development Lab (MDL) Facilities, the University of Tennessee Mechanical, Aerospace and Biomedical Engineering (MABE) Department has performed a conceptual study on the application of a robotic welding system in the QPS magnetic coil manufacturing effort. The QPS includes a toroidal series of magnetic coils designed to generate a precisely defined magnetic field when an electric current is passed through them. The magnetic field provides containment for plasma that is being processed to obtain fusion energy.

The proposed QPS magnet configuration is shown in Figure 1.

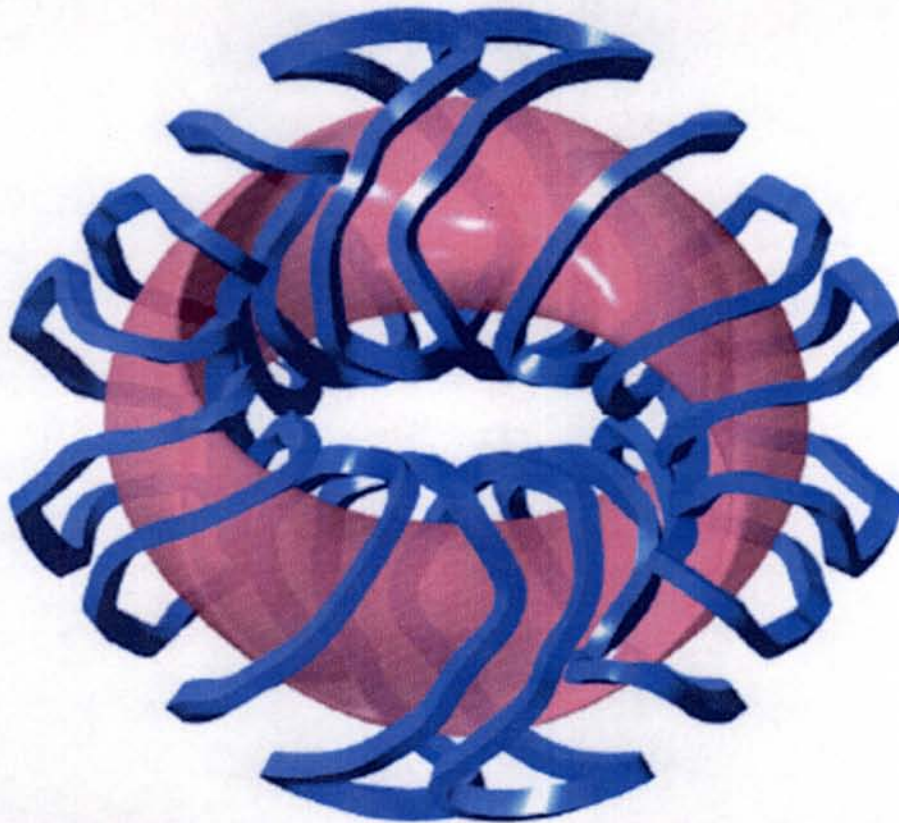


Figure 1: QPS Magnetic Coils and Plasma

The manufacture of these magnetic coil assemblies requires the welding of multiple pieces of stainless steel. A manual welding process, as the magnetic coils are very large and complex in shape, has the potential to be very labor intensive and time consuming. However, it has been shown in industry that implementing robotic welding can produce more consistent quality welds and increase the productivity of a manufacturing process while decreasing production costs. However, robotic welding systems do not come in a "one size fits all" configuration. Each application requires a specifically designed system that has been tuned for repetitive production use. This study deals with the requirements, potential benefits, and feasibility of implementing a robotic welding system for use in the manufacture of the QPS magnetic coil assemblies.



Robotic Welding In Industry:

Robotic welding systems have become the standard method for performing welding operations in many industries. In the automotive industry, the Mercedes-Benz Corporation reports that the implementation of robotic welding in the assembly of their auto bodies has significantly improved productivity and quality. The use of these systems is also a standard practice in shipbuilding and in high volume prototyping by many fabrication shops.

CORSA Performance, Inc. has seen significant improvements in product quality and process productivity through implementation of a standardized robotic work cell for the production of their unique, high performance mufflers. The work-pieces for these welds were thin gauge stainless steel sheet metal, like the work-pieces for the QPS project. See the Appendices for a detailed description of this case study.

Dr. Carl Lundin, UT's primary materials joining researcher, recently worked on another implementation of robotic welding. The manufacture of heart pacemaker batteries required high precision welds on very thin stainless steel casings. These welds were very similar to some of the welds necessary for the QPS production process, except that they are on a much smaller scale. They are required to meet high leak test specifications. Robotic welding was implemented for this application because of the repeatability, precision and consistency of the results.

Industry has consistently found that implementing robotic welding systems is both feasible and beneficial when the system is well matched to the application.

Benefits of a Robotic System:

Robotic welding systems offer three main advantages: consistent weld quality, increased output, and decreased variable labor costs.

Consistent weld quality

The welding task associated with the magnet coils is extremely labor intensive. With most labor intensive tasks, quality tends to decrease the longer the activity is continued. Unlike a manual welder, a robotic system is not subject to fatigue and is able to sustain high quality welding for prolonged periods of time. Well designed robotic systems have the capability to repeat any taught action with the same quality results. This attribute is important since there are several different magnet configurations and each configuration is used multiple times.

Increased output

Industrial experience suggests that the average robot can weld at least twice as fast as a skilled manual welder. The increased speed helps avoid potential delay due to the welding operation, and a quicker turnover of magnet coils can be realized.

Decreased variable labor costs

Due to the increased output, overall labor time is shortened and labor costs are reduced. The limited availability of skilled, certified welders may pose a challenge. Conversely, general machine operators are more readily available and more affordable than skilled, certified labor.



Scope of Application:

The first important step in clearly defining the design of a robotic welding system is to understand how the system will fit into the overall magnet assembly manufacturing process. The proposed magnet manufacturing facility is shown below in Figure 2.

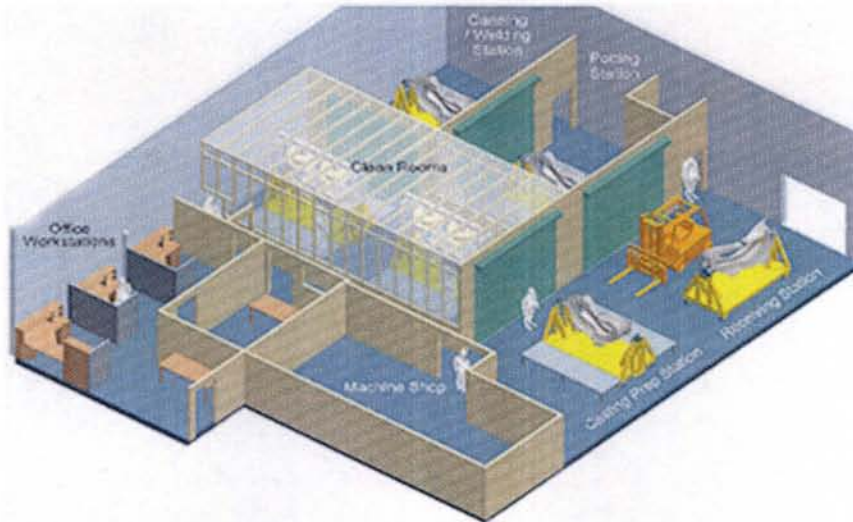


Figure 2: Magnet Manufacturing Facility Layout

Upon arrival at the MDL facility, the castings will be sent into the clean rooms to be wound with copper conductors. Following the winding process, one casting at a time will be rolled into the canning/welding station. Here the stainless steel sheet metal cans will be welded to the casting in order to encase the copper windings. After the can has been welded to the casting, it will be rolled into the potting station, where the enclosed copper conductor will be saturated with an epoxy. After some further processing, the magnetic coil assembly will be complete.

The canning/welding process will be an integral element of the magnet assembly production process. This study will explore the potential of using a robotic welding system in this stage of the production process.

Production Welding Specifications:

For the manufacture of one winding assembly, two can pieces are required to be welded onto a casting. After being wound with the copper conductor, the casting, or winding form, will have a cross section as shown in Figure 3. The copper conductor will be covered with a ground wrap, which will then be covered with a compliant, or "crush plane," material. The stainless steel can pieces would then be tack-welded to each other and the casting in order to maintain their relative positions. The three locations marked by red dots indicate where the can pieces and the casting will be welded together.



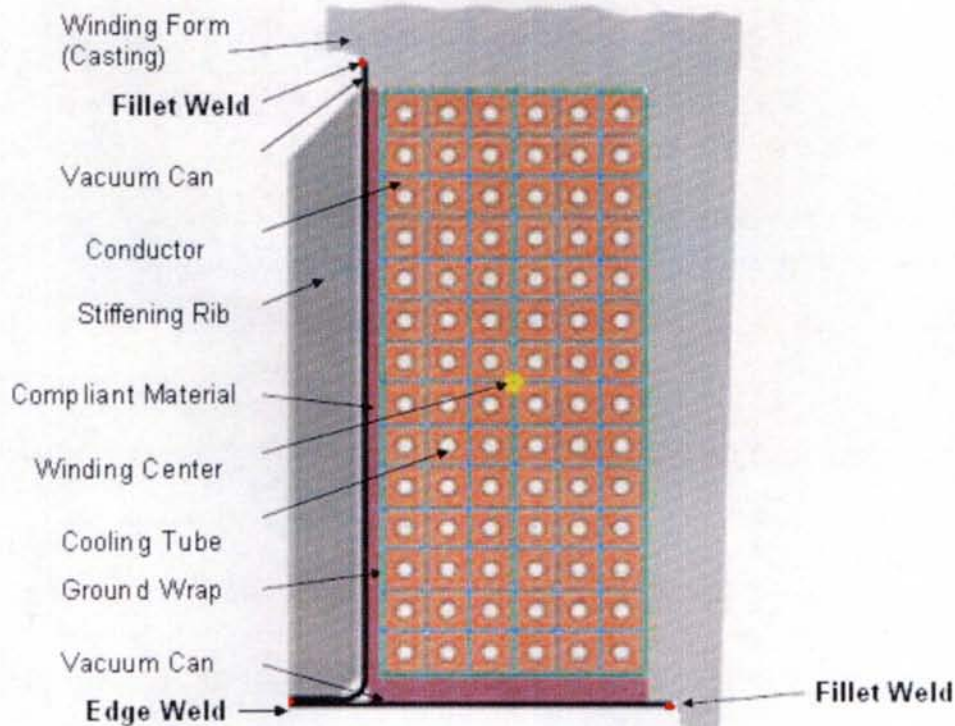


Figure 3: Cross Section of Magnetic Winding

From Figure 3, it can be seen that there will be two types of welds required in the production of the magnet assembly: a fillet weld between the 0.030" can pieces and the thick stainless steel casting, and an edge weld between the two 0.030" can pieces. The nature of the can shape and the desired characteristics of the welds will define the design requirements for the robotic welding system.

Welding System Requirements

- **Ability to Weld Complex Paths**

The magnet castings will be in five different configurations, while each of these configurations will have four corresponding can pieces. An illustration of two of these can pieces assembled to make a full can is shown in Figure 4. It can be easily seen that the system will need to be able to follow a three dimensional welding path.



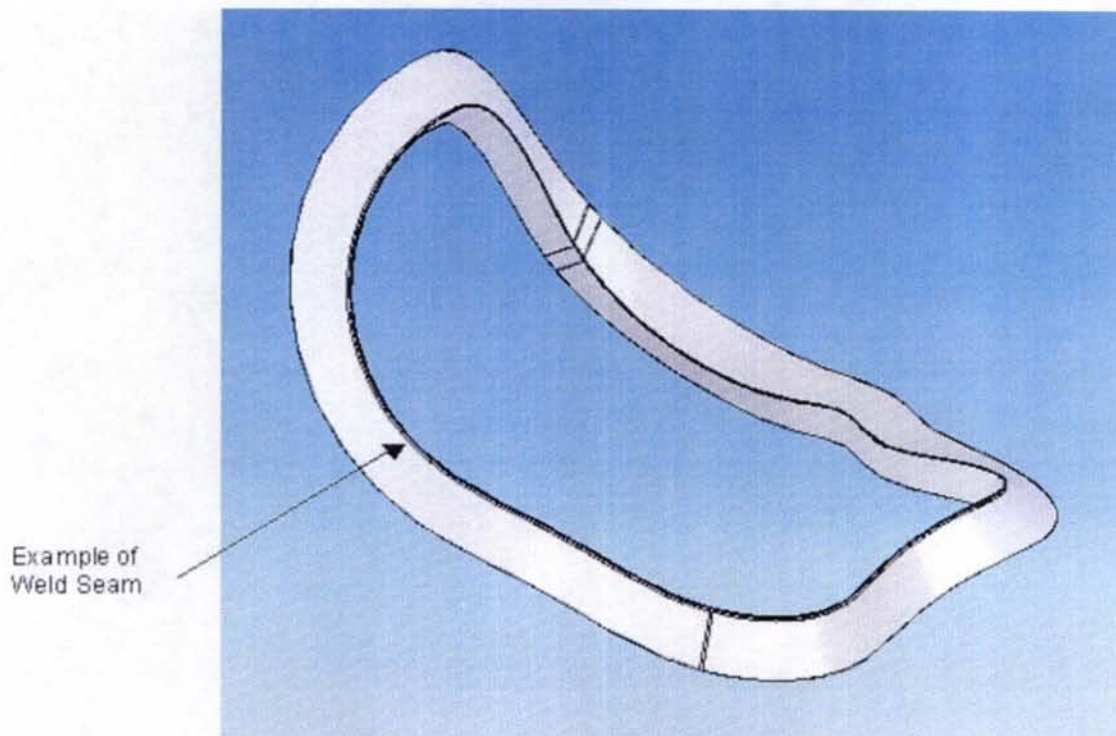


Figure 4: Example of Stainless Steel Can

The robot arm must also have a range of motion adequate to reach all the necessary welding positions. Any proposed system should be able to weld the largest practical segments without repositioning either the robot base or casting section.

- **Weld Quality**

The welds will be required to provide a complete seal between the can and the casting. This is important because the enclosed interior of the can will need to be leak tight, as it will be required to hold a vacuum. Also, in order to ensure good structural integrity of the weld, the weld must be made with as little oxidation as possible.

- **System Adaptability**

The welding process will include the joining of both 0.030" sheet metal to 0.030" sheet metal, and 0.030" sheet metal to the thick casting. As the power requirements are different for both of these welds, the system must have the ability to adapt to different situations, either by automatic sensing or by manual parameter changes.

- **Efficient User Interface**

It is very important that the user interface of the robotic welding system be time efficient and simple to use. This would involve ease in teaching the welding end effector the desired weld path. It will also involve features that will allow operators to recover from fault conditions efficiently such that overall operational efficiency can remain acceptable.



Conceptual Design of Production System:

The proposed work cell design is comprised of a robotic system with operator support and its purpose is to assemble magnetic coils for the QPS project. The details of the conceptual design for the robotic welding system are described below:

The Robotic Work Cell

The elements of the proposed robotic work cell that will produce the magnetic coil assembly are a robot arm with attached welding end-effector, an integrated control system, a robot track and frame, an inert gas purge system, a part positioner, and a human operator to support automated operations.

The robotic welding system used for the preliminary testing, on which this conceptual study is based, uses the Narrow Gap Tungsten Inert Gas (TIG) welding end-effector with the SCOMPI robot and version 4.43 controller software.

The current SCOMPI robotic welding system, as shown in Figure 5, includes a SCOMPI robot with a maximum reach of approximately 5 feet, a Thermal Arc welding power supply, a custom Narrow Gap TIG welding end-effector, an integrated controller cabinet. It also included several other peripheral devices such as a camera and video monitor, cooling water pump, filler wire positioner, and plumbing box with solenoid valves to automatically control inert gas flow. Inside the controller cabinet, there is a main computer connected to two separate controllers, one each for the robot and the welding process. These controllers work together as an integrated control system.

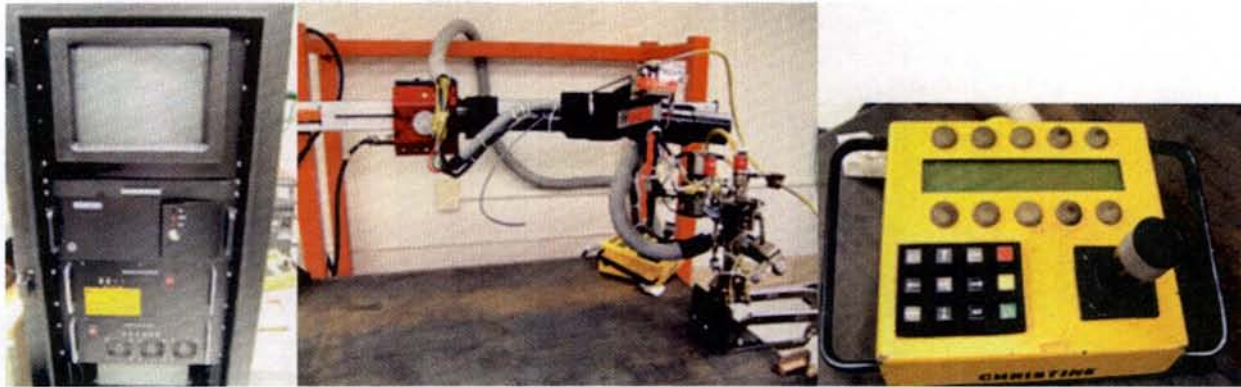


Figure 5: SCOMPI Robotic Welding System Components

The system includes several control functions that require this integration of the separate controllers. It has the capability to perform arc voltage control, in which it moves the robot along an axis perpendicular to the workpiece surface in order to maintain a constant arc length. This requires the robot controller to command motion in response to the welding controller parameters. AVC will be explained in more detail later. Likewise, in the arc-seeking phase, the robot moves the electrode toward the workpiece until the system senses current across the arc; then the robot pulls the electrode away to the specified arc length.



The current version of the SCOMPI robotic welding system was specially designed for TIG welding for a narrow-gap application. It uses a 6 degree-of-freedom commercial robot in which the first joint is a rack-and-pinion track. The weld power supply and robot controller are standard commercial products, while the welding controller, software and unique narrow-gap welding end-effector are custom. The weld power supply and welding end-effector are intended for welding considerably thicker work pieces. Hence, this system, in its present form, is not well matched with the specific requirements for manufacturing the magnet assemblies.

- **Robot Controller and Robot Arm**

The welding requirements for this system are unique in that they require very high precision motion, with position tolerances as small as 0.5 millimeters, with respect to workpieces with maximum diameters of up to 3 meters. This will be a major consideration in the design of this system and the selection of an appropriate robot and controller.

One important characteristic of a welding robot controller is the method in which it learns the weld path. It can do this in one of two ways:

- By a teach-playback operation, in which the operator will use a joystick to teach the robot a series of points along the weld path. In teach-playback mode, the system will interpolate between the teach points, generating a continuous path along which the robot can move at a user-specified constant speed. A variety of methods are available for robots to determine the paths between points, including linear interpolation, higher order interpolation, and various methods of seam tracking, such as visual servoing, laser tracking, and tracking based on variations in electrical parameters through weaving across the weld seam.
- By offline programming, based on a CAD model of the workpiece, by methods similar to those used with coordinate measuring machines (CMMs). The offline programming method will most likely be used for the weld seams along the casting, because an accurate CAD model of each casting exists. However, depending on the availability and accuracy of CAD models of the cans, the weld seams joining the can sections may require the teach-playback method.

The tested SCOMPI system uses the teach-playback method, but upgrades are available which would allow for the use of the offline method.

In short, the robot controller must have a user interface which provides an efficient and reliable method for teaching the weld path. In general, it is desirable to minimize the number of points that the operator must teach, especially in this application in which the workpiece is sheet metal. With such a thin weld seam, there is little room for error in the interpolation between points; therefore, higher order interpolation or seam tracking are desirable to reduce the required number of teach points.

The range of motion is also an important characteristic of the robot. An example of a range of motion based on the SCOMPI system is shown relative to the casting in Figure 6. Any robotic welding system used must have a range of motion that encompasses the entire work piece.



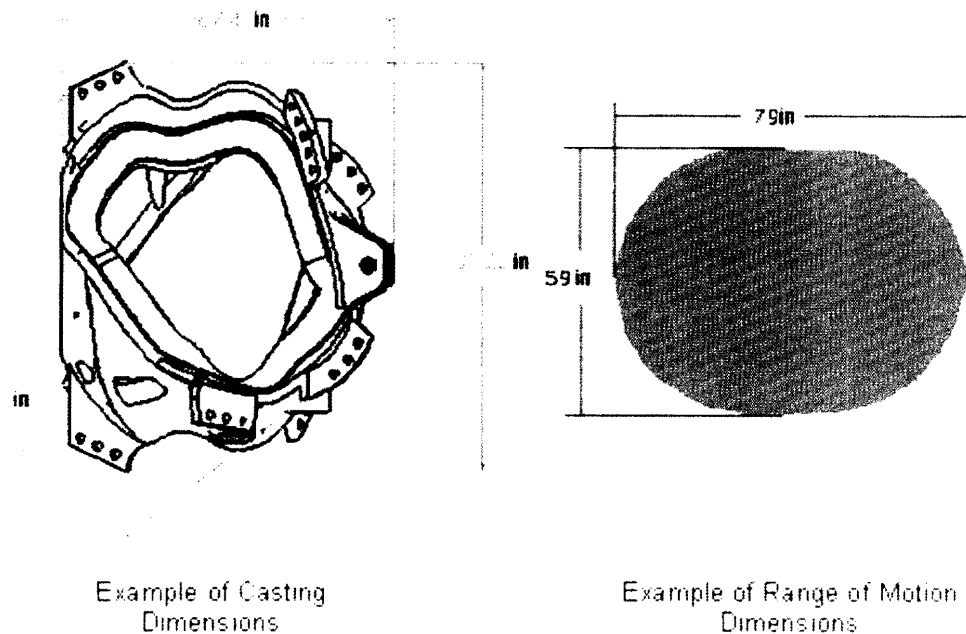


Figure 6: Comparison of Casting Dimensions to SCOMPI Range of Motion

The SCOMPI system is unique among industrial robots because the first of the basic six degrees of freedom is prismatic rather than revolute. This configuration means that adding more sections of track can extend the robotic workspace almost indefinitely. As a result, the range of motion of the robot arm was examined at one position on the track. Note that in the study, range of motion was based on joint limits and not external obstacles.

The robot arm must be able to follow the weld paths at speeds up to 3 millimeters per second without significant oscillations or other position errors along the paths. For the sheet metal to sheet metal welds, the weld beads are generally between 2 and 3 millimeters wide. Therefore, according to an ABB robotic welding systems expert, a target side-to-side tolerance on weld seam tracking would be approximately 0.5 millimeters.

The dynamics of the robot system and robot kinematics must be considered in the selection of a robot arm and the design of the moveable mounting structure. One cannot assume that the robot can produce a high quality weld at every point in its workspace. In general, the robot's capabilities for precise and repeatable motions will be reduced when the arm is folded tightly together or outstretched near its limits, in the same way that human arms are less effective in working near their limits. Also, especially in welding applications, it is desirable to avoid situations where the kinematics of the robot require large motions of the arm in order to produce small motions of the electrode; these situations tend to produce significant oscillations. Within the comfort zone of the work area, it is reasonable to expect high precision motion of the robot, which generally results in high quality welds of sheet metal.

- **Welding End-Effector and Welding Controller**

The welding end-effector can be configured to accommodate many different welding needs. The significant elements of a welding end-effector are an electrode, an inert gas

purge system, a cooling water supply, and a mounting bracket for the torch assembly. There are several other components that could potentially add to the equipment's versatility. For example, the tungsten electrode could be connected to a motor that allows the rotational positioning of the electrode relative to the weld path. Also, a wire feeder could also be connected to the assembly to accommodate Tungsten Inert Gas welding. In the case of the SCOMPI system, the wire feeder positioner has a remote controlled two axis positioner and attached camera that allows the user to precisely position the wire feed relative to the electrode.

The NGT end-effector is shown in Figure 7.

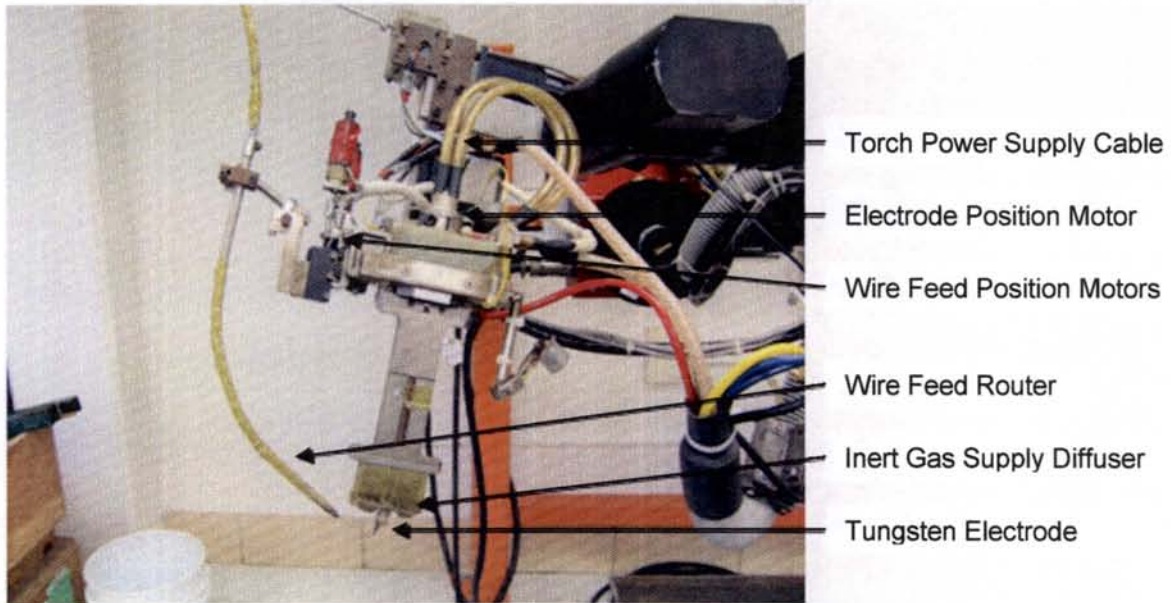


Figure 7: Narrow-Gap Tungsten Inert Gas End-Effector

The welding end-effector provides many important feedback control functions that relate to the welding power supply.

It is important to note that the required welds will be "out of position". It is desirable to have weld seams in a horizontal position with the molten metal facing upward, in order to minimize the effect of gravity pulling the molten metal away from the center of the weld seam; a weld that is not horizontal is termed "out of position". Therefore, a weld type and corresponding parameters should be selected which will allow for fast freezing of the metal.

- **Weld Power Supply**

A weld power supply with an interface to the robotic welding system software is necessary to provide power to the welding circuit. Many weld power supplies can be used for both manual and automated welding. Robot manufacturers supply lists of weld power supplies for which they provide software interfaces.

The weld power supply must have capability to supply steady, controllable current and voltage at power levels low enough for welding of sheet metal. Based on the tests with

the SCOMPI system, using TIG, the ideal current and voltage setpoints for 0.030" sheet metal to sheet metal welds are about 10-12 Volts and 25-30 amps, based on a travel speed of 2.5 mm/s. For TIG welding, the power supply is a current source, and the ThermalArc GMS600 weld power supply that is used for the SCOMPI system has a maximum current output of 600 A. The ideal setpoint for the sheet-to-sheet welds in this application are between 4% and 5% of the GMS600 power supply's capacity; therefore, it does not supply steady current at such low levels. It is essential that a weld power supply is selected that is well matched with the weld requirements for the application.

- **Integrated Control System**

Robotic welding systems utilize control systems that correlate the robot's motion with the welding operations, which requires integration of the robot controller and welding controller. Important feedback control features such as arc voltage control depend upon synergic relationships between the welding process and the robot motion. The two are integrated by a computer system and a pendant user interface. The SCOMPI system utilizes the iRMX operating system, a real-time version of DOS, and a "Three-Color Human Interface" to coordinate the two controllers.

The user interface is an integral part of the integrated control system. The computer system or pendant control should provide the ability to modify both robot motion and welding parameters. In the case of the SCOMPI system, there are two ways in which the operator can make modifications to the process and parameters. First, the computer system can be used to store files that contain default welding parameters such as current, weld speed, and arc length, while also storing files that contain saved weld paths. Second, the pendant control can be used to teach the robot a new weld path, and to quickly tune welding parameters without having to access files on the computer.

Many measurable aspects of the welding process and robot motion are controlled through closed-loop feedback control, which utilizes the computer with real-time operating system to integrate the separate controllers. One common feature that comes on many robotic welding systems and is found on the SCOMPI system is Arc-Voltage Control (AVC). AVC is based on the concept that there is a direct correlation between the voltage drop from the electrode to the workpiece and the distance between the electrode and the workpiece. It provides adaptive control during the a welding process by constantly adjusting the electrode position relative to the weld seam in order to keep the voltage at a constant level. This feature will be absolutely necessary part of any system used in the magnet assembly production for two reasons. First, the welding of stainless steel sheet metal can result in significant material distortion due to heat stresses. The AVC feature will allow the robot to maintain a constant distance between the electrode and the work piece as its shape distorts. Second, if the chosen system will utilize the teach-playback method of programming the weld seam, the AVC control could be used to provide additional precision in tracking the seam as the robot controller interpolates its path from the programmed points.

- **Inert Gas Distribution System**

When an inert gas or semi-inert gas is not used to create a purge around the welding areas of stainless steel, atmospheric gases come into contact with the heated metal and oxidation occurs. Porosity and brittleness are problems that can also be caused by



oxidation in welding. Oxidation weakens the weld's strength and causes the deterioration of key properties. One of the solutions to oxidation that occurs during welding is the use of an inert gas purge. The inert gas replaces atmospheric gas in the vicinity of the welding arc and significantly reduces the available oxygen. For the purpose of this study, Argon gas was selected for use in the inert gas system for its desirable low thermal reactivity, plentiful availability, and its low cost. Pure Argon is the standard purge gas used for TIG welding of stainless steel. The testing setup is illustrated in Figure 6.

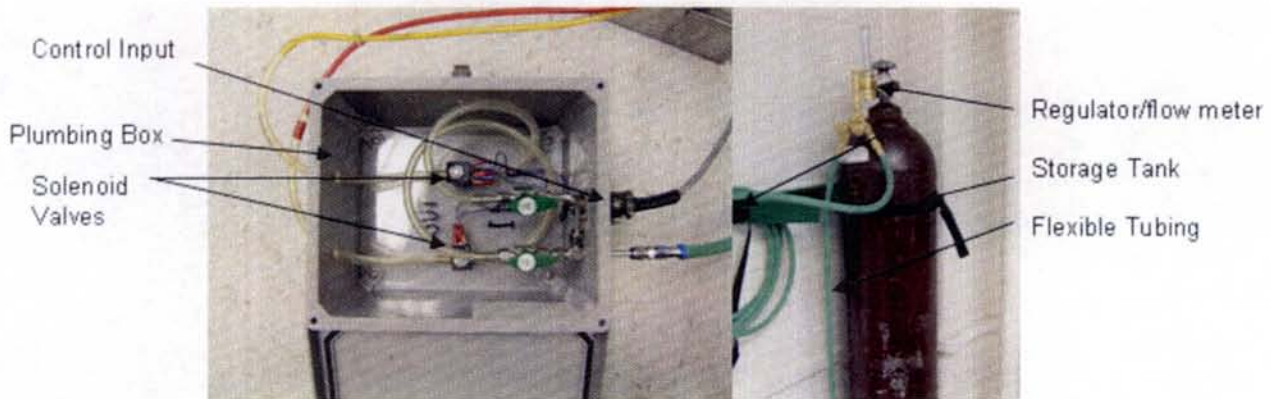


Figure 8: Inert Gas System Setup

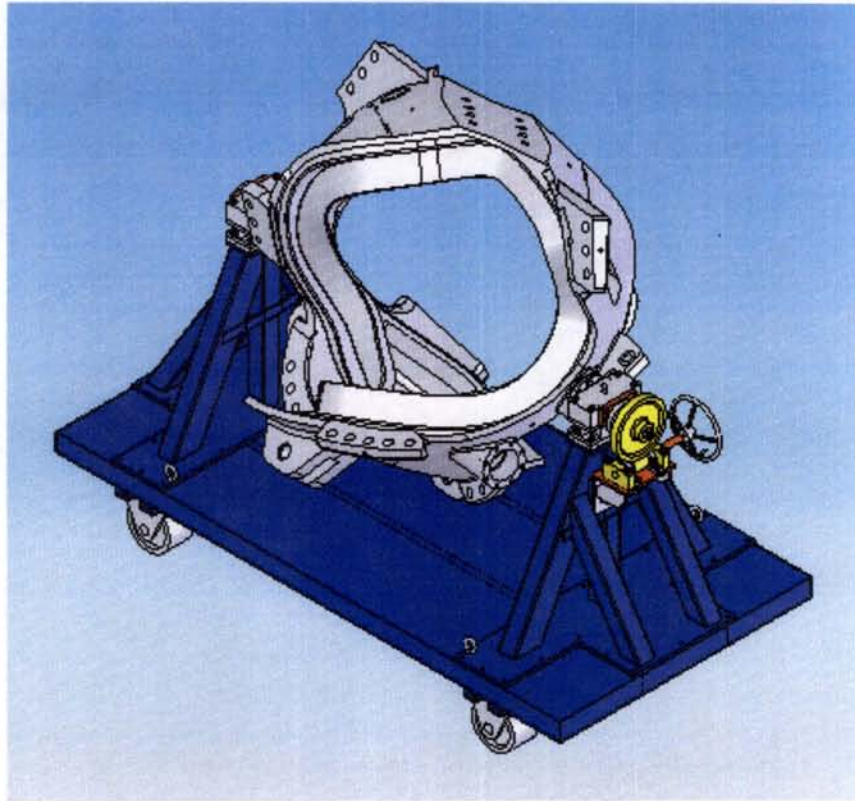
The Argon system for the work cell will be similar in function and method of delivery to the system that was used for testing.

- **Part Positioner and Robot Positioner:**

Many robotic welding applications use a part positioner to effectively expand the working space of the robot to achieve specific tasks. A part positioner moves, holds, and maintains the position of the workpiece within the range of motion of the robot. In some cases, part positioners are servo controlled and have the ability to move the part in correlation with the robot's motion. The magnet assemblies are extremely heavy and inconvenient to move. Therefore, the desired part positioner should move the castings as minimally as possible. The most important feature of the part positioner for the castings should be the ability to maintain stability while placing the casting within the range of motion.

In applications where it is inconvenient to use a robotic arm that is large enough to reach the entire workpiece from a single base position, a robot positioner can also be used. A robot positioner moves, holds, and maintains the position of the base of the robot as necessary such that the tool electrode can reach all necessary points on the workpiece.

The casting cart that has been developed by MDL could function as a part positioner if augmented with a suitable servo rotational drive. This would allow the castings to be rotated and positioned within the comfortable range of motion of the robot. Figure 9 displays an example of a casting rotated in position and mounted on the cart.



**Figure 9: Example Casting Mounted on Cart and Rotated 60° from the Ground.
(Securing struts are not shown)**

Once a casting is rotated to the desired position and secured in place, the robot will need to be oriented in order to remain within the range of motion and to comfortably reach the desired welding points within the casting. To reach these points, the robot positioner will move the robot base in the horizontal, vertical, and forward/backward directions, or the x, y, and z directions.

Based on the SCOMPI system, it can be shown that by arranging the track in a vertical position, the robot is able to accomplish the desired vertical movements. This track configuration will also help reduce the oscillation joints experience during movement. The oscillation reduction will help create higher quality welds. X-direction movement is accomplished by mounting the vertical track to a rack and pinion, lead screw, or worm gear that is situated horizontally. Forward/backward motion is obtained by mounting the system along racks and pinions, lead screws, or worm gears that are situated in the z-direction. Figures 10 and 11 display a possible configuration of the track mount.



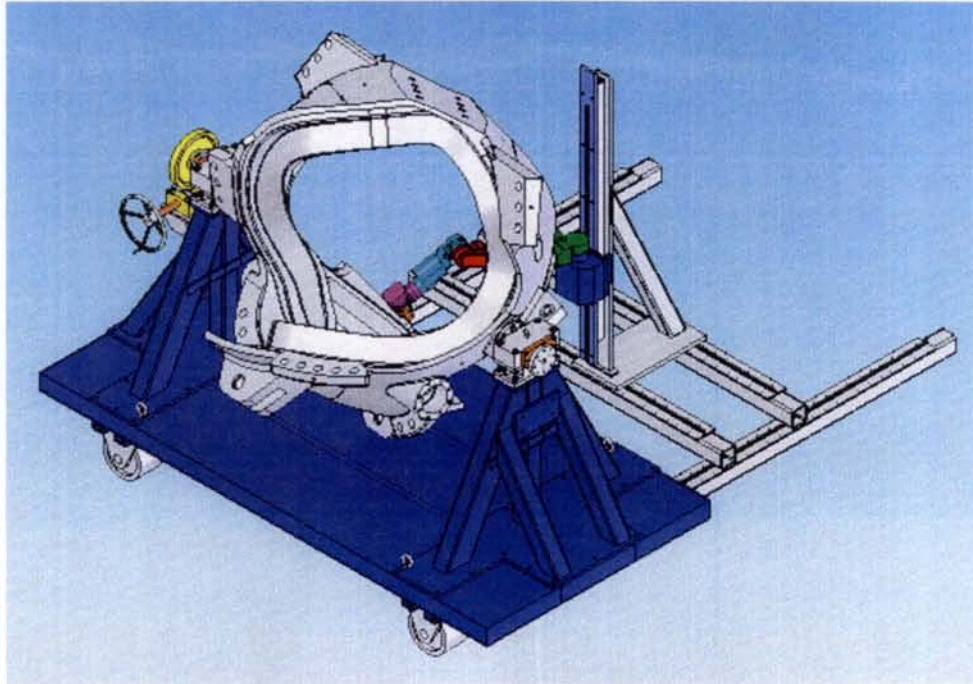


Figure 10: Track and Casting Positioning Example – Isometric View

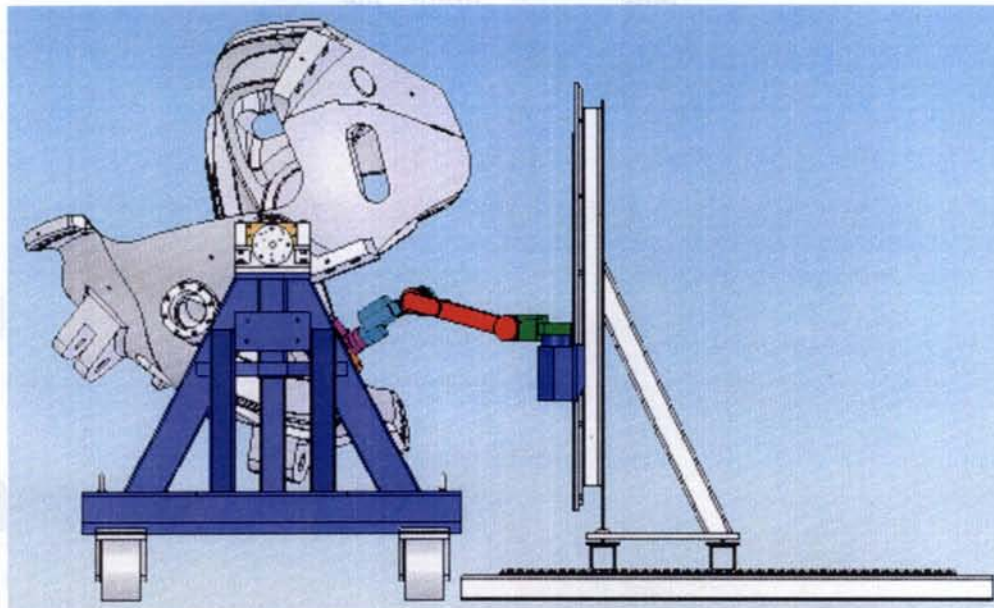


Figure 11: Track and Casting Positioning Example- Side View

The vertical movement is already accounted for in current SCOMPI software. The forward/backward and horizontal movements will need to be either manually controlled or automatically controlled. Manually controlling the positioning is the best option considering the robot will not need to be re-positioned horizontally after every weld. Greater stability and rigidity is obtained by manual control. Re-positioning is only required when the robot is nearing the maximums of its range of motion. If automated control is



desired, these controls would need to be incorporated into the software, and stability and rigidity of the mounting structure would need to be improved.

The can welding application requires very high precision motion of the welding end-effector with respect to a very large workpiece; therefore, rigidity and stability of the part positioner are essential. The robot positioner must also be very rigid, and the mechanical design should have negligible backlash. It should have capability to hold each desired position against any forces that it could encounter, with negligible movement. It is desirable for the positioning structure to have brakes, so that the base can be locked in place before the weld path is taught to the robot, thus reducing the number of active degrees of freedom of the system. In the design of this positioning structure, it is important to consider that the robot cannot necessarily produce welds at all points within its range of motion; the range that the electrode can reach at all desired orientations is smaller than the overall range of motion.

- **Operator Support**

Operator support refers to elements where a human will interact directly with the production process. Although it is anticipated the same individual will perform them, the operator support function has been subdivided by its two primary roles: working the manual work cell and supervision of the automated processes.

Part Preparation:

The manual cell will be required to perform tasks that are not suitable for automation. The primary focus of manual operations is the preparation of sections of the can for final welding by the automated system. The operator must perform a limited set of tasks, to include cutting and forming can pieces, setting them into position, and tack welding them in place. The sheet metal pieces for the can must be fabricated with sufficient tolerances to produce good weld seams. The operator may also be required to manually adjust the part or robot track position.

In response to the complex shapes involved, pieces of the can will be individually built by a craftsman and tested for fit before being attached. The pieces will then be tack welded to each other and the casting. This method is preferable to clamping many pieces at a time due to its minimal bulk and reduced interference. Once a suitably large section has been assembled, the robotic welder will be used to weld the three long seams – two where the can connects to the casting and one at the corner where the can connects to itself. The short seams between the can pieces can be either manually or automatically welded.

In order to accomplish its tasks, the manual cell must include a skilled welder, TIG welding equipment (power supply, torch, Argon supply, etc.), and sheet metal cutting and bending tools. The welding equipment must be capable of welding pieces as thin as 0.025 in. To meet this demand, the power supply must be capable of producing a current as low as 20 amps.

Programming and Supervision of the Robotic Process:

An operator will, through the user interface, input the task for the automatic welding process using the pendant controller and then oversee the automatic welding process (i.e. troubleshoot the robot and its controller, stop and adjust the automatic process as necessary, etc.). The operator involved in the automatic welding process need not be an accredited professional welder, which allows for versatility of operations. This person



must, however, be familiar with welding processes and the operation of robotic systems as he will be responsible for the selection and tweaking of system control parameters.

Evaluation of Current SCOMPI System Relative to Conceptual Design Requirements:

Upgrades, modernization, and matching of the welding equipment to the desired operation will offer significant benefits. The following are considerations or potential problems with the current NGT welding system:

- The NGT welding end-effector is a very complex, custom, prototype piece of equipment; inherently, this leads to a risk of component failures. It includes features, such as a weaving tungsten electrode, moveable filler wire, and several other adjustable components that are not needed for this application.
- The purge gas supply at the electrode is designed for welding inside a narrow gap, not on the casing of a large electromagnet. It may be difficult to obtain a sufficient purge gas supply at the weld seam.
- The software runs on the IRMX operating system, a real-time version of DOS. There are newer alternatives that provide enhanced features and product support.
- The current software does not allow the operator to save multiple robot paths and welding tasks; each time the path and welding parameters are saved, all previous versions are overwritten.
- Manuals were written for the standard MIG SCOMPI system; no manuals exist for the custom NGT software and hardware.

Potential Systems to Meet Conceptual Requirements:

There are two available options for using the SCOMPI robotic welding system. The first option is to use the narrow-gap TIG (NGT) welding system in its current state; this option is not likely to be feasible for this application, since the system was not designed for it. The second option is to use the current commercial SCOMPI robot, robot tracks, and robot controller, while upgrading the software to the newest version and mounting a standard MIG weld torch as the end-effector. SCOMPI only offers new software for MIG welding, thus requiring a switch to MIG welding for these operations. Feasibility of MIG welding should be investigated. Upgrading to the newest version of the SCOMPI robotic welding system would provide the following benefits:

- A less complex, standard commercial MIG weld torch can be mounted on the robot end-effector, in place of the NGT torch.
- The new software runs on a real-time operating system called QNX, which is commonly used system in industrial applications today.
- The new software must allow the user to save multiple robot path programs and welding tasks.
- MIG welding is better suited for robotic welding, since the operator does not have to position both the electrode and the filler wire.
- A commercial system will have much better documentation.

One major advantage of newer robotic welding systems is that they will be much easier to teach. On the previous ITER project, SCOMPI used offline-programming software called



ROBOCAD. SCOMPI has since changed to computer aided manufacturing software called *Delmia*, made by Dassault Systemes, the maker of *Catia* and SolidWorks. They have models of their robots in the robotics package for this software, and the models of the work pieces can be imported. Therefore, offline-programming using the SCOMPI robot would require the purchase of a license to the *Delmia* software.

A visual seam-tracking feature is also available with the newer software. For the weld seams for which there are no accurate CAD models, this would allow the robot to track the weld seam, thus requiring the operator to teach fewer points. This would be especially beneficial in this application, where the weld seams are very thin, allowing little room for error in the linear interpolation between points.

The following chart shows the estimated cost of upgrading the SCOMPI robotic welding system, including all relevant options.

Table 1. Costs of Upgrading and Updating SCOMPI System

Item	Estimated Price
SCOMPI SYSTEM 345 C or 345 SE Software Version 4.5	\$15,000
<ul style="list-style-type: none"> ▪ Teach Pendant ▪ Using current robot controller) ▪ Software Curvispace Version 4.50 	
GMAW, FCAW, MCAW WELDING	\$10,000
<ul style="list-style-type: none"> ▪ Curvuweld Software, Version 4.50 (tandem option included) ▪ Welding controller is included in Lincoln Power Supply 	
<i>New computer, QNX license and Delmia license</i>	\$7,000
<i>Robot Positioner</i>	\$30,000
<i>Lincoln Power Wave 455M/STT Power Supply</i>	\$15,000
<ul style="list-style-type: none"> ▪ Part number K2263-1 ▪ Including: water cooler, interface cables, welding controller, and wire feeder 	
<i>Binzel W550 welding torch</i>	\$700
<i>Standard torch holder</i>	\$700
<i>System Integration Costs (approximated at 25% of component costs)</i>	\$18,000
Total	\$97,000

Another option is to completely replace the SCOMPI robotic welding system with a new system from another manufacturer. As representative examples, ABB was selected as



the robot manufacturer, and Lincoln was selected for the welding equipment. Each major robot manufacturer, including ABB, has a few robot models that are intended for welding.

The magnet production application is unique in that it involves welding of a very large work piece with very small position tolerances for the welding end-effector. Therefore, a custom system will be required. It is common for robotic welding systems to be custom; fully standardized systems are only available for smaller work pieces. Because of the custom design, a separate system integrator will be required. A list of these can be found on the Lincoln Electric website. The ABB regional salesperson recommends Wolf Robotics, which can be found online at <http://www.rimrockcorp.com/>. The system integrator would be involved in the design and fabrication of the robot positioning structure, the selection and integration of appropriate welding equipment with the robotics equipment, and the training of operators.

ABB systems use software called Robot Studio for their simulations and offline programming. This software could be used to teach the weld paths offline, by importing the CAD models of the castings and possibly the cans. A link to the website for this software can be found at <http://www.abb.com>. Additionally, ABB systems use a separate seam tracking system made by ServoRobot, which uses laser-based triangulation as the tracking method. According to the ABB salesperson, tracking accuracies as small as 0.5 mm are to be expected with these systems. More information on these can be found at <http://www.servorobot.com/>.

Significant advancements have been made to robotic welding systems, including the industrial robots themselves, in the past several years since the SCOMPI system was designed. Many of these will be needed for the QPS application, such as improvements in the user interface, robot motion control, seam tracking and offline programming. Some advanced features may be difficult to implement in an upgrade and modernization of the current SCOMPI system. Therefore, a complete new robotic welding system is recommended.

Conclusions:

The testing performed as part of this study has shown that it is feasible for both the sheet metal-to-sheet metal welds and the sheet metal-to-casting welds for this application to be done robotically. Further investigations are needed in several areas. The design of a robot and positioner system will require a detailed motion study. Also, modernization of the control system will be necessary. Additionally, welding equipment and weld end-effector that is well matched with the requirements for these welds should be used.

Overall, a robotic welding approach is feasible for use in the magnet production effort, and will provide significant benefits in increased productivity and weld quality.



Appendix:

CORSA Performance, Inc. Case Study

SUCCESS

WAVEFORM CONTROL TECHNOLOGY™

Surface Tension Transfer® (STT®)



A manufacturer of high performance stainless steel marine and automotive exhaust systems uses Lincoln Electric's System 10 robotic welding system to dramatically improve production and weld quality.

- PROBLEM -

Reducing spatter and increasing production speed while maintaining high weld quality on thin gauge, stainless steel parts used in specialty exhaust systems for high-performance vehicles.

- SOLUTION -

Lincoln Electric's pre-engineered System 10 robot welding cell with a Surface Tension Transfer (Invertec™ STT II) power source.

- RESULTS -

Dramatic reduction in per-part welding time, the virtual reduction of spatter, and excellent weld quality.

Performance vehicle owners love the roar of their engines while accelerating. But that same sound translates to a head-pounding drone and resonance during cruising speeds, making it hard to hear the radio or carry on a conversation.

CORSA Performance, Inc. of Berea, Ohio, developed its patented Power-Pulse RSC (Reflective Sound Cancellation) technology to deal with the issue. This unique muffler technology offers noise-suppression during cruising, and enhances the engine sounds during full-throttle acceleration.

About CORSA Performance
CORSA Performance, which opened its doors in 1989, is an engineering and manufacturing company that specializes in high performance stainless steel marine and automotive exhaust systems. CORSA is the only marine/auto aftermarket manufacturer with in-house hydro forming capabilities. The company also has titanium welding and forming capabilities.

CORSA enjoys an 85% marine industry market share, supplying well-known boat manufacturers including Baja Marine™, Donzi™, Formula™, Cobalt™ and Crownline™. The company's Power-Pulse automotive mufflers have been utilized on a host of vehicles, including Corvettes™, Camaros™,

Firebirds™, Dodge™ Vipers™, Cadillacs™, Chevrolet™ and GMC™ Trucks and S.U.V.'s. CORSA's catalytic converter-back exhaust systems have also become a General Motors™ Service Parts Operations Licensed Product.



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WAVEFORM CONTROL TECHNOLOGY

SUCCESS

Surface Tension Transfer (STT)

quality was an equally significant factor in the firm's decision-making, according to Jim Browning, CORSA's owner and president. "When a CORSA system is pulled from the box, the first thing the customer notices is the welds," said Browning. "So while production speed was important to us, we also needed a system that would create consistently high-quality, spatter-free welds."

The solution

CORSA's team researched a number of robotic welding systems. One was Lincoln Electric's System 10.

The System 10 is a pre-engineered, two-fixed table welding workstation, which is assembled and shipped ready to install. It utilizes a six-axis FANUC Arc Mate 50iL robotic arm with 3kg payload, and Fanuc R-J3 controller. Lincoln Electric recommended this system to CORSA because it is well-suited for applications with small parts. The unit features a complete metal surround flash and safety barrier and bi-fold safety doors with interlocks. An operator is able to load and unload one side of the cell while the robot welds simultaneously on the other side — facilitating excellent production rates.

"The quality of the parts Lincoln produced was what finalized our decision to buy the System 10."

"We took our parts to Lincoln and watched as they welded them on-site with the robot," said Paul Goth, Robot Programmer/Process Engineer at CORSA. "The quality of the parts Lincoln produced was what finalized our decision to buy the System 10."

Because of the thinness of the stainless steel used in the parts, Lincoln recommended the STT II power source to CORSA. Unlike standard CV MIG

machines, the STT has no voltage control knob. The STT uses current controls to adjust the amperage independent of the wire feed speed. This makes it much easier to make welds which require low heat input without melting through the base material. Also, distortion, spatter and smoke are minimized.

The result

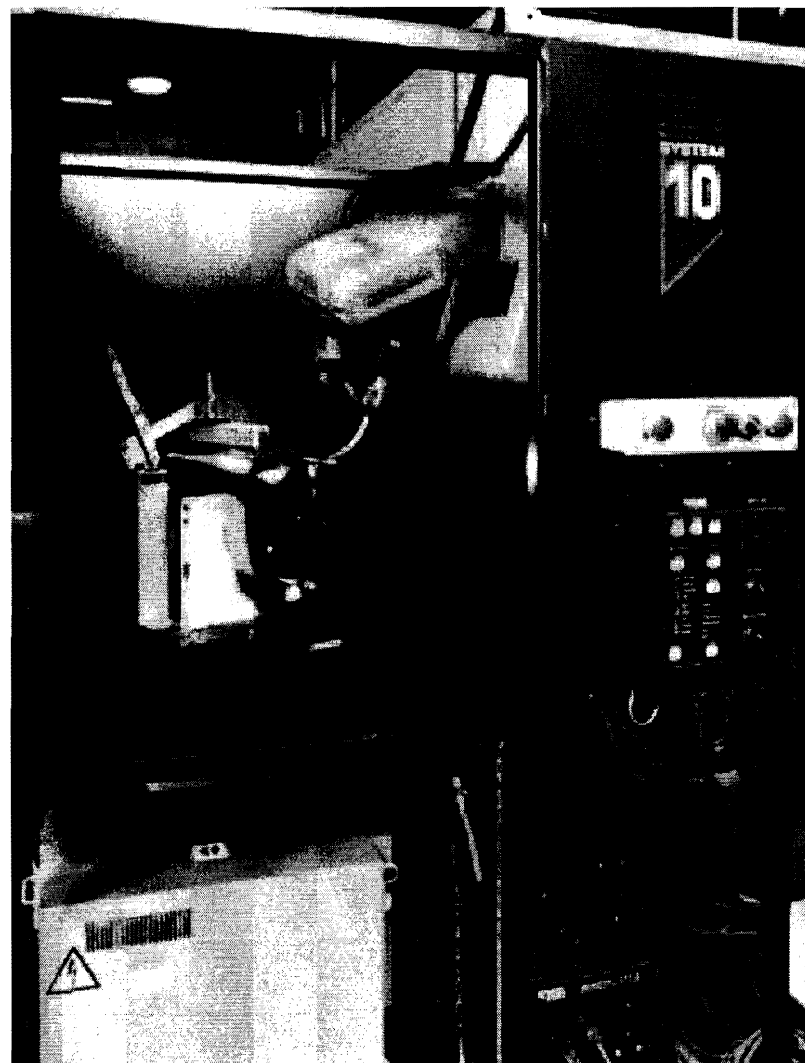
After CORSA's new System 10 robotic arc welding robotic system was installed

in September 2001, welding production improved from 44 to 180 Power-Pulse mufflers per day.

CORSA quickly realized that the arc welding robot could be utilized to grow business in other areas, and has since converted 12 of its manual welding stations to robotic stations.

CORSA's Welding Operations

Parts that are welded robotically at CORSA



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WELDER CONTROL TECHNOLOGY

SUCCESS

Surface Tension Transfer (STT)

Performance are chosen based on their volume and throughput in the shop. Each part design has its own set of fixturing and tooling which is built in-house in the company's tool room. "Your imagination is your only limitation," said Goth. "If a part is currently being MIG or TIG welded, I imagine the System 10 robot welding the part and then determine if the robot can do the job with the proper fixtures."

There are currently 12 parts welded by the System 10 at CORSA with many



more planned for the near future. This Success Story focuses on two examples — the most popular components in each of the company's market segments.

C5 Corvette and Camaro Muffler

The C5 and Camaro muffler is a long, 22-gauge, 304 stainless steel oval cylinder-shaped case with an 18-gauge end cap. The end cap is a stamping that comes into the CORSA Performance

plant from an outside vendor while the case is rolled and formed in-house. At the welding stage, the System 10 robot completes the welding by making two 28" fillet welds around the circumference of the part on each end cap. The C5's thin case is prone to melt through, yet needs to have a weld with good penetration. For the C5 application, CORSA uses a tri-mix gas (90% helium, 7.5% argon and 2.5% CO₂) with .035" 316L wire.

Before automation, it took one GTAW welder 20 minutes to weld one C5 muffler. Today, the System 10 is able to produce the muffler in under two minutes. And since a single production worker can operate the robot, the company's skilled welders have been reassigned to other welding duties. Bottom line, the System 10 has increased per-day production volumes by 500%.

Marine Silencer Tips

This part consists of a 16-gauge, 316L stainless steel formed case with a ring welded onto it. The tubing for this part is cut to length and formed by CORSA, and the ring comes from an outside vendor. The welding for this part requires the robot to make four small stitch welds to hold the ring inside the tube and then one continuous 12" circular weave weld around the outer circumference of the part. For all the marine parts, CORSA uses a tri-mix gas (90% helium, 7.5% argon and 2.5% CO₂) with .035" 316L wire.

The silencer tip had been welded manually using TIG, with a per-part welding time of three to five minutes. Today the arc welding robot has slashed that to 35 seconds per part.

After welding, all parts are polished to either a satin or a mirror-like finish. "The advantage of STT technology is that we don't have to deal with spatter, so we can go straight to polishing, saving us labor time," remarked Goth. "The robot gives us high quality MIG welds that look like TIG welds."

"We are still getting compliments on our welds from our customers."

According to Goth, STT and System 10 provide smooth, strong welds that have excellent fusion. "We feel that the weld quality we are getting now is even better than what we were getting with manual TIG methods. The welds are more uniform, much straighter and you don't see the starting and stopping points as you do with TIG welds," he said. "Since switching to the robot, we are still getting compliments on our welds from customers." CORSA Performance is also pleased with how easy it is to change welding parameters when setting up welding procedures. "I can change one setting, such as amperage, and not have to worry about affecting other parameters like wire feed speed," noted Goth. "The machine can even be programmed to do such unique things as a weave pattern. And, we have reduced scratches and other blemishes that resulted from too much part handling with manual welding methods."

By switching to robotics, we not only benefit from increased throughput in our system, but the cost of each part has gone down," said Browning. "Since installing the robot in our shop, we have reduced the backlog in our sales and

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WAVEFORM CONTROL TECHNOLOGY

SUCCESS

Surface Tension Transfer (STT)

STT on Sheet Metal

CORSA Performance Line

been able to meet customer demands. We couldn't be meeting our current production volume without it. It will pay for itself many times over."

Programming and Service

One of the most important aspects of purchasing a welding robot, especially for a company that has never used robotics before, is the ability to program and troubleshoot the machine.

Goth has responsibility for developing welding programs for all the company's parts. "Lincoln did the initial programming for the C5 muffler, but since we've added more parts, I've been able to do all the programming in-house," he said. "I went to a three-day training seminar at Lincoln Electric where I learned the basics. I learned the rest by working with the robot and testing its capabilities. I continue to consult with several of our expert welders to help me achieve a weld that is strong and looks nice."

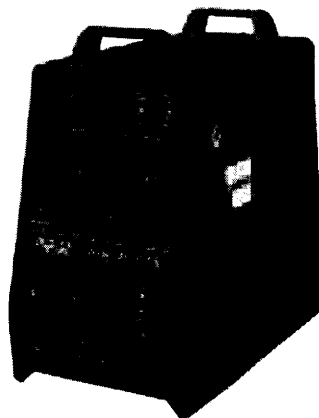
Once Goth installs a program, the operator has to simply push a few buttons on the robot's teach pendant to call up a specific program. This makes it easy to switch from one part to another.

Goth has also been pleased with the service Lincoln has provided. "When we run into a problem, I just call the company's hotline and Lincoln technicians have walked me through the solution," he said. "They won't hang up until my problem is solved."

What's Next

In the future, CORSA Performance plans to continue adding robotics to its welding operations. "We are continually looking for ways to increase quality and reduce costs, and the robot has proven itself in both regards," said Browning.

Featured Lincoln Product



Invertec® STT II

The STT II combines high frequency inverter technology with advanced Waveform Control Technology in place of traditional short-arc GMAW welding. The STT II's precise control of the electrode current during the entire welding cycle significantly reduces fumes, spatter and grinding time. In addition, the unit offers independent control of wire feed speed and current.

WHAT IS NEXTWELD?

The challenges facing industrial fabricators today are increasingly difficult. Rising labor, material, and energy costs, intense domestic and global competition, a dwindling pool of skilled workers, more stringent and specific quality demands.



Through our commitment to extensive research and investments in product development, Lincoln Electric has established an industry benchmark for applying technology to improve the quality, lower the cost and enhance the performance of arc welding processes. Advancements in power electronics, digital communications and Waveform Control Technology™ are the foundation for many of the improvements.

NEXTWELD brings you a series of Process, Technology, Application and Success Story documents like this one. NEXTWELD explains how technologies, products, processes and applications are linked together to answer the important questions that all businesses face:

- How can we work faster, work smarter, work more efficiently?
- How can we get equipment and people to perform in ways they've never had to before?
- How do we stay competitive?
- How do we maintain profitability?

NEXTWELD is the future of welding but its benefits are available to you today. Ask your Lincoln Electric representative how to improve the flexibility, efficiency and quality of your welding operations to reduce your cost of fabrication.



THE WELDING EXPERTS

THE LINCOLN ELECTRIC COMPANY
www.lincolnelectric.com
1-219-481-5100

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Surface Tension Transfer (STT)

PROCESS



WAVELENGTH CONTROL TECHNOLOGY™

Surface Tension Transfer® (STT®)

Surface Tension Transfer® (STT®) welding is a GMAW, controlled short circuit transfer process developed and patented by The Lincoln Electric Company.

Unlike standard CV GMAW machines, the STT® machine has no voltage control knob. STT® uses current controls to adjust the heat independent of wire feed speed, so changes in electrode extension do not affect heat. The STT® process makes welds that require low heat input much easier without overheating or burning through, and distortion is minimized. Spatter and fumes are reduced because the electrode is not overheated—even with larger diameter wires and 100% CO₂ shielding gas. This gas and wire combination lowers consumable costs.



Conventional CV short circuit transfer using CO₂ and .045" solid wire.



STT® using CO₂ and .045" solid wire.

a d v a n t a g e s

GOOD PENETRATION AND LOW HEAT INPUT CONTROL

Ideal for welding on joints with open root, gaps, or on thin material with no burnthrough.

REDUCED SPATTER AND FUMES

Current is controlled to achieve optimum metal transfer.

REDUCED COSTS

Ability to use 100% CO₂ or argon shielding gas blends with larger diameter wires.

GOOD BEAD CONTROL AND FASTER TRAVEL SPEEDS

Can replace GTAW in many applications without sacrificing appearance.



Patented. This product is protected by one or more of the following United States patents: 4,717,807; 4,897,523; 4,888,247; 4,835,390; 4,954,891; 4,972,084; 5,001,326; 5,003,154; 5,148,001; 5,961,863; 6,051,810; 6,160,241; 6,274,854; 6,172,233; 6,215,100; 6,204,478. The application of the STT process for root pass pipe welding and wallpapering of industrial vessels with nickel alloy sheets are patented. The application of processes marketed by other welding manufacturers that are similar to STT may infringe on these patents: 5,676,857; 5,742,029; 5,981,906; 6,093,906.

The future of welding is here.™



ADVANCED CONTROL TECHNOLOGIES

PROCESS

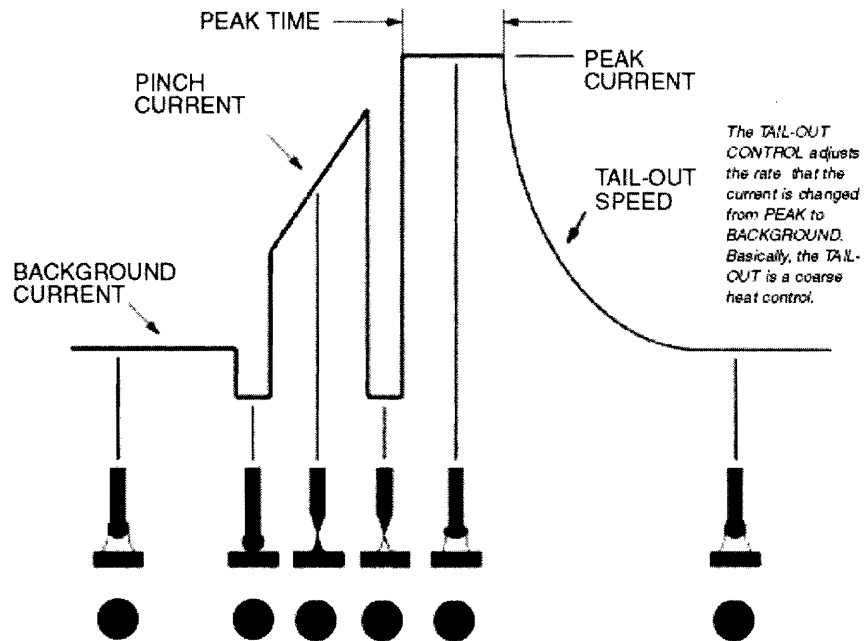
Surface Tension Transfer® (STT®)

How

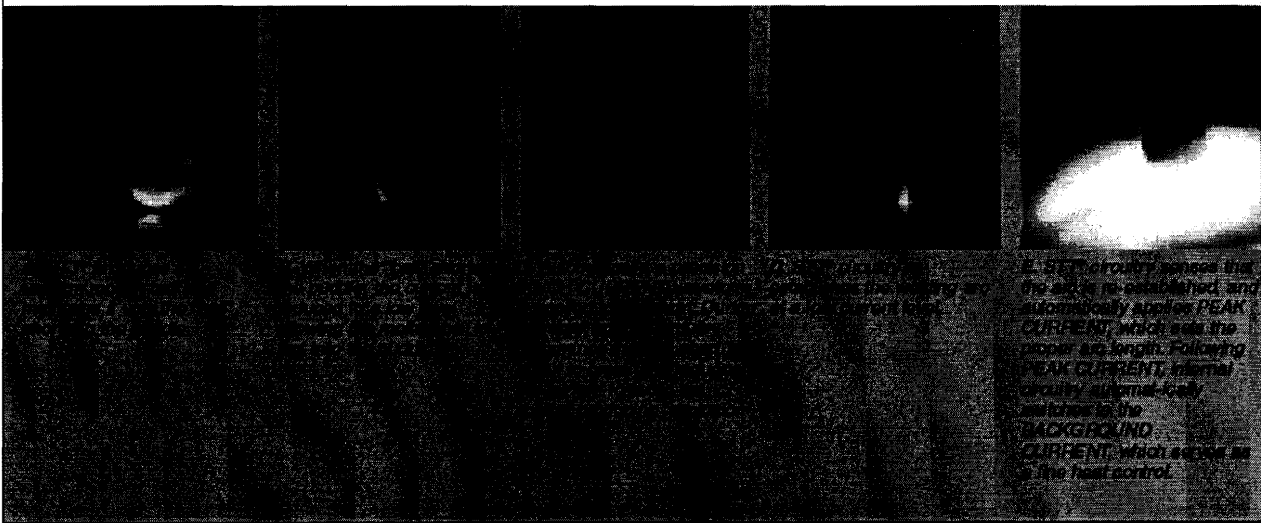
STT® works

A BACKGROUND CURRENT between 50 and 100 amps maintains the arc and contributes to base metal heating. After the electrode initially shorts to the weld pool, the current is quickly reduced to ensure a solid short. PINCH CURRENT is then applied to squeeze molten metal down into the pool while monitoring the necking of the liquid bridge from electrical signals. When the liquid bridge is about to break, the power source reacts by reducing the current to about 45-50 amps. Immediately following the arc re-establishment, a PEAK CURRENT is applied to produce plasma force pushing down the weld pool to prevent accidental short and to heat the puddle and the joint. Finally, exponential TAIL-OUT is adjusted to regulate overall heat input. BACKGROUND CURRENT serves as a fine heat control.

THE STT PROCESS



The TAIL-OUT CONTROL adjusts the rate that the current is changed from PEAK to BACKGROUND. Basically, the TAIL-OUT is a coarse heat control.



The Tail-Out phase of the STT process is shown here. The power source reacts by reducing the current to about 45-50 amps. Immediately following the arc re-establishment, a PEAK CURRENT is applied to produce plasma force pushing down the weld pool to prevent accidental short and to heat the puddle and the joint. Finally, exponential TAIL-OUT is adjusted to regulate overall heat input. BACKGROUND CURRENT serves as a fine heat control.

The future of welding is here.



WAVEFORM CONTROL TECHNOLOGY™

PROCESS

Surface Tension Transfer® (STT®)

Comparing

STT® to conventional processes**Advantages of STT® replacing short-arc GMAW:**

- Reduces lack of fusion
- Good puddle control
- Consistent X-ray quality welds
- Shorter training time
- Lower fume generation & spatter
- Can use various compositions of shielding gas
- 100% CO₂ (on mild steel)

Advantages of STT® replacing GTAW:

- Four times faster
- Vertical down welding
- Shorter training time
- 100% CO₂ (on mild steel)
- Improved quality welds on stainless, nickel alloys and mild steel
- Consistent x-ray quality welds

When

to use STT®

STT® is the process of choice for low heat input welds.

STT® is also ideal for:

- Open root – pipe and plate.
- Stainless steel & other nickel alloys – petrochemical utility and food industry.
- Thin gauge material – automotive.
- Silicon bronze – automotive.
- Galvanized steel- such as furnace ducts.
- Semi-automatic and robotic applications.

Utilizing

STT® on Lincoln Welding Systems**Adjust WIRE FEED SPEED to:**

- control the deposition rate.

Adjust PEAK CURRENT to:

- control the arc length.

Adjust BACKGROUND CURRENT to:

- control heat input (fine).

Adjust TAIL-OUT to:

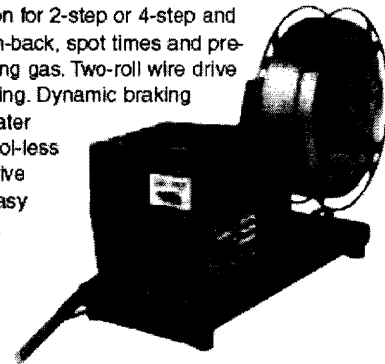
- control heat input (coarse).

Adjust HOT START to:

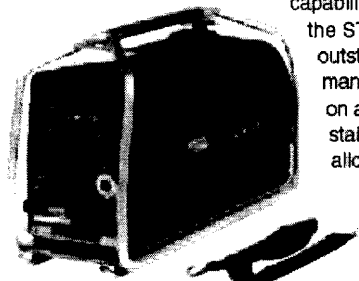
- control the heat (current) at the start of the arc.

**LINCOLN WELDING SYSTEMS
FEATURING STT****LN-742**

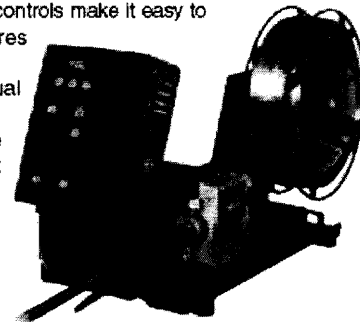
The LN-742 semiautomatic wire feeder features a trigger mode selection for 2-step or 4-step and time controls for burn-back, spot times and pre-flow/post-flow shielding gas. Two-roll wire drive for positive wire feeding. Dynamic braking system minimizes crater sticking problems. Tool-less quick release wire drive tension system for easy wire or gun changes.

**LN-15**

LN-15 is one of the smallest and most maneuverable wire feeders available on the market today. Control Cable model includes STT® capabilities and is compatible with the STT® II power source for outstanding welding performance including pulse welding on a wide variety of steel, stainless steel, aluminum and alloy materials.

**STT®-10**

The sophisticated STT®-10 Process Controller was designed specifically to work with the revolutionary STT® II power source. Microprocessor controls make it easy to develop optimal procedures and set the range of operator adjustments. Dual procedure control can increase or decrease the energy in the arc without changing the wire feed speed.



The future of welding is here.



WAVEFORM CONTROL TECHNOLOGY

PROCESS

Surface Tension Transfer® (STT®)

Lincoln Welding Systems featuring STT® (cont.)



Invertec® STT® II

The STT® II combines high frequency inverter technology with advanced Waveform Control Technology® in place of traditional short-arc GMAW welding. The STT® II's precise control of the electrode current during the entire welding cycle significantly reduces fumes, spatter and grinding time. In addition, the unit offers independent control of wire feed speed and current.

Power Wave® 455M/STT/Power Feed™ 10M Dual

The Power Wave® 455M/STT is a digitally controlled inverter power source capable of complex, high-speed waveform control. It is designed to be part of a modular, multi-process welding system. By installing various modular options, the power sources can be reconfigured to be used in robotic or hard automation systems, and can communicate with other industrial machines to create a highly integrated and flexible welding cell. This product features Lincoln Electric's STT® process for applications in which heat input control, minimal distortion, reduced spatter, and low fumes are essential.



Power Wave® 455M/STT Power Feed™ 10R Robotic

The Power Feed™ 10R is a high performance, digitally controlled, modular wire feeder designed to be a part of a modular, multi-process welding system. It is specifically designed to mount to a robot arm or to use in hard automation applications. This four drive roll feeder operates on 40VDC input power and is designed to be used with ArcLink™ Robotic Power Waves®. This product features Lincoln Electric's STT® process for applications in which heat input control, minimal distortion, reduced spatter, and low fumes are essential.

Customer Assistance Policy

The business of The Lincoln Electric Company is manufacturing and selling high quality welding equipment, consumables, and cutting equipment. Our challenge is to meet the needs of our customers and to exceed their expectations. On occasion, purchasers may ask Lincoln Electric for advice or information about their use of our products. We respond to our customers based on the best information in our possession at that time. Lincoln Electric is not in a position to warrant or guarantee such advice, and assumes no liability, with respect to such information or advice. We expressly disclaim any warranty of any kind, including any warranty of fitness for any customer's particular purpose, with respect to such information or advice. As a matter of practical consideration, we also cannot assume any responsibility for updating or correcting any such information or advice once it has been given, nor does the provision of information or advice create, expand or alter any warranty with respect to the sale of our products.

Lincoln Electric is a responsible manufacturer, but the selection and use of specific products sold by Lincoln Electric is solely within the control of, and remains the sole responsibility of the customer. Many variables beyond the control of Lincoln Electric affect the results obtained in applying these types of fabrication methods and service requirements.

Subject to change - This information is accurate to the best of our knowledge at the time of printing. Please refer to www.lincolnelectric.com for any updated information.

Test Results Disclaimer

Test results for mechanical properties, deposit or electrode composition and diffusible hydrogen levels were obtained from a weld produced and tested according to prescribed standards, and should not be assumed to be the expected results in a particular application or weldment. Actual results will vary depending on many factors, including, but not limited to, weld procedure, plate chemistry and temperature, weldment design and fabrication methods. Users are cautioned to confirm by qualification testing, or other appropriate means, the suitability of any welding consumable and procedure before use in the intended application.

WHAT IS NEXTWELD®?

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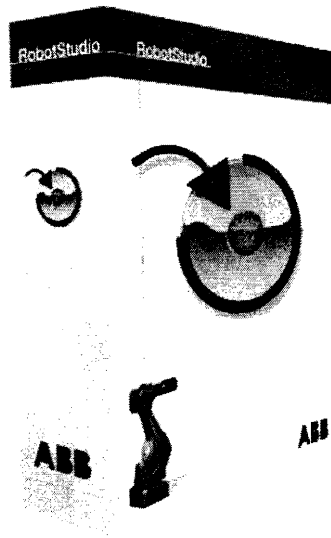
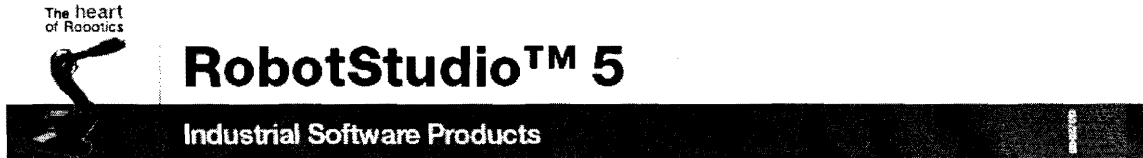
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ABB Information



RobotStudio™ for IRC5

There is increasingly competitive pressure on the industrial market. Customers require higher efficiency in production in order to lower prices and raise quality.

Allowing robot programming to add time to the manufacturing start of new products is unacceptable today as is shutting down existing production to program of new or modified parts.

Taking the risk of manufacturing tooling and fixtures without first verifying reach and accessibility is no longer an option. The modern production site verifies the manufacturability of new parts during the design phase.

When programming your robots offline programming can take place in parallel with the system build.

By programming the system at the same time as it is manufactured, production can start earlier, reducing time-to-market.

Offline programming reduces the risk by visualizing and confirming solutions and layouts before the actual robot is installed and generates higher part quality through the creation of more accurate paths.

To achieve true offline programming, RobotStudio utilizes ABB VirtualRobot™ Technology. ABB invented VirtualRobot™ Technology more than ten years ago.

RobotStudio 5 is the leading product for offline programming on the market. With its new programming methods ABB is setting the standard for robot programming worldwide.

ABB



RobotStudio 5™

Industrial Software Products

Enjoy the power of True Offline Programming™

CAD Import

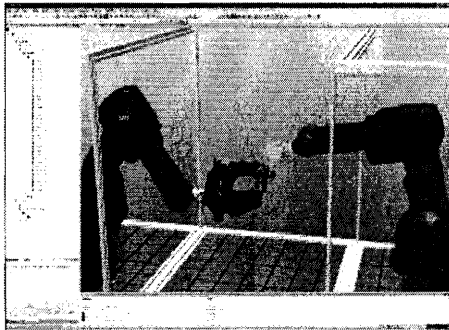
RobotStudio can easily import data in major CAD formats including IGES, STEP, VRML, VDAFS, ACIS and CATIA. By working with this very exact data the robot programmer is able to generate more accurate robot programs, giving higher product quality.

AutoPath

This is one of the most timesaving features in RobotStudio. By using a CAD-model of the part to be processed it is possible to automatically generate the robot positions needed to follow the curve in just a few minutes, a task that would otherwise take hours or days.

Autoreach

Autoreach automatically analyses reachability and is a handy feature that lets you simply move the robot or the work piece around until all positions are reachable. This allows you to verify and optimize the work cell layout in just a few minutes.



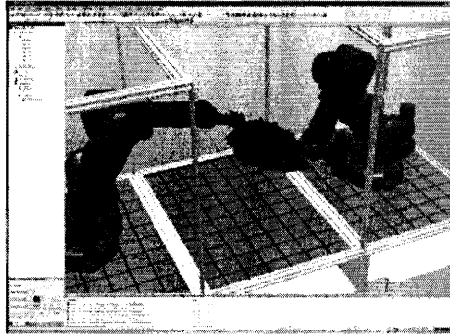
Path Optimization

RobotStudio can automatically detect and warn about programs that include motions in close vicinity to singularities, so that measures can be taken to avoid such conditions. Simulation Monitor is a visual tool for optimizing robot movement. Red lines indicate which targets you can improve to make the robot move in the most effective way. It is possible to optimize TCP speed, acceleration, singularity or axes to gain cycle time.

Collision Detection

Collision detection prevents costly damage to your equipment. By selecting the objects concerned, RobotStudio will automatically monitor and

indicate whether they will collide when a robot program is executed.



Virtual FlexPendant

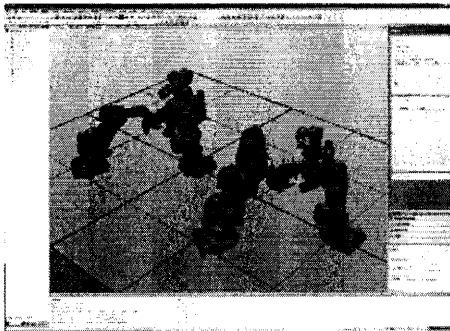
This is a graphical representation of the real flex pendant, powered by the VirtualRobot. Essentially, everything that can be done in the real flex pendant can be done in the virtual flex pendant making this a great teaching and training tool.

True Upload and Download

Your whole robot program can be downloaded to the real system without translation. This is a unique feature thanks to the Virtual Robot Technology that is a technique only provided by ABB.

MultiMove

With RobotStudio 5, ABB takes its Virtual Robot Technology to the next level. It is now possible to run several virtual robots at the same time, and there is support for MultiMove, the new IRC5 technology for running several robots from one controller.



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Automated Welding System

Final Report

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TERMS, DEFINITIONS, AND ACRONYMS

QPS	Quasi-Poloidal Stellarator
MDL	Magnet Development Lab
Ar	Argon gas
TIG	Tungsten Inert Gas
MIG	Metal Inert Gas
GTAW	Gas Tungsten Arc Welding



Introduction/Background:

The UT robotics senior design team examined the feasibility of applying a robotic welding system for the production of magnet coils developed by the Magnet Development Lab (MDL). The magnets are being built for the Quasi-Poloidal Stellarator (QPS) fusion energy research project. Each magnet requires a can to be formed around the copper windings. This task demands high quality welds be made along complex three dimensional paths between two significantly different combinations of stainless steel.

Robotic welding systems have proven to consistently produce high quality welds in industrial use. The consistency of robots is due to the repeatability and precision built into each system. Expected benefits of an automated weld system include, but are not limited to: faster overall weld speeds; consistent, quality welds; and less overall welding downtime.

The SCOMPI robotic welding system was used as the basis of this study. Through testing, it has been determined that the SCOMPI system is not appropriate for the types of welds required by the QPS project. However, the results of this study support implementing a robotic welding system. The results, observations, and conclusions of the study are explained below.

Objectives:

The objective of this project is to determine the viability of using a robotic welding system for the three dimensional welds of the magnet coils. This is accomplished by demonstrating sheet metal-to-sheet metal welds and sheet metal-to-casting welds. These welds are illustrated in the tests designed for this study. The data retrieved from this project will be used to evaluate the effectiveness of applying a robotic welding system to the magnet coil assembly and as a basis for investigating the benefits of using other systems rather than the SCOMPI system.

Equipment Details:

Robot

The SCOMPI robot is shown in Figure 1. It has a total of six degrees of freedom; the first joint is prismatic, and the following five are revolute. Link five includes a 90° bend. The prismatic joint is a rack-and-pinion track; the limits of this joint can be extended indefinitely by adding more track sections.



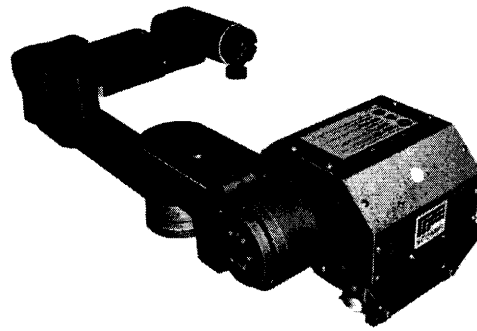


Figure 1. SCOMPI Robot

This is a non-standard kinematic design. While most industrial robot arms are anthropomorphic, or similar to a human arm, the SCOMPI robot has only two degrees-of-freedom at the wrist rather than three. With this configuration, yaw rotation of the tool tip requires movement of the longer links, rather than just the wrist. This means that it is common for small motions of the end-effector to require large motions of the arm. The last link includes a dovetail quick-connect for attaching the end-effector. This provides a simple, easy method for attaching and detaching end-effectors.

Narrow Gap Tungsten Inert Gas (NGT) Welding End-Effector

The welding end-effector is attached to the robot arm by means of the dovetail quick connect. The end-effector consists of two primary components: the torch assembly and the wire feed apparatus. Both of these components are connected by an angle mounting bracket.

The first of these components is the torch assembly. The torch assembly is made of a metal casing that encloses an insulating ceramic tube through which the current from the weld power supply is routed. The tungsten electrode is surrounded by an inert gas purge diffuser, which is designed for supplying purge gas to a narrow gap. An attached motor can rotate this electrode to various orientations. The torch assembly power cables, as well as some other non-critical parts of the NGT torch, are cooled by water.

The second part of the welding end-effector is the wire feed apparatus. This consists of a wire feed supply motor that can vary the filler wire supply rate and two wire feed positioning motors that can be used to position the end of the filler wire relative to the electrode. The NGT weld torch is shown in Figure 2.



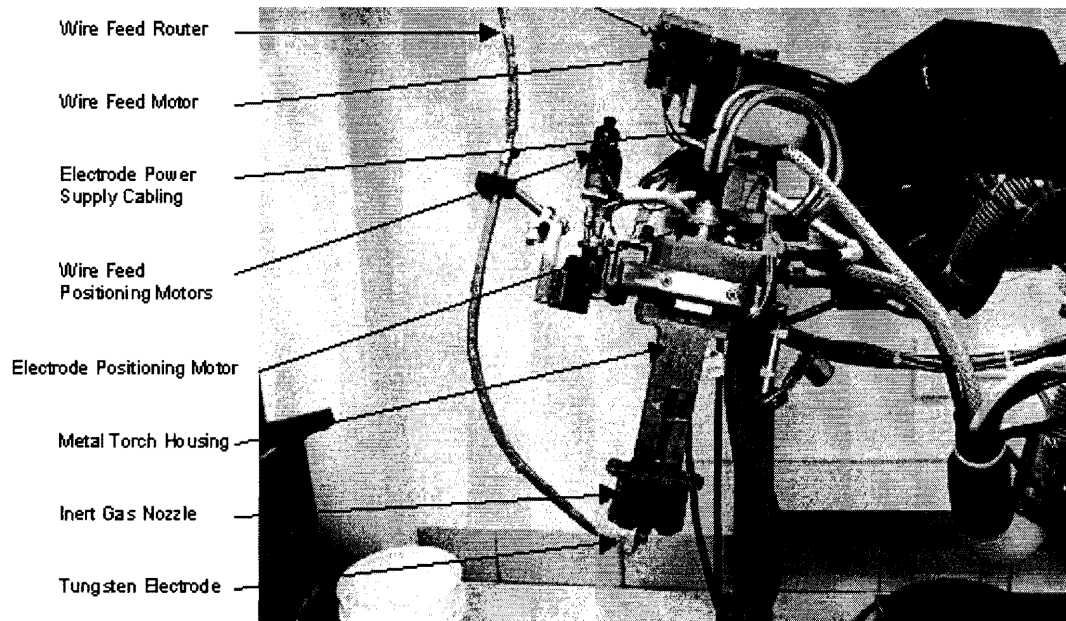


Figure 2: Welding End-Effector

Controllers

The control system for the SCOMPI system consists of a robot controller and welding controller that are linked by software, which runs on the iRMX operating system, which is a real-time version of DOS.

- **Robot**
The robot controller generates all control signals related to the motion of the robot arm. This involves both positioning and orienting the end-effector.
- **Welding**
The welding controller generates all control signals related to the inert gas purge system, the welding power supply, the wire feeder, and the electrode rotational position.
- **Real-time SCOMPI software**
Important feedback control features such as arc voltage control depend upon synergic relationships between the welding process and the robot motion. The integrated SCOMPI control system allows the integration of both controllers for the purpose of coordinating the welding process with the robotic motion.

Pendant

The pendant controller for the robotic system consists of a "Three Colored Human Interface" as shown in Figure 3.



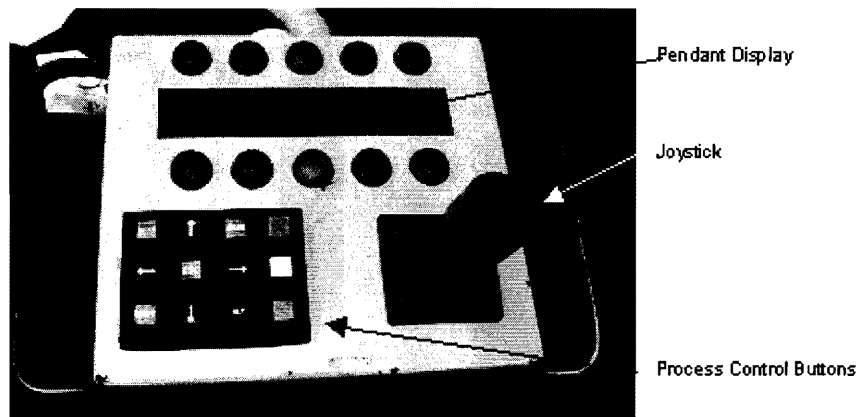


Figure 3: Three Color Human Interface

The joystick allows the user to move and teach the robot. Several different methods are available for moving the robot, including several different base reference frames for Cartesian control. The three process control buttons provide intuitive control of any automatic movement or welding process that is performed by the robotic system. The pendant also gives the operator a convenient way to adjust significant welding parameters.

Welding Power Supply

An ArcMachines 600GMS welding power supply was used with the system. This power supply is rather versatile, as it has the capability to perform either MIG or scratch-start TIG welding. A 17 pin connection was used for communication between the weld power supply and the welding controller, for sending command signals such as input current and voltage setpoints. The connection was also used to provide current and voltage feedback to the controller.

Track Mount Assembly

A specially designed mounting structure for the track was needed for test purposes. Specifically, the range of motion of the robot needed to be centralized about the test parts. This was accomplished by mounting a five foot piece of track horizontally and four feet up from the ground. 3" x 3" x 3/16" Square tubing was used as the main structure support. This material caused the structure to be and to be extremely rigid. Figure 4 displays the track mount.



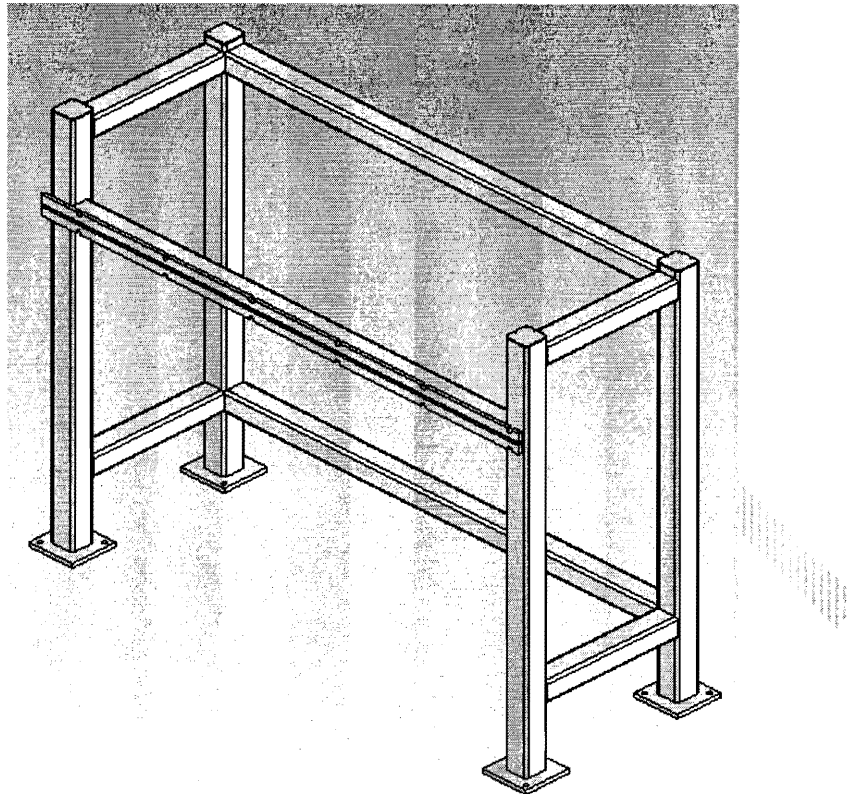


Figure 4: Specially Designed Track Mount

During operation it was discovered that mounting the track horizontally presented a couple challenges for the robot. Mainly, this configuration caused the joints to experience some oscillation. Some of the robot links have cross-sections that are rectangular; like cantilever beams, it is better to have the thicker cross-section dimension vertical, in order to minimize the effects of gravity. Vertical mounting of the track will likely relieve much of this oscillation.

Part Holders

The nature of the tests conducted required special part holders to be designed. These holders were clamped to the welding table and then the parts were clamped to the holders. This allowed all parts to remain rigid and stable during welding operations.

- **Phase 1**
Phase 1 testing required an Argon purge on the backside of the test pieces. To accomplish this, the test pieces were positioned with the back of the weld seam exposed to a channel that was filled with Argon. Figure 5 displays the phase 1 part holder:



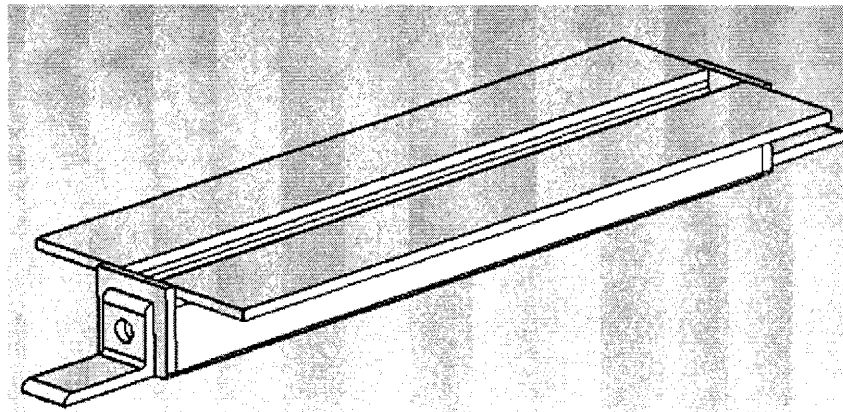


Figure 5: Phase 1 Part Holder

The wings of this holder provided sufficient clamping area for phase 1 parts. This holder was fitted with a $\frac{1}{4}$ " tube fitting, which allowed argon to fill the channel.

- **Phase 2a**

This test required a fixture that simulated the welding conditions on the casting; however, rather than having a contoured shape, straight paths were created. Figure 6 shows a phase 2a part holder:

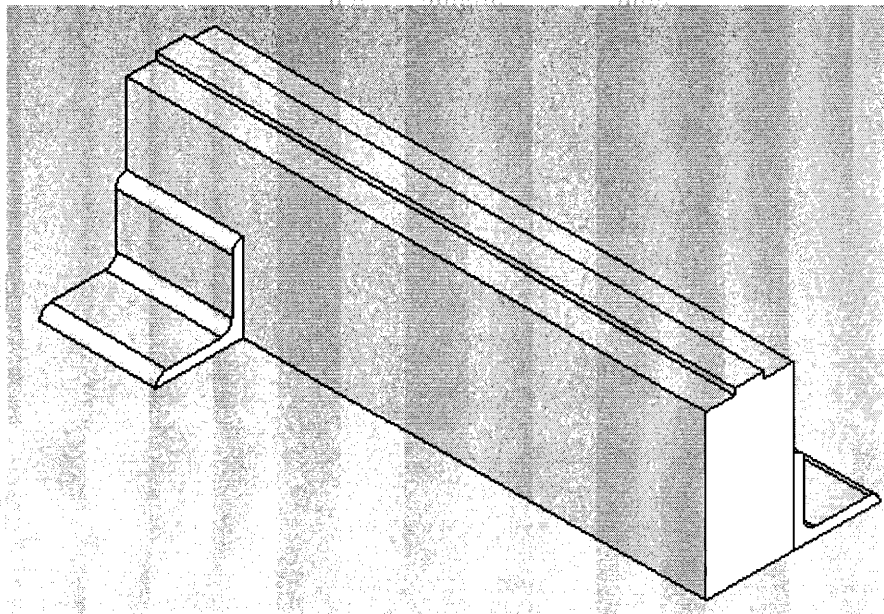


Figure 6: Phase 2a Part Holder

Unlike the phase 1 holder, the phase 2a holder became part of the test piece. In other words, the sheet metal pieces were welded to this fixture, and like the sheet metal, these parts were made from A316 stainless steel. The machined groove on top of the piece simulates that of the actual casting. In order for the parts to be welded correctly and to prevent thermal



distortion, each piece needed to be securely clamped lengthwise; therefore, a separate clamping structure was created. The following figure presents the clamping surface:

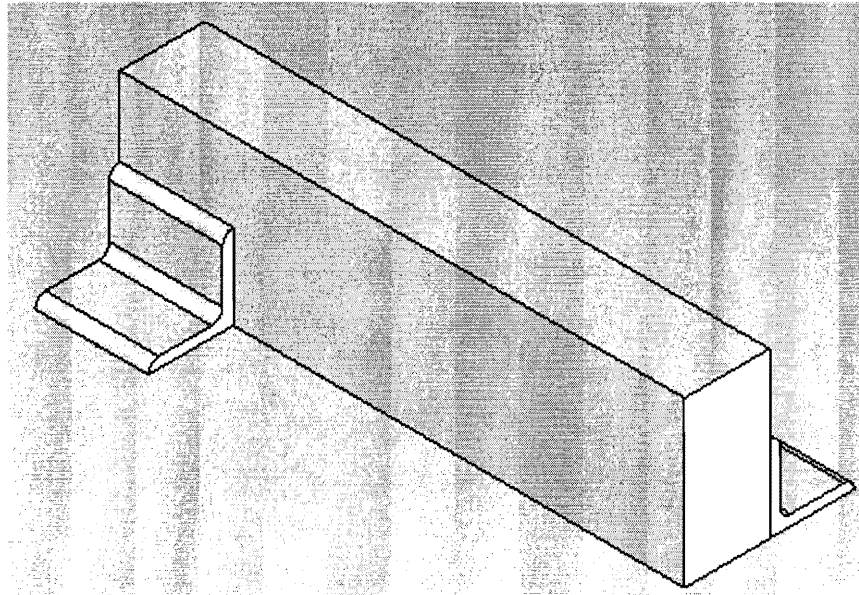


Figure 7: Phase 2a Clamping Structure

- **Phase 2b**
Phase 2b utilized the inchworm provided by MDL as the part holder. No special holder needed to be designed and fabricated for this phase. Below is a picture of the inchworm.



Figure 8: Picture of the Inchworm



Inert Gas System

A purge was constructed to create an inert atmosphere around the welding area. Argon gas was determined to be the appropriate inert gas for the application, and a distribution system was designed to work with the existing system already established in the welding end-effector. The distribution system consisted of a compressed gas cylinder, a regulator/flow meter, the plumbing boxes supplied with the robot, a y connector valve, and the associated tubing. The regulator/flow meter was attached on the discharge end of the cylinder to provide controlled release of the argon. The total flow rate typically ran from 20 cfm to 50 cfm, with the two supply paths splitting the flow. The y connector valve split the flow at the exit of the regulator/ flow meter and provided a supply of Argon through the tubing to the plumbing box and to a hose that applied the inert gas directly to the testing area. From the plumbing box, the gas was delivered to the weld held, which exhausted the gas around the electrode.

Robot Kinematics Study:

A study was performed in order to quantify the range of motion of the SCOMPI system and consider additional positioning requirements to reach the entire weld seam. In this study, the Denavit-Hartenburg (DH) convention was employed to locate the coordinate systems needed to calculate the position transformation. From the coordinate systems, the four link parameters – link length, link twist, link offset, and joint angle – were determined. Length and twist are fixed for any given link. Link offset is variable for prismatic joints, joint angle for revolute. These parameters, listed in Table 1, were input into a transformation matrix. The position and orientation of the tool holder (end of link 6) was the computed in MATLAB for a series of joint positions. The track position was not changed as it merely translates the computed position along the track axis. The various joint limits can be seen in Table 2.

The first joint is a prismatic joint that provides translation along the track. As can be seen from the following figures, together with the first three revolute joints, it dominates the system's range of motion. Joint 2, the first revolute joint rotates parallel to the track. Together with Joint 3, it forms a "shoulder." Joints 3 and 4 combine to provide a sweeping motion (see Figure 9) on the plane determined by the angle of Joint 2. This combination permits large displacements perpendicular to the track. Joints 5 and 6 are revolute joints that primarily orient the end-effector.



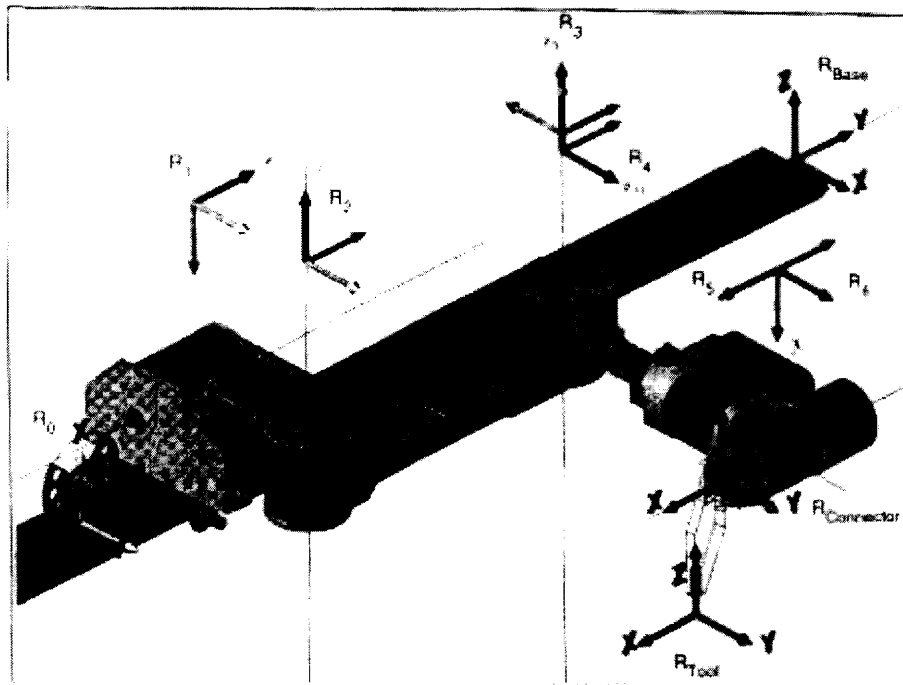


Figure 9: Coordinate Systems for Transformation and DH Parameters.

Table 1: Kinematic Parameters

Link	a (in)	alpha (deg)	d (in)	theta (deg)
1	3.35	0	q_1	0
2	7.36	-90	0	q_2
3	16.54	0	0	q_3
4	0	90	0	q_4
5	0	90	14.65	q_5
6	0	0	3	q_6

Table 2: Joint Limits: J1 in Inches, Others in Degrees

Joint	Lower	Upper
1	0	48
2	-204	15.2
3	-88	132
4	-45	198
5	-360	0
6	-90	-90



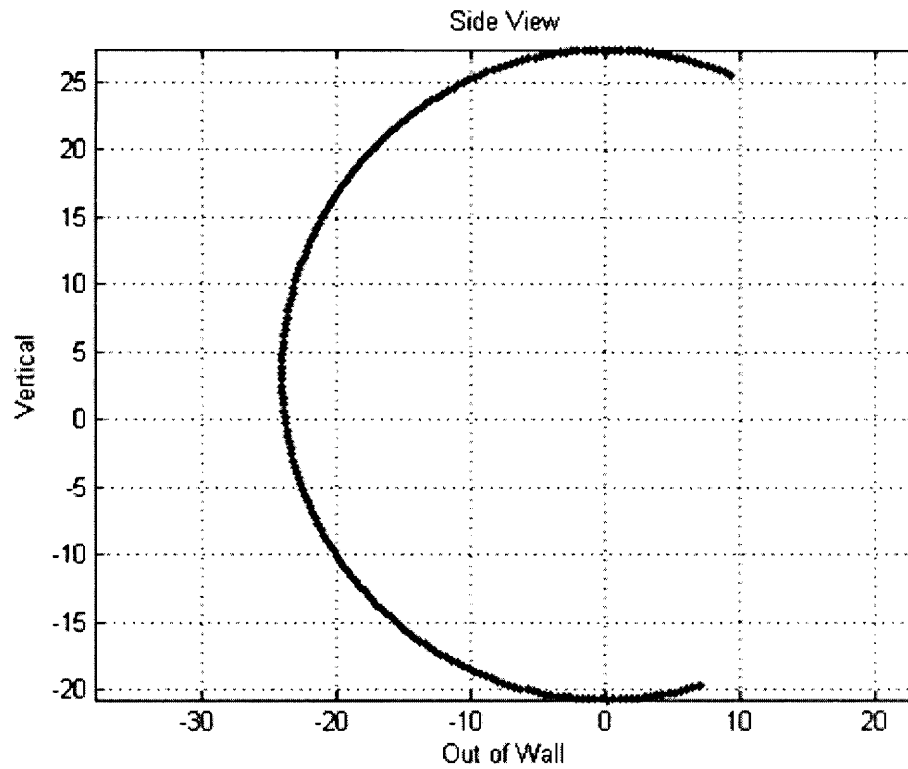


Figure 10: Motion due to Joint 2

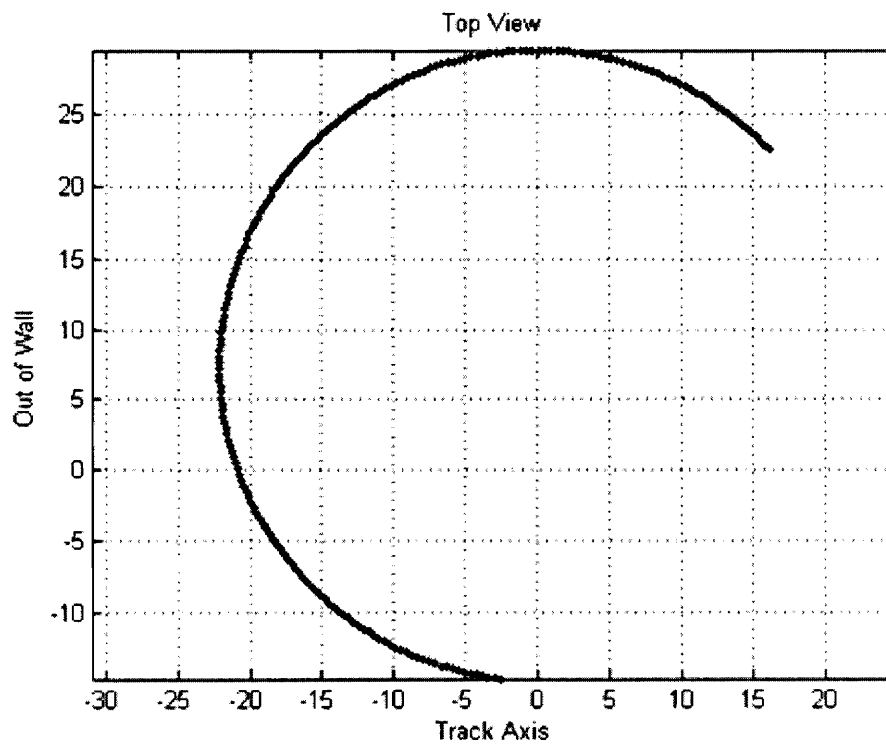


Figure 11: Motion due to Joint 3



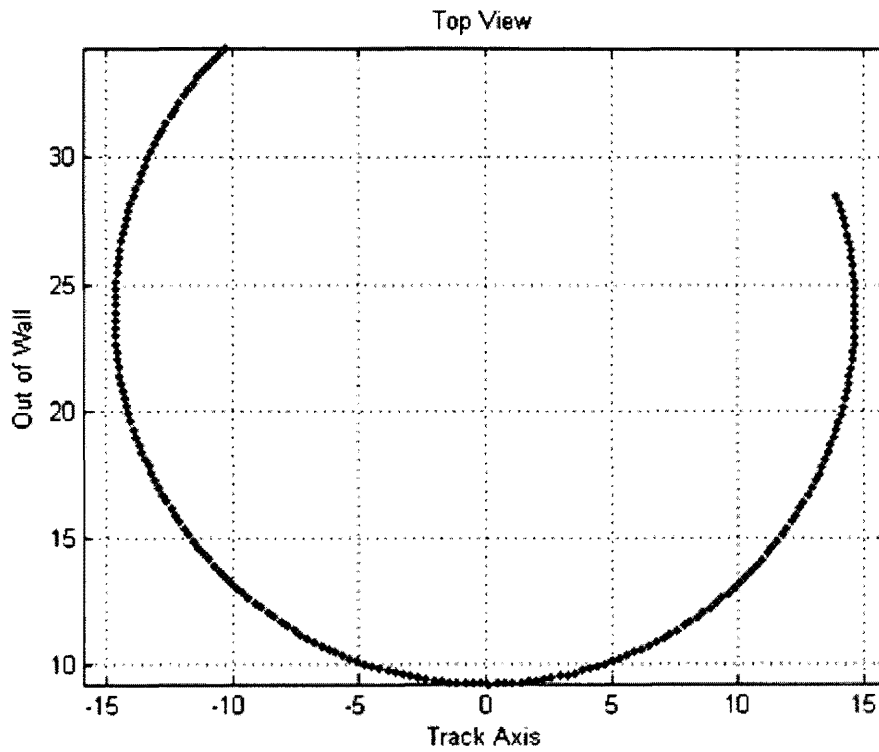


Figure 12: Motion due to Joint 4

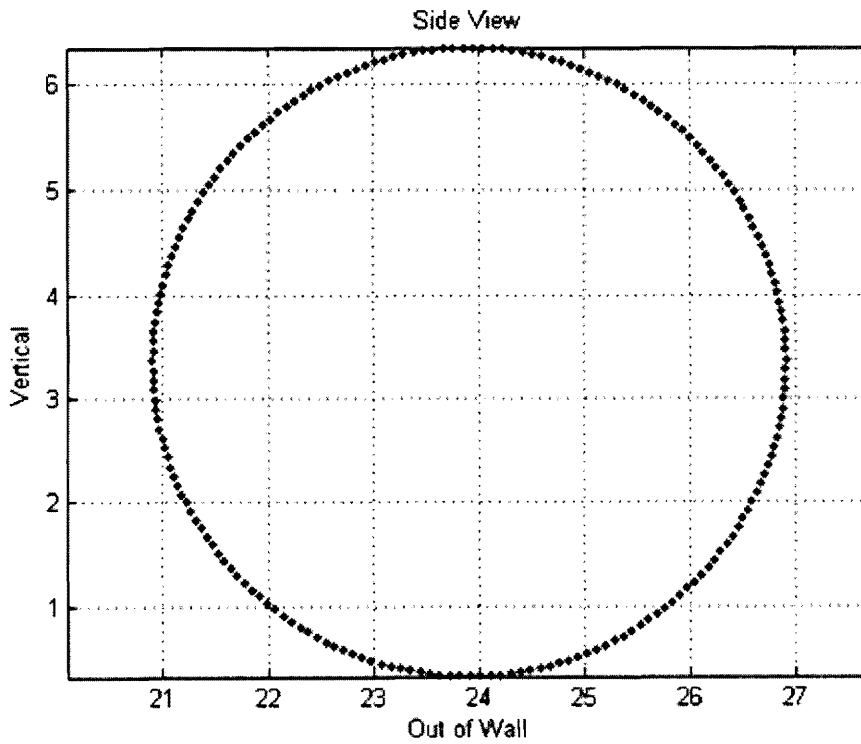


Figure 13: Motion due to Joint 5



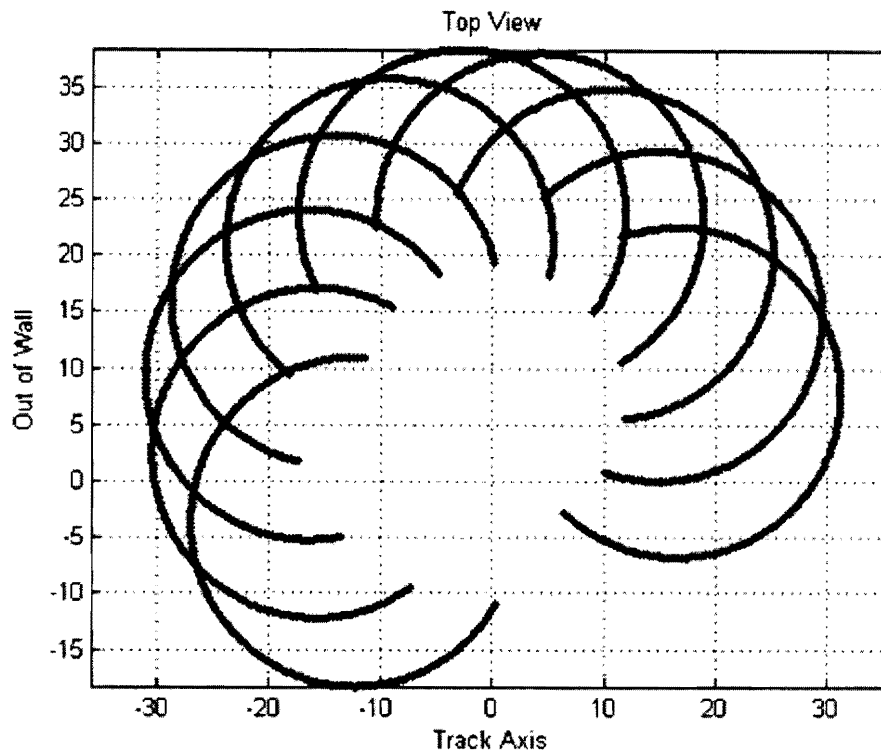


Figure 14: Combined Sweeping Motion of Joints 3 and 4

The final goal of the kinematics study is to determine the range of motion, or set of points that can be reached at some orientation, of the SCOMPI robot. Diagrams of this range of motion, without an end-effector, are shown in the Appendix. Note that, in the side view, the range of motion is shown to extend through track, located approximately at the origin of the plot. This situation is only possible if the robot is near and reaches around the end of the track.

Equipment Operation Overview:

Programming Parameters

The Welding Process:

Configuration file: gtaw.cfg

Over 100 parameters for the welding process are defined in the file gtaw.cfg. Some can only be adjusted in this file, from the computer, and others can also be changed from the pendant during the welding process.

The welding parameters are divided into two primary categories: transient parameters and steady-state parameters. The transient parameters define all the motions of the robot and the actions of the welding power supply in the process of striking an arc. Some of the significant transient parameters include the current at which an arc is to be struck, the speed at which the welding electrode approaches the work-piece to strike the arc, the current level at which the system senses an arc, and the time between the system sensing an arc and changing to the steady-state current.



The steady-state parameters define the speed, current, arc length, and deposit rate of wire feed for the weld. The system has been designed to allow pulsing between a “primary” and “background” set of steady-state parameters, if desired. In cases where pulsing would be used, the length of time that each “pulse” of parameters lasts can also be defined here.

The rest of the parameters within the gtw.cfg file are primarily related to hardware, weaving of the electrode during welding, and feedback control of the system. Because the hardware used during testing remained constant and weaving was not necessary for the welding of stainless steel sheet metal, parameters related to these items did not need to be adjusted. The settings for the feedback control loops were also not changed, as the settings seemed to be adequate for testing.

Joint Configurations:

Configuration file: joint.cfg

There are several important parameters related to the robot control that can be adjusted in the configuration files. The file joint.cfg includes the translation/rotation, velocity and acceleration limits for each joint, as well as the link lengths and joint limits. All of these parameters can be changed. The limits on the track can be changed, and it is sometimes convenient to adjust other joint limits to obtain more desirable linkage configurations during welding. This is possible, but there are a few deadbands in the software, which limit motion beyond certain points.

Configuration files: welding.kin and finger.kin

Any time the end-effector geometry is changed, changes must be made in the software to account for that. There are two separate files that include the coordinate transformations from the reference frame of the quick-connect at the end of the last robot link to the frame corresponding to the tool tip: finger.kin and welding.kin. Any time the end-effector is changed, both of these files must be updated accordingly. Both files must include exactly the same rotations and translations; otherwise, the system gives erroneous errors. Contrary to standard conventions for coordinate transformations, the rotations are all defined with respect to the original quick-connect reference frame.

Teaching Weld Paths

The first step in using the SCOMPI robot is to “synchronize” or calibrate each joint. No operations can be performed without first synchronizing. This process consists of moving each joint such that two notches, one on each side of the joint, are aligned, and saving that calibration position. It must be re-synchronized every time the robot controller is powered up; even if the computer is turned off, it does not need to be re-synchronized as long as the robot controller stays on. Also, any time the motors stall during operation, it is best to re-synchronize. Motor stalls are most likely to happen if the electrode sticks to the part surface during the arc striking phase.

The SCOMPI robot motion can be commanded from the pendant in four different modes. In joint mode, each joint can be moved individually. Base mode allows the tool tip to move in Cartesian space with respect to the base reference frame, which is located at the center of the track. Tools mode allows the tool tip to move in Cartesian space with respect to the reference frame of the welding end-effector. In Cartesian mode, the robot’s motion is restricted to the programmed weld path; it moves only along the line determined by the weld path.



Before performing any welding operation, the operator must teach the weld path. The minimum allowable weld path length is approximately 3/4"; the system does not allow for shorter tack welds. For this version of the software, the only available option for teaching a weld path is the teach-playback method, with linear interpolation between teach points. The "Teach" menu in the pendant includes options to teach two important items: the "Workspace" and "Contour". The workspace consists of the set of teach points which determine the weld path. The system performs linear interpolations between teach points. The contour essentially sets limits on that workspace; in other words, defining a contour allows the operator to set limits on the motions that the robot can execute during a welding operation, while allowing a greater range of motion when the robot is not in a welding process. The system requires that both a valid workspace and contour are saved before beginning a welding operation.

This system is designed for welding multiple passes. Therefore, it includes advanced features for teaching 2D and 3D workspaces and contours that are not needed for welding sheet metal. Under the "Teach-Workspace" menu in the pendant, the dimension should be set to 1 for single-pass welds. The "Size" corresponds to the number of teach points.

In teaching points, it is important to make sure that no two consecutive point-to-point line segments differ by more than 30% in angle or length. This is an important consideration when transitioning between straight and curved sections of the weld path. It also means that it is impractical to move across tight bends in a single weld path. When the desired weld path crosses a tight bend, it should be taught as two separate weld paths.

This version of the SCOMPI software can only save a single workspace, contour and set of welding parameters at one time. Newer versions allow for multiple weld paths and welding parameters to be saved. With this version, each time a new path or set of parameters is saved, the previous version is overwritten. In order to save multiple configurations and weld paths, the filenames must be changed on the computer. Once the workspace and contour are saved, the software allows the welding process to be controlled from the pendant

Weld Phases

In the course of a successful weld, the operation will pass through ten distinct phases. These phases are illustrated in Figures 15 and 16 with data taken from an actual welding run. In the figures, I_{set} and V_{set} are the current and voltage setpoints; I_a and V_a are measured current and voltage; V is the travel speed; and P_d is the vertical displacement, as determined through robot kinematics.

Move

The weld torch moves in curvilinear mode to the beginning of the weld path.

Purge

In order to expel atmospheric gasses from the weld area that could cause oxidation, argon is run for a duration of PPBT before attempting to strike an arc.

Seek Arc

During the seeking phase, the tip moves closer to surface until an arc is detected by passing preset current and voltage thresholds. If an arc is not detected before the tip contacts the work piece, it will touch the surface to produce an arc before drawing away.



Lift Up

Once an arc is present, the tip begins to pull away from surface. In the lift up phase, the tip is raised to the desired arc length. The phase duration is PLUT, and current is maintained at arc start current, PICF.

Upslope

Current and voltage transition from their starting to steady state values during the upslope phase. The upslope time is given by PUST. At this point, the weld head is still stationary.

Rising

In the rising state, current setpoint reaches its steady state value. The torch begins to move, reaching steady state travel speed at the end of the phase. The length of the rising state is defined by PRSL, a distance – not time – variable.

Steady

The bulk of the welding is accomplished during steady state operation. Current, arc length, travel speed, and deposit rate, if filler wire is used, are maintained at their respective setpoints as torch progresses along the programmed trajectory. These parameters can be modified in the course of the weld through the pendant.

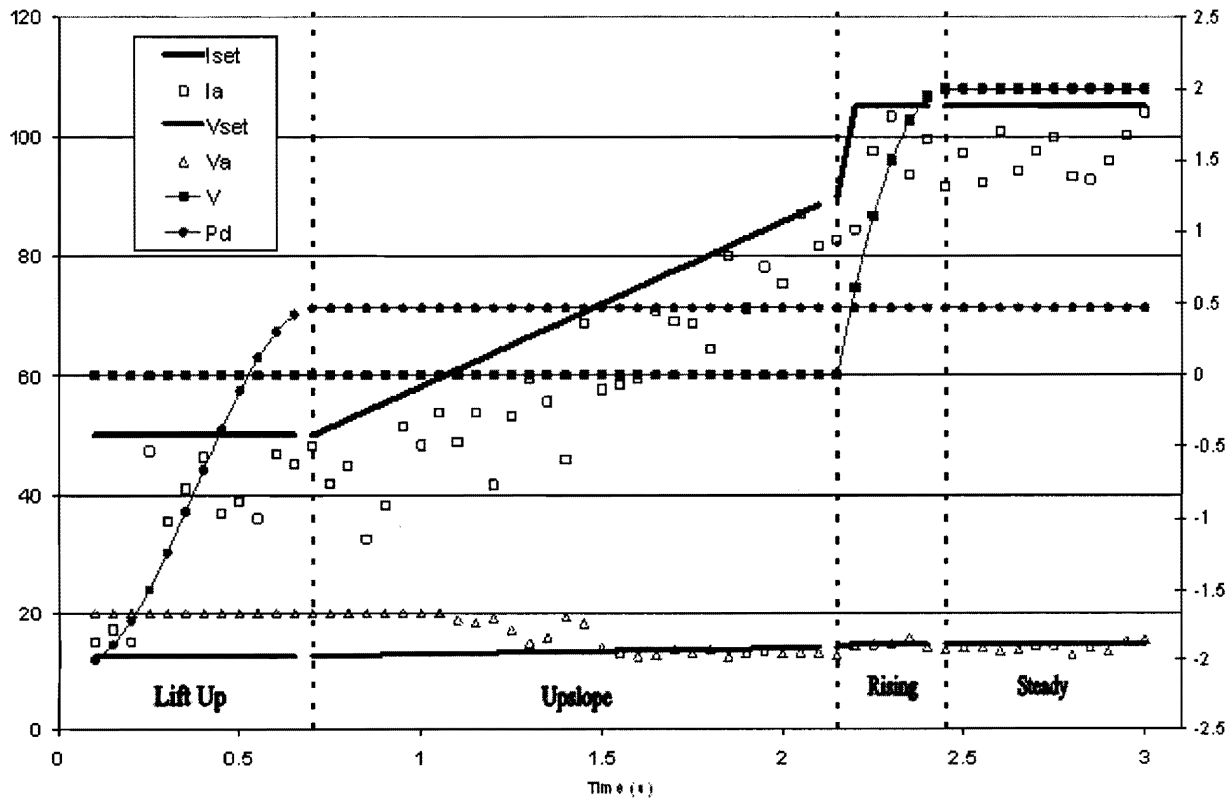


Figure 15: Arc Starting – Lift up, Upslope, Rising, and Steady State Phases.

Settling

As the torch approaches the end of the weld path, it slows down and stops. Like the rising phase, settling duration is of a set length, in this case PSSL.



Downslope

During downslope, the arc and any wire feed are maintained as the torch remains stationary to fill the crater produced by the melt pool. The current is then reduced until the arc extinguishes itself.

Purge

Argon flow continues in order to protect the still-hot metal of the weld bead.

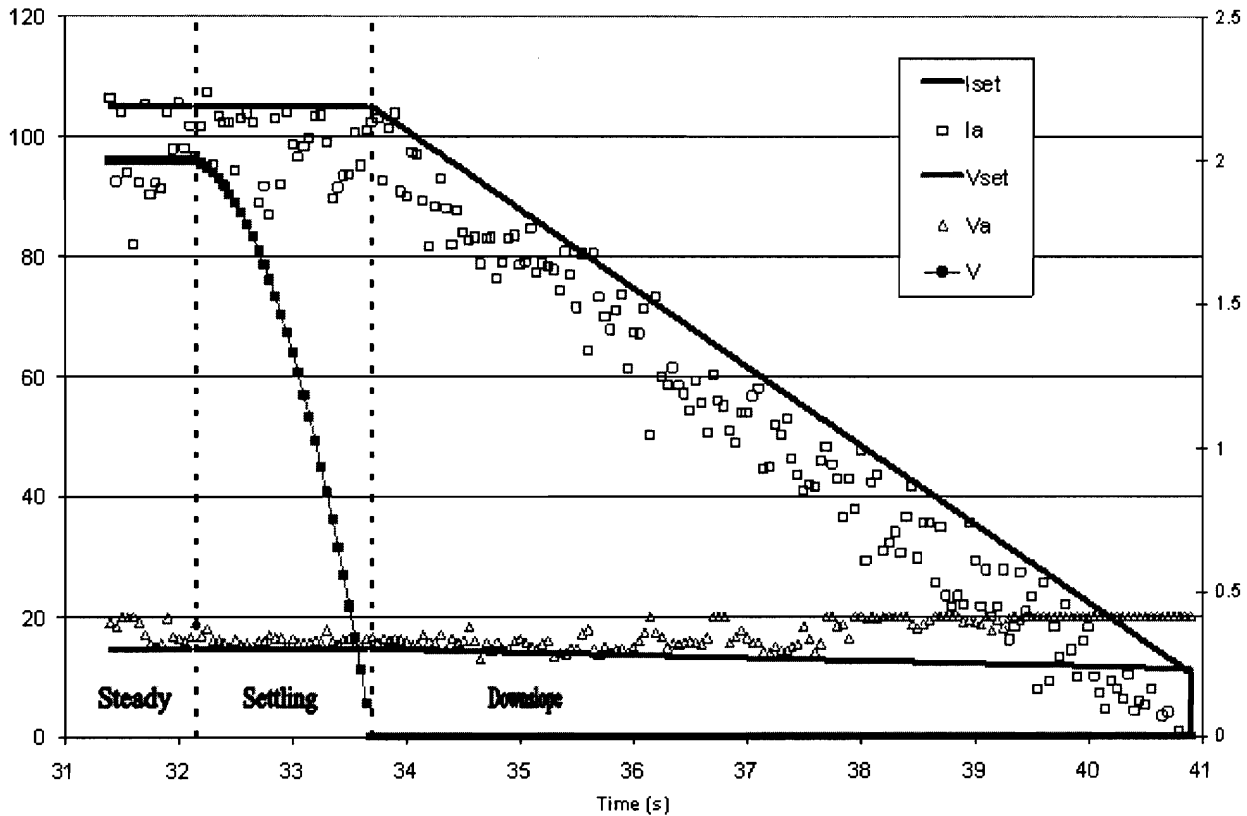


Figure 16: Arc Extinction – Steady, Settling, and Downslope Phases.

Arc Length Calculation

In order to estimate the arc length while welding, eight parameters and two measurements are used. Upper and lower limits for both arc length and current as well as the voltage across the arc corresponding to these conditions are saved into a configuration file. Voltage and current measurements are taken during the course of the welding operation.

The only way to know how the arc length is calculated by the SCOMPI system is to analyze the source code for the program, which is beyond the capacity of this project. This method, however, has been tested with data collected while welding and agrees with the system's estimated arc length.



First, linear interpolation is used between the current limits to produce an estimated voltage for both the lower and upper arc length limits at the measured current (dashed lines). Linear interpolation is again used with the measured voltage, arc length limits, and new voltage estimates to arrive at an arc length estimate.

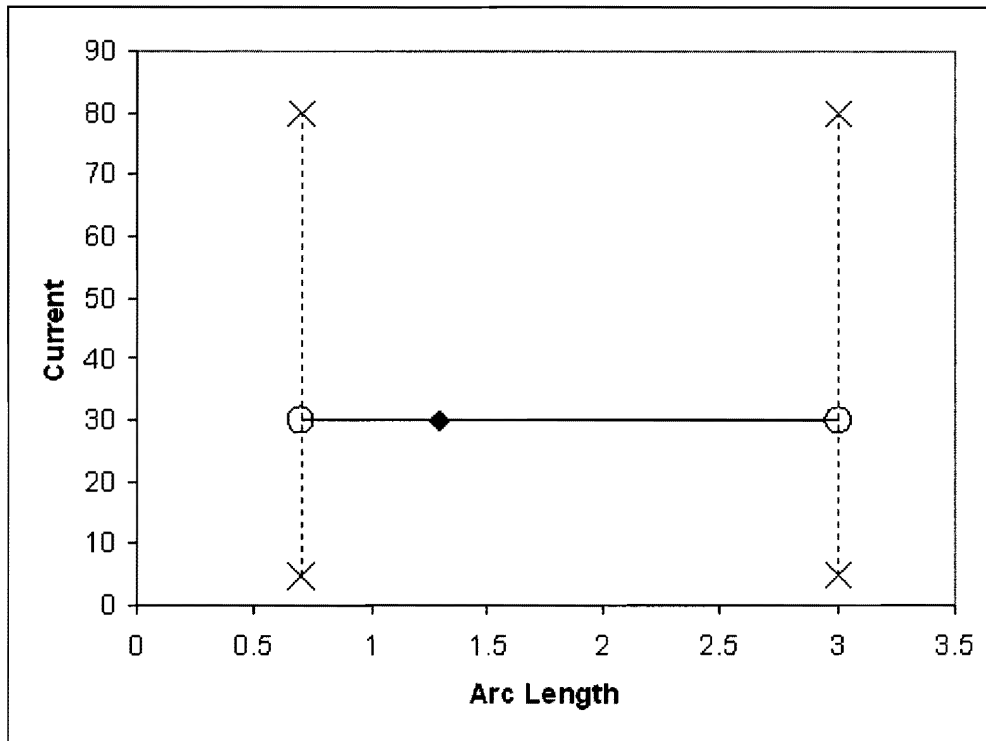


Figure 17: Schematic of the Interpolation Scheme to Estimate Arc Length.

In Figure 17, the crosses represent point in the configuration file, the circles are the location of voltage estimates produced by the first interpolation, and the diamond is the calculated arc length. Each of the points represents a known voltage. Inputs for the figure are listed in Table 3.



Table 3: Arc Length Calculation Inputs

ELAL	0.7	Lower bound arc length
EUAL	3	Upper bound arc length
ELCF	5	Lower bound current
EUCF	80	Upper bound current
ELLV	6	Lower arc, lower current, voltage
ELUV	9	Lower arc, upper current, voltage
EULV	15	Upper arc, lower current, voltage
EUUV	20	Upper arc, upper current, voltage
Current	30	
Voltage	9.52	
Lower voltage	7	
Upper voltage	16.7	
Arc Length	1.30	

Test Plan:

The following test plan was developed to accomplish the project objectives. Phase 1 was designed to simulate sheet metal-to-sheet metal welds, and phase 2 was designed to simulate sheet metal-to-casting welds.

- **Phase 1**

Two test configurations were used. For both configurations, the edges of the stainless steel sheet metal were folded up to simulate the prototype can piece provided by MDL.

Configuration 1

- Straight 6 inch sections
- No filler wire
- Thicknesses of sheet metal: 27 mil and 37 mil

Configuration 2

- Curved sections
- No filler wire
- Thickness of sheet metal: 27 mil

Data to be collected and analyzed for both configurations

- Temperatures
- Welding parameters used

- **Phase 2**

Two simulations were designed. Phase 2a was designed to prove a robotic welding system can complete a straight, sheet metal-to-casting weld, and phase 2b was designed to prove a robotic welding system can maneuver a complex three dimensional weld path. Together 2a and 2b simulate sheet metal-to-casting welds potentially experienced during welding of a magnet coil.



Phase 2a

- The use of filler wire was investigated
- Thicknesses of sheet metal: 27 mil and 37 mil

Phase 2b

- The verify function was utilized to prove a robot can maneuver a complex three dimensional path
- Only the verify was needed for this phase, no welding was completed

Data to be collected and analyzed

- Welding parameters used

Results:

The results of testing varied from repeatable, high quality welds in Phase 1, to inconsistent, lower quality welds in Phase 2a. The testing plans were rather open ended in order to allow the continual tuning of various parameters and the development of significant results. Although many tests were done for Phase 1, the three cases that are detailed here illustrate the increase in weld quality as testing progressed. The progression of Phase 2 testing shows that the desired welds were beginning to go beyond the limitations of the SCOMPI system. Inconsistency marked the attempts at welding the sheet metal to the block.

Phase 1

One early test, Case #1, examined the effect of arc length on weld quality. The test was conducted using the edge of a 0.027" stainless steel sheet using the parameters shown in Table 4. This test showed that a small, controlled arc will produce a better weld bead with less excessive melting. With a smaller arc, the voltage difference across the arc and therefore, energy input, were reduced. Provided the electrode did not stick to the work piece, the system was also more likely to maintain the arc.

Case #2 was the result of a continuing effort to improve weld quality on 0.027" stainless seams. This case reiterated the need for tight contact between the two pieces to be joined. It showed substantial improvement over previous tests using similar parameters. Once again, weld quality was reduced if a gap was present between the two edges. The test also demonstrated a need to control sugaring, a sign of oxidation, by maintaining a smaller arc.

Case #3 was, in addition to testing weld parameters for 0.037" sheets, used to collect temperature data. This test took advantage of previous experiences to dramatically improve the resulting weld quality. In addition to clamping, multiple tack welds were done prior to the weld to ensure that the joint did not separate. Arc voltage control (AVC) was used to compensate for vertical deviation due to distortion, material melting, or robot oscillation. Instead of inputting an arc length, a voltage was set that the system attempted to maintain. Travel speed was also increased, resulting in reduced heat exposure. Another important change was the orientation of the tungsten electrode in the direction of travel, which concentrated the arc on solid metal.

Throughout the project, manual welds were used as a benchmark for comparing results. One of these, performed for 0.027" sheets is shown with the test cases.



Table 4: Parameters for Different Welds

	#1	#2			#3
Current (A)	20	18	22	22	30
Voltage (V)	--	--	--	--	11
Arc Length (mm)	4→1	1	1	1.3	--
Travel Speed (mm/s)	2.0	2.0	2.0	2.0	3.0
					AVC on



Figure 18: Case #1



Figure 19: Case #2

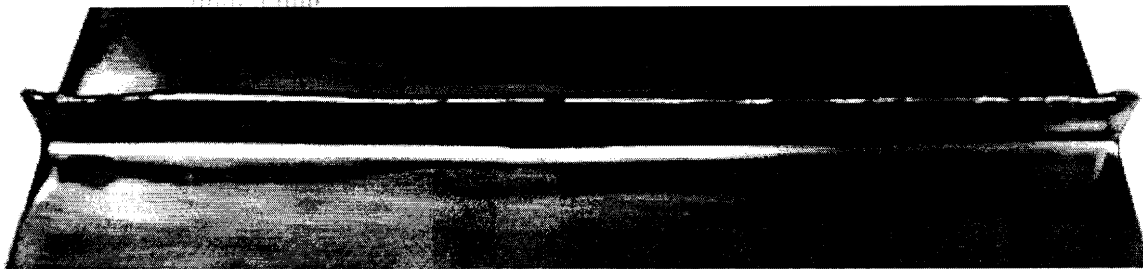


Figure 20: Case #3



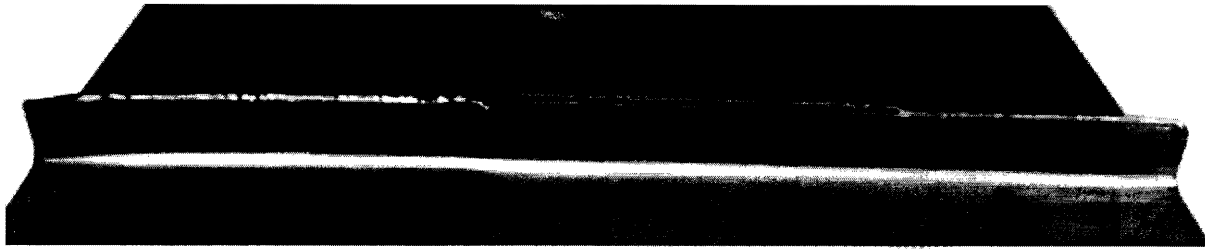


Figure 21: Manual Benchmark Welds

Phase 2a

The fillet welds of Phase 2a posed a different challenge than the sheet-to-sheet welds of Phase 1. It was necessary to use just enough energy to melt the block without destroying the thinner sheet. Through experience and consulting with professional welders, it was determined that the fillet welds could, and even should, be performed without adding any filler metal. This was due to the fact that the distance from the sheet metal to the top of the block provided enough material to act in the same way that filler wire would. To concentrate heat into the block, the weld path was offset from the joint slightly to the side of the thicker piece. Despite these findings, the team had great difficulty producing welds of consistent quality.



Figure 22: Phase 2a welds

Some Phase 2a welds were satisfactory, while many were not. In the end, good results were unable to be repeated even though the same parameters were used multiple times. Through this, the limitations of the SCOMPI system in this application can be clearly seen. However, a properly designed welding end-effector could provide the necessary features to weld such a configuration.

Phase 2b

Phase 2b verified that the robot could maneuver a user-taught three-dimensional path similar to the weld paths on the magnet assemblies. A 12 inch weld path on a mock up can was taught. This can segment required the teaching of 20 intermediate points along the weld path. This path was taught so that the welding end-effector would have to change orientations as it moved along the weld path. After the path was taught, the "Verify" function was used to view the movements of the robot as they would occur in the welding process.



As the robot traced the path, minor oscillation occurred relative to the total length of the path. Otherwise, the welding end-effector was able to trace the weld path fairly smoothly. Based on this, it can be concluded that the SCOMPI system is adequate to weld complex three-dimensional paths. However, it does not provide extremely precise control in these paths. Most likely, it would not be able to ensure the precise welds that the magnet assemblies would require.

Temperature

Temperature data was collected and analyzed to ensure that all materials within the can during welding of the magnet assembly can withstand the heat generated. The expected limiting factor is the temperature at the outer surface of the copper coil bundle. This prediction led to a measurement strategy that attempted to replicate conditions that will be experienced by the coils near the weld.

Equipment used to acquire temperature measurements consisted of a National Instruments CompactDAQ chassis equipped with two NI 9211 channel thermocouple input modules. Each module is capable of a maximum single channel sampling rate of 15 S/s when only one channel is used. Both modules were equipped with an internal sensor for cold junction compensation. Input was provided by Type K thermocouples with a soldered junction. The system was connected to a PC, which allowed the data to be recorded and stored for later analysis.

In order to obtain a temperature profile during the weld, thermocouples were placed both along and perpendicular to the weld seam and at various depths. Thermocouples were placed nearest the end of the weld path between two pieces of the crush plane material as shown in Figure 25. The top piece was 1/8" thick; the bottom was 1/4". TC #1 is 1 cm from the end of the test piece, approximately the location of the arc start. A spacing of 2 cm was maintained between TC #1, 2, and 3. By TC #3 the weld process is presumed to be in steady state, with the only differences between further points being caused by the time at which the torch passes. The horizontal position of the thermocouples and the weld direction are shown in Figure 23.

Five cm from the leading edge, in line with TC #3, a series of thermocouples were placed perpendicular to the weld seam. TC #4 and 5 were placed between the crush planes, at distances of 1 cm and 3 cm from the joint, respectively. In addition, TC #6 was placed below the second crush plane, against another aluminum backing plate, and TC #7 was between the first crush plane and the test piece. Figure 24 is an end view showing a vertical profile of the test setup. The eighth thermocouple was exposed to ambient air.

The most notable limitation of the temperature test performed is the lack of filler materials that will be present during production. The major component not replicated was the copper winding material with insulation and epoxy filling. The copper will serve to absorb and dissipate thermal energy from the weld, thereby lowering the temperature near the weld seam. As a result, observations are expected to be conservative compared to what will be experienced during production.



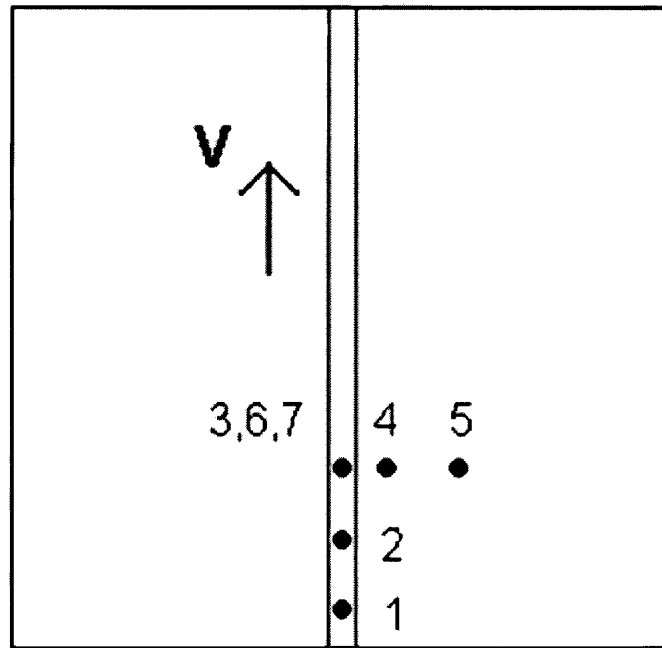


Figure 23: Schematic Layout of Thermocouples along Weld Path.

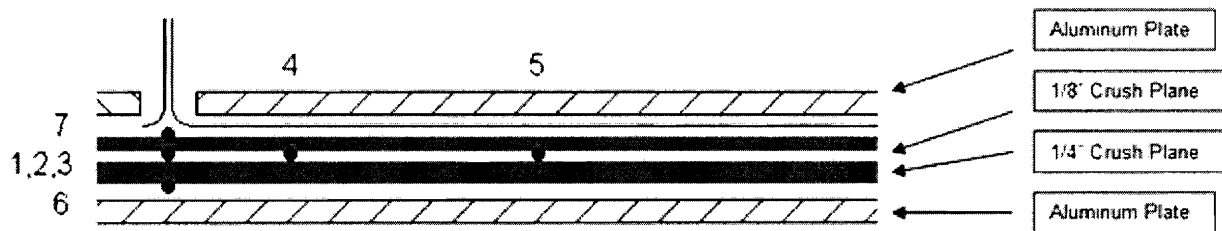


Figure 24: End View of Thermocouple Placement for Phase 1 Temperature Testing.



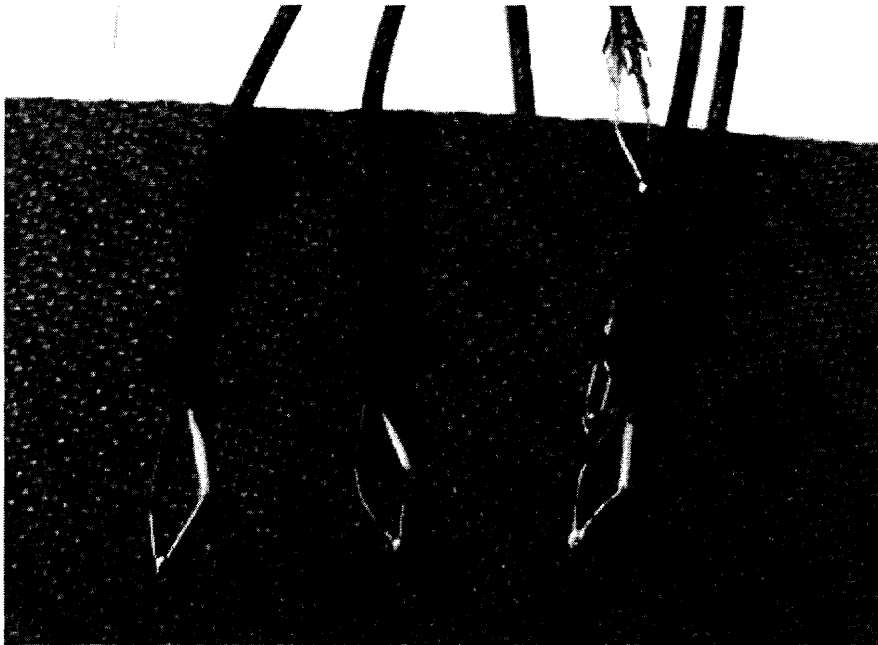


Figure 25: Placement of Thermocouples between Crush Plane Layers.

The stainless steel pieces were tack welded while in the fixture and allowed to cool before commencing the test run. Before beginning the test, all of the temperatures on the test piece were within 1°C of each other and about 3°C warmer than the room air. Steady state parameters for the weld are listed in Table 5.

Table 5: Welding Parameters for Temperature Test

SPCF	30 A	Current
PAVC	11 V	AVC Voltage
SPAL	1.8 mm	Estimated Arc Length
SPSS	3 mm/s	Travel Speed
PICF	50 A	Arc Ignition Current
Purge	40 cfh	Argon Purge Rate

The effect of arc ignition on the temperature experienced can be seen by comparing measurements from under the weld seam. Temperatures at the arc start location were 50°C higher than steady conditions. The difference is due to the lack of movement during this phase and, in this case, ignition current that is greater than the steady current.

As expected, the greatest temperature was observed at TC #7, directly beneath the weld seam. At greater distances from the weld seam, whether depth or later, temperatures were reduced, eventually nearing the ambient room temperature. Thermocouples 5 and 6 recorded only 7.2 and 6.0°C temperature increases, respectively.



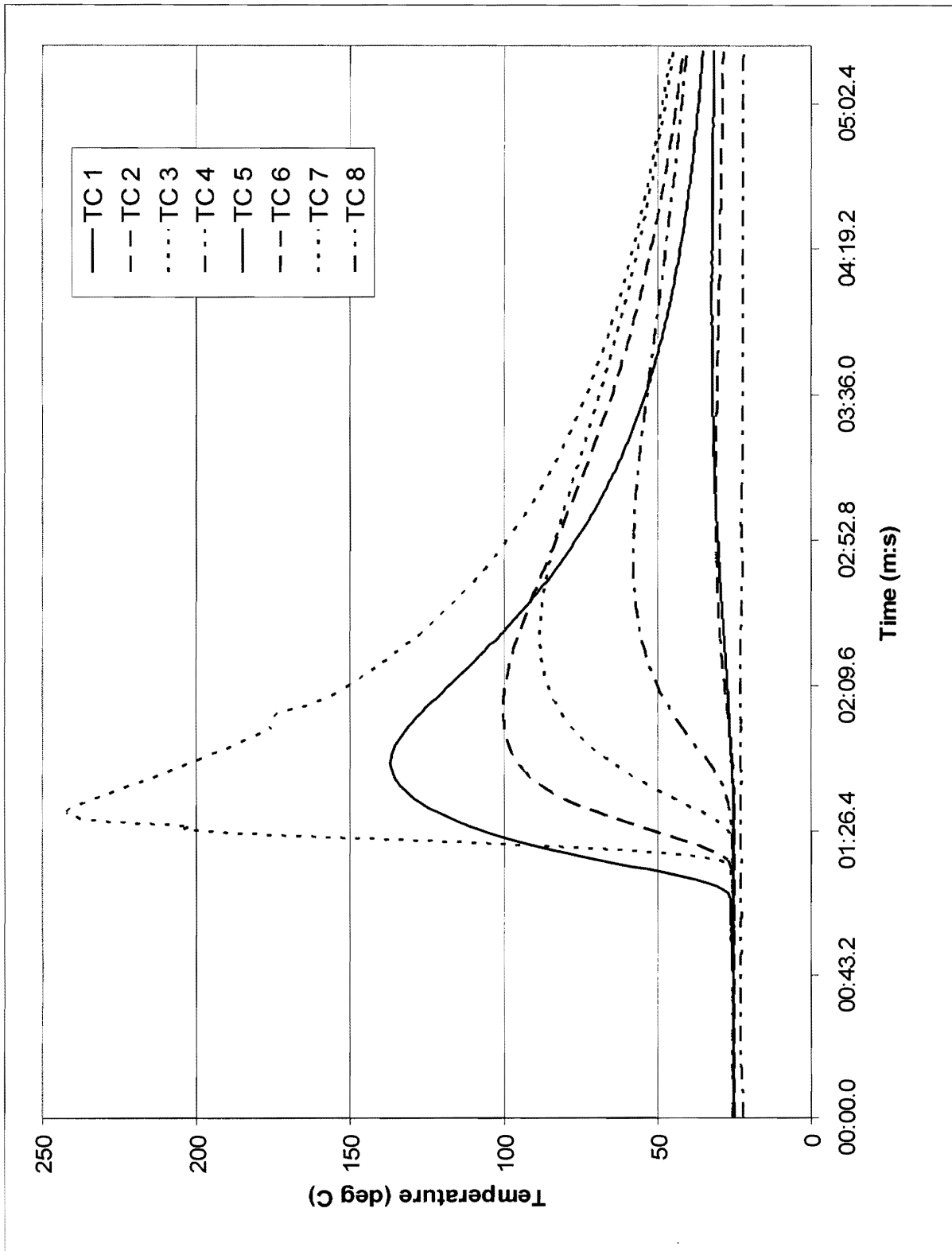


Figure 26: Temperature Measurements During a Sheet Metal Weld.



Table 6: Maximum Temperatures along the Weld Seam

Distance from end (cm)	Max temp (°C)	Thermocouple
1	137.0	1
3	100.2	2
5	88.3	3

Table 7: Distance from the Weld Seam vs. Temperature

Distance (cm)	Temp (°C)	Thermocouple
0	88.3	3
1	57.9	4
3	32.3	5

Table 8: Temperature Variation from Depth

Location	Temperature (°C)	Thermocouple
Top	241.9	7
Middle	88.3	3
Bottom	30.9	6
Ambient	23.1	8

Observations and Issues:

The SCOMPI Robot

Some issues have been observed with this robot. An attempt was made to weld along the edge of a cut piece of 0.015" thick pipe with a 2.5" diameter. With this small radius, it was found that so much side-to-side oscillation occurred that the electrode could not remain over the 0.015" wide edge. Even on straighter weld paths that require less changes in orientation, it has been observed that the maximum allowable travel speed is approximately 3 millimeters. At high speeds, the robot oscillates about the weld path such that it creates an uneven weld bead.

Welding Power

The welding power supply for this system was intended for use on much thicker materials. In TIG welding, the power supply is a current source. The maximum output current for the Thermal Arc GMS600 power supply that is used with this system is 600 A; the optimal current for the 0.030" resistance sheet-to-sheet welds is approximately 4% to 5% of this maximum. Therefore, this power supply is not capable of supplying steady, well-controlled current at such low levels.



This power supply requires a scratch start for TIG welding; it does not have capability for a high-frequency, touchless arc start. In scratch starts, it is common for the electrode to stick to the work-piece. Scratch starts are difficult for human welders to do without sticking the electrode to the workpiece; they are even more difficult for a robot. This software system includes several parameters for the scratch start process, including the arc start current, lift-up compensation (difference between specified arc length and lift-up distance), approach velocity, and lift-up velocity. Adjustments to these parameters can reduce stickage on arc start, but no set of parameters has been determined that eliminates stickage.

Welding End-Effector

This welding end-effector is designed for welding in a narrow gap, which would hold the purge gas in place more effectively than the setups required for this application. The purge gas is distributed over a wider area than a standard TIG torch, which results in an incomplete purge in this application. Therefore, it is difficult to minimize oxidation in welds performed with the NGT torch

One major issue with this welding end-effector is the method for measuring the voltage drop across the arc. One lead for this voltage measurement is connected near the tungsten tip, and the ground lead is connected to the housing of the welding end-effector. Therefore, the welding end-effector housing must be electrically connected to the work-piece. This means that the welding end-effector housing, robot housing, robot track and track mounting structure are all at approximately the same potential as the work-piece, and all are parts of the welding circuit. The robot could strike an arc with its own housing. This design was implemented in the previous ITER project, where this system was originally used, because the robot track was connected to the work-piece. Although there is continuity between the work-piece and the welding end-effector housing, there is a significant potential difference through the path between them, from the work-piece through the robot track and robot housing to the welding end-effector housing. Another problem with this measurement is that the voltage measurement wires run fairly close to the welding cable, which carries very high current. This leads to a potential for significant noise in the measurements, unless the wires are very well shielded.

Accurate measurement of the arc voltage is crucial for the real-time arc voltage control (AVC). Arc voltage control is especially important in these sheet-to-sheet welds, because it is needed to account for the changes in the shape of the work-piece that can result from weld distortion. These problems with the voltage measurements cause significant variations and large jumps in the calculated arc length, as the control system attempts to account for these by sending commands to the robot to move closer to or away from the work-piece. Therefore, with inaccurate, noisy measurements, the system is not able to sustain a steady, constant arc length.

Other Hardware Problems

Several other hardware problems were experienced during testing. Some water cooling lines ruptured and had to be replaced. Several communication cables were found to be faulty; fortunately, the previous project was a dual system, so a full set of spare parts is available. On the NGT welding end-effector, the camera and one wire feed positioning motor also do not work.



Summary and Conclusions:

The purpose of this project was to determine the feasibility of using a robotic welding system in the production of magnetic coils for QPS. Various tests were performed with the SCOMPI robotic system to investigate the potential capability of a robotic welding system to meet the critical requirements of the desired welding operations. These requirements included the ability to weld complex paths, to weld the two different combinations of material (sheet metal-to-casting and sheet metal-to-sheet metal) required in the magnetic coil production, and to produce quality welds. Additionally, a temperature investigation was conducted to observe thermal effects during welding.

The parameters found to be most important were weld speed, current, and arc-length. It was found that satisfactory welds could be obtained in welding the sheet metal-to-sheet metal configuration of the can by using the SCOMPI system. The robotic system was able to correct thermal distortion of the material by maintaining the arc length at a constant level.

Parameters for consistent quality welds on the sheet metal-to-casting weld proved difficult to establish as the higher energy applied to melt the block steel would frequently melt through the sheet metal. While some quality welds were performed, they could not be reproduced in a reliable manner. The difficulty in performing these welds showed that the welding application was being pushed beyond the equipment design capabilities.

The temperature study proved that the crush plane is a decent insulating material. The maximum temperature experienced beneath a 1/8" piece of crush plane was 140°C, and this occurred at arc ignition. The minimum temperature was 30.9°C, and this was recorded directly under the weld seam and beneath 3/8" thick crush plane. At 3 cm perpendicular from the weld seam, the temperature reached 32.3°C under 1/8" thick material. If better insulation is desired, 1/4" crush plane should be applied on all exposed sides.

Testing proved that it is possible to teach complex weld paths through the SCOMPI user interface by the teach-playback method. However, this method is very time-consuming for complex, three-dimensional weld paths. Depending on the travel speed, significant tracking errors have also been observed. A switch to offline programming is recommended. Newer systems from other manufacturers include advanced software packages for simulations and offline programming, as well as more user-friendly interfaces.

From limitations of the SCOMPI system experienced during testing, it has been determined that this system is not appropriate for the types of welds required by the QPS project. However, the results produced from this system prove that applying a robotic welding system is feasible and is in the best interest of the QPS project.



Reference Documents:

DOC-CS-001, Robotic Welding Conceptual Study for QPS

Manuals – Base System, Welding Process

Safety Documents

Technical Drawings



Appendix:

Configurations, Parameters

See attached GTAW.CFG sheets.

SCOMPI QUICK START GUIDE

Before beginning any welding operation, go through the safety checklist. Also, make sure the shielding gas valves are open and the welding power supply breaker is switched to the “on” position. Make sure all control knobs on the welding power supply are set to zero. When the welding circuit is powered, do not touch any component of the system, as some components may be electrically connected with the welding circuit.

Procedure:

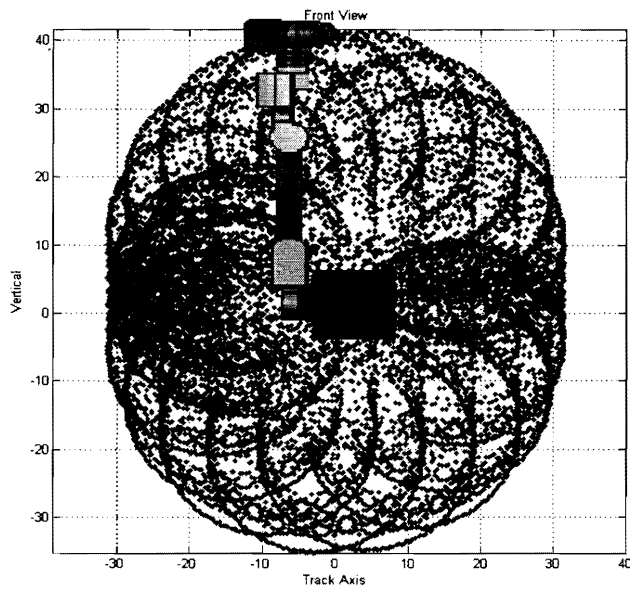
- 1) Turn on the computer, welding controller, robot controller and pendant controller in the control cabinet.
- 2) The computer will show options to boot DOS or IRMX. Select IRMX and press “enter”.
- 3) At the prompts, type the following:
login: robot
password: scompi
- 4) Type “scompi 4.43 test3/def4.42”. This will activate pendant control.
- 5) From the pendant, synchronize all six joints. This consists of aligning the notches on each side of the joint and saving that position; this is a calibration routine.
- 6) Select “Teach” and then “Workspace”. Choose to teach the points in “Tools” mode.
- 7) Check to make sure that the dimension is set to 1. Then select “Size”. Set this to the number of teach points you wish to save. This can be modified later.
- 8) Select “Create”. Move the robot to the first desired teach point on the weld path. Press the STORE button on the pendant to save the point. Store all subsequent points on the weld path.
- 9) Press the ESC button on the pendant until you return to the “Teach” menu. Select “Contour”, followed by “2 Ends”. This will limit the robot motion during a welding operation to the ends of the saved weld path.
- 10) Return to the pendant Main Menu. Select “Process-Welding-Automatic-Compute” and press ENTER.
- 11) You should see a screen with several options, two of which are “Execution” and “Primary”. Go into Primary and set the desired welding current and travel speed. The arc voltage and arc length are linearly dependent; therefore, it is only necessary to set one of them. Arc voltage is set by the “AVC” option. Press ESC to return to the welding menu.



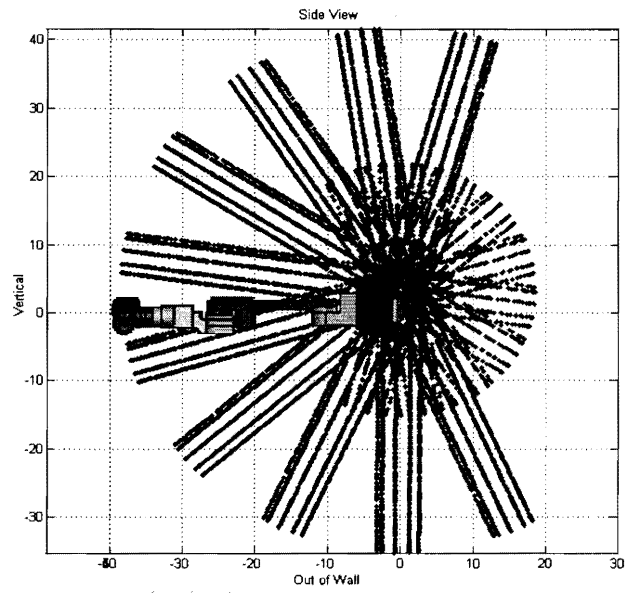
- 12) Select "Move-Hyperpoint" and choose to move to hyperpoint number 1 on the weld path. Hyperpoints are the saved teach points.
- 13) Select "Execution-Verify". The system should go through the welding process, without power to the welding circuit. Check to make sure the robot is following the weld path as desired.
- 14) Return to the welding menu and move the robot back to hyperpoint number 1. (Repeat step 12.)
- 15) Check to make sure that the work-piece and all system components are ready for welding.
- 16) IMPORTANT: Turn on the water cooler.
- 17) From the main welding menu, select "Execution-Weld". This should start the welding process.
- 18) When the welding process is complete, wait until the pendant returns to the menu before turning anything off; otherwise, it will stop the post-purge of shielding gas.
- 19) Turn off all welding circuit power before touching any component of the welding system.



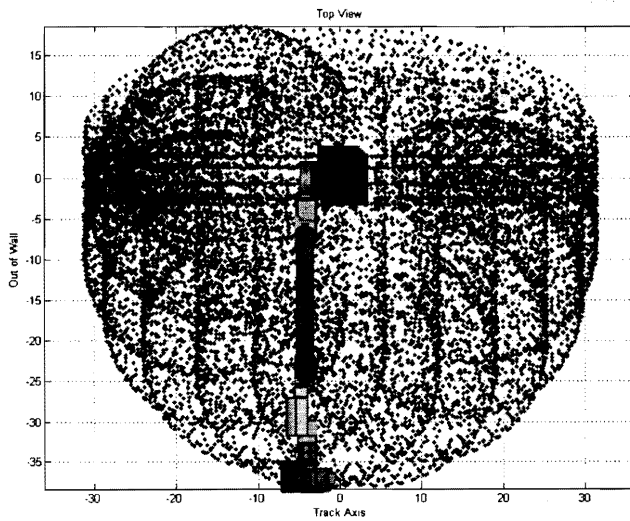
Range of Motion



Front View



Side View



Top View

All dimensions are in inches.

