REPORT

April 28, 2006
EWI Project No. 47961GTH
DoT Transaction Agreement No. DTRS56-05-T-0001

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines

Task 5 Report
Real-Time Quality Monitoring for the Detection of Weld Defect

Submitted to:

U.S. Department of Transportation
Research and Special Programs Administration
Washington, D.C.

EWI®

MATERIALS JOINING TECHNOLOGY

Task 5 Report

Project No. 47961GTH
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on

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines
Task 5 – Real-Time Quality Monitoring for the Detection of Weld Defect

to

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Research and Special Programs Administration
Washington, D.C.

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Executive Summary

Advanced automation techniques were used to improve weld quality, process control, seam tracking, and robustness. To this end, and to increase robustness of the resultant weld quality, real-time quality monitoring (RTQM) is of particular interest and the objective of this task was to advance the state of the art toward a reliable system.

A literature review was conducted to establish and highlight the state of the art for RTQM. The results are described below.

The search for a reliable and consistently repeatable method for RTQM has been a longstanding goal, heightened by the advent of practical robotics in the 1980s and pursued since that time. It continues to be elusive in terms of the ability to correlate detection of actual welding defects in real time with the results of nondestructive evaluation (NDE). Certainly there are plenty of data acquisition systems on the market for process fault and alarm indications based on wire feed speed, arc voltage, and welding current sensors. However, it has been consistently shown that these systems, while they have merit, fall far short of the ability to reliably detect real welding defects, to the extent that it is not uncommon for them to be in place, but idle, in a manufacturing environment.

Work in this task advanced the state of the art in terms of achieving constant welding power input at constant contact tip-to-workpiece distance (CTWD), thus achieving constant welding heat input at constant welding travel speed. This was coupled with high speed on-board DAQ to achieve RTQM, in these terms.

Based on a review of RTQM and work to develop and implement software and hardware in Tasks 3 and 4 of this project to be used in RTQM functions in Task 5, the following conclusions can be stated regarding RTQM:

1. The literature review indicated several novel approaches to produce building blocks to full RTQM.

2. Based on practical approaches to control of welding current, arc voltage and CTWD, constant welding power was achieved.

3. On-board high-speed DAQ provides the capability to monitor welding parameters in real time, including:

- Welding current
- Arc voltage
- CTWD
- Shielding gas flow rate.

4. The system is ready to be evaluated for correlation between indicated defects and actual defects using RT for initial evaluation, and intentional disturbances to welding operation to capture RTQM response and recording of said disturbances. Both this and real-time corrective action remain as subjects for future work.

Acknowledgements

This report was prepared by Edison Welding Institute, as an account of work on Project No. 47961GTH, under Contract to the U.S. Department of Transportation. Funding for this work was provided by the U.S. Department of Transportation.

Legal Notice

1.0 Introduction

Increasing demand for gas will require major investment in new long-distance gas transmission pipelines with significant expansion of existing infrastructure using shorter sections of small- and medium-diameter pipelines to extend and loop existing lines and increase capacity. Tie-in welds can also be very frequent due to ditch, river, road, and rail crossings as well as other topographical features and these are often the weak link in a system. Tie-in welding may represent 50% of the welding costs of some pipelines. Small- to medium-diameter and tie-in welds are typically performed using cellulosic welding techniques which are generally not suitable for pipelines over Grade X70 or corrosion-resistant alloys. A prerequisite for these applications is single-sided welding since internal welding machines and alignment tools are not practical. These will need to be constructed as economically as possible, but the trends toward higher operating pressures and higher strength steels require improved pipeline integrity through overmatching weld metals and better quality processes.

A major challenge in high-strength pipeline construction is producing small- to medium-diameter girth welds that have high quality and integrity. Manual shielded metal arc welding (SMAW) is currently used on these pipeline applications where the resulting weld deposit has marginal properties, high hydrogen content, and high defect propensity. This process is not suitable for higher strength materials used in high integrity applications. This project will develop innovative gas metal arc welding (GMAW) and hybrid laser-GMAW processes and technologies for single-sided pipeline girth welding of small- to medium-diameter pipe. A key requirement is the welding from a single side with no internal backing tools or internal welding machine.

Only advanced processes coupled with automation techniques have the potential to improve the robustness, quality, productivity, and integrity of single-sided pipeline root passes, and assure resistance to flaws through the use of in process monitoring and adaptive control techniques. These processes include rotating electrode GMAW, pulse short-circuit GMAW, pulse short circuit GMAW with wire feed modulation, variable polarity GMAW using fuzzy logic short circuit transfer, and hybrid laser-GMAW. These processes have been targeted toward root pass welding on narrow groove joint preparations with or without gas backing.

The project is broken down into the following tasks:

1. Task 1 – Development of Innovative Root Pass Welding Processes
2. Task 2 – Property Testing of Preferred Root Pass Welding Techniques
3. Task 3 – Improved Root Pass Techniques
4. Task 4 – Process Control Systems for Pipeline Girth Welding

5. Task 5 – Real-Time Quality Monitoring for the Detection of Welding Defects
6. Task 6 – Preferred Process/Technique Demonstration
7. Task 7 – Productivity/Economic Analysis
8. Task 8 – Final Report.

This report concerns Task 5, “Real-Time Quality Monitoring for the Detection of Welding Defects”.

2.0 Background

Pipelines will be an integral part of our energy distribution systems for the foreseeable future. It is predicted that natural gas consumption will double over the next 20 years. Operators are currently considering the installation of many tens of billions of dollars of pipeline infrastructure. In a number of cases, the cost of exporting the product will have a dominating influence on the viability of the upstream production facilities. These facilities will progress only if the industry can substantially reduce capital expenditure and improve design for pipeline integrity. Whether the application is an onshore gas transmission line or a deepwater pipeline, there is a need to constantly improve the productivity, quality, integrity, and reliability of pipeline girth welds to reduce construction costs. There is also a need for improved technologies suitable for the higher strength steels currently being developed. Furthermore, advanced welding technologies are currently only deployed on large-diameter pipelines where the costs of internal backing clamps or internal root welding machines can be justified. The vast majority of small- to medium-diameter pipelines (24 in. and less) are welded manually, which may be more cost-effective at present, but do not always provide the highest integrity pipeline and raise specific metallurgical concerns on pipelines exceeding the strength levels of grade X70.

High-strength pipeline materials (over X70) offer cost savings, but are more sensitive to process variation to assure properties. The ideal welding process produces welds with good bead shape and fusion, matching or over-matching material properties, and is cost effective. There should be no cracks or flaws in the weld deposit. Cracking susceptibility increases as the hydrogen content, stress, and hardness of the microstructure increase. For high-strength pipelines, manual welding processes cannot meet the required combination of properties, diffusible hydrogen, and weld integrity to assure cracking resistance. Low-hydrogen automated welding processes are preferred to control microstructure to optimize strength and toughness on X70 and above. The overall productivity of a pipeline construction spread is usually controlled by the cycle time of the root pass welding operations. Internal welding machines have historically assured good root pass quality on high-strength pipelines. While welding speed is important, the costs of equipment and the time to align and setup the weld preparation are also important. On large-diameter tie-ins and small- to medium-diameter pipelines, root side access is generally not provided due to cost constraints and equipment limitations. There is a technology gap to deploy high-strength materials on single-sided pipeline welding applications.

Data acquisitions systems now have the potential for real-time quality monitoring (RTQM) to detect arc variations indicative of defect formation during welding and to take adaptive action. While the monitoring of transient voltage and current waveforms and calculation of instantaneous power and resistance are now routine the analysis of the waveforms and identification of patterns linked to defect formation are still at an early stage. This task sought to identify the patterns indicating defect formation in conventional GMAW, as well as the most promising of the processes developed in Tasks 2 and 3.

3.0 Objectives

The overall project objectives were to develop innovative welding processes and technologies for single-sided pipeline girth welding. Root pass welding techniques were emphasized since they have the greatest potential to improve pipeline integrity and facilitate the use of new and existing GMAW fill pass techniques.

Advanced automation techniques were used to improve weld quality, process control, seam tracking, and robustness. To this end, and to increase robustness of the resultant weld quality, RTQM is of particular interest and the objective of this task was to advance the state of the art toward a reliable system.

4.0 Literature Review

A literature review was conducted to establish and highlight the state of the art for RTQM. The results are described below.

The search for a reliable and consistently repeatable method for RTQM has been a longstanding goal, heightened by the advent of practical robotics in the 1980s and pursued since that time. It continues to be elusive in terms of the ability to correlate detection of actual welding defects in real time with the results of NDE. Certainly, there are plenty of data-acquisition systems on the market for process fault and alarm indications based on wire feed speed, arc voltage, and welding current sensors. However, it has been consistently shown that these systems, while they have merit, fall far short of the ability to reliably detect real welding defects, to the extent that it is not uncommon for them to be in place, but idle, in a manufacturing environment.

The closest achievement to RTQM has been using real-time radiography, but this is a very expensive technique to apply, especially in the context of field use. A site test comparison of real-time radiography with conventional film radiography for the fitness-for-purpose assessment of butt welds in offshore pipelines has been reported(1) and showed good correlation between the results of film radiography and real-time radiography. In 1984 a real-time radiography system was tested on a lay barge in the North Sea. Inspection time was cut from 4.5 to 1.5 min and inspection cost was reduced by 20% compared to film radiography.

While these are steps in the right direction, it is well recognized in the welding engineering community that defects can readily go undetected using this method, and that false-positive indications from DAQ are not matched to NDE results which indicate an acceptable area of the weld.

What is required is to show that NDE results indicating welding defects can be correlated to excursions from the recognized DAQ profile captured during the weld. Without good correlation, RTQM is really still in the realm of a DAQ data record, rather than a reliable method to detect real defects.

The development of an adaptive feedback control system for automatic welding(2) was described in relation to the operation of the M-1000 welding head from CRC-Evans and included a brief description of RTQM. However, this is really a real-time data logging system, and is not used to control the welding operation in real time for true RTQM. Such data logging capability is also provided by competing products in the commercial marketplace, such as Serimer-Dasa.

A computerized system(3) designed for automation of a GMA pipe welding system named Rotoweld 2000 was developed for twin-wire GMAW for open root pipe butt welds for 1G welding in a pipe fabrication shop. The system is shown schematically in Figure 1 and a function control diagram for root penetration control is shown in Figure 2. Ultimately, a process operating tolerance was developed for root face (1 through 4 mm) and root opening (2 through 6 mm) requirements which show an interesting contrast to the remit in this project to weld with a closed root. The productivity of the mechanized GMAW process was triple that of standard manual SMAW.

The fairly recent deployment of phased-array ultrasonic testing (PA-UT) in the industrial market, as opposed to the medical field, has opened up new possibilities for real-time NDE. However, to date it has only been applied after the weld has been completed, rather than in-process, during welding.

Almost all true real-time quality monitoring for arc welding has been tested only on artificial "defects" in the research field, rather than on real welding defects. The use of welding current, arc voltage, and wire feed speed signature recognition and pattern matching algorithms has been used, and is being field deployed.

A Japanese paper (no translation available) described the development of an in-process quality assurance welding system.[(4)] Examination of figures and tables with captions in English showed this to be related to GTAW and semi-automatic GMAW for Type 304 stainless steel, and of insufficient relevance to RTQM for control of mechanized GMAW pipe welding.

Research and development for adaptable modular computer-based equipment for orbital welding applications[(5)] was carried out for a range of carbon steels, stainless steels, and duplex stainless steels. This paper is considered of insufficient relevance to RTQM for control of mechanized GMAW pipe welding as the topic for line pipe welds involved a plasma arc welding (PAW) root with GMAW fill, and concentrated on optimization of the plasma nozzle design.

Multi-torch control of welding during production[(6)] was approached using three dynamic welding models; a lumped analytical formulation of the weld bead geometry, a numerical simulation of the distributed thermal and phase field, and an experimental linearized model with non-stationary parameters. To account for nonlinearity and thermal drift effects, the welding parameters were identified in-process by the multivariable adaptive controller through surface temperature measurements with an infrared pyrometer. The models were tested for linear seam welding of pipe with GTAW, rotated pipe welds with GTAW, and twin-wire GMAW. In the analysis, the productivity and quality of the welding process is described by a small number of "lumped" weld characteristics such as bead geometry (width, depth, and height). These are directly sensed or estimated through localized thermal measurements on the weld surface, and regulated by distinct heat input from multiple torches. Closed-loop control of the thermal field requires temperature sensing on the entire accessible weld surface, as well as real-time modulation of a continuous heat distribution on it.

The relative advantages and disadvantages of techniques involved in fully controlled and automated pipeline welding systems are described in general terms for onshore and offshore pipeline fabrication in an article from Vermaat technologies in The Netherlands.[(7)] The article is based on twin-tandem GMAW with four torches in a double-down 5G application for cross-country pipeline construction. The system allows both root and hot passes to be deposited simultaneously. Real-time monitoring and data logging create the opportunity for QA/QC systems and enable on the spot comparisons with mechanized ultrasonic NDE results.

A method and apparatus for monitoring arc weld quality[8] is claimed in a Caterpillar patent published in 2001. The sensors and controls used have the net affect of alerting an operator to excessive CTWD and excessive melt-through, primarily through an alarm, or the process is shut down automatically. Sensors used are for welding current, arc voltage, wire feed speed, and shielding gas flow rate. Sensing for porosity is claimed, but is inferred through a low shielding gas flow rate, not by direct detection of porosity.

Filter design for monitoring defect formation in welding processes[9] was applied to mash seam welding to develop a correlation between welds with lack-of-fusion (LOF) defects and ones without. Welding defects such as LOF are not easily detected by simple monitoring of welding current and arc voltage. The authors used a filter design approach, common in the signal processing field, to develop algorithms aimed at detection of LOF. By using linear transfer functions with the voltage as input and the current as output, the linear transfer function was estimated as the ratio of two polynomials. Fairly good correlation was found with the actual welding current (Figure 3). Using the inverse of resistance (1/R), termed Rmodel, values above 0.136 mΩ corresponded with welds with no LOF (Figure 4). Such a technique could be applied on-line for RTQM. Transfer functions would have to be developed for arc welding which would be a more complex case than a resistance mash seam weld.

Work on the development of signature images for welding fault detection has been reported.[10] Signature image processing is a technique for handling time series data from welding processes in real time for quality control and fault detection. Much work has been conducted developing a range of sensors for welding and vision systems have also been investigated extensively. Through the arc sensing or measurement of the electrical signals for welding current and arc voltage offer several advantages including robustness, simplicity, and non-intrusive sensing. In essence, the idea of signature image processing is straightforward, comparing welding current and arc voltage signatures of welds known to meet the required acceptance standards with the signature for a weld in progress. This can be represented graphically, as shown in Figures 5 and 6. High-speed DAQ is used to capture the current and voltage waveforms. In the paper, the detection of a 2-mm displacement of the welding wire is demonstrated, but it is conceded that evaluation at finer distances is difficult. Much more accurate wire placement is required for GMAW in general, but particularly for narrow-gap pipeline welding. The author’s expectation is that the welds will be assessed simply by comparing signature images as first stated.

More recent work by the same authors[11] on industrial application of welding signatures for real-time quality assurance and process improvement has been used to show weld fault detection capability for four defect types: joint, step, gas flow, and oil contamination. The context was sheet metal welds for automotive and light manufacturing. The main premise is a database of current and voltage waveforms for welds of good integrity. The attributes and the inferred quality of an individual weld are determined by comparing the current and voltage for a particular weld to the database and "measuring" quality by the departure from the average current and voltage trace (Figure 7). While this worked in a laboratory environment, the paper indicated that this has yet to be deployed in an industrial environment.

Most GMAW pipe welding systems require manual intervention to correct slight variations in joint geometry as the bug traverses the weld seam. More recent systems can be equipped with seam tracking using through arc sensors or laser seam tracking devices. It is also necessary to maintain a constant torch height, or more precisely, CTWD. In recent research,[(12)] a robust and reliable torch height control has been developed. This system uses active through-arc control of stick-out in mechanized girth welding. The system is based on monitoring welding voltage and current during the root run. In dip transfer, the wire extension during the short circuit is proportional to the CTWD.

The average resistance of a series of short circuits is therefore calculated on line by the monitoring computer (Figure 8). Shortly after initiation of the arc, the process stabilizes and the calculated resistance may be assumed to represent the CTWD at the predetermined value. The resistance is continuously monitored and if it deviates from the preset level (Figure 9) the torch height is adjusted. This approach has proved very acceptable for controlled short circuiting transfer (Figure 10). However, since fill passes may be made with a lateral weave using pulsed GMAW (GMAW-P) or flux-cored arc welding (FCAW), it is unlikely to be an effective approach for fill runs. To circumvent this problem, the concentricity of the ring gear with respect to the pipe is recorded during the root run and used as a preset correction factor for the remaining runs (Figure 11).

It is believed by the author[(12)] that this approach can be extended to pulsed transfer and initial feasibility trials have been conducted with encouraging results. However, this applies to single wire GMAW-P, and it would be quite a different matter to apply it to dual tandem GMAW-P (four wires) for high-speed fill passes.

A fully integrated, real-time adaptive control system (patent pending) for hybrid-laser welding has been developed for shipyard welding[(13)] (Figure 12) and could be deployed for other applications such as pipe welding. This system is based on a 25-kW CO_2 laser working with GMAW for fabrication of I-beams. The laser seam tracking capability is also used for weld contour inspection after the welding operation (Figure 13), but the system does not provide true RTQM while welding progresses. The authors describe work at Applied Research Laboratory

(ARL) to develop and evaluate infrared (IR) and ultraviolet (UV) sensors for measurement of volumetric integrity. By evaluating the ratio of the averages of IR and UV spectral signatures, the authors claim ARL has been able to measure weld integrity. The intent would be to integrate such capability into the existing contour measurement to provide both contour and volumetric assessment.

5.0 Results of Experimental Work

5.1 Automatic Torch Height Control (ATHC) Functionality

ATHC uses the data-acquisition current sensor which was attached to the welding circuit. The operator manually sets the torch height on the welding bug and begins welding. When the torch height is at the desired position the operator then sets the ATHC. This engages the ATHC and maintains the arc voltage level to the set point by adjusting the torch height to maintain a constant CTWD. The ATHC can be turned off at any time and the operator can manually jog the torch height at any time. The STX Control software is responsible for making the automatic torch height adjustments during welding with the ATHC.

5.2 ATHC Hardware

The data acquisition system inside the industrial control cabinet has a 10:1 voltage sensor for measuring welding current in the welding circuit. This sensor was attached between the Spin Arc welding torch and the workpiece. The sensor continually gathers current data during welding. The STX bug's torch height axis is automatically adjusted by the STX Control software when the ACC is engaged.

5.3 PXI Industrial Computer System with Data Acquisition

Originally, the STX bug system was controlled by RS-232 ASCII commands through a serial port on a laptop computer. Because the STX bug was being used by a welder, the software program user interface was designed to look like a typical welding robot pendent. A data-acquisition card was used with the laptop computer to sense I/O signals also provided by the STX control box. The available signals included wire jog, through the arc seam tracking signals, inclinometer information, and general I/O. The general I/O was defined and used to connect to the welding power supply so that arc initiation and STX travel start began simultaneously.

As a result of the cost-matched EWI 48248GTO project, a PXI industrial computer system with data acquisition capabilities was available for use in this project (Figure 14). The PXI computer replaced the laptop used earlier. The PXI computer from National Instruments included data acquisition boards that were used to connect and control all signals from and to the Spin Arc torch. The 48248GTO project also resulted in a software program, Intellicontrol, which can be used for data acquisition during the welding process (Figure 15). The data acquisition included monitoring and saving data from the welding current, arc voltage, wire feed speed, and shielding gas flow rate (Figure16).

To develop adaptive welding techniques, data from the welding process must be gathered, studied, and tested. This data helps determine what relationships during the welding process cause which effects on the output or resultant weld. The first step to adaptive welding in this task began with the development of the data-acquisition system.

The DAQ program calculated the following statistics on a weld run (5 seconds of data) made using the parameters employed in the Task 6 welding demonstration and also reported in Task 1:

- Iavg = 196.6 A
- Vavg = 20.8 V
- Irms = 252 A
- Vrms = 22.5 V.

- Pulse Freq = 198 Hz
- Ipk = 413 A
- Iback = 45 A
- Tpk = 1.87 ms
- Tback = 3.17 ms.

Average values were in close agreement with the ADM data logger that was used for all welding parameter data reported in Task 1. These are also the settings used for the high/low pipe mismatch tests in Task 1.

RMS value for welding current (250 A) and arc voltage (22.5 V) were very similar to those reported by the on-board high-speed DAQ integrated with the welding tractor and the control system. Example welding current and arc voltage waveforms are shown in Figures 17 and 18 and Figures 19 and 20, respectively. These waveforms illustrate the Dip Pulse operating mode used in conjunction with the Spin Arc welding torch.

6.0 Discussion

Constant welding current and arc voltage were maintained by using the current feedback controlled ATHC. This system compensates for pipe ovality and/or variation in CTWD caused by any height variation introduced by the welding track height around the pipe. Using current control to maintain the CTWD controls both the welding current and arc voltage to maintain constant welding power at a constant welding speed. Using the welding tractor and bug with the CTWD control achieved the desired result of constant welding power and was verified using the on-board high-speed DAQ.

Welds made using the system described exhibited even penetration depth and width and were also tolerant to pipe mismatch of ±1.5 mm as required by industry expectations. Using the Dip Pulse mode of metal transfer control produced welds with smooth surface profiles on the top face of the root beads in the flat position and out of position.

Although direct correlation of weld quality indications to subsequent RT results were not made, the systems is capable of recording data in real time and could be alarmed or configured for process shut down if parameters strayed beyond expected levels outside of a reasonable tolerance band of, for example, ±10% on RMS welding current, and ±5% on RMS arc voltage. The onboard sensors include a shielding gas flow sensor that could be set up to alarm or shutdown welding operations outside of reasonable gas flow rates, thus avoiding porosity resulting from loss of gas shielding.

7.0 Conclusions

Based on a review of RTQM and work to develop and implement software and hardware in Tasks 3 and 4 of this project to be used in RTQM functions, the following conclusions can be stated regarding RTQM:

1. The literature review indicated several novel approaches to produce building blocks to full RTQM.

2. Based on practical approaches to control of welding current, arc voltage and CTWD, constant welding power was achieved.

3. On-board high-speed DAQ provides the capability to monitor welding parameters in real time, including:

    - Welding current
    - Arc voltage
    - CTWD
    - Shielding gas flow rate

4. The system is ready to be evaluated for correlation between indicated defects and actual defects using RT for initial evaluation, and intentional disturbances to welding operation to capture RTQM response and recording of said disturbances. Both this and real time corrective action remain as subjects for future work.

8.0 References

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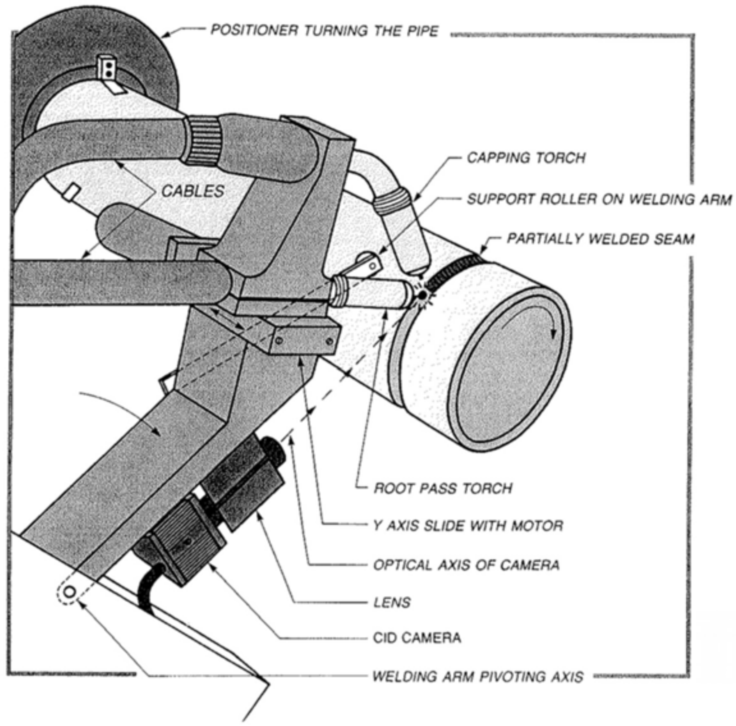

Figure 1. Schematic of Rotoweld 2000 Computerized System Designed for Automation of a GMA Pipe Welding System Developed for Twin-Wire GMAW for Open Root Pipe Butt Welds for 1G Welding

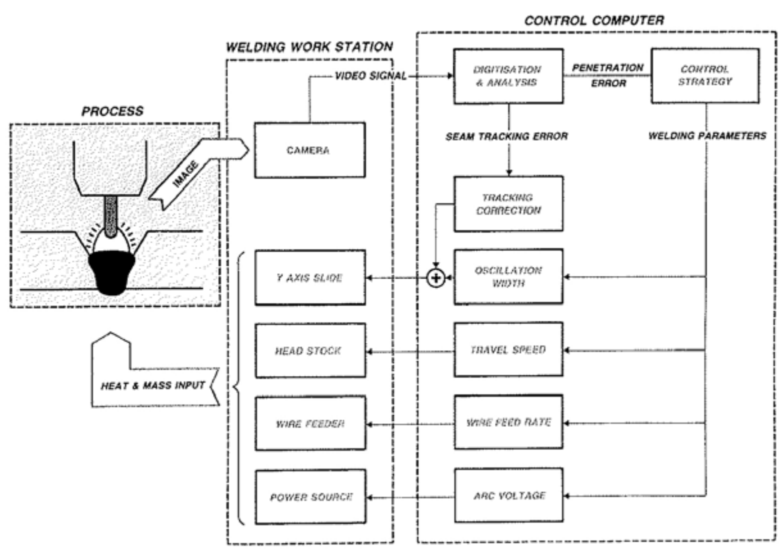

Figure 2. Function Control Diagram for Root Penetration Control

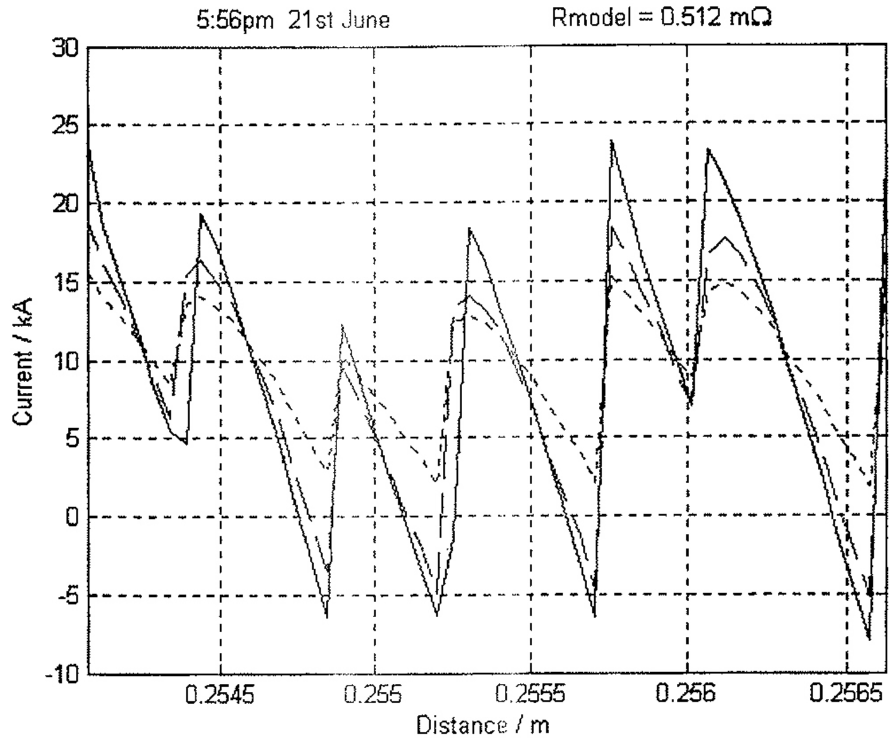

Figure 3. **Correlation Using Linear Transfer Functions**

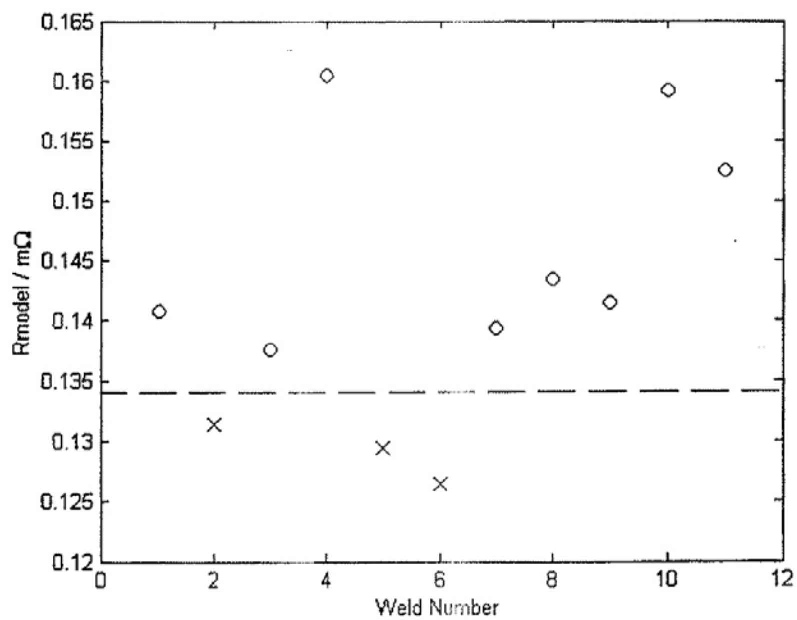

Figure 4. **Correlation of Rmodel**

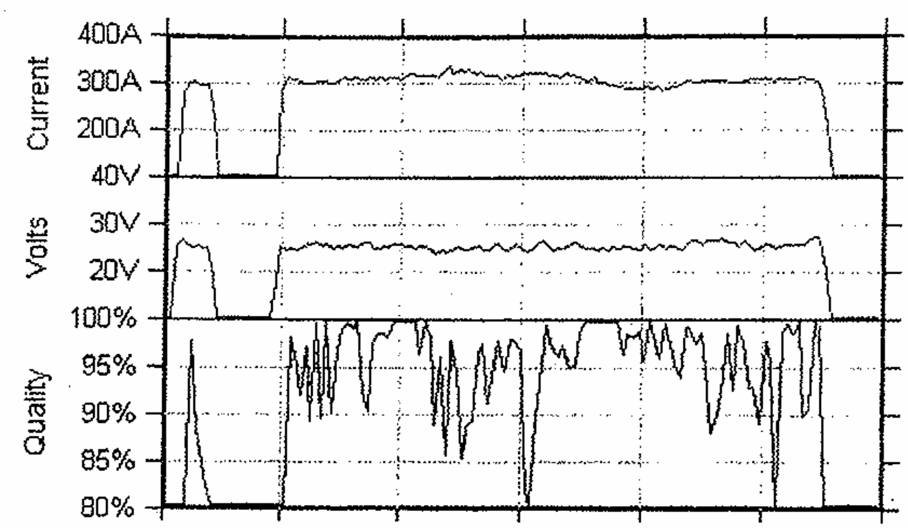

Figure 5. Current, Voltage, and Quality Traces for Two Robotic GMA Welds Immediately Before a Routine Contact Tip Change

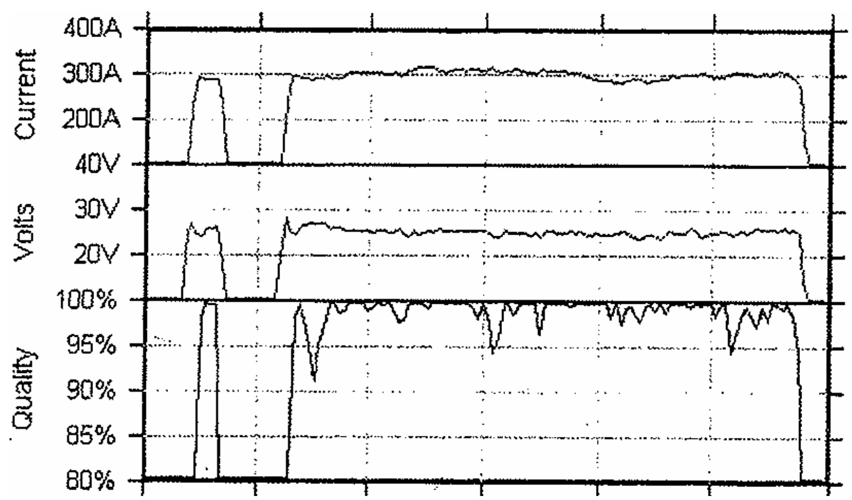

Figure 6. Current, Voltage, and Quality Traces for Two Robotic GMA Welds Immediately After a Routine Contact Tip Change

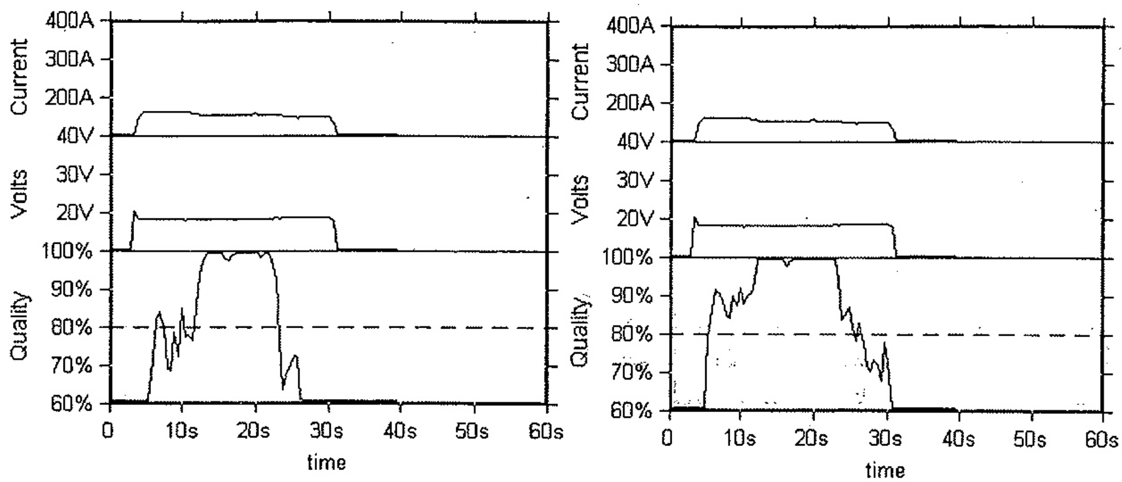

Figure 7. Illustration of "Quality" Attributes of Current and Voltage Signals

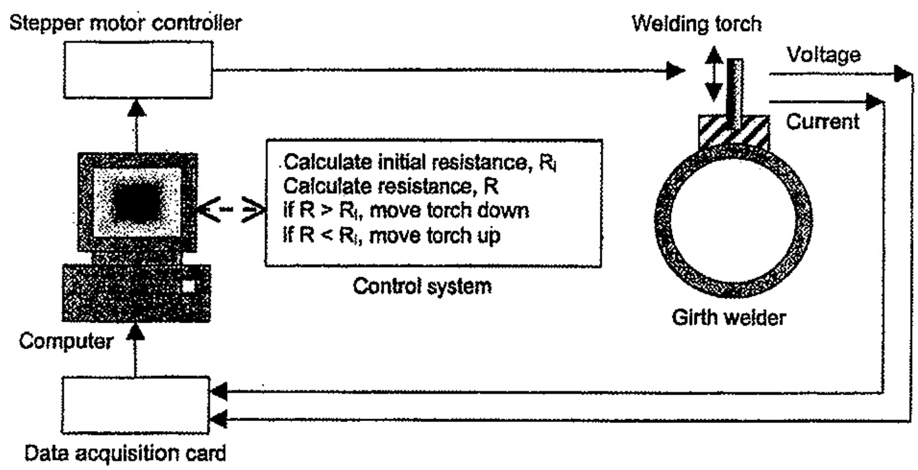

Figure 8. Data Monitoring and Control Circuit

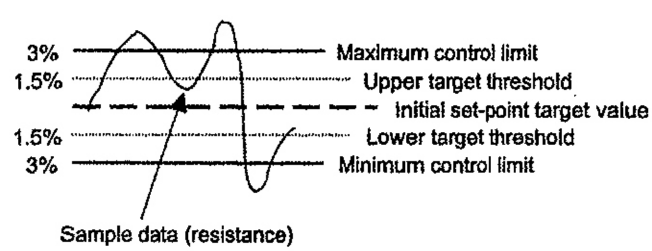

Figure 9. Illustration of Resistance Control Limits

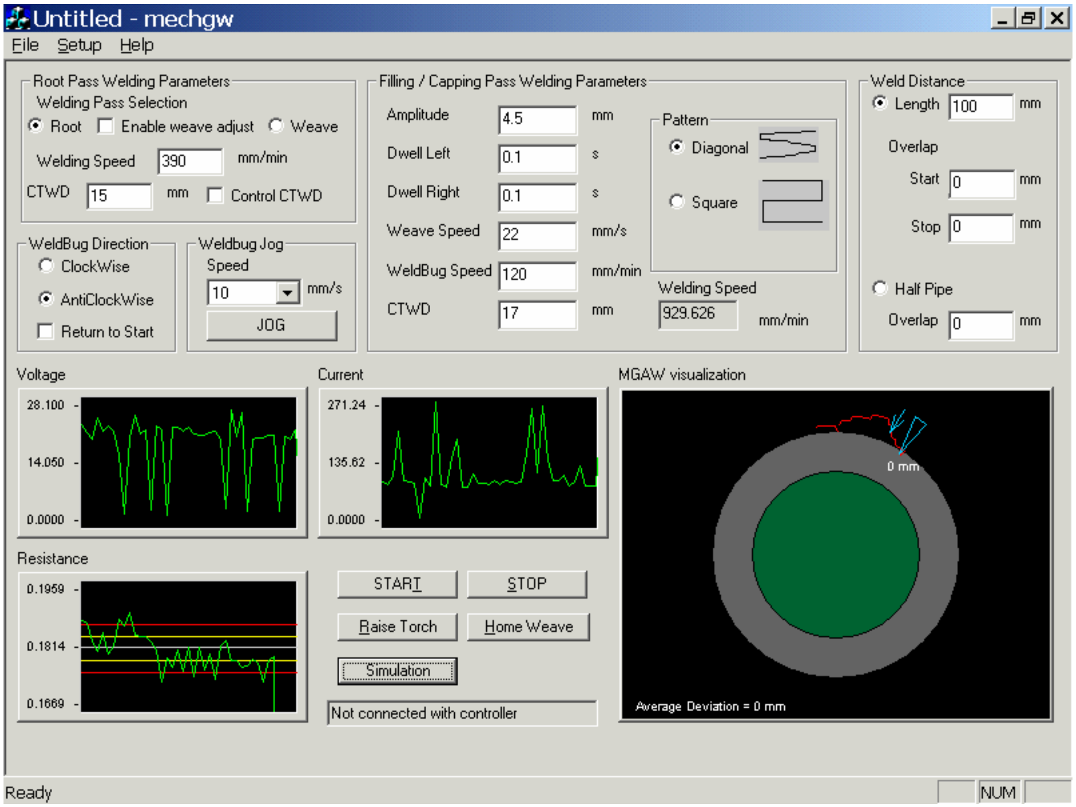

Figure 10. Graphical User Interface for Resistance Based CTWD Control and RTQM System for Pipe Girth Welding(12)

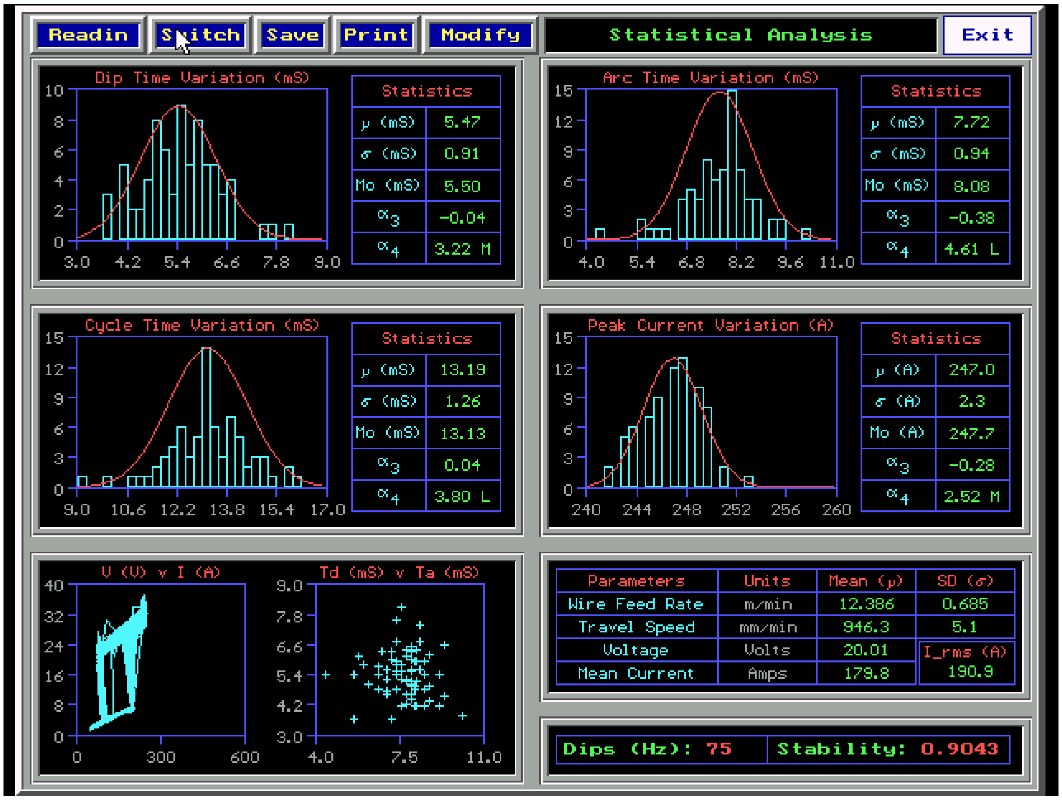

Figure 11. DAQ for Dip Transfer Root Pass in Pipe[12]

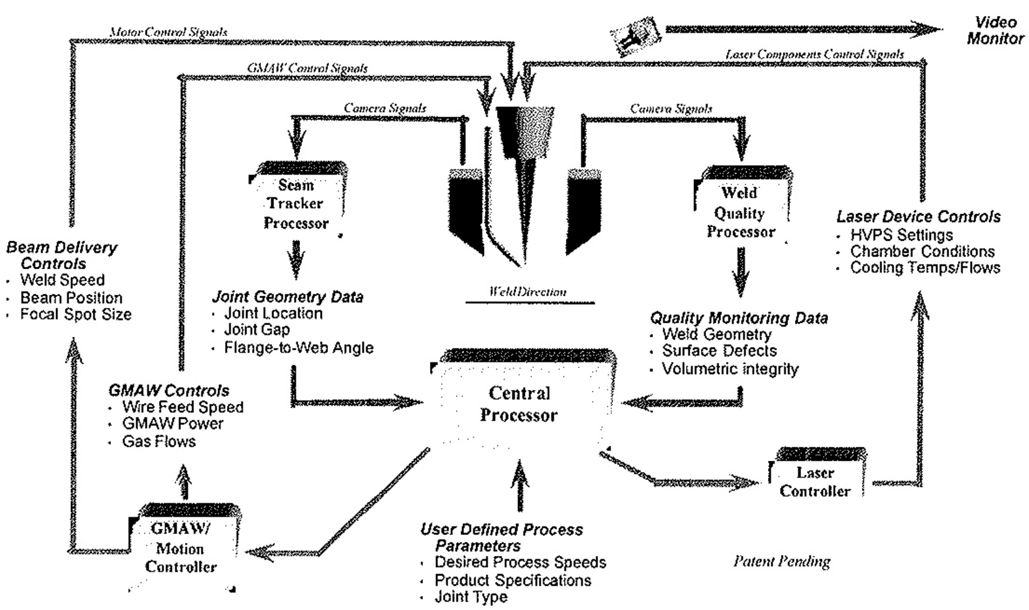

Figure 12. Adaptive Control for Hybrid Laser/GMAW

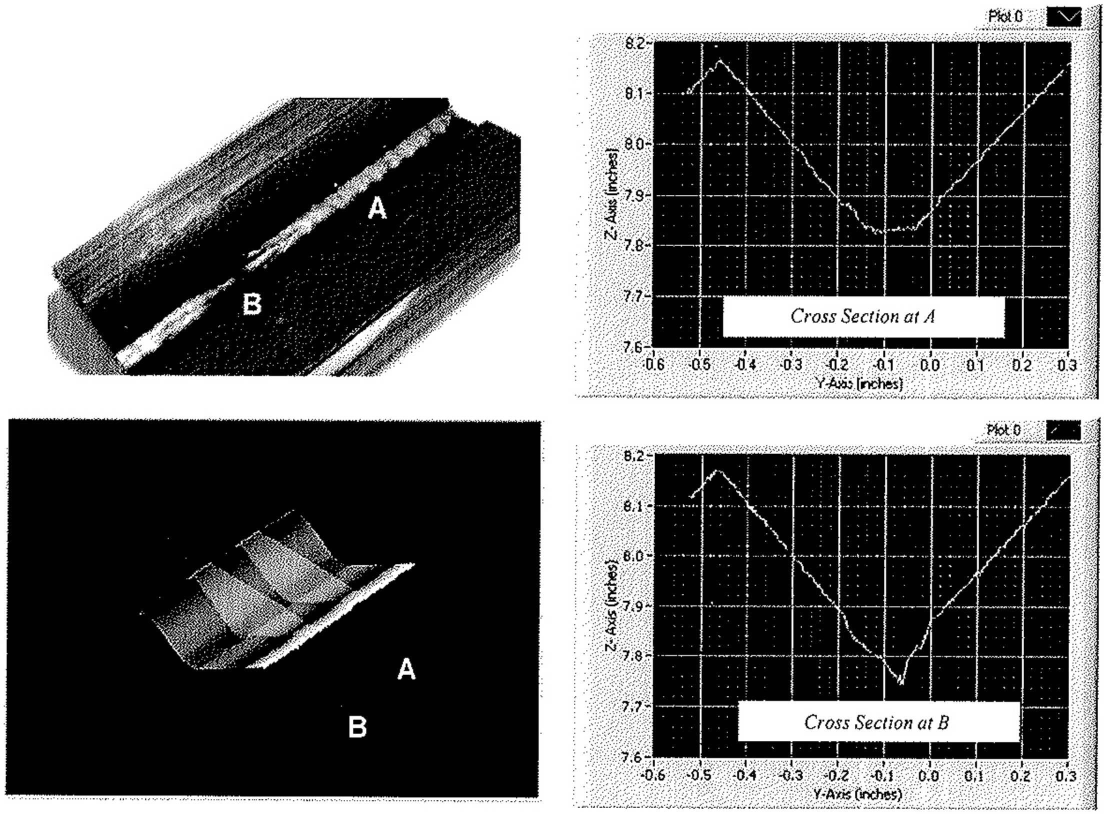

Figure 13. Illustration of Laser Seam Tracking Output

Figure 14. Operator at the Industrial Control Cabinet Housing the Integrated Hardware and Software for Process Control and DAQ

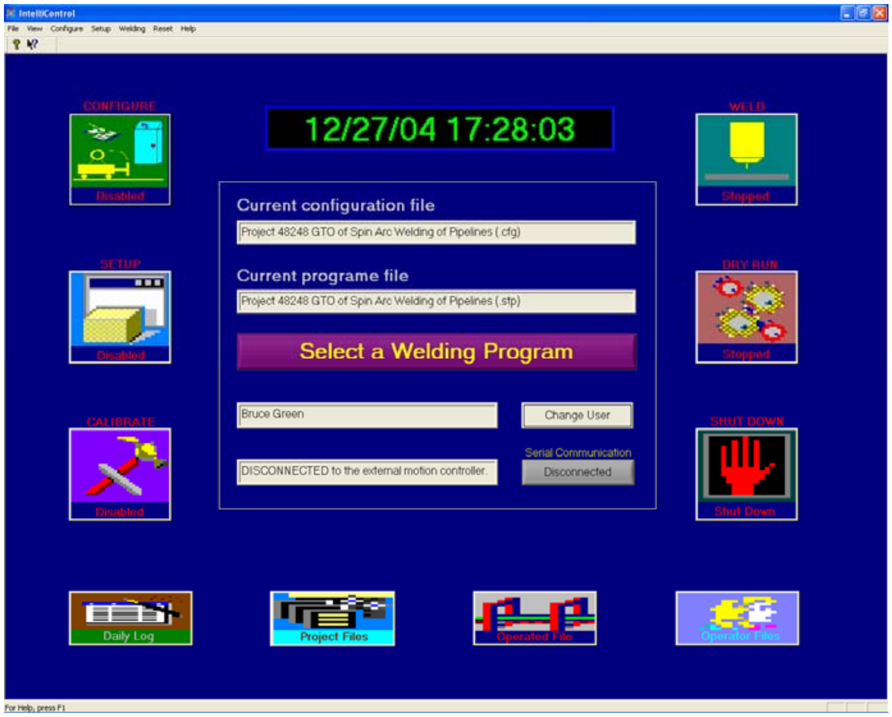

Figure 15. Intellicontrol Software Main Panel

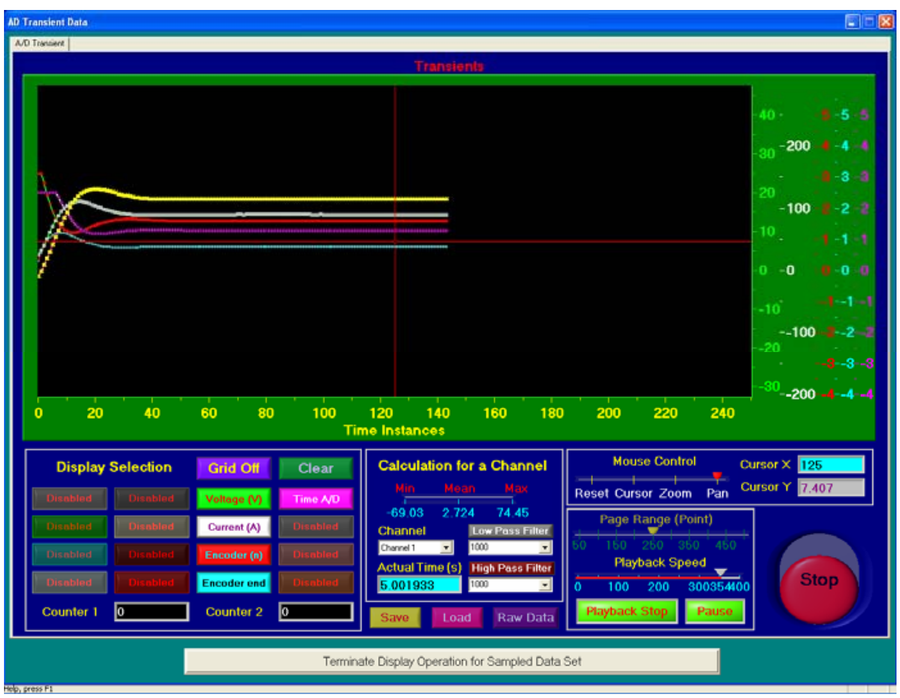

Figure 16. Intellicontrol Software Interface Module During Data Acquisition of Welding Parameters and Spin Arc Control

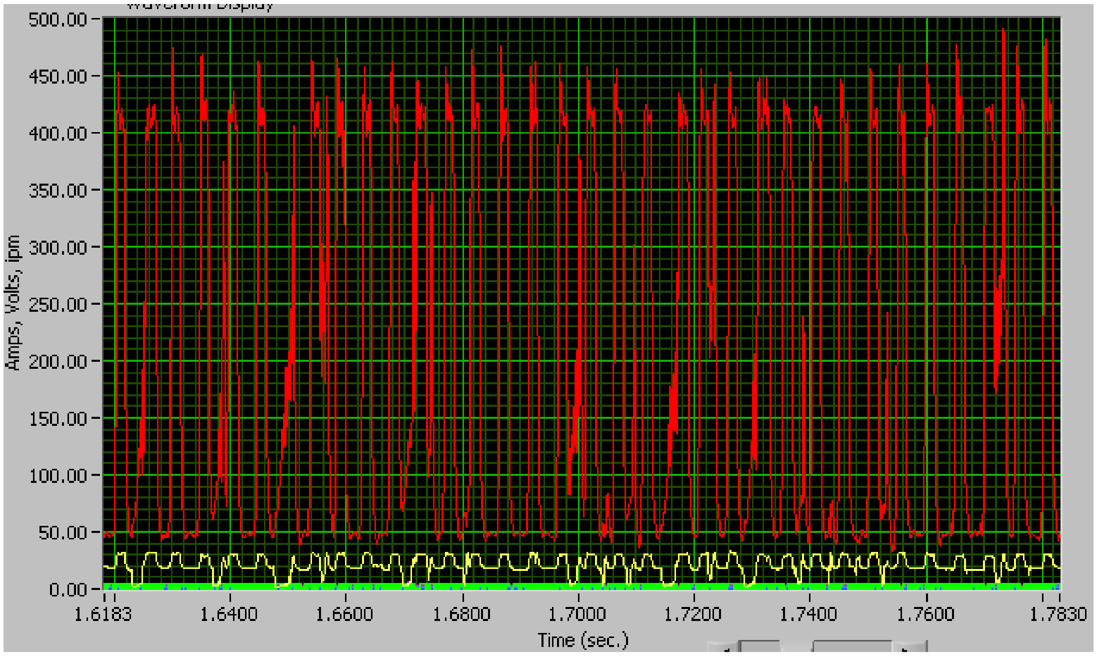

Figure 17. **Welding Current Waveform for Dip Pulse Mode of Spin Arc Operation**

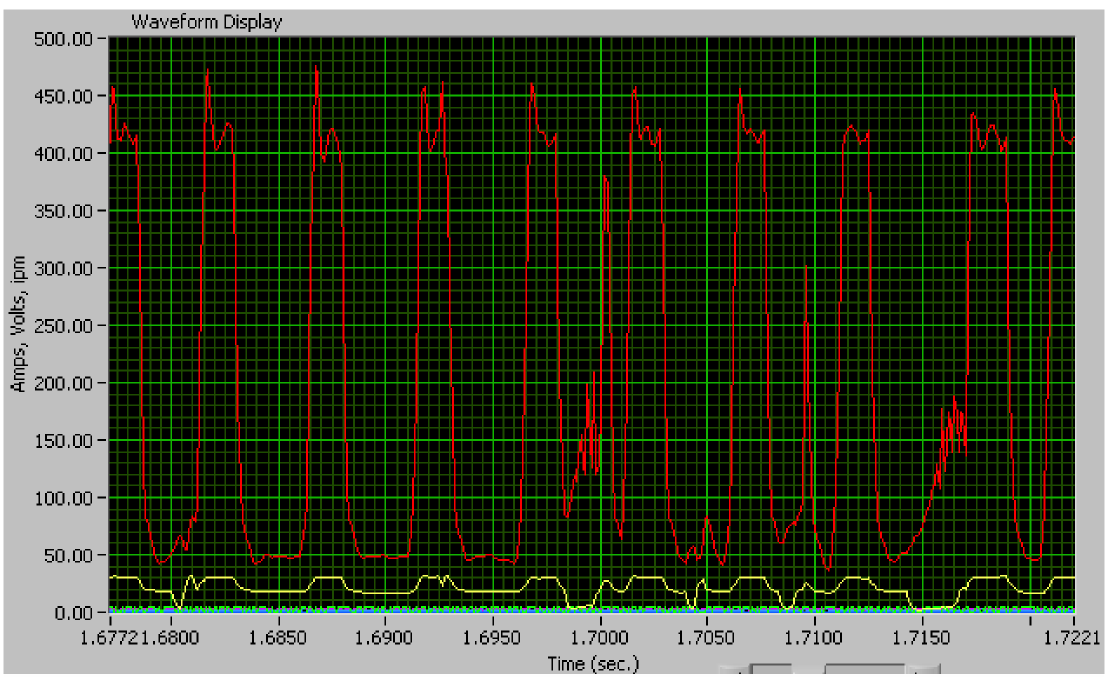

Figure 18. **Shorter Timebase of Welding Current Waveform**

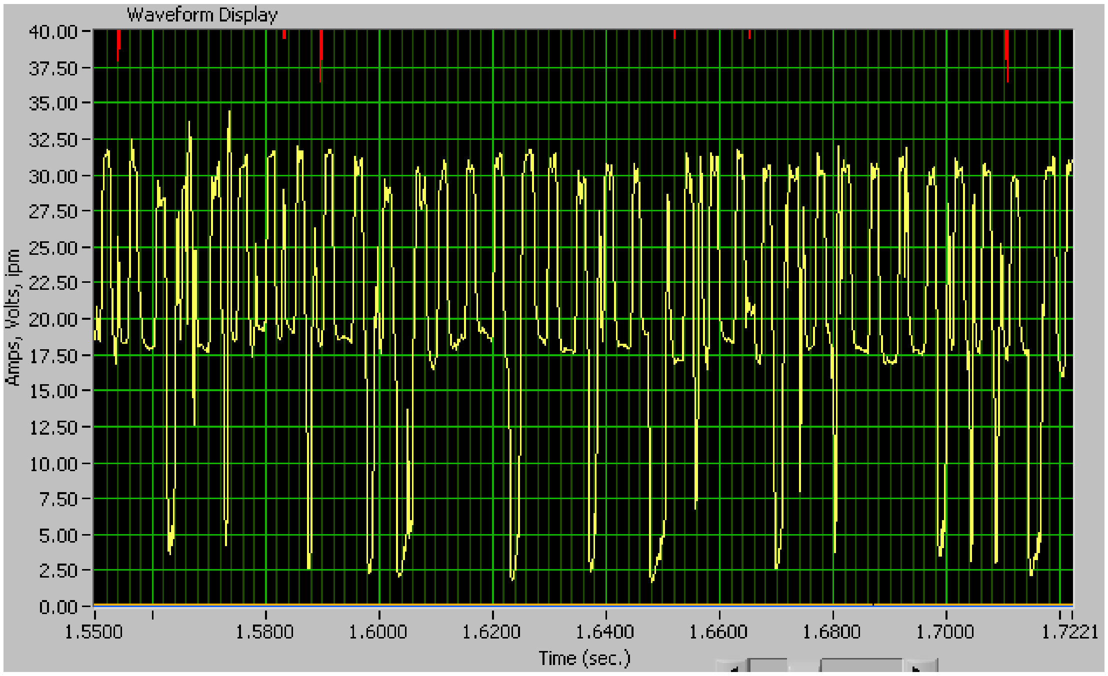

Figure 19. Arc Voltage Waveform Showing Dip Pulse Mode of Spin Arc Operation

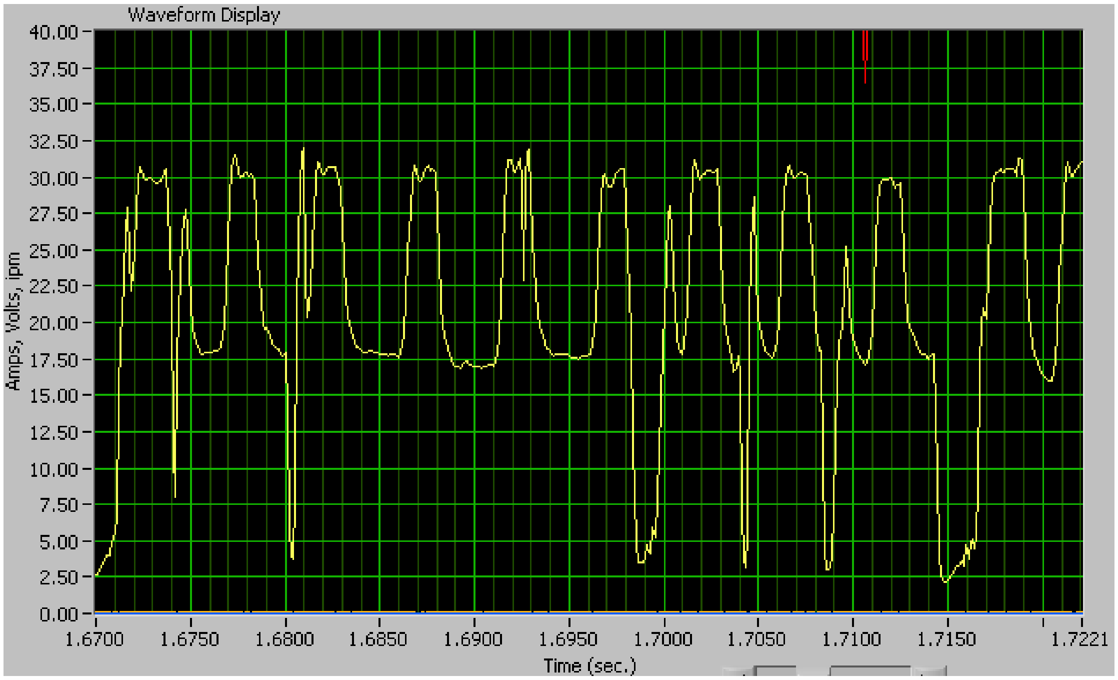

Figure 20. Shorter Timebase of Arc Voltage Waveform