

# Robotic Adaptive Algorithm for Solving Fit-up Variations in Welding at Industrial Scale

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**Abstract** - Open root pass welding in Gas Metal Arc Welding (GMAW) is always challenging due to the nonlinear random variations in pipe gaps and the presence of tacks. Manual welding requires a lot of skill from senior welders to react and control many variables promptly. In the transition to robotic welding, tracking solutions based on laser or vision systems have emerged to address the tracking issue. However, adapting the welding parameters (e.g. wire feed speed) and motion parameters (e.g. travel speed) is still essential in getting a consistent, high-quality weld. This work presents an adaptive control approach to pipe welding. The method combines a vision-based system that replicates the perception of welders with real-time control to live-adjust welding and motion parameters based on the instantaneous pipe gap, learning about the tack and fusing it on the root pass - a critical challenge for robotic welding applications. The controller monitors the state condition and communicates the proper process and motion update with the robot according to the real-time gap and tack state. The resulting closed-loop system enables higher quality and consistency of weld throughout the pipe welding.

**Keywords:** Gas Metal Arc Welding, artificial intelligence, adaptive control, vision, robots

## 1. Introduction

Welding is a widespread manufacturing technology that enables the fabrication of complex and large-scale structures at a competitive cost and time. However, the traditional reliance on the role of human welders introduces many risk factors, so the new trend in technology is maturing the use of automation, robotics, machine learning, and AI toward converting human reliance from manual welding to machine control and autonomy. On the other hand, the demand for constructing new infrastructures with squeezed timelines is increasing, and autonomy is now a bottleneck necessary to cover this growing demand. In 2023, over 45,000 arc-welding industrial robots are expected to be installed annually worldwide [1]. Cobots are younger products in the robotic market at a faster adoption rate than industrial robots for welding applications because of the high mix nature of welding jobs. The current autonomy level of these robots faces many challenges that open many opportunities for advancement in control integration with welding requirements.

Welding comes with various randomness in the process of joining two parts. A manual welder needs over five years of experience in a single welding process to deliver a good weld. A senior welder with 10+ years of experience is required for challenging welds. For example, open root pipe welding with Gas Metal Arc Welding (GMAW) is a challenging manual job. There are seam tracking problems, nonlinear variations in pipe gaps, fit-up misalignments, and the presence of tacks that need the welder's skill to adjust the welding promptly. State-of-the-art in welding control applications is evolving to capture and integrate the perception and cognition of skillful welders into the autonomy of robots [2, 3, 4]. Seam tracking was among the early challenges, and laser systems emerged about a decade ago to provide a solution [5]. Fast-paced advancement in image processing has led to many innovations by getting more information from welding scenes in real-time than laser [6]. As a result, the control approach is now changing to adopt innovations through the integration of vision systems, machine learning, and robotic communication for the live control of welding and motion variables [7]

This paper presents an adaptive control approach based on an intelligent vision system to live-adjust welding parameters on the power source and motion parameters on the robot. These adjustments are based on the instantaneous pipe gap, identifying the tack, and fusing it on the root pass. A significant challenge in the transition from manual welding to robotic welding and the control solution well receipt in the industry drove this variation management.

## 2. Welding Process as a Control Statement

According to each pipe size and wall thickness (schedule), a weld procedure specification (known as WPS or recipe) is used to generate a high-quality weld. The quality of the weld is examined against destructive and non-destructive tests. Procedure qualification records (known as PQRs) are evidence that a recipe is deemed appropriate for a certain pipe size and schedule. The recipe works fine throughout the entire weld if the pipe variations are minimal. However the initial fit-up is not perfect and comes with many variations including the pipe gap width and manual tacks present on the root pass. This will require the manual welder to adjust some of the welding process and motion parameters on the fly. That's what is making welding a state of art and not an easy job to automate even when a recipe is available.

Robotic welding solutions have emerged to address seam tracking challenges using a laser scanner or a camera. Minimal to no work has been done to address welding recipe adjustment challenges. A root pass recipe typically has information about motion parameters and welding parameters. Motion parameters commonly used are the pipe travel speed and the weave amplitude. Welding parameters commonly used are peak, background, and tailout in a non-synergic waveform and trim and ultimarc in a synergic waveform. Wire feed speed is also an important factor in any waveform. A sample waveform of synergic STT (Surface Tension Transfer) [8] is shown below.

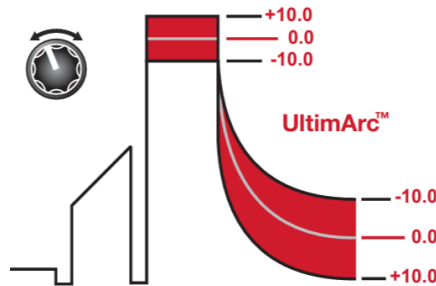


Fig. 1: A sample synergic STT waveform [8].

Note that all these waveform parameters have a direct effect on the voltage and amps of welding. Together with motion parameters, they define the “true energy” of the weld which often is measured in KJ/in and ideally, it has to be maintained fairly constant during one pipe revolution.

Automatic adjustment of the motion and waveform parameters would be a significant help to the operator. This will alleviate the need for the presence of an operator to identify the time to change parameters as well as dexterous adjustments in a timely manner.

## 3. Controller Solution

The aforementioned problem is a multivariable adaptive control problem and different approaches exist to address that. Some MIMO systems' input and outputs can be decoupled and therefore a decentralized control approach is suitable for them (Figure 2).

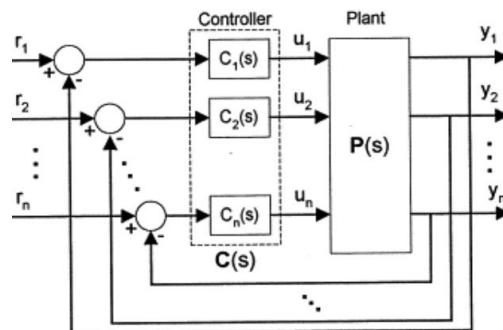


Fig. 2: A sample MIMO system controller.

In some other ones, the inputs and outputs are coupled, and it requires more synergy to control all of the outputs. Welding is deemed to be of this type and therefore a decentralized approach is not a good option.

Also, for varying-parameter model systems (such as welding that deals with gap-width variations discussed in part 2), nonlinear, robust, or adaptive control approaches are available. The changes in the pipe gap width can be nonlinear but designing a nonlinear controller and sending controller output to the powersource and also motors/drives seem to be overcomplicated. It's worth noting that the nonlinearity in pipe gap width cannot be modeled easily due to its randomness.

We used an adaptive feedback control strategy to sense the gap width of the pipe, command the motors and powersource to adjust the parameters, and monitor the results. We do not directly measure the true energy, but we believe adapting to new gap widths and fusing into the tacks will accommodate maintaining fairly consistent true energy.

### 3.1. Gap Width Control

We consider three scenarios for the pipe gap width according to any given recipe. We assume the recipe is designed/tested for a “normal” gap and requires adjustments if the gap width changes. If the gap is 30% higher than the normal gap, we call it “wide” and if it is 30% tighter than the normal gap, we call it “tight”. For these three scenarios, we will come up with a different set of motion and welding parameters built upon the original recipe. For example, if the gap is “wide”, the wire feed speed can be 10% more than the original one. It can be 10% less than the original one if the gap is “tight”. The quantification of the mentioned percentages comes from a welding expert. Ideally, some mechanical and other tests have to be done to verify that the weld quality is still fine after these changes are applied to a wide or tight gap.

### 3.2. Tacks Control

We also consider the presence of a tack to be another scenario. Therefore, a fourth set of parameters (motion and welding) is needed when the torch is going over a tack on the root pass. These parameters are set in a way to generate higher energy and do a “tack fusion” as welders refer to it. Therefore, they typically have higher wire feed speed compared to the original recipe and higher trim or peak & background currents. Again, an expert welder can help how to choose them based on a given recipe.

### 3.3. Controller Structure

The solution provided is very similar to a gain-scheduling adaptive strategy. That is, a vision-based system measures the gap width using a camera.

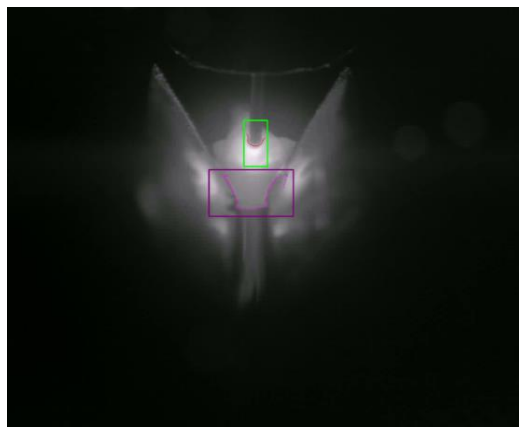


Fig. 3: Our vision-based identification.

Artificial Neural Networks (ANN) have been trained based on thousands of annotated weld videos. The main idea is to recognize the tack pattern and the gap width based on the puddle weld's brightest or darkest points.

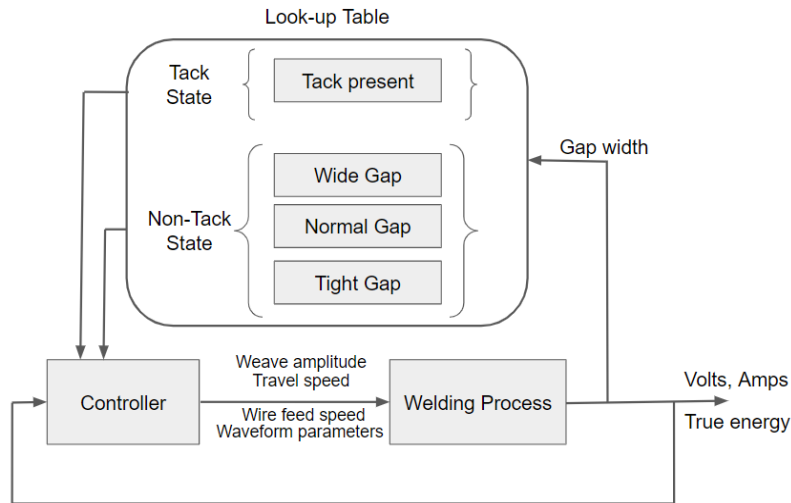


Fig. 4: Controller block diagram.

The measured gap width or tack status is then fed into a lookup table. Classification is performed to identify whether the gap is normal, tight, wide or the torch is entering a tack. According to these four scenarios, the proper set of motion (travel speed and weave amplitude) and welding (wire feed speed, trim or peak, and background) parameters are applied to the welding process. The controller makes decisions based on the gap width but a by-product of this algorithm is that the voltage and amperage and therefore the true energy will also maintain their value despite gap variations. This will make the weld bead more consistent in different gap-width regions.

We prepared ten pipes with three tacks on them. The pipe sizes were 6 to 10 inches in diameter, with a root opening of 3/32 inches. The included angle is 70 degrees with 2.5-degree tolerance. The tacks were 3/4 to 1 inch long with a feathered portion of about 1/4 inch on each side. The vision system successfully found 29 tacks (96.6%). Also, the PLC loaded the tack fusion parameters in all cases, but in three cases, it stayed too long on the tack state (90% success rate).

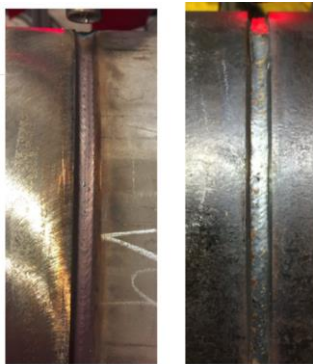


Fig. 5: Sample root passes welded using gap width and tack adaptive control.

Two samples of welded pipes using this algorithm are shown above. As can be seen the weld bead is consistent despite pipe variations.

#### 4. Conclusion and Future Work

An adaptive approach was presented to address tack fusion for root pass GMAW welding. Also, it will adjust motion (such as travel speed and weave amplitude) and welding (such as wire feed speed and peak & background or trim & ultimarc)

parameters to deliver a consistent and high-quality weld despite pipe variations. We considered three scenarios for different gap widths according to a given recipe.

The granularity of gap width levels can be extended from three levels to more. Hypothetically, the controller can do a fully adaptive framework and adjust all parameters based on the percentage change of gap width. Also, controllers based on fuzzy logic can also be used to adapt the welding and motion parameters based on changes in the gap width. This is very close to what the manual operator does when they face gap variations.

Also, we only considered one state for tack. That can also be extended to more states depending on tack type being a stitch, a long tack, or a short tack, etc.

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