An Adaptive Seam Tracker for Welding Heavy-Section Aluminum

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Abstract—**The process of welding aluminum presents a considerable challenge to the application of robotic welding. Heat distortion and fixturing errors often require alteration in welding parameters and the welding torch position and orientation in real-time. A nonadaptive robotic welding system, or a system with only limited sensory ability, is consequently unable to perform well in many aluminum welding tasks. A strong need exists in the aluminum fabrication industry for sophisticated flexible automated welding systems, which implement expert systems for weld process control and multipass weld planning, and apply advanced sensory technology for real-time seam-tracking and joint geometry measurement.**

I. Introduction

THE INTRODUCTION of robotic welding systems is underway in industry as part of a general move toward automating production lines. Robotic implementation is being initiated to satisfy a perceived need for high quality welds in shorter cycle times, and to acknowledge the recognized value of shifting the workforce from welding to sections of the production line with higher potential productivity and better environmental quality.

In general, robotic welding systems which cannot adapt in real-time to changes in the joint geometry along the weld seam and to the seam position itself have only limited success in many welding applications. The difficulty stems from heat distortion of the weldment or to an overall shift in the weld seam caused by fixturing errors, conditions often found in the welding of aluminum.

A solution to this problem requires the application of some form of adaptive joint geometry sensing system for guidance of the welding torch. The object of the research project described in this paper is to address the general aluminum welding problem by integrating a laser-based part-profiling sensor with a welding robot.

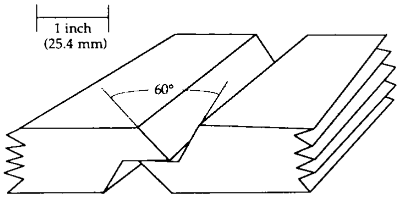

Fig. 1. Aluminum joint configuration.

II. Rationale for Adaptive Sensing

The joint fit-up in aluminum, which is machined and wire brushed prior to welding, is good, but the seam placement and geometry can change significantly due to the input of heat from the welding process. In addition, aluminum is less forgiving to minor changes in the weld parameters than steel, and is much more susceptible to contamination. A typical aluminum heavy-section slip-joint weld seam is shown in Fig. 1.

An adaptive robotic welding system with seam-tracking sensors is necessary to weld typical aluminum sections, as a "blind" robotic welder is unable to correct for variations in seam placement and joint geometry and is unable to respond to movement of the joint due to heat distortion. The most commonly used adaptive welding strategy, and one which represents an inexpensive and robust technology, uses the arc current itself to guide the torch. The technique is known as through-arc sensing [1].

After manually teaching the robot the rough seam path, a low-current electrical signal through the welding wire is used to guide the robot to the root at the start of the seam. The arc is then turned on and the torch is moved along the taught path. The torch is not moved in a straight line along the path but instead is weaved from side to side. As the torch approaches the joint sides, the arc current increases. To guide the torch laterally through the seam, the center of the weave is continuously adjusted to make the current peaks level.

Typical through-arc systems can deal with complex seam geometries, and can perform multipass welds, with only a series of offsets required from the root pass to weld the remaining passes. Some systems can change the wirefeed rate or the torch speed to compensate for a varying root gap. A notable advantage of through-arc sensing is the fact that the position of the seam, via the torch, is measured directly, not at some distance ahead. This greatly reduces data processing time and enhances potential accuracy. The welding speed is not enhanced as a significant amount of speed is sacrificed by

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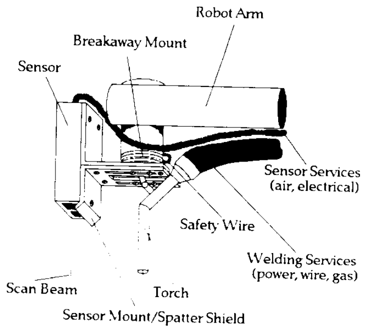

Fig. 2. ARTIST end-effector.

weaving. However, most typical welding speeds can be accommodated.

Although these systems are ideal for many applications, the problem of severely varying joint geometries cannot be solved by through-arc sensing alone, as not enough information about the geometry of the seam is available to account for varying top-edge offsets and gaps, and areas that consequently require a multipass plan altered from that normally used cannot be properly welded.

The requirement for more detailed measurement of the joint points to a vision-based system for solution to the general problem. After an evaluation of vision-based robotic systems on the market today, it was felt that an investment in vision technology would be better spent in development of a system tailored to the joint types and welding processes specific to the sponsor's needs rather than in adapting an off-the-shelf system designed with sheet-metal welding, for example, in mind.

III. System Development

The adaptive system being developed, which has been dubbed the Adaptive Real-Time Intelligent Seam Tracker, or ARTIST, is depicted in Fig. 2. A diagram of the architecture of the ARTIST system is shown in Fig. 3.

An IBM PC/AT-compatible microcomputer serves as the system supervisor, commands the motion of the robot, directs and processes the sensor scans, and establishes the required weld parameters. The programming language used in the microcomputer is "C," chosen primarily for its flexibility and high execution speed.

The host robot is a Unimate 760 Series electric six-axis articulated arm, using a VAL II controller. The VAL II language allows a supervisory computer to send commands to the robot controller over an RS232C link as though it were the Unimate terminal. This function is exploited as the sensor data is processed by the microcomputer to provide target points to which the robot sequentially moves the welding torch.

The laser profile gauge was developed by Chesapeake Laser Systems, Lanham, MD, from technology required in the development of a robotic laser welding system, the Laser Articulated Robotic System (LARS) [2]. The sensor uses the laser triangulation method to derive the standoff distance to the target surface. The source beam is emitted in the near infrared (780 nm) by 5 mW semiconductor laser, and the projected laser spot on the surface of the part is sensed by an off-axis 1024-element linear CCD array.

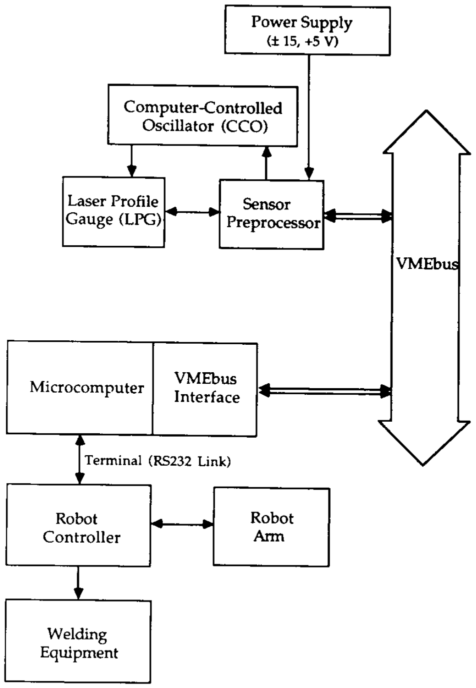

Fig. 3. ARTIST system architecture.

The chief advantages of this sensor over other laser scanning sensors include the following: 1) the position of the beam is completely programmable, 2), the exposure time for the CCD array is adjustable in real time, and 3) the scanning is accomplished with no moving parts, as an acousto-optic crystal bends the beam through the scan angle rather than a rotating mirror. These advantages make this sensor extremely versatile, robust, fast and accurate. The sensor can resolve distance to within ±0.005 in (±0.127 mm), at a nominal standoff distance of 10 in (25.4 cm). It has a useful range of 1.5 in (3.8 cm).

The microcomputer can direct the sensor preprocessor over the VME bus to move the laser beam to any of 1000 points along a scan line 1.25 (31.8 mm) inch in length. It can also control the exposure time for the CCD array from point to point along the scan, thus allowing the system to adapt to changes in the material surface condition across the seam.

To weld with the system, the operator locates the welding torch near the beginning of the seam and commands the system to begin welding. The robot moves the sensor, which is located about 4 inches (10.1 cm) in front of the welding torch, in a search pattern until the beginning of the joint is found. The robot then positions the welding torch at the start of the seam and begins to weld the root pass using torch position and orientation data which are derived from sensor scans of the joint. The system is capable of welding with a torch speed in excess of 70 in/min, (178 cm/min) using 1/16 inch (1.6 mm) diameter wire. The wire feed rate is set automatically to adapt to the changing joint geometry.

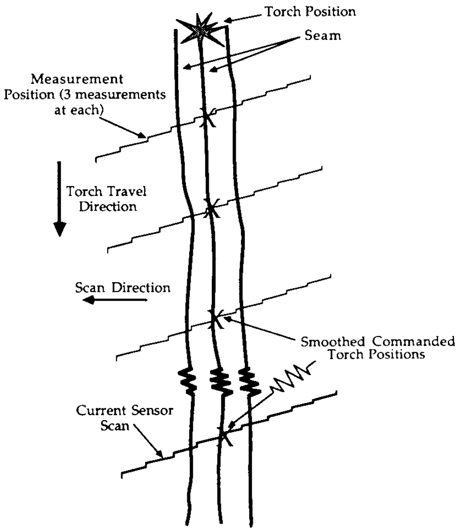

Fig. 4. ARTIST scanning detail.

When a tack or the end of the seam is reached, the system takes the required action, to either burn through or to crater and stop. Following the root pass, the data gathered by the vision system is processed to plan the remaining weld passes, with simple offsets to the root pass being used by the robot to guide the torch. These offsets are calculated by expert welding-system software.

The autonomous adaptive ability of ARTIST is achieved through a complex series of calculations and communications grouped into four major operations: data acquisition; image recognition/segmentation; target point generation; and microcomputer/robot controller communication.

A. Data Acquisition

The sensor, directed by the microcomputer, scans the seam as shown in Fig. 4. Scans are separated by approximately 0.5 s. The sensor preprocessor returns a scaled representation of the torch-to-laser spot standoff distance to the microcomputer at each lateral beam position, currently at 17 points, spaced 1/16 inches (1.6 mm) apart. The scaled values are then converted to real distances by the microcomputer through the use of a calibrated lookup table, and the raw sensor datapoints are smoothed with a simple low-pass filter.

B. Image Recognition/Segmentation

An expert system recognizes the type of joint represented by the scan data, to distinguish, for example, between a normal joint and a tack weld.

Heuristics for Seam Recognition: Seam recognition in the presence of noise in the scan data is a complex process, especially when a certain degree of variability in the seam geometry is introduced. Creating a static knowledge base of the various seam types, including their variations and pattern matching with the current scan, is a viable option. However, this concept may not be suitable for real-time applications. Some misalignment between the center of the scan window and the root of the seam is inevitable during the seam tracking process and may lead to the loss of some features of the scan, which would add to the many variations in the seam types.

The ARTIST system uses an approach, based on heuristic reasoning, for real-time seam recognition which makes possible a high degree of certainty in seam-type selection. By applying a set of rules, the system narrows the possibility to a particular seam type and then examines the heuristic judgement using verification rules specific to that seam type. This strategy, in most cases, obviates the need for a detailed pattern-matching between the given scan data and the various seam types stored in the static knowledge base. Presently, the system can recognize a slip-joint weld seam, a fillet weld seam (not implemented currently), tack welds, and the end of the seam. Tack welds and the end-of-seam condition are recognized by analyzing the seam environment rather than just a single scan. The system does not immediately conclude what the seam type is but generates a "presently unknown" seam type, which at a later stage is classified into a tackweld or end-of-seam condition.

Seam recognition is performed in three stages. In the first stage, the scan data is preprocessed using simple heuristic rules resulting in an object–attribute–value (O–A–V) triple for each seam type which the system has been designed to recognize. This triple, called "cur_scan_cntxt," contains the dynamic knowledge and can be explained in O–A–V terms as

object: possible seam type in the current scan context;
attribute: certainty factor of the seam type being true in the current scan context;
value: a real number between + 1 and − 1 indicating the system's degree of confidence in the preceding attribute being true or untrue.

In the second stage a set of heuristic rules is applied, based on the current values in the dynamic knowledge base, to narrow the scope of the various possibilities. The values of the certainty factors are adjusted in light of the outcomes as the rules are applied. In the third stage the judgement is verified by pattern matching the given scan with a specific seam type that the system has already identified as most likely. This patter is available in the system's static knowledge base.

The preceding approach, using heuristic reasoning, has two advantages: 1) the detailed pattern-matching process is not necessary for every scan, since simple heuristic rules help in narrowing down the various possibilities; and 2) the verification process, which is actually pattern-matching, can be accomplished using relatively few details in the static knowledge base. This is due to the fact that the previous heuristic reasoning establishes a high degree of confidence in the seam type for the current san before passing it to the verification module.

C. Implementation of the Seam Recognition Scheme

The seam recognition scheme consists of the following three steps.

Preprocessing Module: The input to this module is a set of scan points that has undergone smoothing by weighted averaging. The output is an OAV triple representing the certainty regarding the current scan's seam type. This certainty is quantified to a value between +1.0 and −1.0, reflecting the system's degree of confidence in its belief. A value of +1.0 indicates that the system believes the hypothesis is true while −1.0 is associated with the hypothesis being untrue. The steps involved in preprocessing the scan data are as follows.

Find the total average of the scan points (cur_avg).

Rule 01: If the absolute difference between the cur_avg and the first scan point is less than a threshold value, then

certainty factor (slip joint) = −1.0,
certainty factor (tack weld) = −0.0,
certainty factor (undefined seam) = 0.0,
certainty factor (presently unknown seam) = +1.0.

Rule 02: If Rule 01 is applicable, and if the cur_avg is greater than the first scan point, then the certainty factor (tack weld) = 0.5.

Rule 03: If Rule 01 is not applicable, then

certainty factor (slip joint) = +0.8,
certainty factor (tack weld) = −1.0,
certainty factor (undefined seam) = −1.0,
certainty factor (presently unknown seam) = −1.0.

If Rule 03 is applicable, then find the current scan's characteristic features.

Find out Possible Seam Type: This module narrows down the scope of the possible seam types based on the certainty factor values in the dynamic knowledge base (cur_scan_cntxt).

Rule 11: The seam type of the current scan is most likely to be the same as that of the previous scan. If the certainty factor (previous scan's seam type) is greater than 0.5, then the possible seam type is the same as the previous scan.

If Rule 11 is not applicable then the possibilities are as follows.

Rule 12: The system has crossed from an undecided region to a normal weld-seam region. In this case the previous undecided region can be identified as a tack weld. Also, the seam type in the current scan is most likely to be the same as that in the region before the tack weld. If the certainty factor (previous segment's seam type) is greater than 0.5, then the possible seam type is the same as in the previous segment.

Rule 13: The system has crossed from a normal weld seam into a tack weld region. If the certainty factor (presently unknown) is greater than 0.5, then no decision is made regarding the current scan's seam type, which could be a tack weld or end of seam.

Verification: This module verifies the system's judgement regarding the possible seam type for the current scan. Presently the system immediately verifies all the normal weld-seam types, with and without variations. If the output of the verification module does not match the possible seam type isolated in stage two, then a detailed pattern-matching is executed. This measure, however, is seldom necessary as the decision is nearly always found to be correct.

The scan data for verification are represented in terms of salient features of the seam geometry. These include the length of the left and right flat edges, the left and right bevel edges, and the included angle between the bevel edges. For example, the rule for a slip-joint verification is as follows.

Rule 21: (Verification of Slip Joint): 1) The sum of the lengths of the left and right flat edges should be greater than a threshold, 2) the length of the left bevel edge should be greater than a threshold, 3) the length of the right bevel should be greater than a threshold, and 4) the included angle should be between certain limits. The threshold values are based upon material specifications.

Following seam recognition, an image segmentation algorithm is then applied to the profile of smoothed points to derive four positions on the joint: the two top edges and two root edges [3]. It operates by repeatedly dividing the profile horizontally, followed by line-fitting, until the upper or lower edges are reached.

After removal of the distortion in the position of these points due to the small torch motion during scanning, the points defined by the segmentation algorithm are used to divide the image into sections representing the left and right top plates and the left and right bevels. Once these regions are defined, a least-squares line fit is applied to each, producing a four-segment model of the joint. A completed line fit on smoothed datapoints is shown in Fig. 5. The dark squares, identifying borders between joint segments, represent the output from the segmentation algorithm.

D. Target Point Generation

The joint model, which is represented in the coordinate system of the sensor, is analyzed to derive a tilt angle of the profile and two linear coordinate values of the desired torch wire-tip position. The tilt angle is calculated by averaging the slopes of the plate top surfaces. The desired torch position is defined at a standoff along the line that originates at the root and bisects the angle between the bevel segments. The standoff distance is based on the application of welding rules to the particular geometry of the joint.

An estimate of the pitch is obtained from the difference in altitude of the current and previous scans, with additional input from the history of the torch altitude. The seam roll is estimated by the tilt of the image.

E. Microcomputer—Robot Controller Communication

The microcomputer serial input/output is connected to the RS232 port on the robot controller that normally hosts the controller terminal. By using the microcomputer as a surrogate terminal, any communication possible with the terminal can be affected by the microcomputer

The five-degree-of-freedom location of the target position is communicated to the robot controller by answering a prompt from the controller, just as the terminal would, with the Eulerian values of the target point converted into the special robot coordinates X, Y, Z for position, and orientation, altitude, and tool for rotation. Reference [4] contains a complete explanation of these translations and rotations. Tool

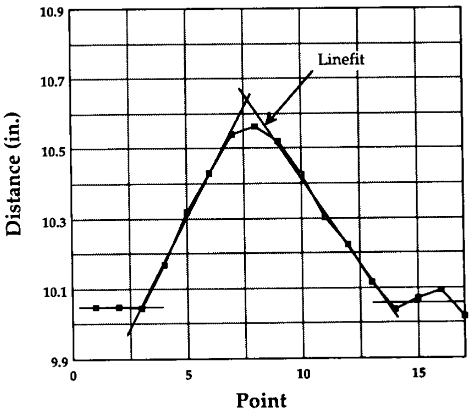

Fig. 5. Joint profile.

angle denotes a rotation about the torch axis and is used to center the sensor scan on the seam.

Each resulting new point, smoothed with preceding points, replaces the just-commanded point on a ring buffer, a continuously replenished table of target points, in the robot controller. For cycle time of 0.5 s and a torch speed of 1.0 in/s (25.4 mm/s), the buffer would contain eight points, for example. To ensure an integral number of points between the current torch and scan positions, which is necessary for proper initialization of the seam path, the scan processing time can be delayed slightly for each scan.

The controller directs the robot to move in a straight-line motion, from point-to-point, through the table of points, by repeatedly executing the VAL command

MOVES *robotpos:torchsens:trans*(x,y,z,o,a,t)

where *robotpos* is the global position of the torch when the scan for this next point was begun, *torchsens* is the transformation from the torch position to the sensor coordinate system, and the transformation list in *trans* contains the aforementioned five degrees of freedom of position and orientation of the desired torch position in sensor coordinates and the tool rotation value calculated on the previous scan.

Communication errors between the microcomputer and the controller are resolved by attaching a code symbol to the next prompt message from the controller. When a bad message is received, the controller requests a second transmission of the transformation list.

IV. Future Development

A knowledge-based expert system (KBES) will be developed in a later phase of the project. The KBES will allow control of the welding process with much less human intervention, as it will set current and voltage levels, torch travel speed, and torch position and orientation automatically to optimize the weld quality for a particular joint geometry during the welding process.

The five-axis control of the robot limits the scanning system to the welding of fairly simple shapes. A two-axis weld-positioning table will be integrated with the system and another expert system will control the table motion during the welding process, to optimize the torch welding position and speed.

The final area of future development includes an improvement in the complexity of the path and an increase in the types of seams which the system can weld. The requirement for a clearly defined seam beginning and end will be eliminated, and less definable transitions, such as sharp slopes and corners, will be dealt with, with sensing assistance from a collision avoidance device.

V. Conclusion

The introduction of a highly sophisticated sensor and software that allows nonpreprogrammed operation markedly improves the ability of a robotic welding system to address the general aluminum-welding problem. In doing so, ARTIST addresses a practical need of the project's industrial sponsor and brings the goal of widespread application of intelligent welding systems to the factory floor closer to attainment.

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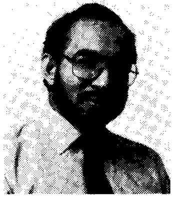

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