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An Adaptive Real-time Intelligent Seam Tracking System

The concept of a real-time seam tracking system for welding automation and the initial design for building a prototype is presented. The Adaptive Real-time Intelligent Seam Tracker (ARTIST) uses a robot held, laser based vision system for automation of arc welding processes, and is currently under development at the Applied Research Laboratory of the Pennsylvania State University. The design of ARTIST builds upon the concept of a zero-pass technique. The 3D information of seam geometry is collected and processed for real-time guidance and control of the welding torch trailing behind the laser based vision sensor. This zero-pass concept eliminates the need for preprogramming of the weld path and thus, potentially enhances the welding cycle time for small batches. The ARTIST is designed to support multipass arc welding and to handle any tack welds which are encountered during the seam welding operation.

Introduction

Arc welding within an industrial environment is labor intensive, time-consuming, hazardous, and often proves to be arduous. Robots have been used for welding through a variety of methods. The preprogrammed path approach involves teaching relevant points along the seam before the welding operation can be performed. This can be very tedious and time-consuming, especially for complex and irregular seams, and a large batch size is required to justify the usage of a welding robot. Under the present state of the art, the robot assisted welding systems suffer from their inability to recognize variations in the seam geometry of workpieces of the same type because the robots lack intelligence and adaptivity to accommodate for uncertainties, errors, and noise that are usually prevalent in the work environment.

Most adaptive welding robots are characterized by the presence of a vision system. An example is the single pass nonpreprogrammed visually guided arc welding robot with self-training features[1] which operates in two modes. During the teaching mode, the robot autonomously tracks the seam and generates a 3D model of the seam. In the welding mode, visual feedback is used to position the welding torch, while the seam model positions the vision system in front of the torch.

The Adaptive Real-time Intelligent Seam Tracking (ARTIST) system, currently under development, is essentially a zero-pass system which is characterized by the absence of an additional teaching phase,[2] i.e., it will learn and weld in the same pass. Such a system is of particular relevance to welding automation where the workpieces to be welded are not of the same type. This system will also allow the seam information collected by the vision sensor to guide and control the welding torch in real-time as well as positions the sensor for the next scan. *Figure 1* shows a conceptual view of the ARTIST. The major control functions of the ARTIST are to be carried out by the image processing module (IPM) and the robot control module (RCM).

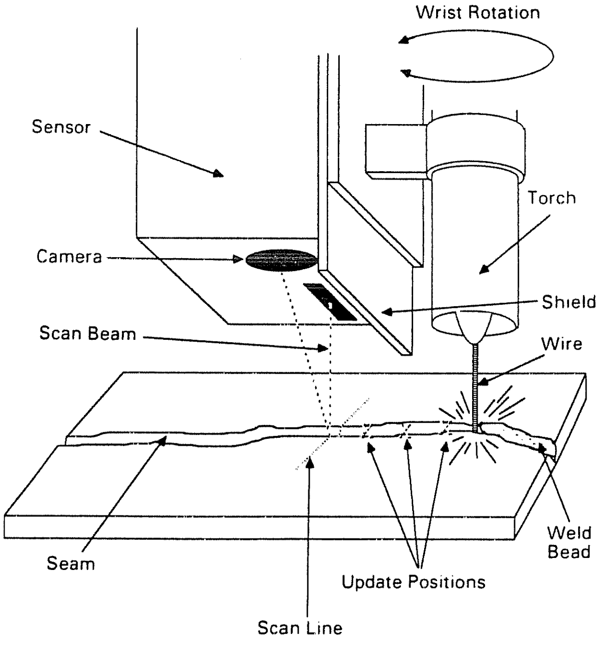

Figure 1
Conceptual View of the ARTIST

The IPM, hosted in a microcomputer along with other control modules, receives the data from the laser sensor preprocessor in the form of standoff distance of the sensor origin from specific points on the welding seam. This information, along with the (x,y) position information of the sensor, already resident in the supervisory controller, is used to calculate the 3D position of the seam in tool coordinates. Additional data about the seam geometry helps in calculating the pitch and yaw angle of the torch tip, and the roll angle for the sensor location.

The 3D seam information received from the IPM is transmitted to the robot control module (RCM). On the basis of this information, the RCM calculates the joint angles through which the robot is commanded to move. The IPM and RCM essentially run in parallel and are allowed to communicate with each other.

The complete process of seam tracking and welding has been divided into three phases. The first phase involves the location of the beginning of the seam. The actual seam tracking is done in the second phase. This also includes the control of the welding parameters as the torch moves along the seam with a preset velocity. The third phase of the process is the location of the end of the seam and the execution of wrap up procedures, like turning off the welding equipment and moving the robot to the home position upon reaching the end of the seam.

The objective of this report is to present the basic concepts of the seam tracking system ARTIST, along with some details of its development that have been completed during the initial design phase.

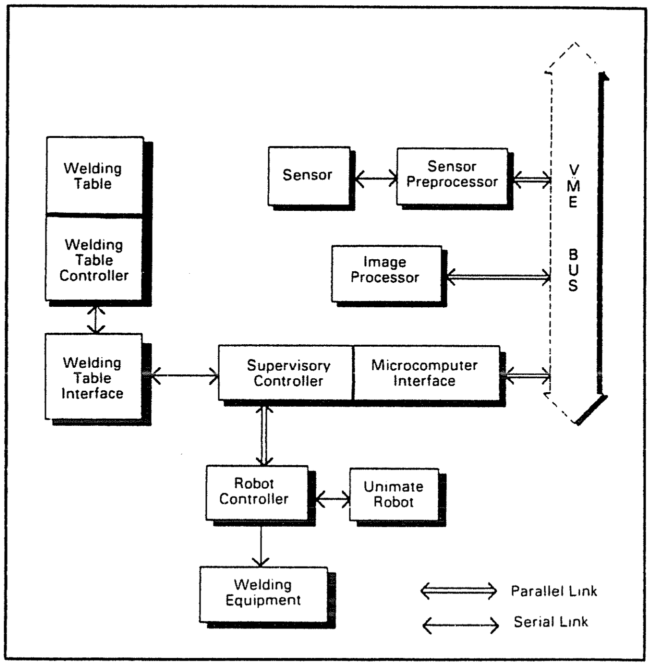

Figure 2
Simplified Block Diagram of the ARTIST

Description of the Experimental Setup

The seam tracking system ARTIST is being developed on a six axis, gantry robot (Unimate 6000) equipped with a VAL-II controller. A simplified block diagram for the seam tracking system is shown in *Figure 2*.

The supervisory controller communicates with a laser sensor preprocessor over a VME databus. The laser sensor is designed for use with high-speed welding systems and can provide surface profile information at up to 1000 measurement points. Each point can be measured within several milliseconds, at an accuracy of ±0.005 inch along a line 1.25 inches wide. The sensor operates on the principle of laser triangulation to provide 3D measurements of the target surface. The laser sensor is mounted on a bracket attached to the wrist of the welding robot. The sensor rotates about the sixth axis to follow curved seams, as shown in *Figure 3*.

The vision sensor is equipped with a spatter shield and an optical filter to adapt to the smoke-filled arc welding environment. The sensor operates on the principle of laser triangulation to provide 3D measurements of the target surface. The high data rate and reliability of the sensor are essential for high-speed seam tracking without path preprogramming. The sensor is equipped with a preprocessor which transforms the raw data into a sequence of bits representing the sensor origin's standoff distance. The position of the sensor coordinate system's origin relative to the tool coordinate system's origin is established during the calibration process of the laser sensor. This data is communicated over the VME databus to the image processing module

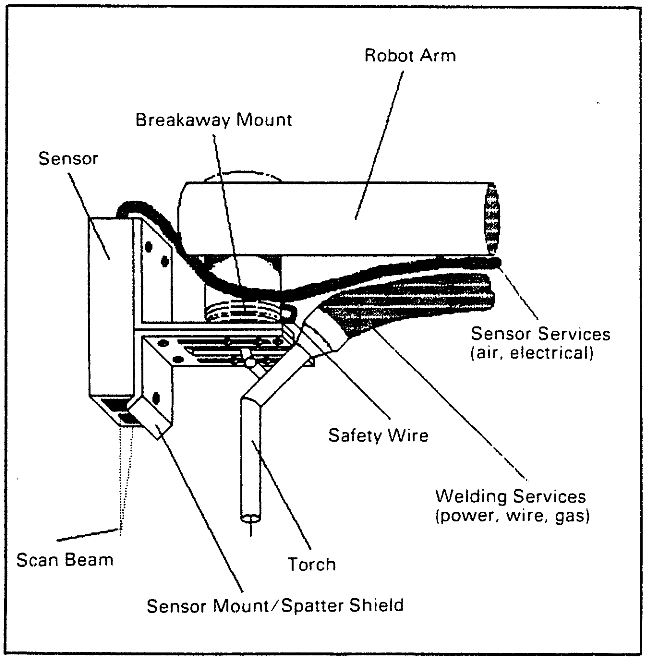

Figure 3
Mechanical Layout

which is an integral part of the the supervisory controller's functions. The functions in the supervisory controller combine model-based control algorithms with knowledge-based heuristic procedures[3] to regulate the parameters, like data rate and dwell time that are critical for operations of the laser sensor in real-time.

Functional Characteristics of Individual Software Modules

The software for the ARTIST has a modular structure, and its operations involve interactions between individual modules. A description of the functional requirements of the various modules is given below.

The image processing module (IPM), which is presently resident in the supervisory controller hardware, is responsible for on-line identification of seam characteristics. The IPM is the most complex part of the system software and incorporates both algorithmic and heuristic procedures. The functions of the IPM include:

- Processing of scanned data.
- Recognition of seam type.
- Determination of seam geometry.

Other functions of the supervisory controller are as follows:

- Computation of end effector velocity along the seam.
- Communication of position and velocity parameters from the supervisory controller to the robot control module (RCM).

The robot control module (RCM) software is an integral part of the robot system and is supplied by the robot vendor. The functions of the RCM include:

- Control of robot arm and welding process.
- Information communication from robot controller to the supervisory controller for supervising identification of seam characteristics.

Identification of Seam Geometry

Identification of the 3D positions of relevant points along the seam is carried out in the following four steps.

Step 1: Collection of surface profile data using the laser triangulation technique as illustrated in *Figure 4*.

Step 2: Filtering the erroneous data such as those that may result from specular reflection of the laser beam from shiny spots on the weldment.

Step 3: Processing the filtered data to locate the root and the flanks of the seam.

Step 4: Transforming the location of the seam data (root and flanks) from the sensor coordinate system to the tool coordinate system.

Redundant data allows error detection, and thus facilitates the filtering process. This could be implemented by recording a pair of points (one measurement interval is several milliseconds apart) at every target point as the sensor scans across the surface. This is illustrated in *Figure 5*. A discrepancy between the values of the pair of points in excess of a given threshold would result in discarding one or both of these points.

For every scan across the surface, the measurement pattern in terms of number of points scanned would roughly be the same.

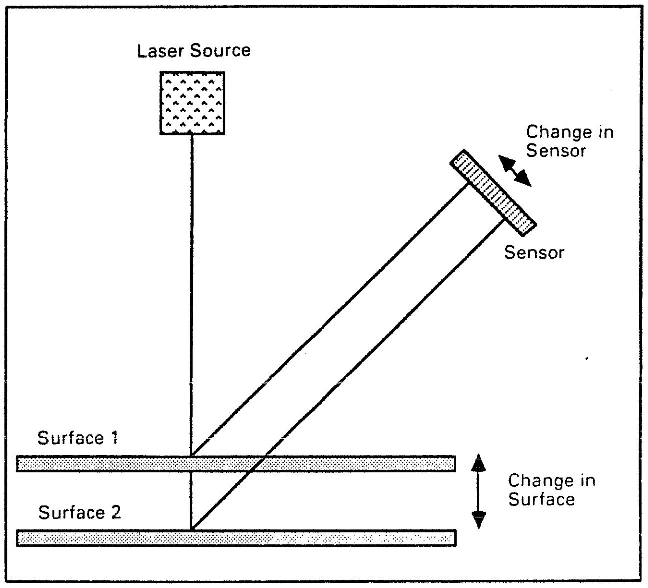

Figure 4
Laser Triangulation Technique

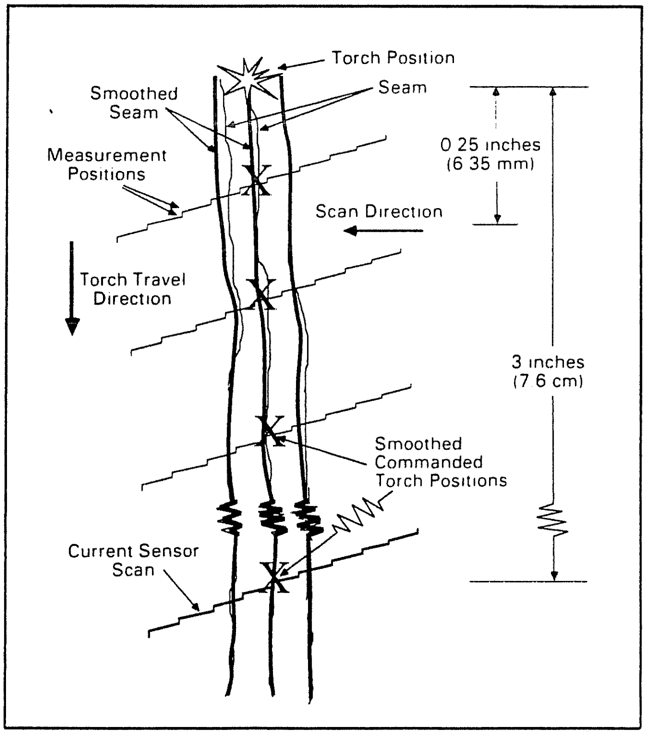

Figure 5
Seam Tracking Detail

On this basis, a recursive relationship[4,5] can be established for estimating the coordinates of points that have been discarded. The recursive relationship, however, assumes that the surface geometry does not abruptly change from scan to scan.

The programmability of the laser scanner allows the exposure to be adjusted in real-time. This feature helps in obtaining the correct standoff distance by accommodating minor changes in the surface reflection. The laser scanner can also be programmed to make closely spaced measurements in the vicinity of the seam, thus making it possible to obtain more information about the seam as the surface profile changes across the seam. This information is processed to compute the location of the root of the seam by using the segmentation algorithm of Smati, Smith and Yapp.[6]

The segmentation method has been found to give accurate results in fillet welds and V-preparation butt welds and involves finding the intersection of best fit lines. A straight line fit for the points across the seam is found by taking the total averages. The intersection of this straight line with the V-preparation is then noted and the line is split there. An iterative process is then used to fit the best lines to the sides of the preparation. The intersection of these two sets of lines define the edges of the preparation as well as the location of the root.

In the tool coordinate system as well as in the sensor coordinate system, the x-direction is along the seam, the z-direction is along the torch pointing downwards and the y-direction is across the seam as per the right hand rule. On knowing the z value, and using the x and y values already resident in the supervisory controller, the 3D position of the seam data point is now available. The pitch angle of the wrist is calculated from the angle between the yz-plane of the sensor coordinate system and the normal to the line joining the current root and the previous root. The yaw angle of the weld torch is calculated from the angle between the xz-plane and the normal to the line joining the tops of the edges of the V-preparation. The seam data is then transformed from the sensor coordinate system to the tool coordinate system. The processed data can now be communicated to the robot controller over the serial interface.

The recursive relationship will also generate the predicted value of location of the root of the seam during the next scan in order to position the sensor for taking measurements at close intervals in the vicinity of the root. The recursive model uses the location of the roots from the previous scans to approximate the new location of the root.

Algorithm for Robot Control

The complete process of seam tracking and welding is partitioned into three phases.

Phase 1: Initiation of Seam Tracking. The operator positions the welding torch at the beginning of the seam within an accuracy of a few millimeters. The controller is aware of the position of the weld torch at any instant. Since the relationship between the tool coordinate and the sensor coordinate systems is known from the laser sensor calibration process, the sensor can be moved to the current position of the torch maintaining the proper standoff distance. The sensor can then be made to scan in the vicinity of the starting point and the collected data can provide the correct location of the beginning of the seam.

Phase 2: Intelligent Seam Tracking and Welding Along the Seam. Initially, the sensor scans the surface to locate the direction of the seam. After the direction is computed, the sensor periodically scans the surface to get the surface profile data. This data is processed into 3D locations in torch tip coordinates. An expert system resident in the IPM helps in recognizing the seam type, which could be a butt weld with V-preparation, a tack weld, or the end of the seam. This information is used for describing the length of the seam covered, as groups of scans (segments) of similar seam type. The welding parameters can thus be appropriately selected depending on the segment in which the torch is located.

The interrupt signals which actuate the sensor are generated by the supervisory controller. Until the torch tip reaches the beginning of the seam, the tool coordinate system is located at the sensor origin enabling the sensor to move ahead, collect seam data and buffer it in a point table which is located in the microcomputer. When the torch tip reaches the beginning of the seam, the tool coordinate system is shifted to the torch tip and the robot controller guides the torch tip along the path stored in the point table. As soon as a location (point along the seam) is reached by the torch tip, an interrupt signal is generated by the robot controller and communicated to the supervisory controller, which in turn instructs the laser sensor to scan.

The processed data from the image processing module consists of two parts. The first part consists of the x, y and z distances to the next location, the yaw angle and the pitch angle of the torch tip. This is added to the point table as a new location. The second part is the angle of roll to adjust the position of the sensor with respect to the seam. This data augments the contents of the location, which is two slots away from the current location of the torch tip, and is next in the line to be used. This however, adds a time lag in the sensor movement to accommodate the lateral shift of the seam. But since the locations are near each other (about 200 ms apart in time), the impact of this lag should be insignificant for seams without major fluctuations. The handling of communication across the serial interface and the updating of point table is handled by background processes running on the microcomputer.

Phase 3: Termination of Seam Tracking. The image processing module (IPM) recognizes the end of the seam and sends a special character into the point table. At this time, all signals from the robot controller for scanning more data are ignored by the supervisory controller and the background processes for updating the point table also stop executing. On encountering this "end of the weld path" signal, the robot controller switches off the welding equipment and the robot arm is moved to the home position.

For the succeeding passes, the weld path from the first run would be used as reference and adjusted for thermal distortion by collecting seam data at the locations described in the first run.

Considerations for Testing and Performance Evaluation

The seam tracking system ARTIST is being designed to achieve welding speeds of 60 inches per minute on multipass, single V-preparation joints for aluminum armor. A point to be noted is that a laser scanner of a given power rating can be used only on certain metals. This is decided by the intensity of the reflected beam, which should be under the saturation level of the sensor. The programmability of the sensor, however, does allow minor adjustments in the exposure.

The criteria for evaluating the performance of the seam tracking system include achieving the desired welding speed and maintaining the error of seam tracking within specified tolerances. A typical value of the tolerance in an arc welding process is equal to the radius of the filler wire. For armour welding using multiple passes, this requirement can however, be less stringent. Since the ARTIST must perform under time constraints, it is extremely important to maintain its operations within defined time schedules. In this respect, the time requirements for the following processes in ARTIST's operations are to be carefully considered.

- Communication time for signal from the robot controller to the laser scanner, via the supervisory controller.
- Time for scanning the surface profile (at the rate of several milliseconds per point).
- Time for image processing of scanned data (this can vary for each scan).
- Communication of seam data from the supervisory controller to the robot controller over the RS-232C serial interface.
- Time for transferring the data from the robot controller I/O buffer to the point table by the background processes.

The total time required for the above processes should be less than the time required to move the torch from one location to the next. Failure to do so may result in a slower welding process.

Conclusions and Test Plans

The concepts and a preliminary design for the ARTIST, a real-time intelligent seam tracker for automation of arc welding processes, have been presented in this report. The ARTIST uses a robot held, laser based vision system where the information of 3D seam geometry is collected and processed for real-time guidance and control of the welding torch trailing behind the vision sensor. This approach eliminates the need for preprogramming of the weld path and thus, potentially enhances welding applications.

The ARTIST is designed to support multiple pass arc welding of single V-preparation joints and to handle any tack welds which are encountered along the seam during the welding operation.

The first setup of ARTIST is scheduled to be tested for a planar seam with lateral variations. For most of our applications, the radius of curvature of the seam in the lateral plane is expected to be greater than the critical, which is approximately the distance between the torch and the scanner. At a later stage, a welding table with two degrees of freedom is planned to be introduced to reach points in a seam with 3D variations. The critical radius of curvature in the transverse plane is a function of the distance between the torch and the scanner, and the range of the scanner, which is within ±15 mm of 10 inches. The control algorithm for coordinating the welding table movements with the robot is in the process of being developed.

Presently, the safety aspects of the robot, welding torch and the sensor are planned to be enforced via the safety devices that are supplied with the robot controller. On actuation, these devices switch off power to the robot subsystems. Also the weld torch is mounted on a break-away mount for added protection.

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