Robotic Seam Tracking

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CMU-RI-TR-84-10

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April 1984

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Abstract

The principles of contact and non-contact sensors for robotic seam tracking are reviewed. Non-contacting sensors are based on either an electromagnetic or an acoustic principle. Electromagnetic sensors in the low frequency regime induce eddy currents which can be used for the detection of surface discontinuities. In the high frequency regime (visual spectrum), laser light stripe systems in connection with vision cameras can be successfully used for seam location. Other optical systems and infrared thermography are briefly described. Alternatively, acoustic systems using time of flight measurements can be applied to the characterization of seams. Finally, *through the arc* systems and their limitations for seam tracking are outlined. The need for off-line programming techniques for pathplanning with seam tracking devices is emphasized.

1. Introduction

Automatic seam-tracking is important to a number of manufacturing operations. The availability of sensor based seam tracking and part location systems has become crucial ever since industrial robots have been used in processes like arc welding, glueing or sealing. Around the world, researchers are competing to be the first to produce a general purpose sensor which can be used for adaptive control in robotic seam tracking.

Thus far, several contacting and non-contacting seam tracking devices have been developed, and a few are commercially available. However, none of these seam tracking systems can be shown to meet all requirements of the arc welding users. Numerous lists of the requirements which a seam tracking device must fulfill were established in the past. The authors consider the following points as important:

- General purpose: The same system should be usable for different weld geometries.
- Ruggedness: The system must be functional in an industrial environment.
- The system should be usable in connection with different arc welding techniques.
- The system should operate in real time: Position and weld parameters can be adapted to the welding situation.
- The system should provide three dimensional information on the seam and fit up.
- Sensing devices should be relatively small in size so as not to limit the motion of the arc welding torch.
- The sensory system should be inexpensive in comparison with the total cost of the robotic arc welding system.

2. Seam Tracking Devices

Seam tracking systems presently being investigated may be divided into two major categories: tactile and non-tactile.

Tactile probes are attractive because of their simplicity and reliability [1]. The touch sensor usually consists of one or more LVDTs. Sets of strain gauges mounted on a probe which can elastically deflect are also common. However, in using tactile probes it is difficult, if not impossible, to provide information on the joint fit up. Furthermore, certain weld geometries, e.g., welding into corners, exclude the use of contacting sensors.

In addition to seam tracking, tactile sensors may provide very useful information on overall part location. Let us assume that the parts to be welded together have some simple, well defined geometrical features such as locally plane regions or circular cross section, etc. In these cases, the use of tactile probes can reduce the complexity of real time sensors. The welding of pipe joints is one example where simple touch, e.g., electrical contact between the welding wire and the workpiece surface, allows one to determine the geometry of the pipe intersections and automatically generate a robot welding program. However, if poor fit up or random deviations of the joint intersection prohibit this simple approach, a combination of a part location sensor, e.g., simple touch, with a real time seam tracking system may provide the highest degree of flexibility. The touch sensor detects systematic deviations from the pre-programmed position. The seam tracking system corrects random deviations along the seam trajectory.

The majority of the research projects in seam tracking today focuses on non-tactile sensors. The following sections describe physical principles of non-contacting sensors for seam tracking purposes. Fundamentally, there are only two ways in which information can be transmitted in a non-contact fashion: by acoustic waves or electromagnetic waves. There is a wide spectrum of frequencies available in which non-contact sensors may operate. A sensor emitting electromagnetic waves at a frequency between 10 to 100 khz would typically be referred to as a *magnetic* sensor. Frequencies of approximately 100 Thz have been used in laser light stripe systems, weld pool vision systems, laser scanners and systems based on arrays of photodiodes. Attempts have also been reported on the use of infrared (10 Thz) cameras looking directly at the weld pool. There is a basic difference in how geometric information is obtained through acoustic and electromagnetic waves. This is due to the large difference between the speed of sound and speed of light. Acoustic sensors can easily be used in connection with time of flight measurements, i.e., measuring the time difference between emitting and receiving an acoustic pulse. On the other hand, optical systems operating at a distance of a few centimeters must use triangulation schemes to compute the distance between the sensor and the surface of the object.

Another possible non-contacting method for seam tracking is measuring changes in the welding current or arc voltage. Obviously, this seam tracking technique can only be used with arc welding, and as later discussed in this paper, only if certain geometric conditions are met.

In the following sections, we discuss currently used seam tracking systems and the principles on which they are based.

3. Vision and Structured Light

A common way of characterizing joint location and fit up in arc welding applications is depicted in Fig. 1. A so-called structured light source, a pattern of lines or a grid, is projected at a certain angle onto the surface of the object. The angle between the optical axis of the camera and the light source is constant. The camera's two dimensional image of the projected light stripe principally allows a three dimensional reconstruction of the joint geometry.

Significant progress was made, over the last few years, in the area of image acquisition and analysis. SRI [2] has developed a procedure for constructing weld joint models based on vision data. The true joint location is determined by comparing a model with the original joint prototype specified by the user. This system has been successfully used to control the motion of a robot in welding low carbon, hot rolled steel plates.

Although the light stripe approach seems very attractive, it has several drawbacks. The physical dimension of the camera and the light source normally moving ahead of the welding torch may prevent the torch from accessing walls and corners. Also, the distance between the light stripe projected on the object and the welding torch limits the radius of trajectories which can be negotiated with this system. Furthermore, the continuous exposure of both camera and light source to the welding environment, dust and spatter, results in reduced light intensity and decreased resolution. Interference of the bright arc with the illumination system represents a serious shielding or noise filtering problem. Both image filtering and three dimensional characterization by triangulation require significant computational support. The latter point is not so much a technical constraint, but an economic one.

The noise due to the arc can be overcome by using a so-called *two pass* system. First, the camera performs a search cycle locating and characterizing the seam. The information obtained is then used to adjust the nominal welding path. The welding cycle is started as soon as the search cycle is complete and all torch location points are properly adjusted. The search cycle can be carried out at a much higher speed than the welding cycle. In many manufacturing applications, the search cycle does not represent a serious through-put degradation. The disadvantage of this approach is primarily that local distortions during welding cannot be taken into account. These distortions are caused by thermal expansions of the material.

It should be noted that as an alternative to projecting a stationary light pattern onto the surface of the joints, the surface can be periodically scanned with a focused laser beam. Conceptually, the three dimensional surface pattern will be reconstructed in a way similar to that done with the light stripe.

4. Weldpool Vision

All previously described systems can only be applied to torch guidance. None can be applied to arc process control. Based on a concept originally proposed by Richardson [3], GE has built a vision system in which changes in the weld puddle and the joint are obtained as viewed coaxially with the torch electrode. Puddle geometry is thus monitored, and parameters like puddle size can be used to control welding parameters. Furthermore, a joint tracking system based on structured light is incorporated in the GE weld vision system. The system, as demonstrated during the last AWS show, Philadelphia 1983, could be applied to TIG welding with a speed of 6 inches per minute. Extensions of that system to MIG, which require much higher welding speeds, were reported under development.

5. Arrays of Photodiodes

A robust seam tracking system, as shown in Fig. 2, was developed by P. Drews [4] at The University of Aachen, W. Germany. In this tracking system, a halogen light source is transmitted via fiber optics to the sensor system. (In the halogen light frequency range, the light intensity of the welding arc was shown to be minimal.) An elliptical light spot is projected onto the joint, and a linear array of 256 photodiodes measures the reflected light intensity. The recorded intensity pattern is then related to the actual geometry of the weld joint. The seam geometry is found by determining the relative intensity normal to the seam trajectory. Lower density indicates a longer distance between the sensor and the surface of the workpiece.

6. Infrared

The information content of infrared light emitted from the weld pool has been investigated [5]. The results showed that arc misalignment, groove geometry faults, variations in penetration and impurities could, in principle, be detected by infrared thermography. While such systems are likely to have long term impact on adaptive welding control, significant amount of research still needs to be done to fully expedite their potential for industrial applications.

7. Magnetic Fields

The alteration of magnetic fields by induced eddy currents in electrically contacting media is a simple mechanism by which surface discontinuities, i.e., edges or gaps, can be detected. Fig. 3 shows the geometry of a sensor which can be used for seam tracking applications. Without the presence of the workpiece, two symmetric alternating magnetic fields would be induced. Naturally, the same potential is induced in the sense coils underneath the inducer coils. The presence of a conducting medium (as indicated in Fig. 3) will cause the induction of eddy currents which in turn tend to modify the originally symmetric flux field. According to asymmetries in the workpiece, different potentials are induced in the two sense coils. This difference provides a simple means for locating surface discontinuities. A prototype of the described system was developed at Carnegie-Mellon University [6]. Extensions of that system into arrays of inducers and sensors are currently under development. This system provides and excellent tool for providing measurements of the relative position of gaps or edges in the surface to the sensor. Absolute distance information is possible only if the magnitude of the induced signals is calibrated with respect to a specific material. Another drawback is the need to keep the sensor relatively close to the workpiece (less than 1/2").

8. Acoustic Waves

Acoustic waves can be used to perform a three dimensional characterization of workpiece surfaces. To extract range information, acoustic systems typically use a pulse technique originally developed by Pellam and Galt [7]. The sensing system utilizes a piezoelectric transducer to convert electrical energy into ultrasonic energy, and vice versa. The same sensor, therefore, acts as emitter and receiver. The attenuation of the ultrasonic wave by the medium of propagation constrains the choice of the transducer's resonant frequency. Ultlrasonic waves propagated through air are attenuated in proportion to the square of the frequency. Consequently, the resonant frequency should be chosen as low as possible. To overcome some of the attenuating losses, the transducer's primary transmission surface is spherically concave, resulting in a focused ultrasonic wave.

Other considerations suggest choosing a high operating frequency. High frequencies produce narrower radiation patterns and lead to better resolution when sampling the distance from the transducer to a point on the workpiece surface.

By performing a periodic two dimensional sampling of the distance to the workpiece, moving the sensor back and forth as indicated in Fig. 4, a complete surface characterization can be performed, including seam position. A major problem encountered in the surface characterization process is caused by the limited aperture of the acoustic sensor. In a prototype system developed at Carnegie-Mellon University, the sensor's line of sight must not deviate from the surface normal at the sampling point by more than approximately 5 degrees (sensor frequency 1 Mhz). Otherwise, the amplitude of the received echo is insufficient to provide reliable range information. However, knowing approximately the local surface orientation of the workpiece, which is a reasonable assumption in a manufacturing environment, the sensor can be maneuvered into its angular region of proper operation. Another inherent problem with acoustic waves is the temperature dependence of the speed of sound. In single pass welding, this problem is largely overcome by shielding the sensor from the arc and real time speed of sound calibration by using a reference transducer. More serious problems are expected in multipass welding applications.

Alternatively to time of flight measurements, it is possible to monitor the interference pattern between the emitted and the reflected waves. The interference pattern can be sampled by arrays of microphones at specific locations around the object [8]. Changes in the object's shape will result in changes in the interference pattern. While this system was originally designed for inspection of parts, its principle appears applicable for robotic seam tracking.

9. Through the Arc Sensing

The most common non-contacting seam tracking system today uses arc feedback as the basic control signal. Extensive measurements in the past have shown that the average welding current, or average arc voltage, is proportional to the distance between the electrode and the work piece [9]. Hence, executing a weaving motion with the welding torch normal to the seam trajectory reveals the surface profile of the joint. Weaving of the torch may be accomplished by simple mechanical oscillation or by having the plasma oscillate in an alternating magnetic field. Higher oscillation frequencies, and consequently a more precise seam characterization, can be accomplished with the alternating magnetic field. However, this approach may involve space intrusion problems since the magnetic field generator must be mounted relatively close to the torch tip.

Two control algorithms for *through the arc* sensing have been investigated: template matching and the conceptually more simple differential control. Template matching assumes the availability of a template signal. This signal is expressed as a function of the displacement with respect to the center of the arc weave pattern. The torch must be guided so that the integrated difference between the template signal and the actual signal is minimized.

The difference control strategy simply tries to minimize the difference between the signals obtained at both extremes of the oscillating motion.

Similar to the horizontal control strategy, the vertical distance between the torch and the workpiece can be controlled by comparing the signal as measured at the center of the oscillation to a predetermined vertical current reference.

Through the arc sensing has been successfully tried with a number of different arc welding processes including TIG, MIG, fluxed-core and Submerged arc welding.

Major drawbacks of through the arc sensing result from the fact that the dimensions of the joint must exceed some critical dimension, e.g., through the arc sensing today is not applicable to sheet metal welding. Another principal problem is that a signal can be obtained only after the arc has been established. This means that this method cannot be used for finding the starting point of the weld.

Most manufacturers of arc welding robots offer the integration of *through the arc* systems into their robot controller.

10. Adaptive Control Strategies for Robotic Seam Tracking

Most experiments to date involving real time seam tracking allow at most three degrees of freedom of adaptive change. These degrees of freedom typically refer to the workpiece frame rather than the joint frame of the robot. Ideally, one likes to adjust both position and orientation, i.e., six degrees of freedom, of the tool mounted at the end effector of the robot. More research needs to be directed towards the development of general purpose algorithms which can be executed on today's microprocessors.

A recent analysis [10] using an inverse Jacobian[1] approach showed that a full six dimensional adaptive

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[1] The Jacobian is the differential of the manipulator transform.

trajectory control can be carried out with a frequency of about 30 Hz (Intel 8086/8087). for most welding applications, a control cycle frequency of approximately 10 Hz appears sufficient.

A complication in using preview sensors[2] stems from the need to know exactly the transform relating the tool (torch) and the sensor. Since the chances of misalignment in a manufacturing environment are great, automatic calibration procedures will become mandatory.

Finally, the availability of seam tracking sensors will reduce the robot programming effort since fewer points along the seam trajectory will need to be pre-programmed. On the other hand, the coordinated motion of both sensor and the welding torch, while avoiding interference with obstacles like fixtures, is likely to increase the overall complexity of robot programming. Further complications are due to programming of recovery strategies in the event the sensor fails to obtain a healthy reading. The recovery strategies will differ for different applications and might even require user input. In view of these complications, it is assumed that techniques such as off-line path planning and off-line programming will become vital steps in the successful implementation of robots with seam tracking systems.

11. Summary

The principles of several seam tracking devices have been discussed. The majority of these devices are still in the trial stage, and very little industrial experience with regard to these seam tracking sensors is presently available. Therefore, it is not possible to say what system will ultimately succeed; most likely, a combination of a *through the arc* system with an appropriate preview sensor will prove the most satisfactory.

12. Acknowledgements

This work was supported by the Welding Consortium, The Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA.

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[2] All the aforementioned sensors, except through the arc, are called preview sensors since they locate the seam ahead of the torch.

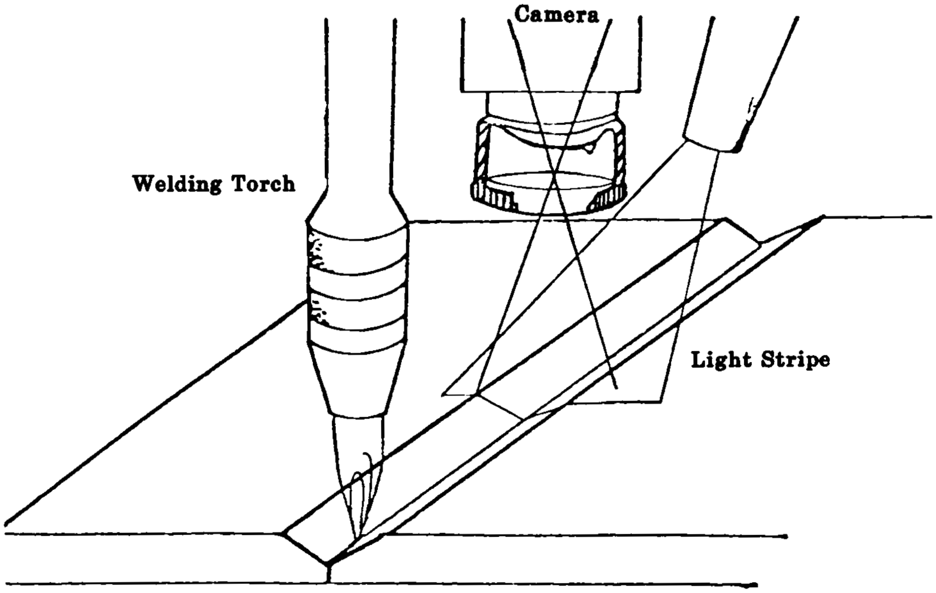

Fig. 1. Structured light stripe system.

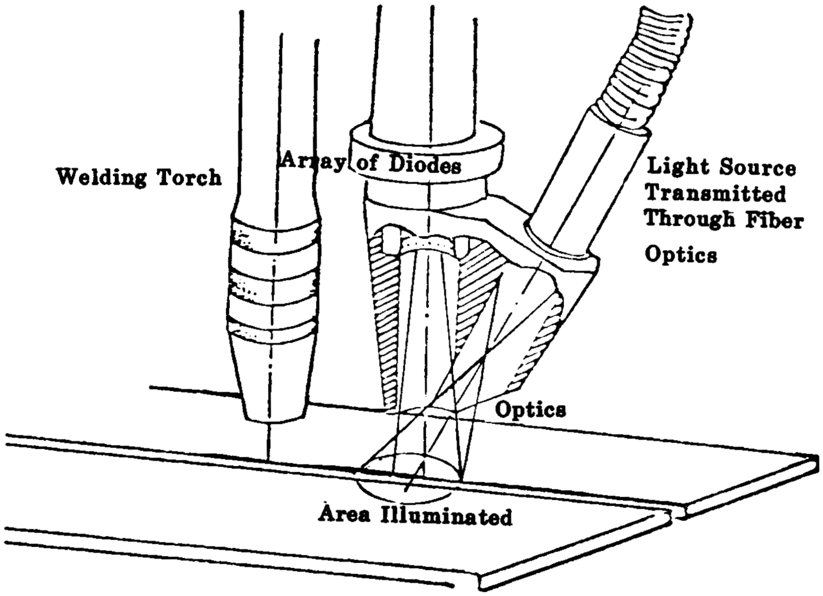

Fig. 2. Joint characterization by linear array of photodiodes.

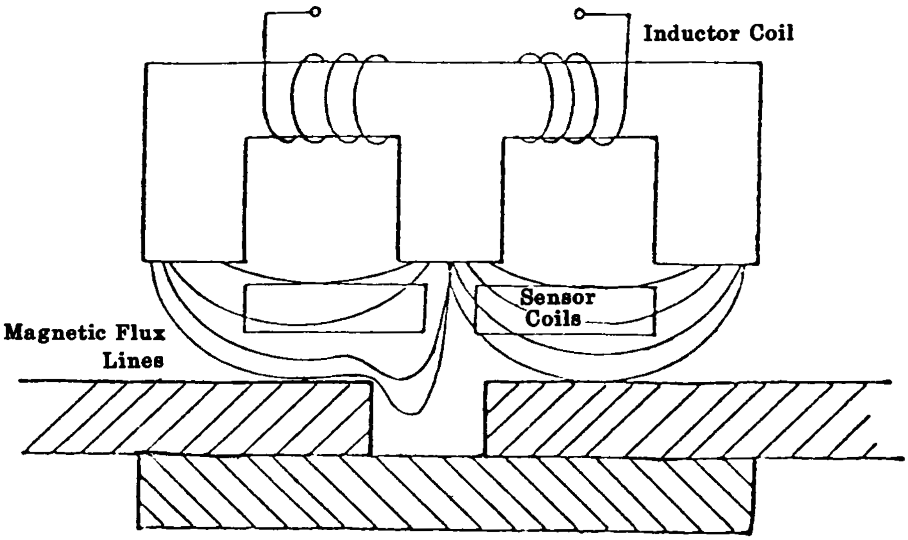

Fig. 3. Detection of surface discontinuities with ultrasonic sensor.

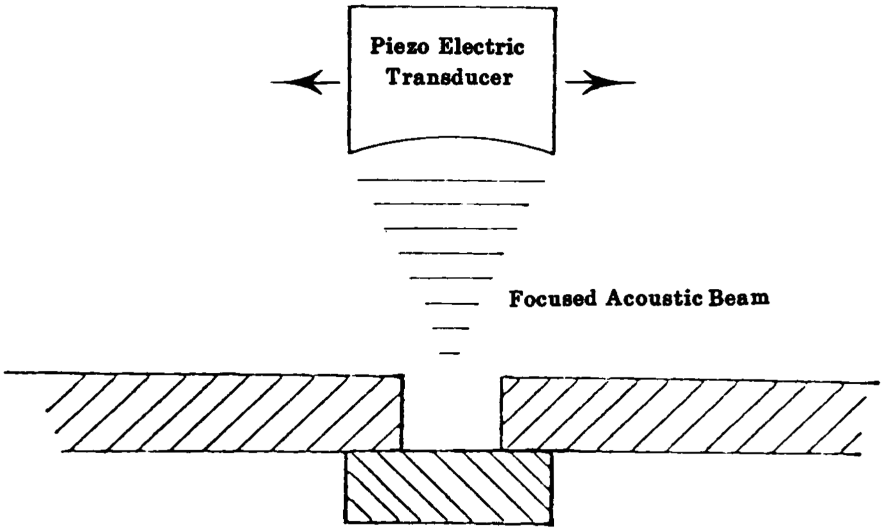

Fig. 4. Detection of surface discontinuities with magnetic sensor.

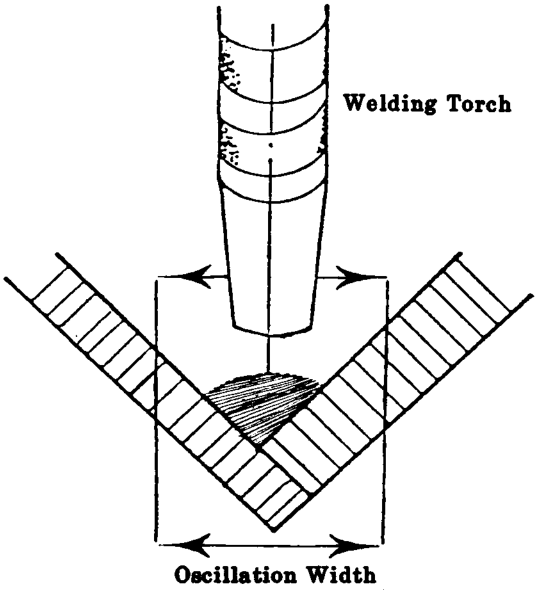

Fig. 5. *Through the arc* sensing system with an oscillating torch.

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