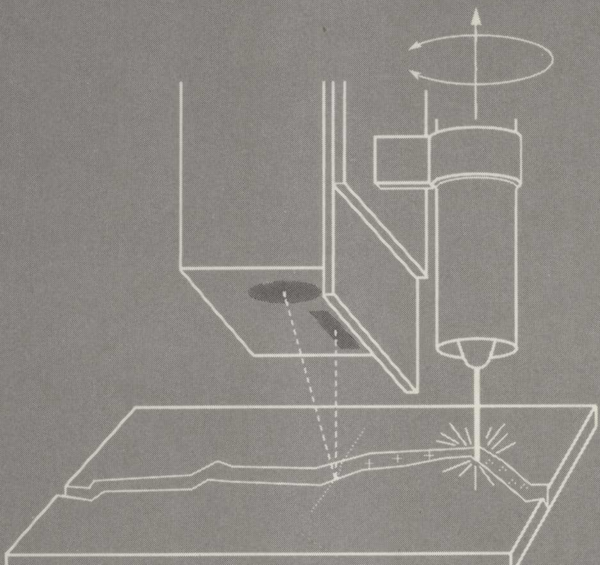
Nitin Nayak and Asok Ray

# INTELLIGENT SEAM TRACKING FOR ROBOTIC WELDING



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# Intelligent Seam Tracking for Robotic Welding

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# Intelligent Seam Tracking for Robotic Welding

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# SERIES EDITORS' FOREWORD

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology impacts all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computing methods, new applications, new philosophies, . . ., new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

In the field of robotics, the classic repetitive manufacturing tasks which have been automated by robots are paint spraying and spot/seam welding for the car industry. This monograph reports advances in robotic science for the operation of seam welding. It presents a systematic treatment of the prevailing industrial technology and a new state of the art intelligent robotic seam welding prototype system on which the authors, Dr Nayak and Professor Ray, collaborated. The authors have made a determined effort to set their work in the context of international robotic seam welding research and conclude by reviewing seven other international prototype systems. The mix of specific research issues and the review of broader research activities reported makes this a particularly welcome contribution to the Series.

*October, 1992*

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# PREFACE

Robotic welding is critical to welding automation in many industries. "Blind" robotic welding systems, however, cannot adapt to changes in the joint geometry which may occur due to a variety of reasons. For example, in systems following pretaught weld paths, in-process thermal distortion of the part during welding, part fixturing errors, and out-of-tolerance parts will shift the original weld path, leading to poor quality welds. Essential to accurate seam tracking is some form of joint sensing to adjust the welding torch position in realtime as it moves along the seam. Realtime seam tracking is attractive from the perspective of improving the weld quality and also reducing the process cycle time. In this monograph, we have addressed the technological aspects of adaptive, realtime, intelligent seam tracking for automation of the welding process in the context of three-dimensional (3D) seams.

The work reported in this monograph builds upon the research conducted during the course of project ARTIST (acronym for Adaptive, RealTime, Intelligent Seam Tracker) at the Applied Research Laboratory of the Pennsylvania State University, USA. The research project ARTIST was sponsored by the BMY Corporation of York, Pennsylvania, USA, and the Commonwealth of Pennsylvania to address requirements of welding steel and aluminium plates and castings used in the manufacture of heavy duty battlefield vehicles. A prototype version of ARTIST was designed and developed for tracking and welding planar seams. Since ARTIST was expected to encounter mostly slip joints during welding, the algorithms for seam tracking are predominantly based on the analysis of vee-grooves. The objective was to demonstrate the proof of concept, develop a prototype of a seam tracking system, and integrate it with the welding equipment for realtime operation.

The ARTIST system comprised of a six degree-of-freedom robot (PUMA 560 robot manipulator with Unimate controller), a laser profiling gage (Chesapeake Laser System), a PC-AT microcomputer serving as the supervisory controller, and welding equipment (Miller Electric Deltaweld 450 welding controller and a Miller Electric S54A wire feeder). At the end of the one year development period, the system was capable of tracking planar seams. The promising results motivated us to extend the scope of this system to tracking general 3D vee-jointed seams. Based on the data collected from real samples, we developed and tested algorithms for interpreting joint features in range images under conditions of variable position and orientation relationship between the sensor and the 3D seam. The analysis of seam tracking error is based on our experience with the operation of the ranging sensor and real joint geometries.

This monograph covers up-to-date and relevant work in the area of intelligent seam tracking. In contrast to many seam tracking systems that have been developed in the past for operation within well-defined working environments, this monograph primarily addresses the tracking of seams in unstructured environments. Essential to tracking seams within such an environment is some form of joint sensing. Chapter 2 provides an overview of the various sensing techniques while Chapter 3 covers the basic principles of processing intensity and range images for extracting and interpreting joint features, and the development of 3D seam environment models. Chapters 4 and 5 discuss the various coordinate frames and robot motion control issues related to seam tracking. Implementation details regarding development of a seam tracking system based on off-the-shelf components are presented in Chapter 6 and the various tracking errors are analyzed in Chapter 7. Finally an overview of the approaches used in existing seam tracking systems is presented in Chapter 8, and possible directions for future intelligent, realtime seam tracking are discussed in Chapter 9.

This monograph is directed towards readers who are interested in developing intelligent robotic applications. Although this work is presented in the context of seam tracking, the issues related to systems integration are general in nature and apply to other robotic applications as well.

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# CONTENTS

# CHAPTER 1

## INTRODUCTION

In the present day global marketplace, manufacturing organizations are facing national as well as international competition, forcing them to further improve their performance. To this effect, the concepts of *computer-integrated manufacturing* (CIM) (O'Rourke 1987) have been introduced in various production environments with the intent of:

- Improving human productivity at all levels;
- Improving product quality;
- Improving capital resource productivity;
- Providing rapid response to the market demands.

The CIM strategy is to integrate the information bases of the various units of automation (e.g., design, engineering, manufacturing, and office administration including, accounting, marketing, and sales) within the traditional framework of manufacturing. In this respect, CIM can be viewed as a closed loop control system where a typical input is the order for a product and the corresponding output is the delivery of the finished product.

Automation of the physical production processes on the shopfloor is a key component of the CIM strategy for improving productivity. In this context, robots have played an important role in the automation of various operations. Robots have been successful in automating simple and repetitive operations while simultaneously enhancing the quality of manufactured products in many production areas. The use of robots is also highly desirable in hazardous manufacturing operations such as spray painting, welding, etc., which pose known health risks to human operators. Although attempts have been made to precisely define the functions and characteristics of a robot, it can be generally defined as any automated machine that operates with the aid of computer-based sensors, controllers and actuators.

Before proceeding into the details of using robots for welding applications, an overview is provided of the various production processes where robotic solutions have been successful in the industry (Chang et al., 1991).

## 1.1 INDUSTRIAL ROBOTIC APPLICATIONS

**Spray Painting.** Spray painting is the earliest and one of the most widely used applications of robots in industry as this task is hazardous to human health and safety and does not require much intelligence. In addition, a robot uses less paint and produces coatings which are much more uniform than is usually possible manually. Several robotic spray painters can be programmed to simultaneously execute a given task with each robot following a continuous path along a straight or curved line. A spray painting robot normally does not require the use of external sensors. However, the part to be painted must be accurately presented to the robot manipulator.

**Grinding and Deburring.** Grinding is necessary to produce a smooth surface for a good appearance or for producing parts within required tolerance after a rough operation such as arc welding. This job is well suited for a robot which can perform the assigned task sequentially with its previous operation, say, arc welding by simply replacing the welding torch with a rotary grinder. To provide a finished surface on metal castings and for removing any undesirable high spots, the robot is taught to move along a continuous path corresponding to the correct shape of the casting. Robots have also been successfully used for deburring operations wherein the unwanted material around the back side of a drilled hole is cleanly removed to leave a smooth surface. In general, for grinding operations, uncertainties exist in the dimensions of the workpiece. This necessitates the use of sensory information to accurately assess the contour of the part. For example, in smoothing an arc welding bead, simple tactile sensors provide information about the surface contour to the robotic grinders.

In addition to rotary grinding and deburring applications, robots are also used for routing, drilling, honing, polishing, tapping, nut running, and screw driving. Although preprogramming of tool points or paths is sufficient in many cases, exact placement of drilled holes, such as those on aircraft structures, requires a template and a compliant-wrist robot.

**Parts Handling, Transfer, Sorting, and Inspection.** Moving parts from one location to another or picking parts from conveyors and arranging them on pallets is one of the most common applications of robots. Other parts handling operations include feeding unfinished parts into machines such as a lathe, punch press, or a furnace. Such simple and repetitive operations are well-suited for robots although they could be dangerous for human workers.

Pick-and-place robots in sophisticated workcells can sort individual parts from batches of unsorted parts when, for either cost reduction reasons or because of tolerance variations in the manufacturing process, dissimilar parts are grouped together. Robots, equipped with appropriate grippers, acquire the parts and bring them to the workstations where a gaging device informs the robot controller of the type and dimensions of the parts in order to place them in the correct bin. In some applications, vision systems are used to determine the type and orientation of the part on a conveyor. The vision systems are located upstream of the robot and the part information is passed to the robot controller after inspection. This allows the manipulator to move to the correct location with appropriate gripper orientation and pick up the part from the moving conveyor.

Vision sensors mounted on robot endeffectors have been used to inspect finished parts or subassemblies in order to increase product quality. Examples are inspection of parts of automobile bodies and printed circuit boards used in electronic devices.

**Assembly Operations.** Assembling a group of parts into a subassembly or a finished product for bulk production is an extremely repetitive and mundane job for human workers. Servo-controlled robotic assemblers can execute this task using hand-eye coordination techniques and tactile sensing. There have been many applications of simple tasks in electronic industry where robotic assemblers are routinely used. However, as the complexity of assembly operations increases, sophisticated robots with external sensors (vision or tactile) and compliant wrists are necessary.

## 1.2 AN OVERVIEW OF ROBOTIC WELDING

As much as 40% of all industrial robots are being used for welding tasks (Ross 1984). Robotic welding is being initiated to satisfy a perceived need for high-quality welds in shorter cycle times. Simultaneously, the workforce can be shifted from welding to other production areas with higher potential productivity and better environmental quality.

Manual welding must be limited to shorter periods of time because of the required setup time, operator discomfort, and safety considerations. Consequently, manual arc welding is less than 30% of the total operator working time (Boillot 1985). In contrast, the welding time fraction is above 85% for a welding robot, yielding an increase in productivity by a factor of 2.8, assuming that the same welding speed is followed in both the cases. As a result, robotic welding has become highly pervasive in the automobile industry.

Welding operations that can be effectively carried out by an industrial robot can be classified into two categories: (i) spot welding; and (ii) arc welding. In spot welding, the robot is first taught a sequence of distinct locations which are stored in the robot's memory. The robot sequentially positions the spot welding gun at these locations during the actual production cycle. Because of the irregularity of the parts to be welded, a (three-dimensional) wrist is often necessary for dexterous positioning of the spot welding gun. The use of heavy welding tools and the reasonably long reach required of the robot manipulator implies that the servomotors for joint movements should be sufficiently strong to avoid undesirable vibrations. However, since the robot activities are pre-taught, no sensory information is needed for feedback control.

The arc welding environment, on the other hand, may require the movement of the torch along irregular seams or the filling of wide joints. A continuous-path servo-controlled robot is often designed for a specific type of welding application. For robotic welding along preprogrammed paths, it is necessary that the parts to be welded be accurately positioned and correctly held in place in order to teach complex three-dimensional paths. Additionally, during welding the parts should be presented to the robotic welder in precisely the same position and orientation. If these stringent part positioning and path programming conditions can be met, then no position sensing is necessary.

Many robotic welding systems, however, do not adapt to realtime changes in joint geometry and therefore, have only limited success in many welding applications. Thermal distortion from the intense heat of the welding arc can cause these changes in the joint geometry. Such variations are also caused due to fixturing errors or improper preparation of the weld joints. Hence, to produce high quality welds through mechanization, strict tolerances are necessary in both joint preparation and fixturing the weldpieces. A solution to this problem requires sensing the joint geometry to properly position the welding torch along the seam in realtime. Techniques for joint sensing have been based on mechanical, electrical, magnetic, and optical sensors, with each method having specific advantages and disadvantages in a given production situation (Brown 1975; Richardson 1982). However, the two most commonly used techniques are through-the-arc sensing (which uses the arc itself to guide the torch) and vision sensing. An overview of seam tracking technology is presented in Chapter 2.

Since the early days of robotic welding, much progress has been made, especially in the area of seam tracking, i.e., moving the torch correctly along the seam.Seam tracking Early systems required the use of separate learning and welding steps. However, this two-pass system becomes very time-consuming when complex seams have to be manually taught, and so requires a large batch-size to justify its use. Furthermore, such a system cannot adjust to the variations in joint geometry that result primarily from thermal distortion during arc welding.

Efficiency of robotic welding can be increased if both, sensing and welding of the seam can be carried out in the same pass. This is clearly an improvement over two-pass welding (popularly known as *first generation* welding systems), where the first pass is dedicated to learning the seam geometry followed by actual tracking and welding in the second pass. The *second generation* welding systems, on the other hand, track the seam in realtime and are characterized by the absence of a separate learning phase i.e., the welding system simultaneously learns and tracks the seam.

The second generation systems, however, are capable of operating only in well-defined welding environments. Some systems accomplish realtime seam tracking by exploiting a special feature of the robot or by dedicating their application to a particular type of seam. In one application, the seam is constrained to lie on a cylindrical surface (Bollinger, et al. 1981). Yet another scheme for controlling the welding torch's position and velocity is applicable only for two-axis control, thereby constraining the seam to lie in a plane (Tomizuka 1980).

The advances in the realtime seam tracking techniques of the second generation are characterized by the following features (Niepold 1979; Linden and Lindskog 1980; Vanderbrug, et al. 1979):

- Usage of vision sensing,
- Techniques to reduce the adverse effects of optical noise from the welding arc,
- Usage of pattern recognition algorithms for extracting the seam's features from its images.

The next generation of welding systems is required not only to operate in realtime but also to learn rapidly changing seam geometries while operating within unstructured environments. In contrast to well-defined working environments, wherein the seam-related information associated with each image is known *a priori*, the unstructured environment is characterized by the absence of this knowledge. The system has knowledge about all the possible scenarios it may encounter along the seam, but the actual sequence of their occurrence is unknown. These welding systems belong to the so called *third generation*, and use concepts from artificial intelligence (AI) to learn and model the global seam environment (Begin, et al. 1985) in order to control the torch-seam interaction.

## 1.3 OUTLINE OF THE MONOGRAPH

This monograph covers up-to-date and relevant work in the area of intelligent seam tracking, and specifically presents the development of a third generation seam tracking system for robotic welding, called the Adaptive, Realtime, Intelligent Seam Tracker . ARTIST is essentially a single-pass system, characterized by the absence of an additional teaching phase. It essentially comprises of a welding torch and a laser range sensor mounted on the endeffector of a six-axis robot. A seam in space can be traced by a five degree-of-freedom (DOF) robot manipulator. However, realtime seam tracking requires that both the sensor and the torch trace the seam, thus requiring a six DOF robot. As illustrated in Figure 1.1, the spatial relationship between the welding torch and the ranging sensor permits scanning the region immediately ahead of the torch. The bracket supporting the torch-sensor assembly is mounted on the endeffector and allows the ranging sensor to rotate ±90 degrees about the torch axis for proper orientation relative to the seam.

The following chapters discuss issues related to the various aspects of realtime intelligent seam tracking in an unstructured environment. Chapter 2 provides an overview of the various applicable sensing techniques while Chapter 3 covers the basics of processing intensity and range images for extracting and interpreting joint features, and the development of 3D seam environment models. Chapters 4 and 5 discuss the various coordinate frames and robot motion control issues, respectively, as related to seam tracking. A discussion on the implementation details for developing a seam tracking system based on off-the-shelf components is discussed in Chapter 6, and the analysis of various tracking errors is presented in Chapter 7. Existing seam tracking systems developed across the world are reviewed in Chapter 8 for the benefit of the reader and possible future directions for intelligent, realtime seam tracking are presented in Chapter 9. The reader may note that the issues related to