INL/CON-08-14897
PREPRINT

Robotic Welding and Inspection System

Trends in Welding Research, 8th International Conference

H. B. Smartt
D. P. Pace
E. D. Larsen
T. R. McJunkin
C. I. Nichol
D. E. Clark
K. L. Skinner
M. L. Clark
T. G. Kaser
C. R. Tolle

June 2008

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint should not be cited or reproduced without permission of the author. This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the United States Government or the sponsoring agency.

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

Robotic Welding and Inspection System

H. B. Smartt, D. P. Pace, E. D. Larsen, T. R. McJunkin, C. I. Nichol, D. E. Clark, K. L. Skinner, M. L. Clark, T. G. Kaser and C. R. Tolle
Idaho National Laboratory, Idaho Falls, Idaho, USA
Herschel.Smartt@INL.gov, (208) 526-8333

Abstract

This paper presents a robotic system for GTA welding of lids on cylindrical vessels. The system consists of an articulated robot arm, a rotating positioner, end effectors for welding, grinding, ultrasonic and eddy current inspection. Features include weld viewing cameras, modular software, and text-based procedural files for process and motion trajectories.

Introduction

The general problem of interest is development of robotics technology to weld, inspect, and repair various cylindrical vessels or containers in a hot cell environment. We are interested in performing such work remotely in very high radiation fields. Prior work [1] discussed the design of a hypothetical robotic system for weld closure of high level waste disposal containers in a hot cell environment. The work considered several conceptual system designs and concluded that one of the designs, employing articulated robot arms and multiple end effectors, appeared to meet the anticipated system performance requirements. Subsequent work [2] discussed research on the evolutionary design of control systems for various machines including a robotic welding cell. The emphasis of the work was achieving modularity of machine design and removal of both process and machine details from the machine control source code. Those efforts led to a conclusion that a full scale test bed was needed to support continued research. This paper discusses certain details of the test bed design.

System Requirements

In this section we consider the main system requirements influencing system design; a comprehensive discussion of all system requirements is beyond the scope of this paper. The dominant performance requirement is efficient operation in a very high radiation field. Efficient operation is measured in terms of system productivity (e.g. number of units welded per unit time). The radiation field used as a basis for design is on the order of 10^3 rad(Si)/hr above the top of the cylindrical vessel and on the order of 10 to 10^2 rad(Si)/hr to the side of the vessel. In all cases we are interested in, the cylindrical vessel is oriented with the axis of symmetry being vertical. The design radiation field consists mainly of gamma particles, but neutrons may also be emitted.

At these high radiation levels, welding and related operations need to be done without personnel present, resulting in a need for robotic systems. The radiation is of sufficient intensity to pose a significant operational hazard to various components of the welding and inspection equipment, including electronics, electrical insulation, lubricants, seals, bearings, drive belts, and other components. Material and component lifetimes and ability to function (in the case of video cameras, for example) are issues requiring careful selection of both [3]. Although radiation-hardened components can be used, they are expensive; a solution is to either shield such components or locate them out of the radiation field. Although it is possible to incorporate radiation shielding into the design of robotic systems, we chose not to deal with this significant burden on the design process. This adds cost to such a system, but it significantly reduces the volumetric envelope of the system, frees up the work space envelope for system motion, aids in maintenance, and is readily achievable with commercially available products.

Next, we are concerned about motion control of the welding torch and tools used in association with weld inspection and repair. It is well known that placement of an object at any point in a workspace requires a motion control system having three axes of motion. Placement of the object at a given point with the object having a given orientation requires three additional axes of motion. Thus, six axes of motion (or degrees of freedom) are required [4]. These are generally represented as three orthogonal translation axes with rotation about each of the three axes, for a total of six degrees of freedom of motion, although other coordinate systems may be used. From this perspective, we can discuss placement of end effectors about a vessel during welding and inspection.

Consider welding a lid to a cylindrical vessel. Placement of a welding end effector at any point in (or near) a weld joint may be accomplished using three orthogonal translation axes of motion. This placement results in the welding torch being maintained in a constant orientation. If the torch were originally oriented with the centerline axis of the torch vertical, that orientation would be maintained during translations.

However, for some welds (e.g. fillet welds), the torch may need to be inclined at nominally 45 degrees from vertical in a plane orthogonal to the welding direction, requiring an additional 4^{th} (rotation) axis of motion. Other welds may require the welding torch to be oriented such that the top of the torch is tilted away from the direction of welding in a plane parallel to the welding direction, requiring an additional 5^{th} (rotation) axis of motion. Finally, the welding torch may need to be rotated about its centerline axis to ensure that the filler wire enters the weld joint without the wire guide contacting the weld joint. This requires a 6^{th} (rotation) axis of motion about the weld torch centerline axis.

We also consider the dimensional tolerances on placement of the welding torch and other tools. The welding torch will need to be positioned laterally within about ±0.1mm of the desired position over the weld joint during welding. Such positioning could be done directly by the robot or by a seam tracking mechanism located on the welding end effector. In the second case, the robot would need to position the welding end effector within about ±1mm of the desired position. The welding torch will also need to be positioned such that the electrode tip is within about ±0.1mm of the desired distance (in a direction parallel to the electrode centerline axis) from the weld joint or prior weld bead during welding to maintain proper arc voltage. Such positioning could be done directly by the robot or by an arc voltage control mechanism located on the welding end effector. In the second case, the robot would need to position the welding end effector within about ±1mm of the desired position. Positioning requirements for inspection systems are nominally within ±1mm of their desired positions.

We also consider trajectories of motion. The nominal welding and inspections operations are relatively simple, requiring circular motion about the centerline axis of the vessel in a nominally horizontal plane. The radius of such circles ranges from about 50 mm to about 3 meters. Due to factors beyond our control, the circular trajectories may be slightly tilted from the horixontal (locally in a weld joint up to about ±10 to ±15 mm), may be offset a considerable distance (up to about ±50 mm in all three principal directions) from the nominal center of the robot cell workspace, and there may be local deviations from circularity (up to about ±10 mm). In addition to the circular trajectories, it is necessary for the system to be able to store and retrieve several end effectors for a storage tray located adjacent to the work space and to retract fully from the work space to allow overhead cranes to place and remove other equipment and various vessels in the robot work space.

Finally, we need to consider control of the system. Various factors, including number of vessel sizes and configurations, dimensional tolerances on vessel components, and tolerances on placement of vessels in position for welding, lead to consideration of three cases for control of robot trajectory. First case, in which preprogrammed motion of the robot without sensor feedback control is adequate for welding. Second case, in which preprogrammed motion of the robot with sensor feedback control is adequate for welding. Third case, in which preprogrammed motion of the robot with sensor feedback control is not adequate for welding.

The major issues associated with control of the system are the large number of operations it must perform and motion trajectories that may be needed. In addition to performing multiple pass welding, the general closure procedure for a vessel requires preweld inspection of the weld joint, tack welding, inspection of tack welds, wire brushing of tack welds. pass-by-pass inspection of weld passes using one or more inspection methods, pass-by-pass wire brushing of weld passes, possible pass-by-pass grinding of weld passes including weld stops and any geometrical irregularities, removal of weld defects by grinding, inspection of ground cavities before repair welding, and possibly other operations depending on specific fabrication requirements. Regarding trajectories, in the hypothetical example presented in [Smartt, et al, 2006a] there were over 10^6 separate trajectories needed with most of these trajectories having arbitrary starting and ending points due to vessel positioning being uncertain prior to a closure production cycle.

Design Solution

The robotic system consists of a pedestal-mounted six-degree-of-freedom articulated robot arm operating in conjunction with a rotating positioner (Figure 1). Circular interpolation is performed using all seven axes of motion. The system has end

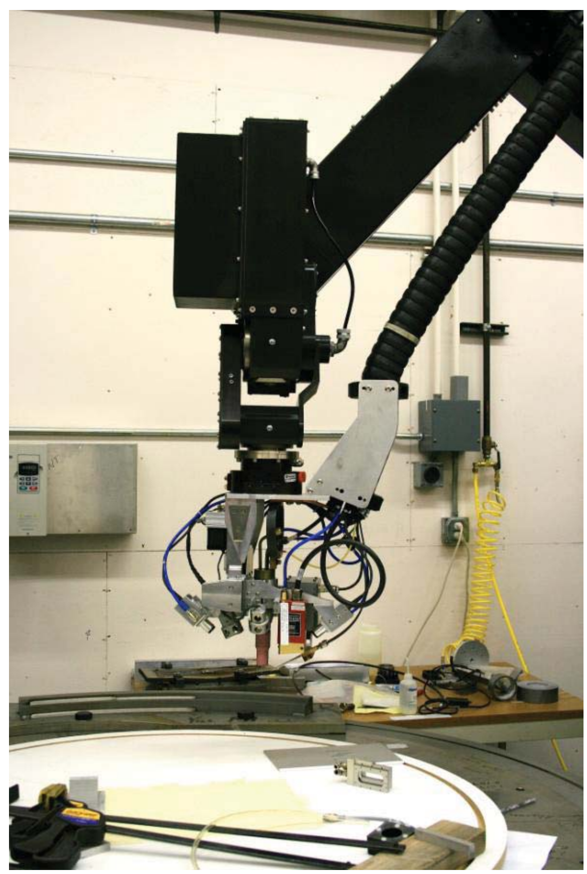

Figure 1: The robot arm with welding end effector mounted.

Figure 2: Welding end effector showing air cooled weld torch, weld viewing cameras, and laser line scanning sensor for visual weld inspection.

effectors for gas tungsten arc welding, weld dressing (grinding and wire brushing), ultrasonic and eddy current inspection, and eddy current inspection of weld repair grooves. Visual inspection of weld grooves, tack welds and weld beads is performed by means of a video camera/laser line scan sensor and weld interpass temperature is measured by a contact thermocouple. The weld end effector is shown in Figure 2 with two weld viewing video cameras aimed at the tungsten electrode and a laser line scanning sensor on the right side which is used for visual inspection of weld joints, tack welds, and weld beads. In our test bed we elected to use a radiation hardened robot, but used many non-radiation hardened components to reduce cost when such substitutions did not affect system performance.

The end effectors are stored behind the robot arm. Quick disconnect tool mounts are used between the robot arm and the end effectors. Additional tools are provided for filler wire trimming, electrode changing, electrode stickout adjustment and validation of inspection sensors.

Ultrasonic and eddy current inspection is performed by the end effector shown in Figure 3. Ultrasonic inspection is based on earlier work [5,6,7,8] which provides for pass-by-pass inspection at relatively elevated temperatures. The device employs membranes on the contact surfaces of the transducers to allow small quantities of water to be used as a means of providing a low impedance contact between the transducers and the vessel being inspected. Design precautions are taken to ensure that only small quantities of water could be lost during an off-normal event. Multiple transducers are used in order to have a sufficient number of sound paths to adequately inspect the volume of a weld. Specific details of the transducer arrangement depend on the geometry of a particular weld joint. The end effector also incorporates an array of eddy current transducers to facilitate surface inspection of welds.

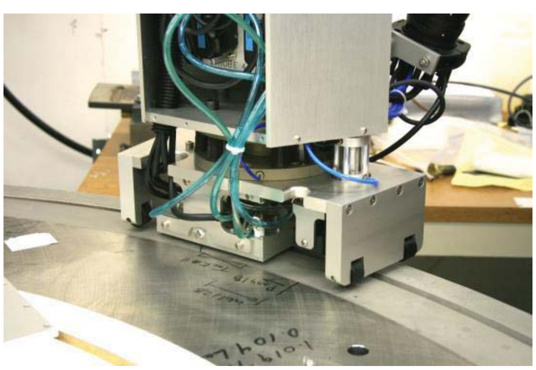

Figure 3: End effector for ultrasonic and eddy current weld inspection.

The weld dressing end effector is shown in Figure 4. This device incorporates a servo providing torque feedback control. The end effector has multiple uses, These include wire brushing to remove oxides and fume deposits from tack welds and weld beads, as well as grinding to remove subsurface weld defects located during inspection. Grinding is also used to correct geometrical irregularities of weld beads.

System control is accomplished by means of graphical human machine interfaces for each of the major system functions (welding, dressing, and inspection). Ethernet communications is used for high level system integration with both time-critical and non-critical subnets for control functions and data communications respectively. Design features include text-based procedural files for process and motion trajectories. Procedure and motion primitives stored in the text files are interpreted and converted into executable code at run time in a manner that allows large preweld uncertainty in vessel positioning [2].

A typical weld made using the system is shown in Figure 5. Two, two pass fillet welds made on a 316 stainless steel coupon are shown. These simulate a weld configuration on a particular large diameter vessel under development in our laboratory. A second, multiple pass, narrow groove weld is shown in Figure 6. This weld is from another vessel under development.

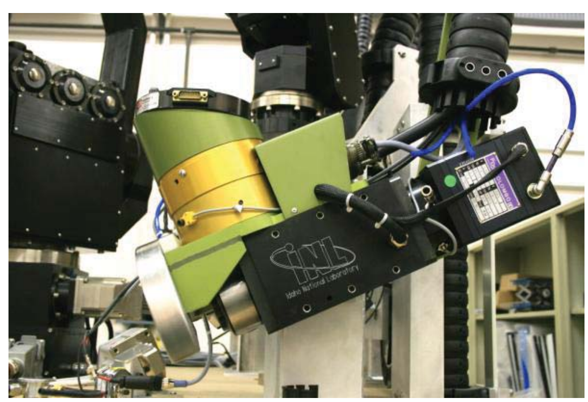

Figure 4: Weld dressing end effector used for wire brushing and grinding.

Figure 5: A pair of two pass fillet welds are shown in a 316 stainless steel coupon. This coupon simulates seal welds in a particular vessel under development.

Figure 6. A thick section narrow groove weld in a 316 stainless steel coupon.

Conclusions

Waste materials are normally contained within a metal vessel for long term storage or disposal. Various sizes and configurations of vessels exist, with one or more lids, with single or multiple vessels, and with purge ports for evacuation and backfilling with a suitable atmosphere. Internal and external shielding may be used to allow access of personnel during welding or shielding may not be provided thus requiring welding to be accomplished by completely remote means.

This system is being used to support development of technology for multiple customers. The overall program includes design of weld joints; specification of weld filler materials; development and qualification of welding, inspection and repair procedures; identification of geometrical constraints for ultrasonic inspection of welds, design of robotic end effectors, development of vessel closure procedures, integration of welding and inspection systems with other processes and equipment needed for vessel closure, training of welding, inspection, and materials handling personnel, and full-scale demonstration of vessel closure technologies and procedures. Related programs include vessel design and drop testing.

Additional work includes development of graphical user interfaces, application of graphical-based and object oriented programming methods, and eventually development of architectures for machine control systems as described in this paper. There was also extensive work on self-validating sensors, weld vision systems, non-contact and in-process ultrasonic inspection methods and equipment, and extensive research into artificial neural networks and fuzzy logic methods for application to both control and sensing that are described elsewhere [9,10].

The system consists of a six-axis articulated arm robot, a rotating positioner, and a set of end efectors for welding, inspection and weld repair. Welding is accomplished using the gas tungsten arc welding process; inspection capabilities include interpass temperature measurement, laser line scanning, video based visual inspection, pass-by-pass ultrasonic inspection, and eddy current inspection.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Energy Research and by INL Laboratory Directed Research and Development under DOE/NE Idaho Operations Office Contract DE-AC07-05ID14517.

References

[1] H. Smartt, A. Watkins, D. Pace, R. Bitsoi, E. Larsen, T. McJunkin, and C. Tolle, “Design of a Welding and Inspection System for Waste Package Closure”, paper 148757, proceedings of 2006 International High-Level Radioactive Waste Management Conference, Las Vegas, NV, April 30-May 4, 2006a.

[2] H. B. Smartt, E.D. Larsen, D. P. Pace, R. J. Bitsoi, and C. R. Tolle, “Design of a Robotic Welding System,” Trends in Welding Research, ASM International, ISBN-13: 978-0-87170-842-7, pp. 623-627, 2006b.

[3] K. U. Vandergriff, Designing Equipment for Use in Gamma Radiation Environments, ORNL/TM-11175, May 1990.

[4] P. J. McKerrow, Introduction to Robotics, Addison Wesley, ISBN 0-201-18240-8, 1991.

[5] John A. Johnson, Eric D. Larsen, Karen S. Miller, Herschel B. Smartt, Timothy R. McJunkin, “Method for the Concurrent Ultrasonic Inspection of Partially Completed Welds”, United States Patent 6,484,584, November 26, 2002.

[6] Herschel B. Smartt, et al., “Apparatus for the Concurrent Inspection of Partially Completed Welds”, United States Patent 6,365,873, April 2, 2002.

[7] Herschel B. Smartt, et al., “Method and Apparatus for Assessing Weld Quality”, United States Patent 6,236,017, May 22, 2001.

[8] Herschel B. Smartt, Eric D. Larsen, John A. Johnson, “Inspection Apparatus for Evaluating a Partially Completed Weld”, United States Patent 6,178,819 B1, Jan. 30, 2001.

[9] J. A. Johnson and H. B. Smartt, "Advantages of an Alternative Form of Fuzzy Logic", IEEE Transactions on Fuzzy Systems, Vol. 3, No. 2, May 1995, pp 149-157.

[10] J. A. Johnson and H. B. Smartt, "Conventional Controllers in Fuzzy Form," 1994 World Conference on Neural Networks, INNS, San Diego, CA, June 1994, Vol. 1, pp. 759-764.