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Development of an auto-welding system for CRD nozzle repair welds using a 3D laser vision sensor

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Abstract

A control rod device (CRD) nozzle attaches to the hemispherical surface of a reactor head with J-groove welding. Primary water stress corrosion cracking (PWSCC) causes degradation in these welds, which requires that these defect areas be repaired. To perform this repair welding automatically on a complicated weld groove shape, an auto-welding system was developed incorporating a laser vision sensor that measures the 3-dimensional (3D) shape of the groove and a weld-path creation program that calculates the weld-path parameters. Welding trials with a J-groove workpiece were performed to establish a basis for developing this auto-welding system. Because the reactor head is placed on a lay down support, the outer-most region of the CRD nozzle has restricted access. Due to this tight space, several parameters of the design, such as size, weight and movement of the auto-welding system, had to be carefully considered. The cross section of the J-groove weld is basically an oval shape where the included angle of the J-groove ranges from 0 to 57 degrees. To measure the complex shape, we used double lasers coupled to a single charge coupled device (CCD) camera. We then developed a program to generate the weld-path parameters using the measured 3D shape as a basis. The program has the ability to determine the first and final welding positions and to calculate all weld-path parameters. An optimized image-processing algorithm was applied to resolve noise interference and diffused reflection of the joint surfaces. The auto-welding system is composed of a 4-axis manipulator, gas tungsten arc welding (GTAW) power supply, an optimized designed and manufactured GTAW torch and a 3D laser vision sensor. Through welding trials with 0 and 38-degree included-angle workpieces with both J-groove and U-groove weld, the performance of this auto-welding system was qualified for field application.

Keywords: Laser vision sensor; Welding path creation; CRD nozzle

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1. Introduction

CRD nozzles are attached to the hemispherical surface of a reactor head by J-groove welding. PWSCC causes degradation in these welds requiring that these defect areas be repaired [1].

Automated welding for CRD nozzle repair is a necessity in this radioactivity environment. Generally, in automated welding, the components of the welding system are not restricted by space or weight. However, when the repair work must be performed in limited areas such as inside of a reactor head, specialized sensors and robots are necessary [2-3].

To recognize the repair welding area around the

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circumference of the CRD nozzle, a laser vision sensor must be utilized [4]. For proper performance, this sensor must to be designed by considering the working environment, including the restrictions of size, weight and position. In this study, an optimum sensor was designed based on numerically quantifying these restrictions.

In general, it is necessary to perform image pre-processing to remove noise due to spatter and double reflection of the arc light image acquired by the CCD camera. In this study, a characteristic algorithm for image pre-processing was used to remove the diffused reflection from the machined surfaces.

An automated repair welding system requires several successive functions, including acquisition of 3D information from the laser vision sensor, configuration recognition of the weld groove, the creation of the weld-path and control of the auto-welding system. In this study, a computer program was developed and integrated into the system to automate each process.

Finally, CRD Nozzle weld repair mock-up trials were conducted to verify the performance of laser vision sensor.

2. Laser vision sensor system

2.1 Laser vision sensor

A laser vision sensor acquires dimensional vector information from a 3D shape using a visual sensor and structured lighting. In general, the system consists of a CCD camera and a line laser for obtaining 2D (2-Dimensional) distance information [5]. Due to the single wavelength property of laser light, external light does not affect a non-contact laser vision sensor; therefore, this type of sensor can achieve a higher degree of resolution with lower cost than any other type of distance sensor. However, sensor operation in the field becomes more complicated due to the data processing needed to obtain an image with the required high degree of resolution [6].

Laser vision sensors have been used in the field for seam tracking, inspection of external weld areas and position recognition of the robot arm among others [7]. In CRD nozzle repair, multi-layer GTAW welding is applied; therefore, a sensor for repair welding is required with the capacity to search for recognizing and tracking the weld-path and measuring bead shapes. These sensing operations are characteristically contradictory to each other. For recognizing and tracking the weld-path, simplification of information is important, but in measuring bead shapes, detailed and specific information is needed. These requirements make it difficult to design a laser vision sensor for repair welding of a CRD nozzle.

2.2 Design

The basic first step in designing the laser vision sensor was to determine the general design parameters based on function, environment and restrictions of the application. The detailed design model, such as size, weight, resolution, and measurement area of the sensor must be established from the general design conditions. In this study, the main role of laser vision sensor is to acquire the distance information of the measurement area with desired resolution. The design parameters related to this role are the distance and angle between the laser and CCD camera and the resolution of CCD. Since the latter is generally fixed, the former are the main design parameters. Fig. 1 shows the design parameters and sensing area. In Fig. 1, the distance (C) and angle (θ)

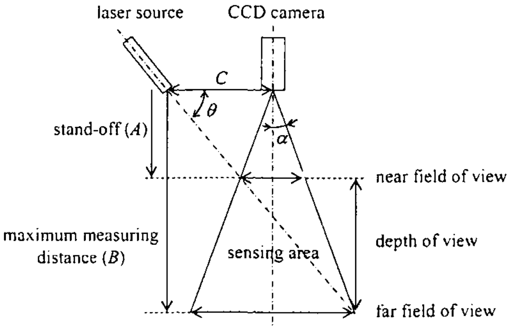


Fig. 1. Design parameters and sensing area.

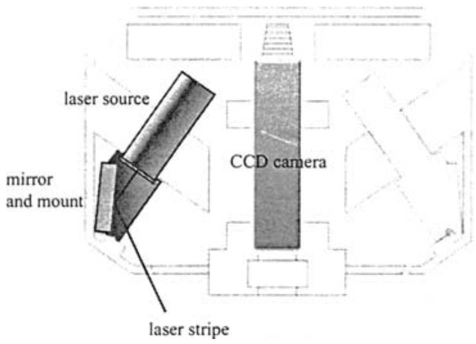


Fig. 2. Laser vision sensor - internal structure.

between laser source and CCD are expressed by Eqs. 1 and 2, where A is stand-off distance, B is the maximum measuring distance, and α is half the camera lens angle.

$$C = A\left(\frac{1}{\tan\theta} + \tan\alpha\right) \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{B-A}{\tan\alpha(A+B)}\right) \tag{2}$$

The design must also include the numerical data and parameters for external constraints found in the restricted area of a reactor head. In this study, the sensor size needed to be large enough to measure the repair area with suitable resolution, but small enough to avoid contact with the internal wall of the reactor head. First, the maximum measurement area was determined, and then the sensor size and structure designed to obtain reasonable resolution. The maximum weight of the sensor was set at 1.2kg, based on the allowable load of the robot. The structure of the sensor was designed with a double laser due to the difference in the laser scan line in the left and right directions of the CRD nozzle. Fig. 2 shows the optimally designed laser vision sensor and Table 1 gives the design specifications.

Table 1. Laser vision sensor – specifications.

Specification	Value
Stand-off (mm)	33.45
Far depth of view (mm)	200.00
Distance between laser and CCD (mm)	59.43
Angle between laser and CCD (degrees)	65.00
Resolution (mm/pixel)	0.21
Laser vision sensor width (mm)	24.00

2.3 Structure

Fig. 3 shows the repair welding system. The system is comprised of a laser vision sensor, an image processor, a main controller, a programmable logic controller (PLC), a manipulator and a welder. The PLC manages the entire system. The main controller controls the manipulator and the image processor performs the functions of image processing, configuration extraction and weld-path creation, working as the main user interface.

The process cycle of the laser vision sensor consists of: 1) scanning the repair area, 2) generating a weld-path through image processing, 3) transmitting the generated weld-path to the robot through serial communication and 4) performing the auto-welding.

The laser vision sensor is comprised of a double diode laser, a CCD camera and an optic system. Two diode lasers were selected with 20 mW of power to satisfy the design constraint and depth of view. The optic system uses mirrors to reduce the sensor size.

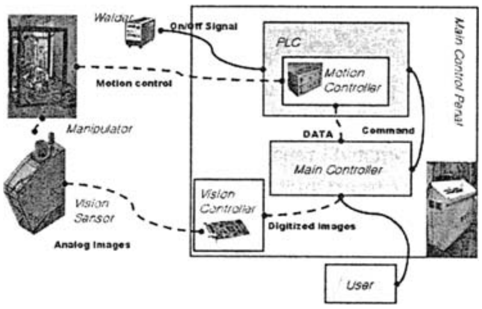
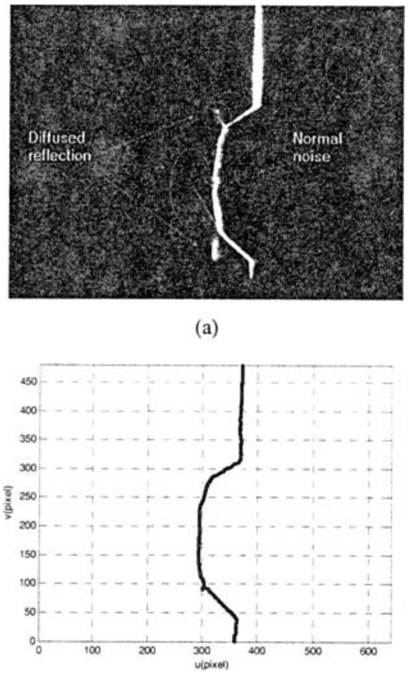


Fig. 3. Automatic welding system.

2.4 Image Processing

The image shown in Fig. 4(a) acquired by the CCD camera includes the laser line and noise due to double reflection. It is necessary to pre-process the image



(a)

(b)

Fig. 4. Image data: (a) Before image pre-processing; (b) After image pre-processing.

signal to determine the laser line and minimize noise. Conventional image processes, such as median filter or convolution mask, have a tendency to increase the noise due to the diffused reflection from the machined surfaces. So a special algorithm for image processing had to be developed.

In this study, a suitable pre-processing method for recognizing the groove shape in the repair area was obtained by a modification and combination of existing filters. First, an advanced half-threshold method was used to strengthen the light intensity contrast. To reinforce the laser line and attenuate noise, an advanced median filter using the distinct mask was used. To remove the remaining noise residue and reinforce the laser line, an erosion and dilation filter was applied. Finally, distance information was isolated by a thinning process whereby the noise in the distance information was removed by a profiling process. Fig. 4(b) shows the extracted distance information after completion of the image pre-processing.

3. Weld-path creation

3.1 Welding trajectory model

The manipulator performs auto-welding on the sloped wall of the CRD nozzle as shown in Fig. 5. The welding trajectory can be represented by a set of points; however, the motion of the manipulator has some inevitable basic tracking error due to interpolation errors. It was determined from experimental trials that the tracking error in GTAW auto-welding should be less than 1.0 mm. A welding trajectory with 0.3 mm maximum interpolation error was generated by dividing the track into suitably small increments.

To obtain uniform weld condition requires a constant linear speed of the welding torch. In this study, the tip speed of torch was maintained constant by controlling the input speed of the manipulator.

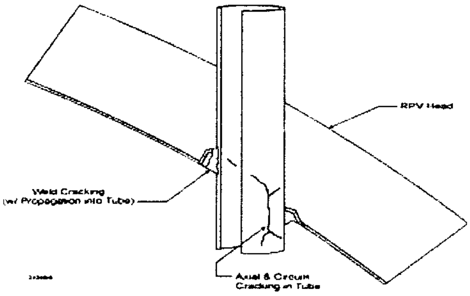


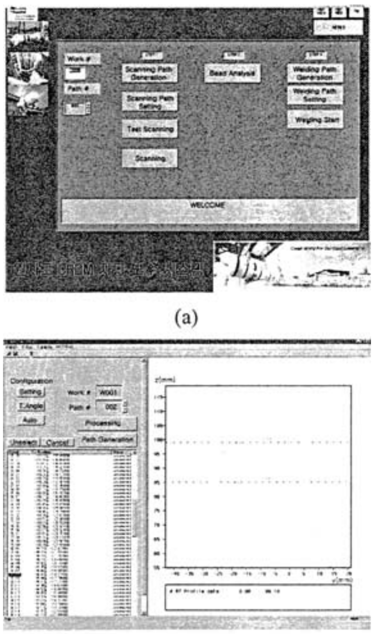
Fig. 5. CRD nozzle welds and cracks [8].

3.2 Weld-path creation

The auto-welding program involves the following three tasks. Task 1: Scan the repair area using the laser vision sensor. Task 2: Analyze the measured data and create the weld-path and operating program for the manipulator. Task 3: Perform auto-welding using the created weld-path and operating program.

To perform the above tasks, the auto-welding program performs two main processes. Main process 1 (Tasks 1 & 3) controls all the hardware, such as the manipulator and the laser vision sensor and serves as a communication between this hardware. Main process 2 (Task 2) automatically generates the weld-path and the control file for the weld-path.

The main program is composed of the several functional program modules. Fig. 6(a) shows the program for main process 1. Fig. 6(b) shows the program for main process 2. The program for main process 2 is executed after obtaining measurements from the laser vision sensor in main process 1. When the information is obtained from main process 1, the user designates the torch points for creating the weld-path considering arc length. The designated points are converted by a coordinate conversion matrix and saved as manipulator coordinate values. The weld-path file is transmitted to the manipulator and then auto-welding is performed.



(a)

(b)

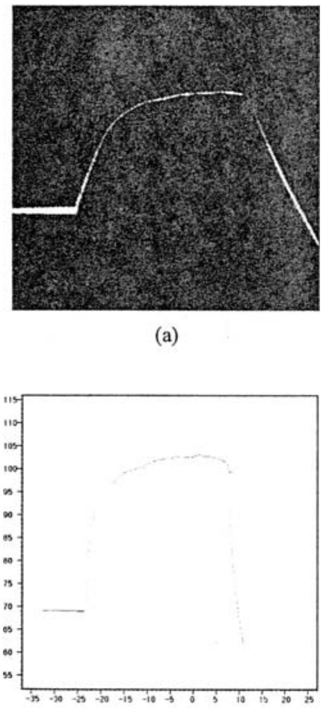
Fig. 6. Main menu: (a) Main program; (b) Sub program.

4. Welding trials

In this study, the performance of the newly developed laser vision sensor and the software for auto-welding was verified by welding trials in a CRD nozzle workpiece. The tracking test was performed in a manufactured workpiece after calibration between the manipulator and the laser vision sensor. Auto-welding was performed in the CRD nozzle workpiece with the angles of inclination set at 0° and 38° consistent with the angle between the nozzle and reactor head.

4.1 J-groove Welding Trials

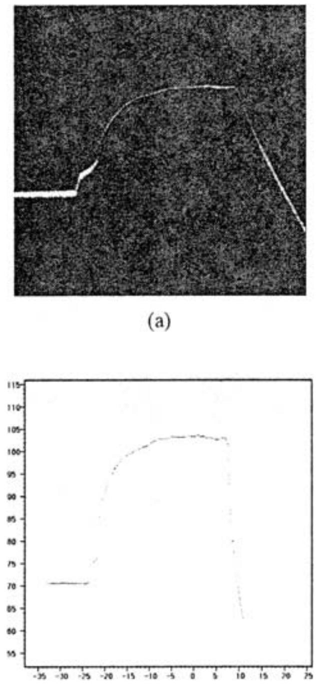
Auto-welding trials were performed for a 60° machined J-groove on a 0° inclination. The welding was performed up to the 18th pass normal to the surface of the groove. To avoid contact between the torch and groove and to maintain a stable arc, proper weld position was controlled by torch rotation. Figs. 7 and 8 show the raw image and profile of the first and last weld pass, respectively. Satisfactory results were obtained with a maximum 0.5 mm tracking error from these welding trials.



(a)

(b)

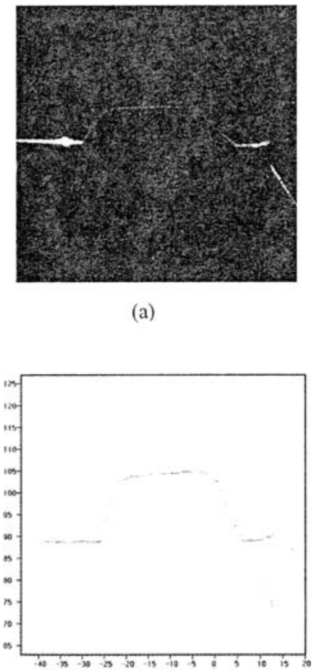
Fig. 7. 1st weld pass in the J-groove on a 0° workpiece: (a) raw image; (b) profile.



(a)

(b)

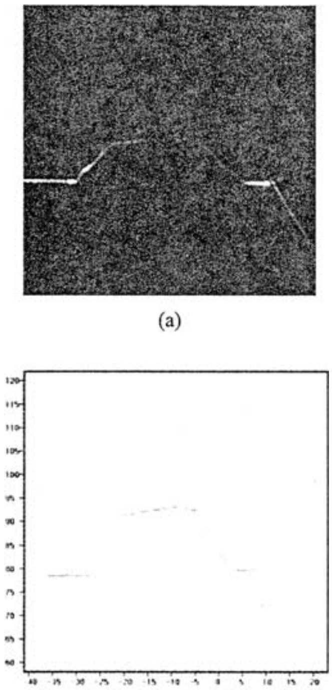
Fig. 8. 18th weld pass in the J-groove on a 0° workpiece: (a) raw image; (b) profile.



(a)

(b)

Fig. 9. 1st weld pass in U-groove on a 38° workpiece: (a) raw image; (b) profile.



(a)

(b)

Fig. 10. 12th weld pass in U-groove on a 38 workpiece: (a) raw image; (b) profile.

4.2 Sloped U-groove welding

Auto-welding trials were performed on an 80° machined U-groove on a workpiece inclined at 38° in the same manner as the J-groove welding pre-viously discussed.

The slope angle of the groove is different between 0°~180° and 180°~ 360° because the sensor moves tangential to the direction of the groove; therefore, the normal direction from the groove for the laser depends on the slope angle of the groove. As with the J-groove welding, proper weld position was controlled by torch rotation.

From the trial results, the extent of the trajectory error was about 1 mm. This error was 0.5 mm more than that of the J-groove welding trials. The difference in error is believed to be from the error in coordinates conversion caused by movement in the z-axis; however, the error did not affect the weld quality. Figs. 9 & 10 show the raw images and profiles of the first and last weld pass, respectively.

5. Conclusions

A laser vision sensor was optimally designed for CRD nozzle weld repairs based on numerically quantifying the working environment found in the restricted area of a reactor head, including the restrictions of size, weight and position.

A characteristic algorithm for image pre-processing was developed for recognizing the groove shape in the repair area by modification and combination of existing filters including an advanced half-threshold method, an advanced median filter using the distinct mask, an erosion and dilation filter and a thinning process.

Welding trials were conducted for J-groove and U-groove GTAW welding in a plate inclined at 0° and 38°, consistent with the angle between the nozzle and the reactor head for verification of the auto-welding system. Satisfactory results were obtained with a 1 mm trajectory error.

The performance of the newly developed auto-welding system was qualified for field application.

References

[1] Charles R. Frye, Melvin L. Arey, Jr. Evaluation and repair of primary water stress corrosion cracking in alloy 600/182 control rod drive mechanism nozzles, 10th Int. Con. Nuclear Engineering. (2002) No. 22653.

[2] S.W. Glass, D.M. Schlader, Inspection and repair techniques and strategies for alloy 600 PWSCC in reactor vessel head CRD nozzles and welds, 10th Int. Con. Nuclear Engineering, (2002) No.22743.

[3] D. Waskey, R. Payne, D. Schlader, Emergent development and application of reactor vessel head penetration inspections and repairs in the United States, Welding and Repair Technology for Power Plants. (2002) N1.1-N1.13.

[4] J.G. Byeon, K.S. Park and Y.J. Kim, Development of repair system for alloy 600 PWSCC in reactor vessel head CRDM nozzle and welds, 6th Int. Con. the Integrity of Nuclear Components, (2006) 184-188.

[5] J.E. Agapakis, Approaches for recognition and interpretation of workpiece surface features using structured lighting, *Int. J. Robotics Research.* 9 (1990) 3-16.

[6] Y. Suga and A. Ishii, Trends of image processing application to welding process control and inspection of weld, *J. JSNDI.* 48 (1999) 729-737.

[7] J. Boillot and J. Noruk, The benefits of laser vision in robotic arc welding, *Welding Journal.* 81(2002) 32-34.

[8] M.R. Robinson, Cracking of RV head penetrations due to primary water stress corrosion cracking (PWSCC), Duke Power Company, (2001).