

Conformable Eddy Current Array Delivery

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Abstract. The external surface of stainless steel containers used for the interim storage of nuclear material may be subject to Atmospherically Induced Stress Corrosion Cracking (AISCC). The inspection of such containers poses a significant challenge due to the large quantities involved; therefore, automating the inspection process is of considerable interest. This paper reports upon a proof-of-concept project concerning the automated NDT of a set of test containers containing artificially generated AISCCs. An Eddy current array probe with a conformable padded surface from Eddyfi was used as the NDT sensor and end effector on a KUKA KR5 arc HW robot. A kinematically valid cylindrical raster scan path was designed using the KUKA|PRC path planning software. Custom software was then written to interface measurement acquisition from the Eddyfi hardware with the motion control of the robot. Preliminary results and analysis are presented from scanning two canisters.

INTRODUCTION

In the UK, stainless steel containers are used to store a nuclear product for long term storage. A sample container is shown in Fig. 1 in which the wall thickness is 1mm. As a result of the environmental conditions in which these containers are housed, the external surface may be subject to Atmospherically Induced Stress Corrosion Cracking (AISCC) [1]. The potential for such defects necessitates periodic inspection which is a significant challenge to conduct manually due to the large number of containers involved. Therefore, automating this inspection is of considerable interest.

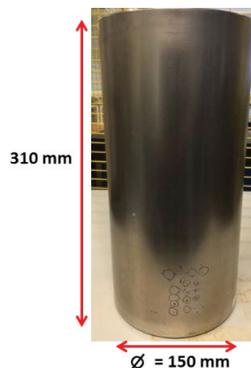


FIGURE 1. NUCLEAR storage container

Since 2010, the Centre for Ultrasonic Engineering (CUE) has been building expertise in applying industrial multi-axis robotic arms to automate the Non-Destructive Testing (NDT) of complex geometry components at the point of manufacture. The work described in this paper sought to apply this expertise to the problem of scanning the nuclear storage containers in order to increase key metrics such as reliability, throughput and coverage of the inspection in comparison to manual scans. To this end, a fully automated proof of concept system was developed to demonstrate potential improvements in these areas. Since ASICCs are a type of surface defect, an Eddy current sensor was selected for detection. Several containers containing artificially generated ASICCs were manufactured by the National Nuclear Laboratory (NNL) in the UK and made available for test purposes in this work. Two of these containers are shown in Fig. 2. The defects were created by depositing a chloride-salt solution onto the surface in a grid formation and then holding the containers in a humidity controlled environment: the matrix of defects is highlighted in Fig. 2. Through the application of several techniques including optical light microscopy, surface metrology and X-ray radiography it was established that the crack sizes ranged from 100s of μm up to a maximum of 3 mm in length. This paper proceeds by describing the system design, data analysis and experimental results.



FIGURE 2. Containers with matrix of artificial ASICCs

SYSTEM DESIGN

A KUKA KR5 Arc HW [2] robot was chosen as the basis of the scanning system, see Fig. 3(a). The six axes of this robot provides great flexibility in positioning the sensor in 3D space; in general there are eight possible joint configurations to reach each point within the work envelope of the robot, see Fig. 3(b). Clearly, the geometry of the container does not require a scanning system with six degrees of freedom, two would suffice. However, the approach developed here is toward a universal NDT scanning system for any part geometry that fits with the working envelope of the robot. Furthermore this technology will directly support future work with the NNL, concerned with scanning complex geometry parts.

A 32 element Eddy Current Array (ECA) with an operating frequency from 100 kHz - 600 kHz and 2 mm diameter pancake coils manufactured by Eddyfi was used as the NDT sensor [3]. An image of the probe and coil configuration is shown in Fig. 4(a) and (b). The coil topology enables axial and transverse cracks to be detected with respect to the direction of motion of the ECA. Note that this coil diameter only permits the detection of the ASICC, to estimate the dimensions of the cracks a smaller diameter would be required. A key property of the sensor is a 7 mm padded front face which conforms to the underlying geometry of the part when compressed against the surface. This primarily serves to minimize coil stand-off but it is also of use for mitigating positional error due to the robot. The positional accuracy of the robot important consideration when designing an inspection system and is investigated in a following subsection.

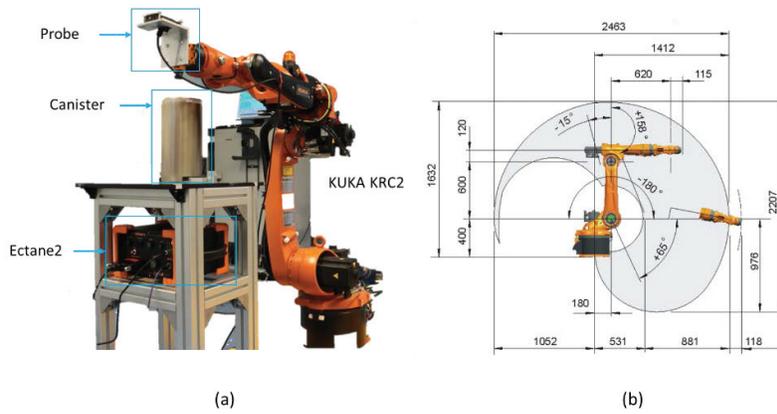


FIGURE 3. (a) Experimental setup (b) Work envelope for KUKA KR5 HW Arc [2].

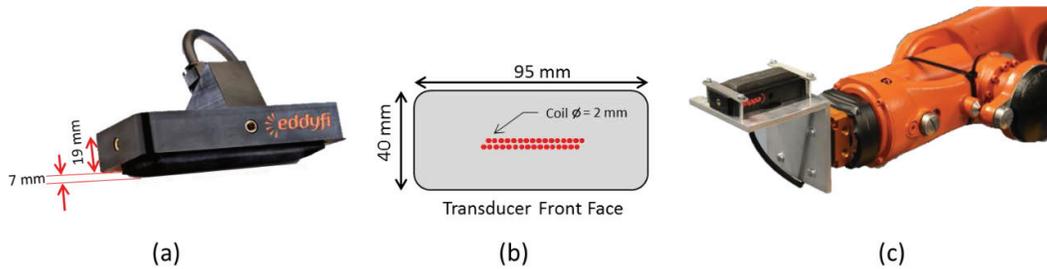


FIGURE 4. (a) ECA probe (b) Coil Topology (c) ECA mounting on the robot

PATH PLANNING

In the context of NDT, path planning is concerned with generating a path for the sensor such that complete surface coverage of the part is achieved [4]. If the required path is simple, it is possible to program it directly on the robot controller online as a sequence of waypoints. However, if the path is more complicated offline programming software is used. Such software provides an environment in which the Computer Aided Design (CAD) model corresponding to the part can be placed within the work envelope of a virtual robot with associated kinematic model. A path lying on the surface of the part is generated and the inverse kinematics can be solved to compute the necessary joint angles to achieve the motion. There exists numerous commercially available software solutions for offline robot programming such as Robotmaster, Delcam and FastSurf. These tend to be complex and expensive software packages. In this work, the KUKA Parametric Robot Control (KUKA|PRC) was used. This is plugin software for the *Rhinoceros* CAD software and provides a visual programming environment in which to parametrically program the robot by connecting blocks, see Fig. 5(a). Importantly the parametric feature of this software means that changes made to the CAD model are immediately reflected in the generated path – this leads to a very rapid development cycle in comparison to the aforementioned packages.

Mounting the ECA at 90 degrees with respect to the wrist produced a path in which the joint angles were well within operating range, see Fig. 4(c). As result it was possible to tweak the path without reaching axis limits. The X-axis of the part coordinate frame was set to be parallel and offset with respect to the robot world coordinate frame in order to avoid wrist singularities Fig. 3(a). A raster scan path was generated to scan the container. The active area of the ECA was 45mm which defined the vertical step size of the raster scan. The probe was kept normal to the sample surface; this can be seen by the tool vectors emanating from the surface in Fig. 5(a). Since defects were positioned only on one vertical half of the containers, the horizontal extent of the raster was limited to 180 degrees (in angular terms). The path is shown in Fig. 5(b). A single scan of a container was made up of four sub-scans. The

output of KUKA|PRC was a KUKA robot language file ready for execution on the robot controller. However, for maximum flexibility in terms of the development cycle, it was decided to control the robot from an external PC, the software system architecture for this is described in the next section.

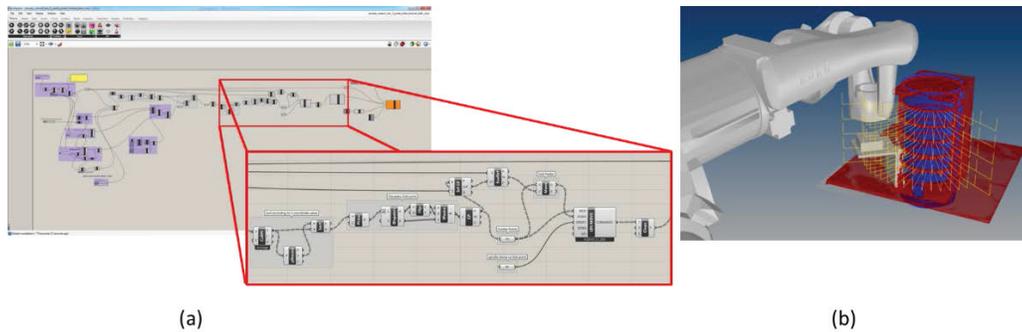


FIGURE 5. (a) Visual programming in KUKA|PRC (b) Raster scan path

SOFTWARE ARCHITECTURE

The Robot Sensor Interface (RSI) [5] was chosen to control the robot from an external computer. By doing this, both the robot and ECA controller could be controlled from a single software application. The main advantage of this approach was that a single program could be written for the robot controller which listened for “go to” points arriving on a network connection. This meant that writing programs on the robot controller could be avoided thus resulting in a shorter development cycle. This differs substantially to the traditional use of such robotics systems which have their origins in the car industry. In such a setting these systems run the same program repeatedly 24/7. The approach developed here, however, enabled the path of the robot to be changed frequently and rapidly to execute any kinematically valid set of coordinates.

The robot is a real-time system with an operating cycle of 12 ms while a standard workstation computer running the Microsoft Windows Operating system is a non-deterministic system. Furthermore, the robot controller expects to receive an Extensible Markup Language (XML) packet via an Ethernet connection every 12 ms, if it does not receive a packet within this timeframe the motion of the robot is halted. Careful consideration had to be given to the software design in terms of multi-threading to ensure that this demand could be met. The positions parsed from the KUKA robot language file output by KUKA|PRC are shown in Fig. 6(a). In accordance with the cycle time of robot, these positions and orientations had to be interpolated resulting in a list of coordinates plotted in Fig. 6(b). The interpolation was carried out through MATLAB functions derived from the RoboNDT software [4], an application developed by the University of Strathclyde and TWI Ltd. and targeted to robotic path-planning for NDT tasks.

The green areas of Fig. 6(b) correspond to positions in which the probe should be in contact with the surface while those in red indicate when the probe should be removed from the surface. A simple radius based filter was used to separate these points. The software architecture is shown as a block diagram in Fig. 7. A C# application was implemented to control and acquire data from the robot and ECA controller (Ectane 2). In order to meet the time demands imposed by the robot controller, the Magnifi Software Development Kit was run as a separate process on the workstation computer. This meant that spikes in CPU usage associated with data streaming from the Ectane 2 did not affect the code handling the 12 ms communications with the robot controller. A visualization module was written to take the four sub-scan ECA images and project them on to the surface of a half cylinder: this was the final output of the system.

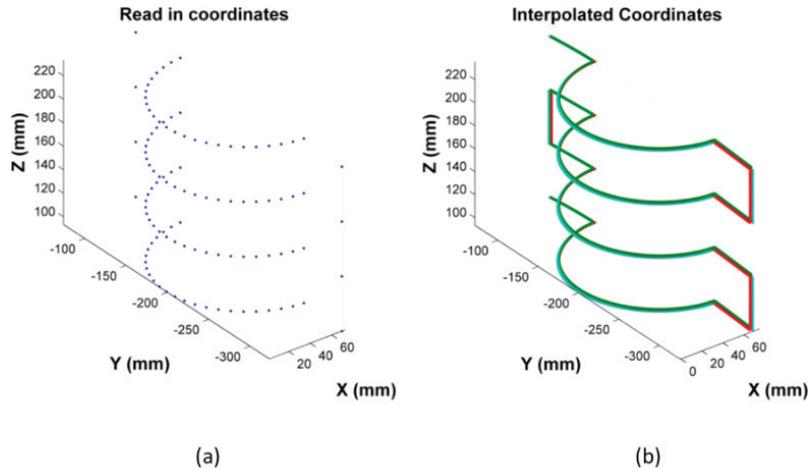


FIGURE 6. (a) Positions parsed from KUKA|PRC file (b) Interpolated coordinates

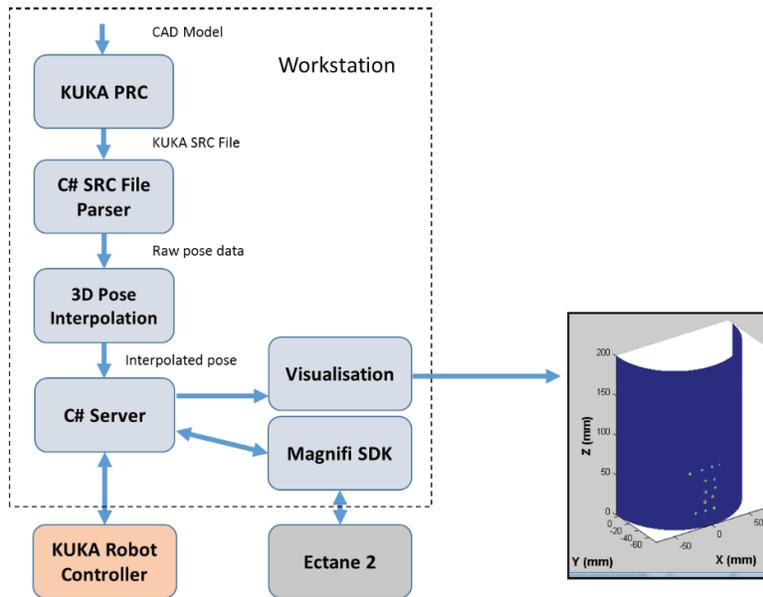


FIGURE 7. Software architecture

ROBOT ACCURACY

As mentioned previously the accuracy of the robot for use in a NDT scanning system in this work is an important consideration. Deviations in the path due to inaccuracies can in result in incorrect reporting of defect positions and in the worst case collisions between the robot and the environment. To understand how robot inaccuracy propagated through to the EC scan data, a calibration container was scanned. Aluminum strips were applied to the surface of a defect free container according to the pattern shown in Fig. 8(a). As can be seen in the resultant ECA scan of the container in Fig. 8(b), the edges of the strips in the sub-scans are poorly aligned. The error in misalignment was approximately 10 mm in the x-axis. Although the robot produces this level of inaccuracy it is repeatable to ± 0.01 mm [2]. Therefore, a static correction could be applied to mitigate this error.

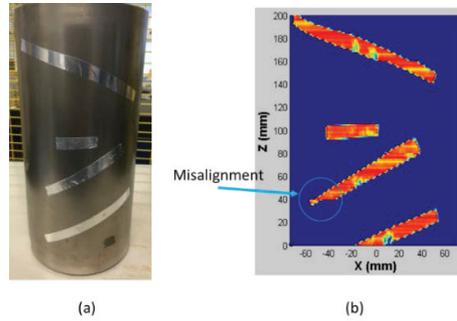


FIGURE 8. (a) Image of calibration container (b) ECA scan of calibration container

To quantify the error in the positional estimate from the robots internal resolvers, as a function of the position of the end effector within the working envelope, a small experiment was carried out. A laser prism reflector was mounted to the extremity of the robot and its center was calibrated as the tool center point (TCP) of the robot, the tool is shown in Fig. 9(a). A program was then written to sweep the reflector through a box raster scan visiting 750 locations within the working envelope Fig. 9(b). A Leica AT901-B laser tracker was used to track the end effector. This is a high precision device with an accuracy of $\pm 0.2 \mu\text{m} + 15 \mu\text{m/m}$ [6] serving as the ground truth system in this experiment.

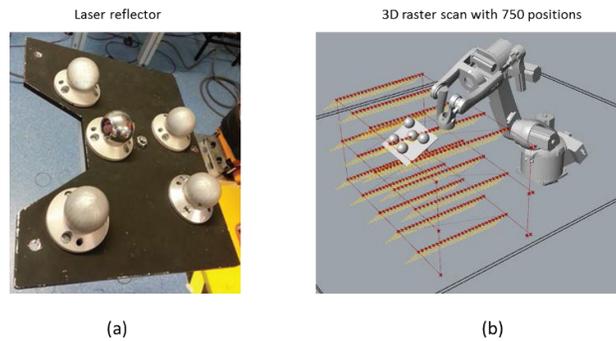


FIGURE 9. (a) Prism reflector (b) Box raster scan

A plot of positional error between the internal resolver and laser tracker is displayed in Fig. 10. A maximum error of 2.7 mm was observed in the overall dataset. The axis-wise errors are shown in Table 1 in terms of the planes plotted in Fig. 10, where plane 1 refers to the lowest plane. It can be seen that a maximum error of approximate 2.7 mm was evident for the X or Z axes for each plane.

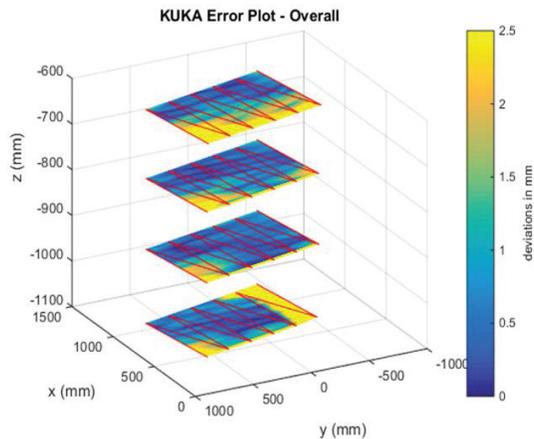


FIGURE 10. Error of KUKA resolvers plotted as planes

TABLE 1. Axis wise errors

Deviations	X-direction (mm)	Y-direction (mm)	Z-direction (mm)	Average (mm)	Height (mm)
Plane ₁	2.7268	0.6167	0.3936	1.2457	283
Plane ₂	1.3365	0.3321	0.2635	0.6440	446
Plane ₃	1.4148	0.3405	0.2726	0.6760	600
Plane ₄	1.6915	0.3509	0.2783	0.7736	755

RESULTS

This section presents results for two containers. The probe was driven at 400 KHz and 5 Vpp while the robot was instructed to move the ECA at 20 mm/s. This resulted in a scan time of approximately 60 s. An image of container 1 is shown in Fig. 11(a) in which the matrix of circular corrosion patches is clearly visible on the surface. Prior to scanning the container, a weak acid was used to remove this corrosion such that there was no visible indication of the defect. The resulting ECA scan (axial) is shown in Fig. 11(b) in which the reactance of the measurements returned from the ECA has been plotted. To produce this image, the measurements across all sub-scans for this container were normalized with respect to the largest value of reactance. These normalized values were then converted to decibels as shown on the color bar in Fig. 11(b).

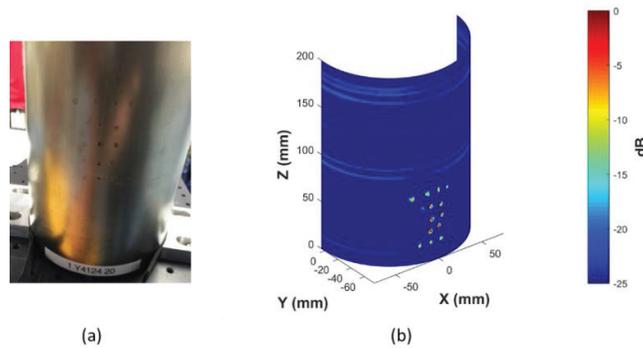


FIGURE 11. (a) Image of container 1 (b) ECA scan of container 1

The ECA was able to clearly detect anomalies in 13 sites of a total of 16 sites of salt deposition. It was known from prior analysis that this container has 3 cracks and 7 potential cracks.

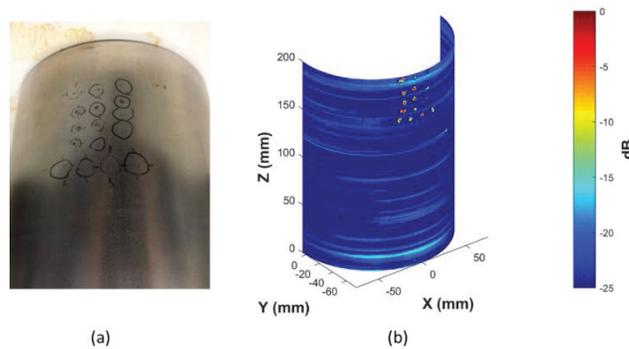


FIGURE 12. (a) Image of container 2 (b) ECA scan of container 2

The ECA scan for container 2 as shown in Fig. 12(a) is plotted in Fig. 12(b). In this case, 12 defective areas are clearly detected by the ECA from a total of 16 sites of salt deposition. From prior analysis it

is suspect that 10 cracks and 3 potential cracks. However as mentioned previously, a smaller coil size would be required to size the dimensions of these cracks.

CONCLUSION

This paper has described the development a proof of concept demonstrator to address a particular problem in the nuclear industry. This problem concerns the NDT of the surface of nuclear storage containers which may be subject to ASICCs as a consequence of the environmental conditions in which the containers are stored. A robot based scanning system making use of an Eddy current array was developed and was capable of performing raster scans of the containers in an automated fashion. The system has shown promising results with respect to detecting anomalous regions on the surface of two test containers. However, a higher resolution probe is required to size these potential cracks, this will be carried out in future work.

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