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MAGNETIC INSPECTION PLATFORM FOR TELEOPERATED REMOTE INSPECTIONS OF COMPLEX GEOMETRY

William Jackson
University of Strathclyde
Glasgow, UK

Dayi Zhang
University of Strathclyde
Glasgow, UK

Ross McMillan
University of Strathclyde
Glasgow, UK

Morteza Tabatabaeipour
University of Strathclyde
Glasgow, UK

Rory Hampson
University of Strathclyde
Glasgow, UK

Adam Gilmour
University of Strathclyde
Glasgow, UK

Charles MacLeod
University of Strathclyde
Glasgow, UK

Gordon Dobie
University of Strathclyde
Glasgow, UK

ABSTRACT

The NDE industry is under constant pressure to increase inspection speeds, while simultaneously reducing costs to keep up with the ever-expanding demands of providing robust inspection for new infrastructure as well as ongoing inspections for currently operating facilities, and the increasing rise in the need for extensions in the planned life of existing plants.

Currently, setting up an automated phased array ultrasonic inspection requires significant manpower, especially on components with complex geometry, this often exposes operators to hazardous environments. This is a particular problem with conventional ultrasonic NDT where operators must regularly exchange probes (an ‘intervention’). Furthermore, inspections are often carried out during planned outages, and the necessary installation time of rigging can represent a significant part of the inspection cost.

To alleviate these challenges, several specialised robotic systems have been developed in industry for performing NDE in areas with well-defined geometries. However, these systems are often limited by a high degree of manual intervention, a lack of general-purpose design, and unsophisticated brute-force data acquisition with little to no data interpretation.

The development of next generation, automated NDE solutions present considerable improvements to the current state of design such as reduced inspection time, greater separation of data capture and analysis, data localization – data are intrinsically encoded with the position they were captured. These benefits lead to a reduction in plant downtime & operator dosage.

The platform presented will achieve these improvements through a set of universal automated deployment tools, implemented through hardware and software advances. By creating a platform consisting of a motorised magnetic base paired with a miniature robotic arm, a very capable and adaptable system is formed. This allows for different sensing modalities with an initial focus on phased array ultrasonics to be delivered accurately and repeatably to the target inspection site. Furthermore, by introducing additional perceptual sensors such as cameras, laser scanners, & a force-torque sensor the system can understand the environment in which it is operating. Through these sensors the user may guide the robot through the plant remotely in a safe and controlled manner. In addition to this these sensors may be used to generate scan paths of critical areas with unknown geometry on the fly as well as adapt the path in a conformable manner.

Keywords: Teleoperated Robot, Magnetic Crawler, Remote Inspection, Virtual Reality, Laser Scanning

INTRODUCTION

The inspection of critical welds within the nuclear, oil & gas, maritime and other sectors is of key importance, often with set standards and certification required [1], [2]. These welds may be located within hard to reach or challenging environments. Additionally, the welds may themselves consist of complex geometries requiring highly specialized inspectors and equipment for the inspection.

To alleviate these challenges mobile robots and novel inspection platforms have been utilised to navigate and provide inspection in challenging environments [3]–[7]. This provides many key benefits such as the lack of personnel having to access the site which may be costly and or dangerous if accessing, hot areas on a nuclear site, areas which require rope access or confined spaces which may need significant venting before inspection may be carried out.

In addition, with a robotic system localised within the plant an inspection may be repeated with a greater consistency allowing the condition to be monitored effectively over time.

Current state of the art approaches for complex weld geometry inspections are often semi-automated and require significant set-up & dismantling requiring extended human hours and possible downtime, such as those shown in FIGURE 1 below.

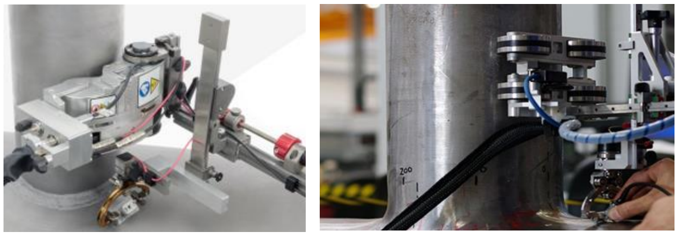

FIGURE 1 EXAMPLE STATE OF THE ART NOZZLE WELD INSPECTION SYSTEMS, LEFT: JIREH NAVIC - 3-AXIS NOZZLE SCANNER [8], RIGHT: PHOENIX NOZZLE SCAN [9]

To alleviate these issues a robotic crawler platform was developed to be able to remotely navigate assets and deploy an NDE probe such as a phased array probe/wedge to a weld/structure requiring inspection. The crawler design comprises of three main components:

1. Magnetic crawler platform
2. Six degrees of freedom robotic arm
3. Sensor payload

Utilising these components gives the inspection platform excellent manoeuvrability around plants constructed with ferritic materials as well as the envisaged use of access tracks to reach key areas.

Additionally, the robotic arm with six degrees of freedom allows the platform to place the sensor payload with great accuracy, and precision.

In addition to an NDE sensor payload the platform may be equipped with cameras, and laser scanners to provide better perception of the environment. The information from the sensors may be relayed back to the teleoperator in real-time, by utilising an array of cameras the visual information may be streamed to a VR headset for an immersive experience. This is visualised in FIGURE 2 the following mock example showing the concept platform within a pressure vessel and a remote operator's perceived view.

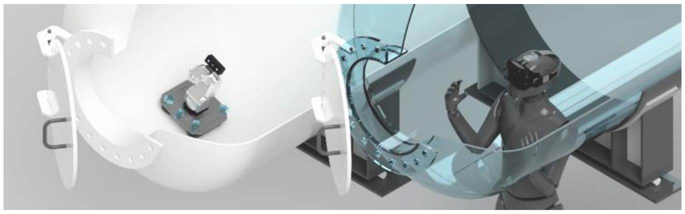

FIGURE 2 RENDERING OF INSPECTION PLATFORM WITHIN A PRESSURE VESSEL AND INSPECTOR WEARING A VR HEADSET AS IF THEY ARE INSPECTING ON LOCATION

1. PLATFORM DESIGN

In designing the inspection platform, multiple iterations were devised which each had their benefits and drawbacks, the first of these utilised a set of tracks, a flat plate for mounting of the robotic arm and tertiary sensors. The magnetic force was delivered through a set of belly magnets, this proved highly effective for flat plate and curved surfaces with a sufficiently large diameter. However, when navigating on a surface with a tighter diameter the lift-off increases causing a significant loss of magnetic force and instability. The design however offers a significant amount of real estate for equipment such as onboard computing, lighting, cameras, and the inspection payload. The tracks also provide excellent control and manoeuvrability. The platform is shown below in FIGURE 3.

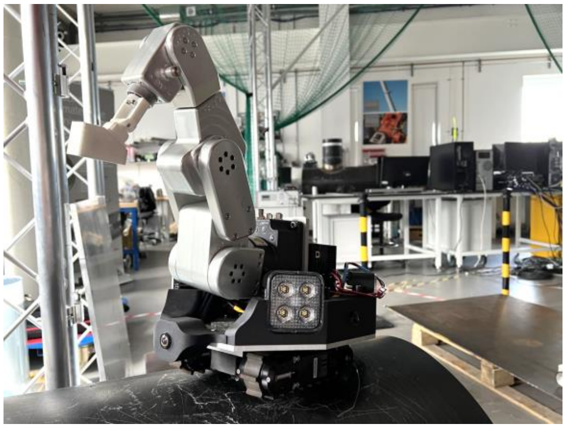

FIGURE 3 INSPECTION PLATFORM UTILISING TRACKS AND BELLY MAGNETS FOR MAGNETIC ADHESION

The current revision as shown in FIGURE 4 utilises the Navic Jireh [10] as a base, this base is articulated in two axis such that each half of the crawler can have independent pitch and roll angles. This allows excellent manoeuvrability and traction to the surface being driven upon as the crawler contorts to maintain full contact. The downside of this design is that the main payload the Meca 500 robotic arm [11] has to be mounted on one side of the crawler off-centre.

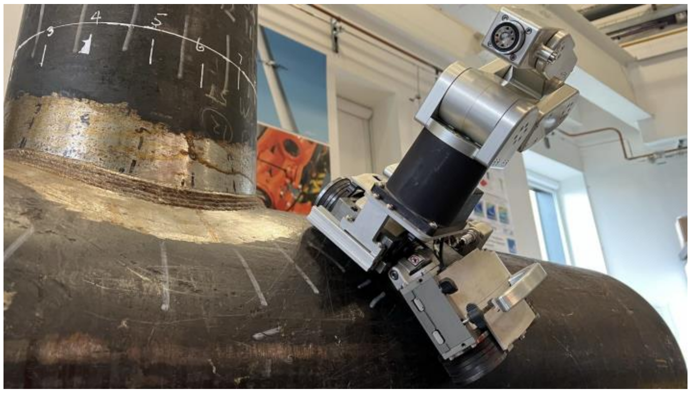

FIGURE 4 CURRENT MAGNETIC CRAWLER, UTILISING AN ARTICULATED BASE

2. ENVIRONMENTAL PERCEPTION

To perceive the environment and accurately deliver the NDE probe to the asset under inspection as well as allowing the inspector to effectively teleoperate the platform it must be equipped with sensors which can adequately relay information about the environment. Three methods have been explored, an array of cameras around the platform, guided wave occupancy grid mapping [7], and laser scanning.

2.1 Visual Perception

To provide the operator with a visual overview of the scene a test platform was developed utilising an array of six cameras, as shown in FIGURE 5. Four cameras are positioned level with the horizon and equipped with wide angle lenses such that the full 360 degrees around the robot can be observed. An additional two cameras located at the front and rear which are angled towards the base to provide a closer view of the crawler base enabling greater control.

FIGURE 5 CRAWLER WITH AN ARRAY OF SIX CAMERAS

The footage is presented to the user via the virtual reality headset as a series of panes along with the crawler base model placed appropriately as shown below in FIGURE 6, it is noted this excludes the downward facing cameras. Trials were conducted in stitching all images together into a cylinder providing a wrap around experience but navigating the crawler proved easier with the "rear-view" camera being flipped and placed above the front camera.

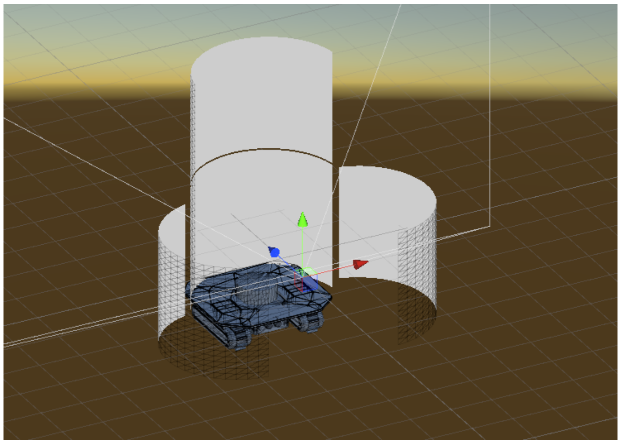

FIGURE 6 VIRTUAL REALITY ENVIRONMENT DETAILING FOUR CAMERA FEEDS AND CAMERA LOCATION SHOWN BY AXIS

The cameras used are the NileCAM21_CUXVR [12], these connect to a Jetson Xaviar which encodes the camera streams and creates a User Datagram Protocol (UDP) stream of the footage utilising GStreamer [13], this is then displayed to the user via Unity [14] (using the SteamVR & mrayGStreamerUnity plugins [15], [16]) as shown previously in FIGURE 6. An example usage of the four-camera system navigating a mock cross vessel duct with access tracks is shown in FIGURE 7.

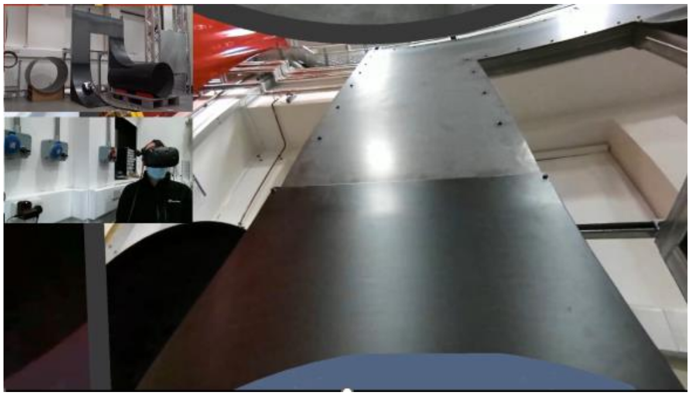

FIGURE 7 SCREENSHOT SHOWING THE VIEW FROM THE VR HEADSET (CENTRE), MOCK CROSS VESSEL DUCT AND ACCESS TRACKS (TOP LEFT) AND REMOTE OPERATOR (MIDDLE LEFT)

2.2 Guided Wave Occupancy Grid Mapping

Guided wave occupancy grid mapping using Electro Magnetic Acoustic Transducers (EMATs) is a way for the crawler to map the geometry of the structure utilising guided waves which interrogate the plate in a strip like fashion providing information such as defect areas and welds/boundaries [7], over time a probability map detailing the location of such indications is developed which can be used for navigation.

This has the advantage that it does not require any lighting for visual inspection and does not have issues with the surface finish which may impact laser scanning [17]. An image of the prototype system is shown in FIGURE 8.

FIGURE 8 PROTOTYPE GUIDED WAVE OCCUPANCY GRID MAPPING CRAWLER

2.3 Laser Scanning

To enable highly accurate scanning of the asset under inspection a lightweight laser scanning system was developed using a single range measurement laser capable of measuring accurately to around 10 µm [18]. Utilising a small sensor such as the optoNCDT 1420 used for laser measurement saves more payload capacity for the NDE inspection probe.

To create a point cloud of the area under inspection the sensor is swept in a spiral following the following procedure, with each step shown graphically in FIGURE 9.

a) Create a spiral of points in front of the crawler.
b) Determine the pose of the arm where the laser is pointing at each point in the spiral.
c) Move the arm through these poses while capturing the range data, the range data is projected to a point relative to the base of the robot. As the joint states of the robot are known and the transformation between the joint the laser is mounted to and the point of projection is known, the unit vector pointing from laser range finder can be calculated. Multiplying this vector with the range measurement results in a point in space relative the robot base.

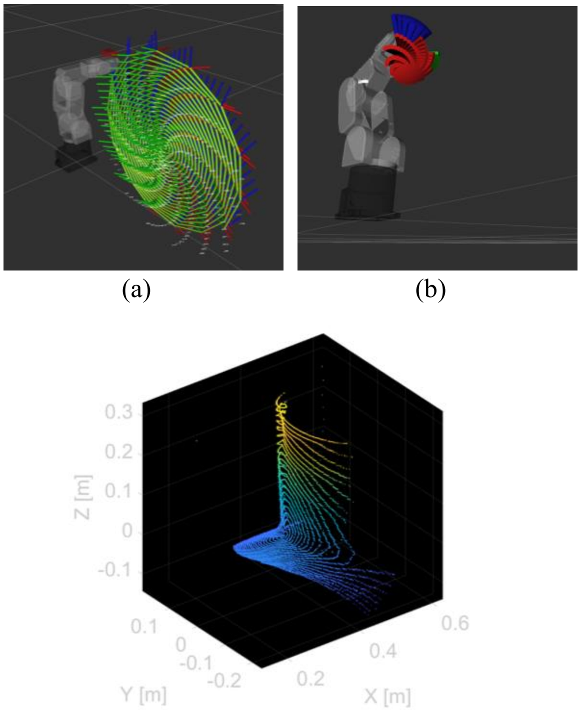

FIGURE 9 LASER SCANNING GRAPHIC DETAILS; (a) THE INITIAL SPIRAL POINTS FOR LASER SCANNING, (b) THE POSE OF THE ROBOT WHERE THE LASER IS POINTING AT EACH SPIRAL POINT, AND (c) THE CAPTURED POINT CLOUD

3. MOCK INSPECTIONS

To verify the ability of the platform (in varying configurations) to inspect a fusion weld a mock inspection of a saddle weld was undertaken. The first step was to ensure that the crawler could reach the full circumference of the weld around the pipe. This was done by manoeuvring the crawler around the pipe manually and ensuring the arm could reach the saddle weld suitably with enough freedom to deliver the NDE payload effectively, an image of the crawler approaching the weld from one of the most compromising positions, at roughly 45 degrees off axis on the main pipe volume is shown in FIGURE 10.

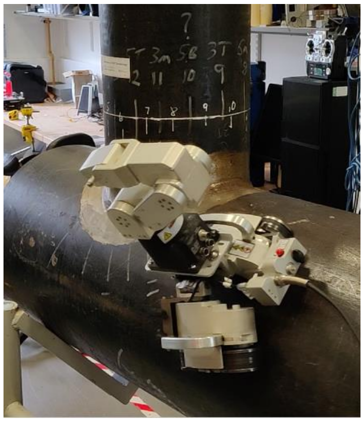

FIGURE 10 CRAWLER POSITIONED TO INSPECT SADDLE WELD

Along with reaching the point of inspection the path must also be created at a fixed distance from the weld centre, the probe should also be maintained normal to the main horizontal pipe as in FIGURE 10, while the face of the probe should point to centre of the nozzle such that when an inspection is undertaken the ultrasonic energy is focused at the weld face. The first step in achieving this was to generate a set of points representing the saddle weld, this was done using Steinmetz equation to solve for the intersection of two cylinders (the main vessel and nozzle) at 90 degrees, the resulting points are observed in FIGURE 11.

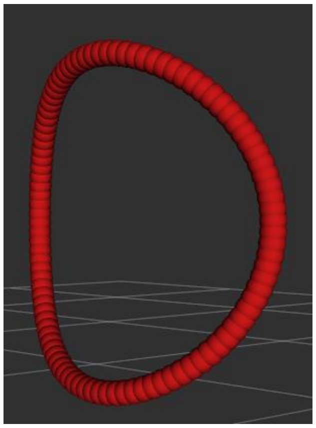

FIGURE 11 CYLINDER INTERSECTION POINTS (OUTLINE OF SADDLE WELD)

Following on from the generation of the points the roll, pitch, and yaw angles must be established. The result of this is shown in FIGURE 12 where the front of the wedge is facing towards the centre of the nozzle, the inspection face of the wedge is angled such that is at the normal of the main vessel surface. FIGURE 13 shows the mock inspection being undertaken of the saddle weld.

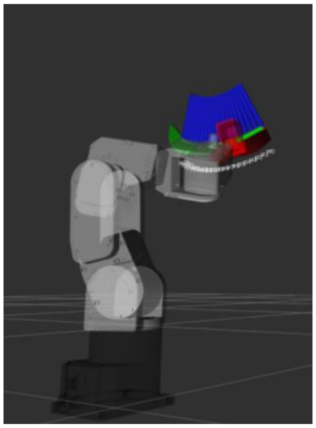

FIGURE 12 SADDLE WELD PAUT INSPECTION PATH

FIGURE 13 PLATFORM PERFORMING MOCK INSPECTION OF THE SADDLE WELD

4 FUTURE WORK

In order to accelerate the laser scanning process and improved the user experience, ongoing work is evaluating an approach where a coarse scan is carried out over the area directly in front of the platform, following this the user will select the region of interest from an image of the scene and a detailed scan will be undertaken – this concept for defining the region in 3D space is detailed in FIGURE 14. The 2D points the user selects on the image will be projected onto an interpolated surface from the coarse scan to define the outer limits for a refined scan which will define create a set of linearly spaced inspection points upon the surface, thus creating an accurate and well distributed point cloud of just the desired area under inspection.

In addition to the refinements in scanning and generating the path for delivering the NDE payload, additional work would include adapting the position of the probe with the addition of a force-torque sensor to ensure consistent contact and alignment. Furthermore, the received ultrasonic signals themselves may be used to refine the position as in [19].

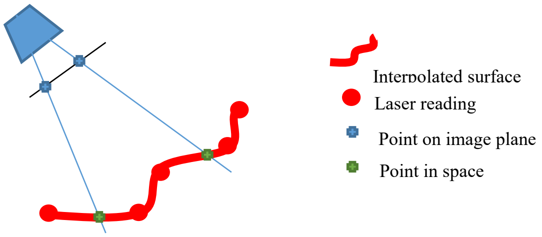

FIGURE 14 GRAPHIC DETAILING PROPOSED SCANNING TECHNIQUE, WHERE THE INTERPOLATED SURFACE IS USED TO DEFINE A REGION FOR A REFINED SCAN

5 CONCLUSION

This paper has provided an overview of a magnetic crawler platform equipped with a small and highly manoeuvrable robotic arm for teleoperated NDE. The platform design was discussed and the advantages of the articulated base, as well as the sensing modalities used to perceive the environment and finally a brief overview of a mock inspection undertaken and future work to improve the capabilities of the platform.

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