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OVERVIEW OF RECENT RESULTS IN RESEARCH TACKLING REMOTE MAINTENANCE CHALLENGES OF FUTURE FUSION ENERGY DEVICES

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Abstract

Future fusion devices will require extensive maintenance to be conducted in human inaccessible areas. This will include inspection and monitoring tasks in confined, difficult to reach spaces, as well as conducting in-situ physical maintenance processes such as cutting and re-welding pipe connections, all with robotics and remotely operated tools.

There exist large areas of technical risk or uncertainty in whether or how these tasks could be accomplished. The UKAEA has produced a framework of 10 Challenges for remote maintenace in fusion energy in order to steer robotics research in support of fusion energy. We present a high level overview of some of the key work ongoing and recent results in relation to these challenges.

The topics of rapid design optimisation and design of long-reach slender manipulators for in-vessel inspection is first presented, followed by adjacent work on the use of laser ultrasound for inspection of welds and plasma-facing components, and work on autonomous mobile robotic inspection in hot cell environments. Finally a discussion on implications and next steps is presented.

1. INTRODUCTION

Feasible, efficient, and reliable remote maintenance is critical to the success of commercially viable fusion energy. In order to deliver investable fusion power plants, challenges of maintainable architectures and maintenance solutions must be solved. In order to distil and crystalise the key challenges of remote maintenance in fusion energy, a framework has been established, identifying and describing 10 key challenges for robotics and remote maintenance in fusion energy [1]. The challenges range from technical to regulatory and include the key unsolved tasks such as remote joining of pipe services and handling challenging payloads such as blanket modules, as well as fundamental enablers such as fusion environment compatible systems that are able to withstand the harsh environments. They touch on productivity and reliability challenges, alongside the need to simplify plant architectures and maintenance schemes as much as possible. The challenges inform priority robotics research areas for the UK Fusion programme, and recent results against the top four of the challenge areas are presented.

The challenges span from technical such as handling of challenging components to commercial such as Maintenance productivity as well as covering topics such as Assurance, trust and regulation.

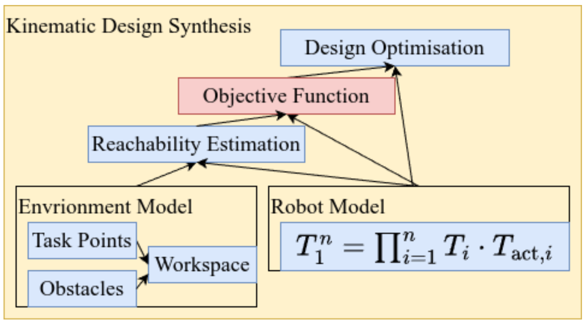
In response to the challenges, the UK Atomic Energy Authority has adopted an approach of leading and collaborating to solve the challenges where possible, through informing others about the nature of the challenges and potential technological solution areas, as well as undertaking a programme of research aimed at addressing those well matched with UKAEA capabilities.

Here, we provide an overview of some recent advancements made against several of the key challenges. Four topic areas are described including rapid design optimisation of remote maintenance solutions, addressing Challenge 1 (Architecture optimisation including design for remote maintenance). Long-reach slender manipulation devices in address of Challenge 3 (Slender mechanisms and operations in confined, cramped spaces). Development of Laser Ultrasonic methods for non-destructive testing of components including pipe welds, in address of Challenges 2 (Service joining including pipes, bolts, connectors and NDE), and the establishment of long-term reliable autonomous inspection capabilities in support of Challenges 7 (Rapid response including inspection and in-situ repair) and 8 (Maintenance productivity).

2. RAPID DESIGN OPTIMISATION OF REMOTE MAINTENANCE SOLUTIONS FOR FUSION

Assessing and improving the maintainability of fusion power plants is a critical step toward feasible fusion systems. A key aspect is the development of cost-effective manipulators, such as the Test and Remote Manipulation system (TARM) (Fig. 1a), originally designed for nuclear decommissioning and fusion remote maintenance. These bespoke systems must operate in cluttered, highly constrained environments with high collision risks, where achieving full task coverage remains a major challenge [2, 3].

(a)



(b)

FIG. 1. TARM system developed for remote maintenance of the Joint European Torus nuclear fusion experiment (left). Proposed framework for design optimisation and reachability analysis in obstacle-rich environments (right).

Novel methods for rapidly generating and optimising kinematic designs for remote maintenance deployment systems under complex geometric constraints have recently been demonstrated [4]. The kinematic design problem is inherently multidimensional and non-convex, combining discrete (topological) and continuous (geometric and joint-limit) variables. A central challenge is to guarantee reachability, i.e., collision-free, continuous trajectories to all task points, while minimising structural complexity and cost.

The framework enables rapid assessment of fusion plant maintainability and iterative refinement of remote maintenance concepts, supporting more efficient and cost-effective plant design. Optimisation is performed through a combination of Genetic Algorithms (GA) [5] and Rapidly Exploring Random Trees (RRT) [6], which jointly ensure design optimisation, traversability of the target environment, and task reachability.

2.1. Framework for Kinematic Design Synthesis

A task-based design framework is introduced to optimise link dimensions and kinematic topology of serial manipulators operating in a constrained task environment using a generalised parametric model. By decoupling structural parameters from actuation variables, the method enables both dimension and topology synthesis. The optimisation can shorten links, restrict joint ranges, or deactivate axes, reducing Degrees of Freedom (DoF) where unnecessary for reachability. The framework (Fig. 1b) integrates classical Denavit–Hartenberg parameters with additional actuation variables for potential rotational and translational DoFs, expressed in the forward kinematics. The resulting robot model is defined from the base to the end-effector as T_1^n, where T_i is the geometric transformation of link i determined by fixed kinematic parameters.

2.1.1. Optimization Objective

Genetic Algorithms (GAs) are effective for exploring high-dimensional, non-convex design spaces with both discrete and continuous variables. Here, the GA is guided by a hierarchical objective prioritising (i) full reachability and (ii) structural efficiency. The objective function integrates strong reachability penalties: the fraction of unreached targets $(1 - R)$, a binary penalty E if $R < 1$, and squared distances F to unreachable points, ensuring only fully reachable designs are retained. Once $R = 1$, efficiency terms dominate: A penalises long links, B large joint ranges, C redundant links, and D unnecessary active axes. A logarithmic aggregation ensures numerical stability and prevents dominance of a single term, with all terms scaled by weighting factors $\lambda_0, \ldots, \lambda_6$:

$$L(\mathbf{x}) = \log\left(1 + \lambda_0(1 - R) + \lambda_1 A + \lambda_2 B + \lambda_3 C + \lambda_4 D + \lambda_5 E + \lambda_6 F\right) \tag{1}$$

2.1.2. Experimental Evaluation and Key Results

The GA, combined with the RRT framework, was evaluated in both 2D (planar) and 3D (volumetric) task spaces. As shown in Fig. 2, in 2D, the environment contained 5 obstacles, 10 targets, and $n = 8$ links; in 3D, 32 obstacles, 10 targets, and $n = 8$ links with mixed prismatic/rotational bounds. The GA converged rapidly to $R = 1$, systematically shortening links and pruning unnecessary axes. Across repeated 120-minute runs on a fixed workspace, designs consistently maximised reachability, indicating asymptotic optimality of the objective.

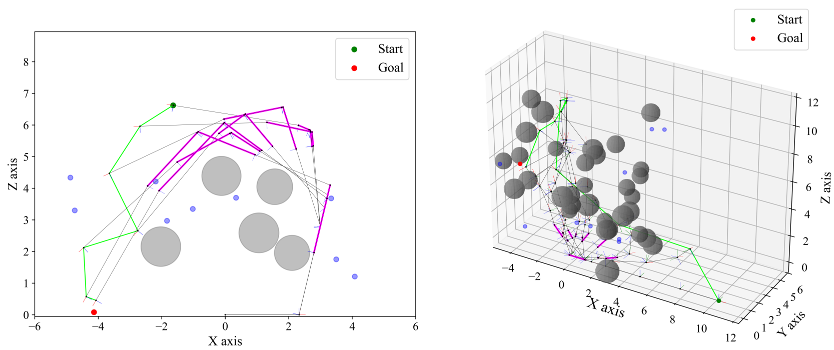


FIG. 2. Example trajectories of the optimised robot in 2D and 3D workspaces, showing joint motions and the RRT search tree. In both cases, a random target is generated within the workspace containing obstacles (grey) and task points (green).

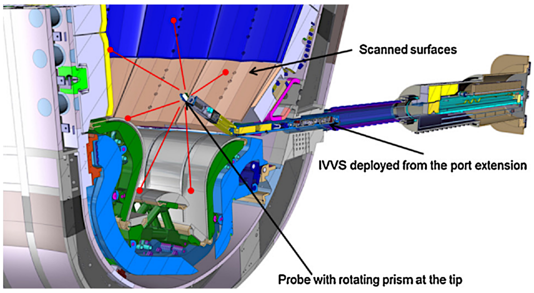
The proposed method provides a practical route to early-stage design, reducing cost and time by automatically identifying compact kinematic structures. Its present scope focuses on spatial reachability, with dynamic aspects such as mass, torque, and payload to be incorporated in future developments. The approach combines a task-based framework that jointly optimises link dimensions, joint limits, and active axes with a hierarchical objective that progressively balances reachability and efficiency, allowing principled pruning of redundant degrees of freedom. Comparative studies in cluttered 2D and 3D workspaces further show that the GA+RRT scheme achieves faster convergence than Adaptive Simulated Annealing (ASA) and Particle Swarm Optimisation (PSO). Together, these results highlight a scalable framework for the kinematic design of long-reach manipulators, with clear potential for application in the confined environments of fusion reactors. Future work will extend the framework by embedding dynamic constraints and exploring machine-learning techniques to enhance adaptability and efficiency.

3. LONG-REACH SLENDER MANIPULATORS FOR RAPID INSPECTION

Within fusion vacuum vessels, it is essential to rapidly inspect plasma-facing components, especially after abnormal events. Inspections target erosion, deposition, cracks, and displaced objects, but robots must operate under high temperature, radiation, and vacuum. The narrow ports and complex geometry demand slender, multi-DOF manipulators, which in turn create major design and control challenges.

3.1. Manipulator design

Robotic systems such as TARM [7] have long supported maintenance in fusion facilities, but their size and deployment requirements make them unsuitable for frequent inspection or minor tasks that must occur soon after shutdown under high temperature, radiation, and vacuum. The ITER In-Vessel Viewing System (IVVS), shown in Fig. 3a, addresses this by enabling rapid inspection between pulses with six deployable probes that reconstruct grey-scale images and 3D surface profiles under ITER's harsh in-vessel conditions [8]. While effective for monitoring erosion, deposition, and dust, the IVVS provides only localised coverage and cannot perform repairs. A step further towards a multi-purpose rapid inspection system is the Articulated Inspection Arm (AIA) developed by CEA (Fig. 3b). Originally designed for ITER and first demonstrated on Tore Supra, the system has been progressively upgraded and is now routinely deployed in WEST and EAST for visual inspection and metrology [9, 10, 11, 12]. The AIA is a long-reach, multi-link manipulator with onboard actuation, able to deploy through narrow ports for inspection and metrology under vacuum, high temperatures (120 °C during operation and 200 °C during baking), and kGy-level radiation. Its main limitations are the added mass and inertia from distributed actuation and the cost of bespoke radiation-hardened electronics.



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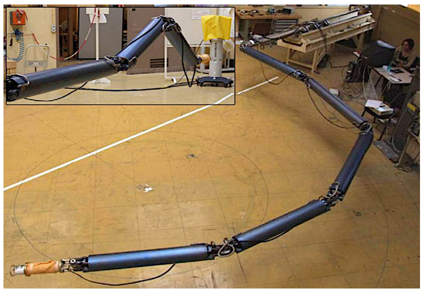


(b)

FIG. 3. Overview of robotic systems developed for rapid intervention in fusion reactors. a: IVVS [8]; b: AIA [13].

3.2. Control strategies

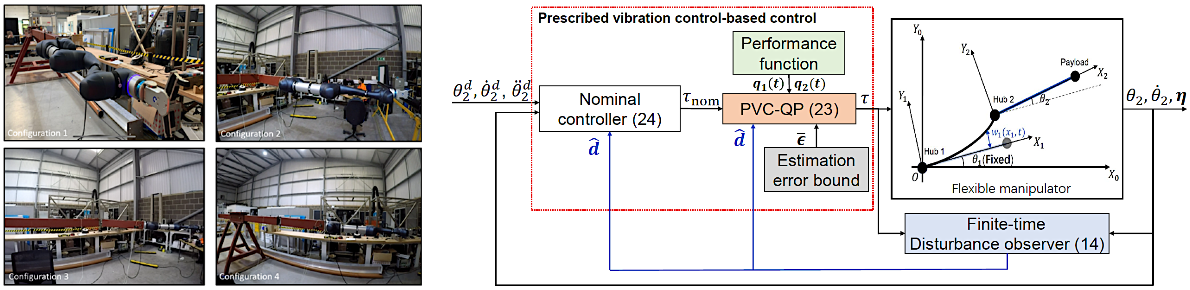
Recent work has targeted vibration suppression in long, slender manipulators where flexibility degrades accuracy. Chen et al. [14] studied a through-wall deployment system, proposing a dynamics-based trajectory planner that generates high-order polynomial joint paths under zero-boundary conditions. By incorporating experimentally derived frequency response functions, the method tailored trajectories to avoid boom resonances, reducing residual vibrations by about 28% in experiments without slowing motion (Fig. 4a). The drawback is its reliance on accurate system identification and offline optimisation, which limits adaptability.

Wang et al. [15] instead developed a prescribed vibration control framework that combines control barrier functions with a finite-time disturbance observer (Fig. 4b). Using a simplified two-link flexible–rigid model, they reformulated the control problem into a quadratic program that enforces vibration constraints while preserving tracking. Simulations confirmed improved accuracy and suppression under uncertainties, but the approach remains restricted to reduced-order models and has yet to be validated on full-scale manipulators.

In summary, feedback methods such as control barrier functions [15] offer robustness but are computationally demanding, while feedforward trajectory optimisation [14] effectively reduces vibrations but requires costly modelling. Model-based input shaping [16] provides an additional path by pre-filtering commands to avoid modal excitations. Future research should integrate these complementary paradigms to enable fast, robust, and safe operation of long-reach manipulators in fusion environments.

3.3. In-Vessel Rapid Inspection System

Building on these results, the IRIS (In-Vessel Rapid Inspection System) project, an international collaboration between UKAEA and the Korean Institute of Fusion Energy, is developing technologies for next-generation rapid



(a) (b)

FIG. 4. Control strategies of slender manipulators. a: Experimental setup with articulated arm in 4 different configurations [14]; b: Control block of the prescribed vibration control [15].

inspection robots. Using K-DEMO as a case study [17], such systems must withstand 100–200 °C, gamma doses of 2–3kGy/h, ultra-high vacuum (10^{-5} Pa), and residual magnetic fields of 40mT.

In its first phase, a methodology was developed to determine the manipulator kinematics via multi-objective optimisation, minimising robot length and joint torques while ensuring reachability of representative inspection targets obtained through a novel surface clustering approach. A prototype with a reduced number of DoF was then built to explore tendon actuation, decoupling of DoF, gravity compensation, and detachable actuation. To address modelling and control challenges typical of slender manipulators [18, 19], a novel framework was developed. This uses a high-fidelity dynamic model to train a Physics-Informed Neural Network (PINN) capable of compensating for feedback uncertainties, tendon elongation, and structural deflections.

Future work will focus on the full-scale manipulator design and the integration of environmentally compatible technologies such as radiation-hardened sensors and cameras for closed-loop control.

4. EVALUATING LASER ULTRASOUND FOR NDE CHALLENGES IN FUSION POWER PLANTS

Remote maintenance in fusion will involve the remote fabrication of safety-critical joints (e.g. welds) or repairs, which will require subsequent remote non-destructive evaluation (NDE) to detect defects and satisfy safety requirements[20].

NDE with laser ultrasound (LU) involves the generation and detection of ultrasonic elastic waves in a target via laser beams, which the Laser ultrasound replicates the capabilities of more widespread piezoelectric ultrasound (PU) for volumetric, sub-surface NDE, without the requirement for physical contact and coupling fluid which renders PU incompatible with certain fusion environments. Defects can be detected, visualised through imaging algorithms, and characterised to assess concern and component fitness-for-purpose. Laser Induced Phased Array (LIPA) technology has been developed and is being employed by the laser ultrasonics team at the University of Strathclyde. Characteristics of LU, such as radiation-tolerance of optical fibre, vacuum-compatibility in optical transduction, and ease of robotic deployment make it an attractive technology for fusion power plant remote maintenance applications.

UKAEA and the University of Strathclyde have collaborated to undertake feasibility studies on the inspection of fusion power plant components using LU for 1. NDE of breeder blanket pipe welds, and 2. inspection of plasma-facing components (PFCs).

In the case of using LU for the NDE of breeder blanket pipe welds, one promising result was obtained from circumferential LU Full Matrix Capture (FMC) and Total Focussing Method (TFM) [21] scanning of a laser-welded pipe sample. The pipe sample had an inner diameter of 90 mm and a wall thickness of 5 mm [22]. A ¡0.5 mm diameter weld stop pore, on the inner surface of the pipe weld, was targeted as a known defect for the LU NDE inspection. The pipe was mounted on a rotating stage and scanned with the LU laser beams on the outer surface (figure 5). The LU lasers were scanned to acquire FMC datasets from a series of 30 linear, periodic 1D LIPAs at 3°intervals around a 90°sector of the pipe [21]. Each array consisted of 34 elements spaced with 0.152 mm pitch, giving a 5 mm array aperture along the spine of the pipe. The start and end points of the rotational scan were chosen such that the target pore defect would come into alignment beneath the LU array at an angular position of approximately 60°into the 0-90°scan. Following data acquisition, the FMC from each of the 30 arrays was processed via the TFM imaging algorithm to produce a 2D reflectivity image of the sub-surface. Differences between these 30 2D images can be easily identified when all 30 are stacked to form the 3D iso-surface plot shown in Figure 6. A single, pronounced indication at the expected depth and lateral offset (beneath the weld) can be seen at 57°into the 90°scan, within 3°of the 60°target (which was positioned by-eye). The indication was coherent

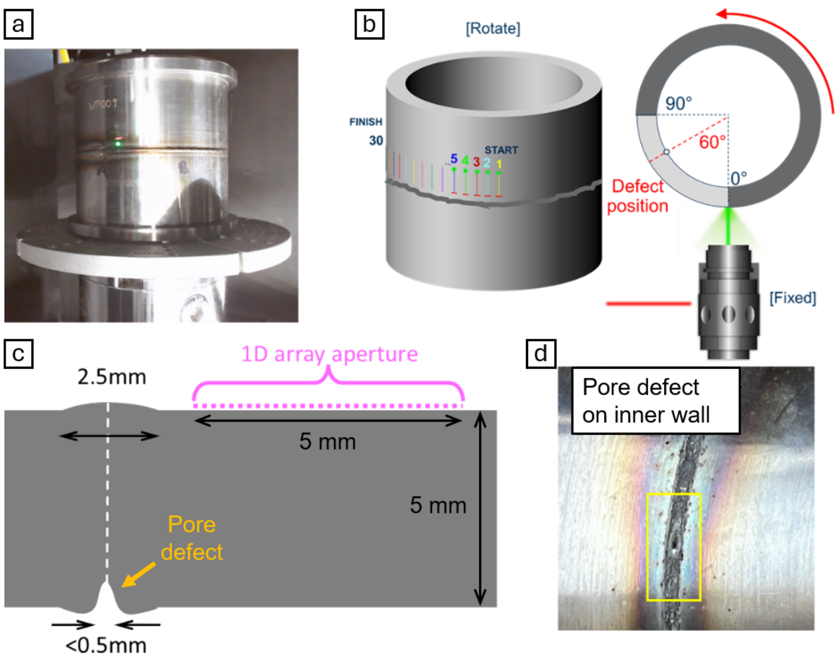


FIG. 5. LU scanning of circumferential pipe weld. (a) Pipe mounted on rotating stage for scanning, with LU alignment beams visible (red and green). (b) Illustration of rotational FMC/TFM scan strategy. (c) Diagram of pipe cross-section in the imaging plane, showing the relative positions of the 1D array aperture and target inner-surface defect. (d) Photograph of the inner-surface pore defect.

across the T-T and T-L wave sets, which are expected to provide the highest signal-to-noise ratio.

The second case study has tested the LU on an EU-DEMO divertor monoblock sample (Figure 7a. The goals of these experiments were to evaluate the compatibility of the method with the small sample dimensions, tungsten material, and investigate the ability of LU to detect the tungsten/copper dissimilar metal interface a key feature whose integrity is critical to the fitness-for-purpose of this component. LU FMC/TFM scanning was used to image the interior of the sample from multiple surfaces with different thicknesses of tungsten. The resulting images are presented in Figure 7d. In all cases, the curved tungsten/copper interface was detected at the expected depth, and thickness measurements with errors of less than 2.5% relative to the design dimensions were obtained. A distinct cross-hatch artefact was identified in the TFM images, and determined to be caused by surface wave reverberations across the small surface of the sample. Strategies to suppress this artefact could be developed in future work.

These feasibility studies have yielded encouraging results that suggest LU can provide useful NDE data in both the applications studied. Future work should evaluate the priority inspection parameters that must be improved before practical field deployment is possible (e.g. acquisition speed) and develop a TRL enhancement roadmap. Since these studies, the laser ultrasound system has also been integrated with a robotic arm, demonstrating compatibility with robotic deployment, essential for operation in a fusion environment.

5. ESTABLISHMENT OF LONG-TERM AND ROBUST AUTONOMY CAPABILITIES FOR ROUTINE INSPECTION OF PLANT

Future fusion power plants and experimental facilities will require significant inspection and light maintenance activities in industrial environments such as the ITER Neutral Beam Hall.

Feasibility of long-term autonomous robotic inspection has been established via a 35-day continuous autonomous inspection trial in the JET Torus Hall, a highly representative environment of future fusion inspection scenarios [23]. This is shown in Figure 8. The deployment included routine measurements of temperature, humidity, gamma radiation, as well as taking photographs and thermal images of key targets along the inspection route, and building a new 3D point cloud map on each patrol. This work established capability for long-term robotic deployments in fusion facilities, but also enabled gathering of data to support research into change detection and dynamic mission replanning. The highly autonomous solution only needs human intervention for abnormal scenarios. Its deployment in JET is the world first case proving the feasibility of using autonomous mobile robots to monitor ex-vessel halls beyond lab demonstrations in practice.

To meet the need of long-term inspection, *AutoInspect*, a flexible software system, is developed by the Oxford

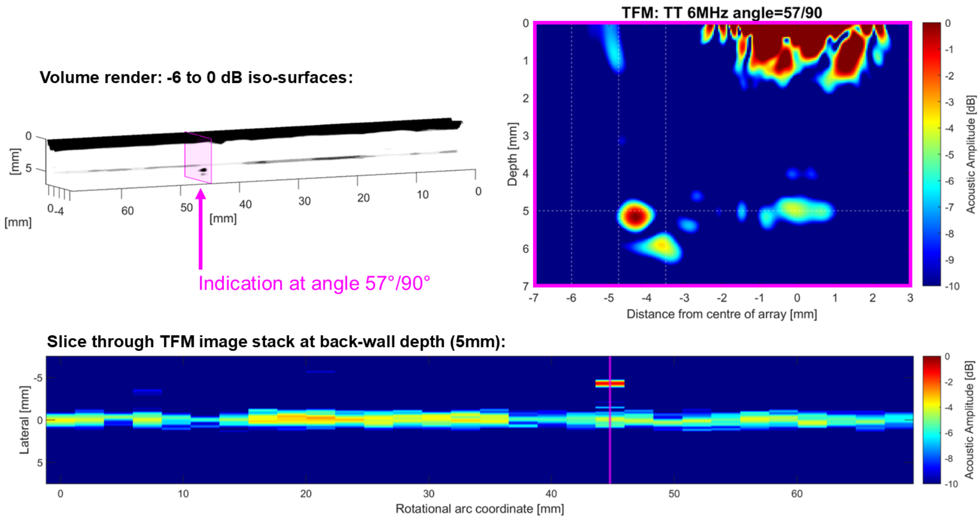


FIG. 6. Resulting LU inspection data after TFM imaging using the T-T wave set. Top left: 3D iso-surface plot formed by stacking 30 individual 2D TFM images. The plane containing the defect indication at angle 57/90°is highlighted in magenta. Top right: 2D Colormap of TFM image at angle 57/90°. White dashed lines mark the back wall depth (5 mm) and weld region (-3.5 to -6 mm lateral offset from the centre of the LU array). Bottom: Colourmap of 2D iso-depth slice (depth=5 mm) through 3D data stack shown in top left.

Robotics Institute for autonomous inspection and monitoring. *AutoInspect* includes two major elements: Frontier and Topological Autonomy (TA). *Frontier* is a mapping and localisation system packaged in a hardware payload. Topological autonomy is used for spatial abstraction and mission planning. The TA spatial abstraction and mission planning subsystem is a robot-agnostic graph-based autonomy framework. When conducting trials with a Spot robot in the JET facility, the robot is localized using a prior map of the environment which is created by tele-operating the robot.

5.1. Extending to multi-robot inspections

Further work has been undertaken to address outstanding issues of conducting multiple parallel robotic operations in fusion environments [24]. Specifically this work explores the safe deployment of Deep Reinforcement Learning methods for control of multiple robots in cluttered environments. This is in support of ambitions of safely deploying multiple robots to conduct maintenance operations in parallel for highly productive maintenance in future plants.

Future directions for autonomous mobile robotic inspection include investigation of tolerance to failures, both at the subcomponent level (e.g. a joint position sensor) and at the whole robot level (in the context of multi-robot systems), for example as a result of radiation damage.

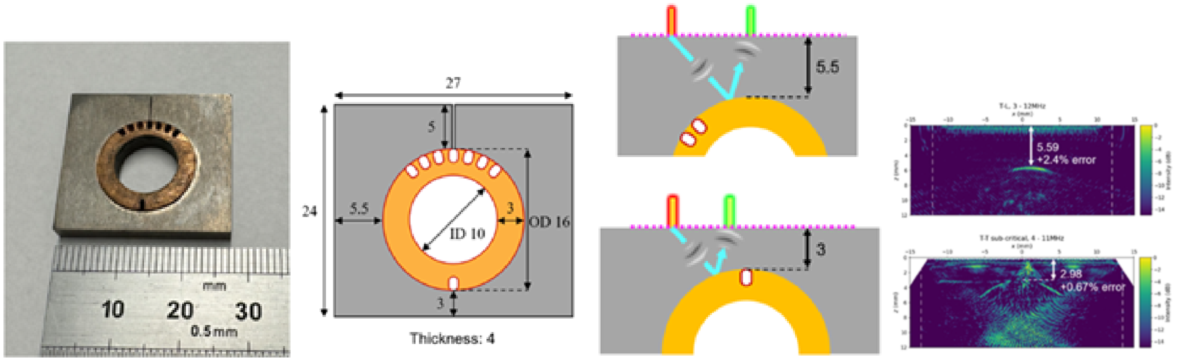
6. DISCUSSION AND FUTURE WORK PLANS

Fusion power plants will need significant maintenance to be carried out through their lifecycle, much of which will need to be conducted by remotely operated or autonomous robots and systems. UKAEA has assessed the key outstanding challenges to deployment and commercialisation of robotic maintenance in future fusion devices, and established a framework of 10 key challenges for communication of these.

We have presented a range of topics marking significant advances in robotics and remote maintenance capabilities in support of future fusion power plants. Four specific topic areas have been addressed, mapping across to solutions and advancements against the 10 challenges framework.

Advances have been shown against rapid optimisation of remote deployment robotics for rapid inspection, the development of long-reach slender manipulators, establishing the feasibility and performance potential of laser ultrasonics for in-situ NDE, and investigating long-term autonomous inspections in hot cell environments.

Ongoing work continues in pursuit of addressing the key challenges of remote maintenance of experimental fusion devices and future fusion power plants. Whilst the presented work highlights some interesting progress, there remain significant outstanding challenges. Work continues against all of the 10 challenges, and while new



(a) (b) (c) (d)

FIG. 7. (a, b) EU-DEMO divertor monoblock sample used for LU PFC inspection feasibility study. Dimensions in mm. (c) Illustrations of the LIPA scans on the 5.5 mm and 3 mm-thick sides of the sample respectively. Dimensions in mm. (d) Results from LIPA scanning of the divertor monoblock sample. TFM images from the 5.5 and 3 mm-thick sides of the sample using the T-L and T-T wave sets respectively.

FIG. 8. Long-term autonomous inspection using Spot robot at the Joint European Torus.

technologies are investigated, maturing technologies such as the ones presented here will be progressed to establish feasibility and applicability.

7. ACKNOWLEDGEMENTS

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