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

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1. THE ROBOTICS AND REMOTE MAINTENANCE CHALLENGES OF FUSION ENERGY

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 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.

2. RAPID DESIGN OPTIMISATION OF REMOTE MAINTENANCE SOLUTIONS FOR FUSION

Novel methods for rapidly generating and optimising kinematic arrangements for remote maintenance deployment systems in the presence of arbitrary complex geometric constraints have been successfully demonstrated. The methods can operate in the presence of geometry specified as a collection of geometric primitives in 3D space, combined with task points representing reachability needs. A combination of Genetic Algorithms and Rapidly Exploring Random Trees is used to optimise kinematic design whilst ensuring traversability and reachability within the environment. Assessing and improving the maintainability and maintenance of fusion power plant architectures is a critical challenge in our ability to design feasible fusion power plants. This work is a step towards rapidly assessing maintainability of fusion plant architectures, as well as automatically iterating and refining remote maintenance deployment solution concepts, enabling efficient and fast fusion plant design.

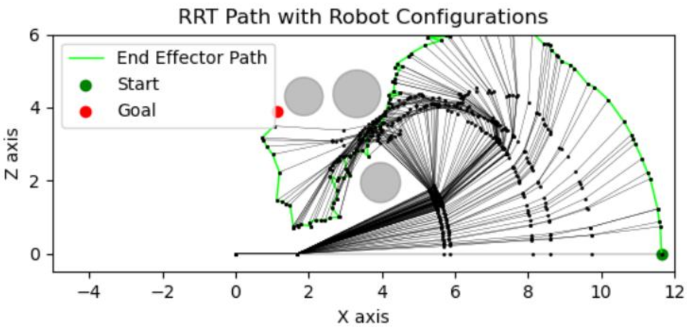

Figure 1 - Example trajectory solution for an automatically optimised kinematic arrangement of a maintenance deployer in arbitrary constraints.

3. NOVEL TENDON DRIVEN RAPID INSPECTION MECHANISM DESIGN

Tendon driven mechanisms with gravity compensation and mechanical force decoupling have been verified in physical testing. Within fusion vacuum vessels, it is desirable to be able to inspect the conditions of plasma facing components rapidly after plasma operations in order to verify normal conditions, in particular following abnormal occurrences. This type of operation would typically inspect the geometry of the environment with the objective of detecting erosion of components, deposition of materials, cracking of components or welds, and objects that have moved. One example of a system that is intended for this task is the ITER IVVS [2], however it is also desirable to have deployment capability compatible with making minor repairs. With K-DEMO as a case study, this work explores mechanisms and materials in the pursuit of a general-purpose rapid deployment arm that can reach anywhere within a vessel under extreme radiation and thermal conditions. Particularly, the novel development solution aims to allow for full in-vessel inspection of PFCs within a few hours, in an environment condition, e.g., at a Gamma dose rate approximate 2 kGy/h, like DEMO's Day 1 after DT-operations. The enabled prospective manipulator with mechanical end effectors targets a total Gamma tolerance over 10 MGy, which needs to be verified experimentally in the next. The bottleneck that limits operation time foreseeably is the radiation tolerance of camera instruments. For instance, an advanced rad-hard lightweight (e.g., ~1 kg) camera available in the market may only be tolerant to 100 kGy total dosage. To enable rapid repair with a rugged durability, the development of novel optic-fibre-based sensing mechanisms is considered a potential solution for realising visual inspection, aiming to achieve an over 10 MGy Gamma tolerance.

4. ESTABLISHMENT OF LASER ULTRASONIC TESTING AS A CANDIDATE VOLUMETRIC INSPECTION METHOD FOR VERIFYING PIPE WELDS

Detection of defects in welds of fusion-relevant pipe samples has been successfully conducted using Laser Ultrasonic Testing (Laser-UT) deployed via a pair of optic fibres. A recent survey [3] highlighted the broad range of developments made in relation to joining pipe services in the maintenance of fusion devices, along with gaps and outstanding work requirements. Non-destructive volumetric inspection remains one of the more challenging technology gaps, in particular within gamma radiation environments. Although under laboratory conditions and at a scale that would be incompatible with most in-situ inspection tasks, the method is a highly interesting one from the perspective of performing volumetric inspection in high gamma environments due to the fibre deployment. This novel NDT approach generates ultrasound by thermal expansion induced by laser power from one optic fibre, then the resulting ultrasound signal is measured using a detection laser via the other fibre. Last-UT methods permit in-depth imaging of objects at a high axial resolution. Laser-UT non-contact, laser-based ultrasound transduction has been evaluated for two in-situ NDE applications in a tokamak power plant: in-bore inspection of breeder blanket pipe welds, and inspection of plasma-facing components. In both cases, the detection and evaluation of relevant defects in realistic samples has been demonstrated. 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 AUTONOMY CAPABILITIES FOR ROUTINE INSPECTION OF PLANT

Feasibility of long-term autonomous robotic inspection has been established via a 35-day continuous autonomous inspection trial in the JET Torus Hall [4]. The deployment included routine measurements of temperature, humidity, gamma radiation, as well as taking photographs and thermal images of key targets along the inspection patrol, 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.

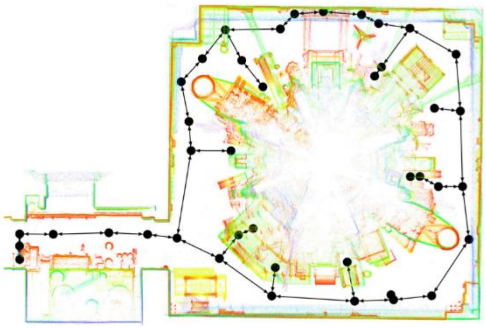

Figure 2 - Topological inspection map with a top-down view of pointclouds with the JET Torus Hall.

6. FUTURE WORK PLANS

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

ACKNOWLEDGEMENTS

This work has been part-funded by the EPSRC Energy Programme grant number EP/W006839/1. The views and opinions expressed herein do not necessarily reflect those of the authority. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk

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