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Automated maintenance feasibility testing on the EU DEMO Automated Inspection and Maintenance Test Unit (AIM-TU)

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In order to reach commercially-relevant availability, future fusion power plants must minimise the duration of maintenance shutdowns. However, as radiation levels increase, so too will the number of maintenance tasks that must be performed without human access. To meet these conflicting constraints, remote maintenance systems must therefore significantly increase their capabilities, performing tasks faster and in parallel. Unfortunately, the current teleoperation-based maintenance approach is inherently limited in these regards. Automation emerges as a potential solution, having demonstrated dramatic productivity gains in manufacturing across the world. The European DEMO project has begun to explore the feasibility of automated maintenance as a route to meeting the challenging availability targets. To this end, the Automated Inspection and Maintenance Test Unit (AIM-TU) has been designed and constructed, providing a highly versatile test platform able to adapt to evolving R&D programmes. It consists of a modular robot cell equipped with two robot arms mounted on linear rails, interchangeable end-of-arm-tooling, a variety of vision sensors and a fully integrated safety system. The hardware is supported by a modular software architecture, which permits different control input modes and provides a digital twin simulation of the cell for virtual verification and validation of control algorithms. This paper provides an overview of the system's capabilities and reports on the first automated maintenance feasibility tests performed on the cell: automatic replacement of JET reactor tiles and automatic contactless inspection of tile anomalies.

Keywords: Maintenance, automation, remote, robotics

1. Introduction

For commercial viability, fusion power plants must minimise maintenance shutdown durations. However, as reactor size, complexity and power increase, so do the number of maintenance tasks that must be performed. Further, future reactors will see increased radiation levels and more flow of activated materials through the plant, so more maintenance tasks will have to be performed remotely to minimise exposure to the workforce. These factors mean that future maintenance systems must be able to perform more tasks, in less time, remotely. To put this in context, for the Joint European Torus (JET) to achieve 80% plant availability (typical of a modern nuclear fission power plant [1]), the duration of major maintenance shutdowns would have to be reduced from the average 273 days [2] to around 30 days, and minor maintenance interventions reduced from 108 days to just 12. This constitutes an 89% reduction in maintenance durations. While JET is not a commercial power plant, producing "scientific data" instead of electricity, these values provide a sense of the step change required in maintenance speeds for future fusion power plants.

For the remote maintenance systems of the future to meet this challenge, two areas must be dramatically improved: task parallelisation and speed. The former is the number of maintenance tasks that can be performed across the plant simultaneously. Task speed refers to the speed with which individual maintenance tasks can be performed. Once a task has been refined and optimised to be as efficient as possible, task speed can only be improved by increasing the movement velocity of the systems involved. Teleoperated systems are inherently limited in these aspects, so cannot scale to serve commercial power plants.

Automation emerges as a potential solution, having demonstrated revolutionary productivity gains in the global manufacturing industry. The vision is of a power plant populated by fleets of industrial robots performing repetitive, well-defined maintenance tasks, with only high-level human supervision and supported by teleoperated robots as required. High-level decisions of what maintenance to undertake, and how, would always be in the hands of humans, but the automated robots would otherwise operate without direct human supervision.

Such a large-scale deployment of robots and automated systems in environments as harsh and complex as fusion power plants is unprecedented, and brings with it significant challenges. The EU DEMO project has therefore begun to explore the use of automated maintenance under its Remote Maintenance work package, through a collaboration between UKAEA's Remote Applications in Challenging Environments (RACE) business unit and the VTT Technical Research Centre of Finland. To enable this research programme, the Automated Inspection and Maintenance Test Unit (AIM-TU) has been designed and constructed at UKAEA's Culham site.

This paper introduces the research programme, gives an overview of AIM-TU's capabilities, and reports on the first automated maintenance feasibility tests performed on the cell: automatic replacement of replica reactor first-wall tiles and automatic detection of tile anomalies.

2. Automated maintenance development programme

The experience derived from JET [3] [4] and ITER [5] has shown that the maintenance strategy of fusion reactors must be considered from the outset and fully integrated into their design, as retrofitting maintenance systems is very costly and leads to suboptimal designs. This will be even more true of automated systems, which rely heavily on good integration and planning to operate effectively. Because of this, it is essential that automated maintenance strategies be explored now, at a point in time when technology demonstrators like EU DEMO are entering their concept design phase, during which the plant architecture will take shape. If the requirements of automated maintenance are not understood and embedded into the designs there exists a significant risk that the next generation of fusion plants will not be able to accommodate automated maintenance. Without it, these plants will not be able to demonstrate the commercially-relevant maintenance that is key to their financial viability.

Hence, the launching of the EU DEMO automated maintenance R&D programme is timely. The initial focus of the programme is to establish the feasibility of generic automated maintenance activities, considering the likely constraints imposed by the fusion environment. The goal is to better understand the effect that fusion power plant constraints have on the automated systems, and highlight areas where further research and development is needed to reach the necessary technical maturity. Primary constraints considered at this stage are:

- Harsh environmental conditions. These lead to accelerated degradation of robotic systems and sensors and, hence, increased robustness requirements.
- Robotic deployment. Robots will need to move in and out of the harsh worksites to increase survivability and maximise use of the limited space available close to the reactor core. This is a significant departure from conventional industrial practice, whereby factories are built around static robot lines and cells. This constraint particularly affects the design of supporting robot infrastructure such as service provision (data & power), stable mounting points, positional datums, rescue & recovery, etc.
- Lack of human access. In many reactor locations, human operators will not be present to perform tasks such as installation, commissioning, calibration, troubleshooting, repair, recovery or rescue, which is the conventional industrial approach.
- Variable and unknown component states. Conventional automation systems exploit the detailed knowledge of tasks and processes to ensure they can be automated robustly. However, maintenance task parameters for components in first-of-a-kind plants are difficult to predict at present, which may demand increased flexibility and adaptability from automated systems.
- Operation in a regulated environment. Deployment of automated systems in a nuclear setting introduces fundamental verification and validation (V&V) requirements to achieve regulatory acceptance. This is particularly challenging when using artificial intelligence, for which V&V is an open, highly complex challenge.

A development roadmap has been established, presented in Figure 1. It shows some representative maintenance tasks selected for initial study and some of the key underlying automated capabilities that must be demonstrated. The tasks are expected to be commonly performed in future reactors, and the roadmap shows qualitatively their increasing complexity.

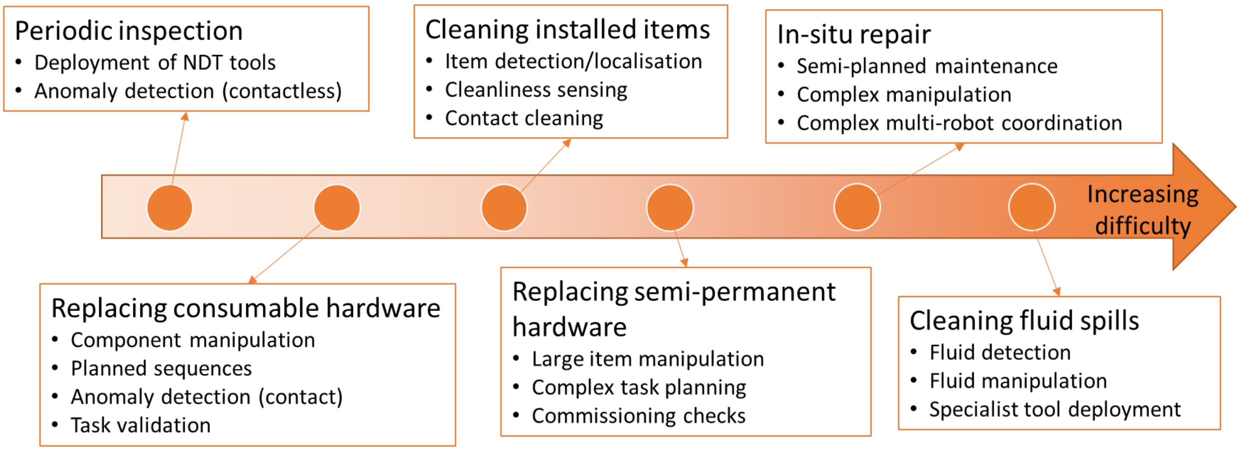

Figure 1. Development roadmap for automated maintenance for fusion power plants.

The first feasibility tests of this R&D programme have been executed on AIM-TU and are reported here. Contactless anomaly detection and component replacement have been targeted first because they are fundamental to general reactor maintenance. The former is needed to determine the state of plant for maintenance planning and statutory compliance, and also to verify the correct execution of maintenance activities. Component replacement is a core element of EU DEMO's maintenance strategy [6] [7]. Using line-replaceable units allows degraded hardware to be quickly switched out with a new unit, helping to return the reactor to operation as fast as possible. The degraded component can then be taken to less hazardous areas for inspection, refurbishment, repair, etc..

3. Overview of the Automated Inspection and Maintenance Test Unit

The Automated Inspection and Maintenance Test Unit has been created to provide a highly versatile test platform able to adapt to an evolving R&D programme. The cell concept was established with the Karslruhe Institute of Technology, using a fuzzy Analytical Hierarchy Process decision-making tool [8].

AIM-TU consists of a robot cell equipped with two robot arms (1300 mm reach, 10 kg payload) mounted on linear rails (1250 mm travel). The robots can be equipped with a range of end-effectors, including grippers and tool changers. 3D printing is used to create physical interfaces which allow the robots to handle many of the components and remote maintenance tooling used in the JET reactor. The cell layout can be changed to suit the needs of the evolving R&D programme thanks to modular flooring platforms. An integrated safety system enables high-speed operation, as well as operation with human access under reduced-speed conditions. The cell has access to a variety of vision sensors, such as wrist-mounted, RGB-depth, polarisation, and event cameras.

Figure 2. Photograph of AIM-TU showing the robots within the safety cell.

Robot control can be achieved from the robot controllers, a cell controller or via Robot Operating System (ROS) with an external PC. The cell is supported by a modular software architecture using Docker containers, which allow software packages to be added to increase capabilities as required. A digital twin of the cell has been developed, implemented through Gazebo and ROS. Digital twin technology allows advanced robot programs to be verified in a virtual space before they are tested on real equipment, and encourages collaboration with third parties by providing an easily-accessible simulation of the cell.

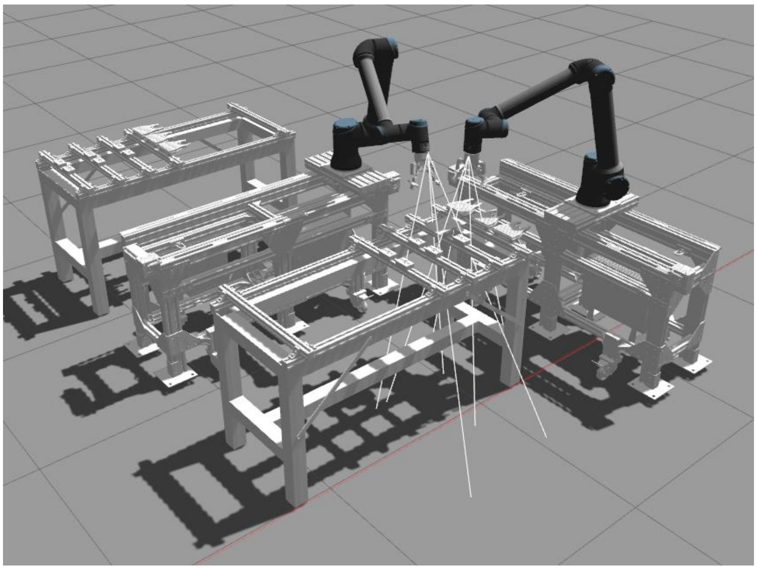

Figure 3. The AIM-TU digital twin.

4. Tile replacement feasibility testing

4.1 Background

The generic task of component replacement has been explored using the replacement of replica reactor inner wall protection tiles as a representative use case, as this is one of the most common tasks performed on the JET reactor. During the Enhanced Performance 2 shutdown between 2009 and 2010, over 4000 carbon-fibre composite reactor tiles were replaced with the "ITER-like wall" of solid beryllium, beryllium coated Inconel, solid tungsten and tungsten-coated carbon fibre composite tiles [9]. Extensive operational data sets were captured during the tile replacement activity, including video footage and operation logs. These data sets have since been recorded during all subsequent maintenance campaigns, meaning a rich library of historical records is available. Therefore, this serves as an excellent reference case to explore not only the feasibility of automated tile replacement, but also its performance against state-of-the-art teleoperation.

4.2 Task description

The tested task simulates the automatic replacement of a damaged JET reactor tile. Two robot arms are used working in coordination, as shown in Figure 4. The "Red" robot handles the 3D-printed tile replicas while the "Green" robot is equipped with a JET boltrunner to tighten/release the tiles. The tiles and tools used in the test are designed for use in JET so are remote-maintenance-compatible, and include alignment features, feathered threads on bolts, etc. The components have not been modified further for use with AIM-TU.

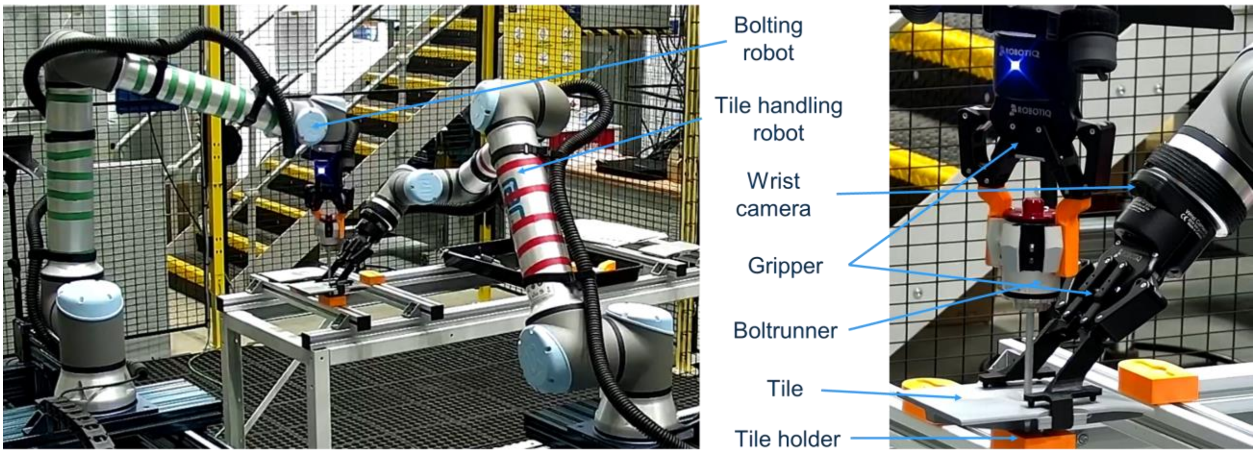

Figure 4. The AIM-TU robots executing an automated tile replacement task.

During the task, the detection and localisation of tiles and tile holders is achieved using the robots' wrist cameras. This vision guidance serves to improve the system's resilience to positional uncertainty of handled components and reactor locations. This is because the need to deploy robots into worksites means they may not be mounted on static, datumed bases, and so the positional uncertainty they will encounter is likely to be higher than is usually found in conventional industrial factory settings. Further, the extreme conditions could lead to small deformations of in-vessel components, which the automated systems would have to cope with during maintenance. Hence, relying on pre-determined coordinates for locating components may not be a sufficiently robust solution for automated maintenance in fusion.

The full task sequence is given below:

1) Red robot detects and locates the damaged tile, and secures it with its gripper.
2) Green robot detects and locates the tile bolt hole, and aligns the boltrunner over it.
3) Green robot engages the bolt and untightens it, using force control to maintain appropriate torque and downward force.
4) Green robot disengages, and Red robot removes the loose tile.
5) Red robot carries the tile to a storage site, detects and locates the holder position, and puts the tile down.
6) Red Robot locates a new tile, picks it up, and carries it back to the installation site.
7) Red robot locates the tile holder and places the new tile down. Red robot maintains a grip on the tile to secure it in place during the bolting operation.
8) Green robot detects and locates the tile bolt hole, and aligns the boltrunner over it.
9) Green robot engages the bolt and tightens it, using force control to maintain appropriate torque and downward force.
10) Green and Red robot disengage, completing the task.

4.3 Results

Once the robot program was verified, the sequence was repeated 20 times under test conditions to assess the system's robustness. 18 cycles were successful. Two failed due to the tile orientation being incorrectly determined by the camera during collection, as the tiles are rotationally quasi-symmetric. After each failure, the system was restarted from the previous step, and the failed step succeeded on the repeat, showing that the detection error is intermittent. All other actions within the sequence were correctly executed every time. These results suggest that automated tile replacement is initially feasible using Commercial-Off-The-Shelf (COTS) equipment, under the tested conditions.

However, development of the vision-guided tile localisation capability is required to improve the robustness of orientation detection for rotationally symmetric components. Strong symmetries could be eliminated during component design, but component geometries may be driven by constraints which require them to be symmetric, or at least appear symmetric from the robot's viewpoint. Although humans could assist remotely, for example to verify detections, relying on teleoperators in this way would slow down the operations, defeating the main purpose of the automation. Thus, fully automated solutions are required, and techniques such as using environmental markers as reference or inferring the component's orientation from the scene context will be explored in further work.

A next stage in the testing is to study the introduction of additional reactor constraints. One example is poor or changing lighting conditions, which are likely to impact the system's ability to detect and localise objects of interest.

5. Contactless anomaly detection

5.1 Background

A key capability of human teleoperators is the ability to detect anomalies in reactor components, both for inspection and for verification of correct maintenance task execution. Automated systems must develop similar robust anomaly detection capabilities. This test explored the ability of the robot systems to detect gross surface anomalies in JET tiles through visual sensors (2D wrist-mounted cameras). As tiles are designed to protect the vacuum vessel, they are more likely to suffer visible degradation during operation. Further, tile surfaces must be carefully controlled to ensure the correct geometries are maintained for the first wall, so errors during installation must be detected and corrected. Hence, tile surface anomalies must be monitored during both pre- and post-maintenance inspection.

In particular, this first test explored the feasibility of applying template matching algorithms, whereby images taken during maintenance are compared against Anomaly-Free Baseline (AFB) images to detect deviations. This approach does not require the large datasets necessary for machine-learning-based training so may be more practical for deployment in first-of-a-kind reactors, for which large datasets of damaged components will not be available.

5.2 Task description

In the test each robot collected images of a group of three reactor tiles from four different positions. Four types of simulated surface anomalies were used consisting of printed paper images (Figure 5), placed on top of the tiles in different positions for each test iteration (Figure 6). In total, 104 images of tiles with surface anomalies were taken.

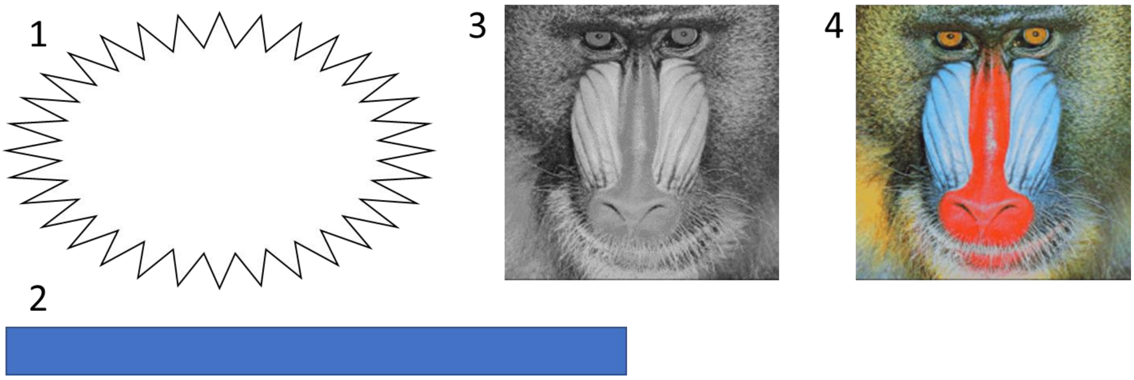

Figure 5. Simulated surface anomalies used. 1) high-contrast, non-orthogonal. 2) low-contrast, orthogonal. 3), low-contrast, organic form. 4) high-contrast, organic form.

The automated anomaly detection system follows four main steps to find defects in images: pre-processing, structural similarity, thresholding, and contouring. These are illustrated in Figure 6. Images are pre-processed using Gaussian smoothing, which reduces noise and blurs details. Each test image is then assessed against the relevant AFB image to produce a structural similarity map (based on luminance, contrast and structure functions), which indicates where the image pixels are dissimilar. A thresholding algorithm is then applied to establish which of these are sufficiently different to be of interest, and a contour detection algorithm is used to bound regions of the image with groups of dissimilar pixels, giving the areas of interest which constitute the anomalies.

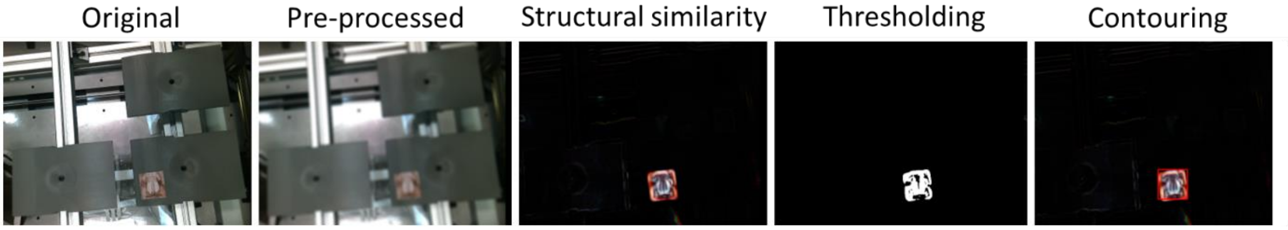

Figure 6. Anomaly detection sequence showing the various stages of the image processing, from the original image to the detection and localization of the anomaly.

The successful detection metric was established based on the Intersection Over Union (IoU) index. This is the ratio between the overlapping areas of the real and detected bounding box, and the combined area of both. Well-detected bounding boxes (and hence, anomalies) will have a high IoU index. For each image set, a range of different thresholding algorithms (binary, zero, Otsu, adaptive, and adaptive-Gaussian) and tuneable parameters were applied to optimise detection performance.

The successful detection rate was then also compared for different camera positions and anomaly types. Once performance of the system under nominal conditions had been established, disturbances were included in the image set to assess the robustness of the approach. These include noise (Gaussian, salt & pepper, and speckle noise), single pixel offset, brightness variations (0.5-1.5 gamma), and discolouration (increased red, green and blue hues), with examples shown in Figure 7.

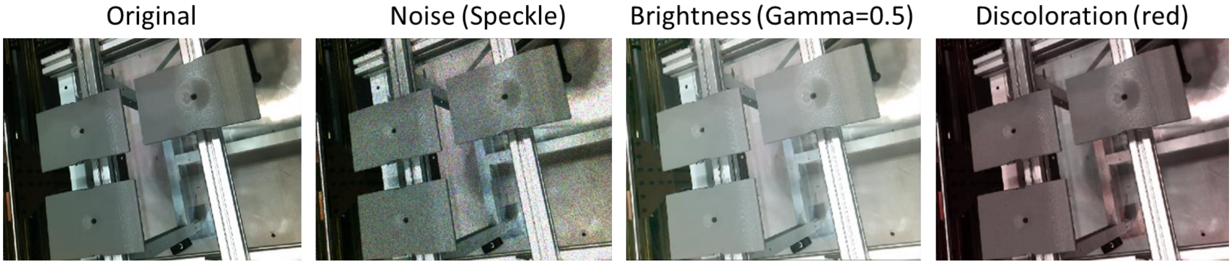

Figure 7. Examples of disturbances included in the image sets: noise, brightness and discolouration.

5.3 Results

Under ideal conditions, detection accuracy was highest for adaptive-Gaussian (100%) and Otsu thresholding algorithms (97%). Performance was similar for all types of anomalies. However, when including disturbances the detection accuracy decreased. Noise reduced detection rates to 93%, single pixel offset to 86% and discolouration to 93%. Most significant of all was the effect of increased image brightness, for which only a 45% detection rate was achieved. This could be problematic in a fusion environment, as it is expected that lighting conditions could be difficult to control given the prevalence of metallic, reflective surfaces and complex, densely packed spaces.

In general, the results indicate that, while the algorithms themselves are effective, the limiting factor may be snapshot repeatability. This is the ability to take an image which is sufficiently similar to the AFB image to allow the anomaly to be detected. There are many factors that influence snapshot repeatability, such as camera position repeatability, sensor parameters (autofocus, auto exposure, etc.), environmental factors (lighting, clutter, image background etc.). In industrial factory settings controlling these parameters is possible, but doing so in a fusion reactor environment may not be. Hence, the template matching approach is not considered robust enough for general deployment in automated maintenance applications. However, some areas of reactor maintenance may lend themselves much better to controlling snapshot repeatability (e.g. activities carried out in a processing cell in the Active Maintenance Facility). In these cases, the fact that template matching only requires a single pre-existing AFB image may prove to be a significant advantage over machine-learning techniques.

Future work will explore a combination of deep learning techniques along with structural similarity algorithms to improve accuracy and robustness to disturbances.

6. Conclusions

The need to achieve commercially relevant plant availability drives the requirement of reducing the maintenance duration of future fusion power plants. As the current teleoperation-based approaches cannot scale to meet the challenge, automated maintenance is proposed as a potential solution. However, its deployment in such harsh environments poses significant technical challenges which require research and development. The EU DEMO project has begun to explore automated maintenance through an R&D programme focused initially on establishing its technical feasibility under fusion reactor conditions. The Automated Inspection and Maintenance Test Unit, a modular and versatile robot cell, has been designed and installed to support this programme.

The first automated maintenance feasibility tests have been conducted. Automated replacement of reactor inner-wall tiles has been performed successfully under test conditions using two cooperating robot arms and vision-guided tile detection/location. An area for improvement is the determination of the orientation of quasi-symmetric components, which was the only part of the automated sequence which failed during testing.

Automated detection of gross surface anomalies in reactor tiles has also been demonstrated. The testing focused on the use of template matching algorithms, which require few pre-existing images for anomaly detection. This is an advantage in first-of-a-kind systems, as large databases of relevant anomaly images may not be available to train machine learning algorithms. The detection system displayed 100% detection accuracy under nominal conditions, but when disturbances were included only accuracies between 45 and 93% were achieved. This shows that, while the algorithms are effective at detecting anomalies, the repeatability of images is a limiting factor when using template matching. Thus, the approach may not be suitable for general use in automated maintenance. Machine learning techniques will be used in the next phase of testing to obtain more robust detection capabilities.

Acknowledgment

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