A robotic additive manufacturing system for in-situ repair of in-vessel tokamak components*

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***Abstract*— This paper presents the development of a multi-degree-of-freedom (DOF) additive manufacturing system for automated in-situ repair of plasma-facing components within tokamak reactors. The system integrates a 3-DOF delta robot and two 6-DOF collaborative robotic arms to address the challenges of maintaining complex in-vessel components. Two case studies are explored: repair and maintenance of tiles and pipework as found in tokamak reactors using fused filament fabrication with polylactic acid. Automated processes, including surface preparation, component identification, and repair using the extrusion method, were implemented and tested. Vibration analysis revealed limitations caused by payload constraints and mechanical rigidity, emphasizing areas for further improvement. Experimental results validate the feasibility of automating in-situ repairs while identifying technology gaps, particularly for applications needing high strength materials such as tungsten alloys in plasma facing components. The findings contribute to enhancing maintenance processes in fusion energy systems.**

I. INTRODUCTION

The tokamak has emerged as the most successful nuclear fusion reactor among all prototypes developed to date, playing a key role in advancing fusion energy research globally [1]. International experiments such as the Joint European Torus (JET) in the United Kingdom and the International Thermonuclear Experimental Reactor (ITER) in the European Union based their designs on tokamaks to achieve and sustain fusion reactions. However, maintaining plasma-facing components, which line the inside of these reactors, presents significant technical challenges. These components are subjected to extreme operational conditions, including intense thermal stress, erosion, and particle bombardment, which degrade their performance and shorten their lifespan. Plasma instabilities, such as disruptions and Edge Localized Modes (ELMs), further exacerbate these issues, causing severe damage to the reactor walls. Traditional maintenance methods for plasma-facing components (PFCs) involve the disassembly, removal, and repair of damaged components. For example, Fig. 1 illustrates Mascot performing maintenance tasks inside JET [2]. This approach not only requires considerable time and labour, leading to prolonged reactor downtime and elevated operational expenses but also results in extended reactor downtime and high operational costs. To deliver of sustainable fusion energy and maximise the scientific and economic benefit, it is imperative to develop solutions for automated in-situ repair of PFCs. In-situ repair systems minimize downtime by eliminating the need for component removal while reducing human exposure to hazardous environments such as radiation fields and vacuum conditions.

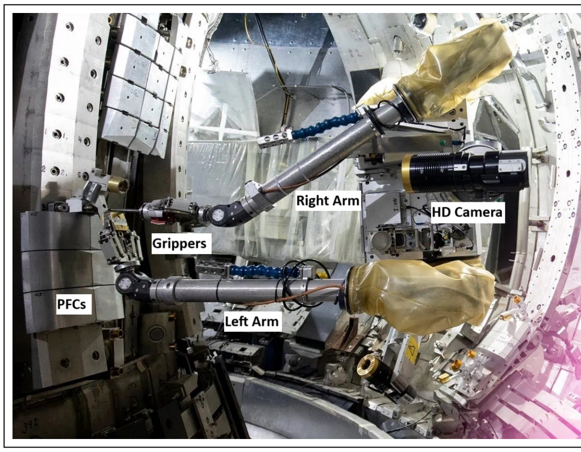

Fig. 1: Mascot dual-hand bilateral telerobotic system performing maintenance tasks

Additive manufacturing (AM), a process that builds components layer by layer, offers a promising solution for automating in-situ repairs. AM technologies, such as fused filament fabrication (FFF) and directed energy deposition (DED) [3], [4], have demonstrated their ability to repair intricate and damaged components efficiently. While FFF provides a cost-effective method for prototyping [5], DED enables the repair of high-strength metallic components with high precision. Integrating AM with multi-degree-of-freedom robotic systems and advanced sensors enables autonomous repairs of PFCs, addressing the challenges posed by complex geometries and limited access within tokamak reactors. This paper presents the development of a multi-DOF robotic system capable of performing in-situ inspection, surface preparation, and additive manufacturing approaches for repairing tokamak components. Two case studies are examined: the repair of plasma-facing components and service pipes using FFF with polylactic acid. The system's performance is evaluated, including vibration analysis, component quality, and limitations of the current setup. The key contributions of this work include:

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- Demonstrating the feasibility of automated in-situ repair using AM technologies;
- Integrating multi-sensor systems for automated surface detection, preparation, and material extrusion;
- Identifying limitations and providing insights into future advancements, such as incorporating metallic materials and directed energy deposition for more robust repairs.

The remainder of this paper is organized as follows: Section II provides a detailed background on plasma-facing component damage, additive manufacturing processes, and their integration into robotic systems. Sections III and IV describe the system design and architecture, respectively, while Section V presents the experimental results. Finally, Section VI discusses the findings, limitations, and future research directions.

II. BACKGROUND

A. Plasma-Facing Component Damage in Tokamaks

Plasma-facing components are critical to the operation of tokamak reactors, as they are the primary interface between the plasma and the reactor walls. During operation, PFCs are exposed to extreme thermal loads and particle flux, leading to various forms of damage:

- Surface Melting and Erosion: Plasma instabilities, including disruptions and ELMs, can generate localized heat fluxes exceeding $20\,\mathrm{MW\,m^{-2}}$. These events result in surface melting and material splashing, particularly on tungsten-based PFCs [6], [7].
- Cracking and Delamination: The intense thermal gradients cause thermal stress, leading to cracking and delamination, especially at high-load regions such as divertor plates [8].
- Dust Generation and Contamination: The degradation of PFCs results in the generation of substantial amounts of tungsten dust, which can destabilize the plasma and disrupt heat flux [9].
- Structural Failures: Additional damage includes edge cracking, heat sink failures, and debonding of material layers under extreme heat conditions [10], [11].

Addressing these issues is crucial to maintaining plasma stability and ensuring the efficiency of fusion reactors. The process of repairing damaged PFCs is often costly and time-consuming, compounded by the limited accessibility within the vacuum vessel and the presence of radiation fields. These factors make manual maintenance highly challenging.

B. Additive Manufacturing for In-Situ Repair

Additive manufacturing has emerged as a viable method for repairing and fabricating complex components [12]. Unlike traditional manufacturing, which often involves material removal, AM builds objects layer by layer based on computer-aided design (CAD) models. Two key AM processes relevant to in-situ repairs are:

- Fused Filament Fabrication: FFF, also known as material extrusion [13], uses a heated nozzle to deposit thermoplastic filaments layer by layer. While FFF is not suitable for high-strength applications, its low cost and flexibility make it ideal for prototyping and testing [14].
- Directed Energy Deposition: DED processes, such as wire-arc and laser-based deposition, enable the repair of metallic components with high precision and mechanical strength [15], [16]. DED has been successfully used for repairing aerospace components like turbine blades and propellers, highlighting its potential for fusion reactor maintenance [17], [18].

AM technologies have demonstrated significant advantages in industries requiring complex geometries and customized repairs. The ability to automate the repair process, coupled with the minimal material waste inherent to AM, makes it a strong candidate for addressing the challenges of in-situ repairs within tokamaks.

C. Robotics and Additive Manufacturing Integration

The combination of robotic systems and additive manufacturing has significantly expanded the capabilities of advanced manufacturing, enabling high-precision, scalable, and autonomous fabrication processes across diverse industries. This integration has been instrumental in overcoming the limitations of conventional AM systems by providing enhanced dexterity, mobility, and automation [19]. Recent advancements in robotics with integrated AM can be categorized into several key areas, illustrating the state of the art:

- Multi-DOF Robotic AM Systems: Traditional AM platforms are often constrained by their limited degrees of freedom, restricting the complexity of geometries they can fabricate. In contrast, the use of multi-DOF robotic arms for AM enables printing on freeform surfaces, optimizing material deposition strategies, and reducing the need for support structures. Hybrid approaches combining AM with subtractive methods further improve precision and surface quality, particularly in high-value applications such as aerospace and biomedical implants [20], [21].
- Mobile and Large-Scale Additive Manufacturing: The use of mobile robotic systems for AM has enabled scalable and on-site manufacturing, reducing the dependence on fixed infrastructure. Researchers at Nanyang Technological University (NTU) have demonstrated mobile robot arms that cooperatively 3D-print structures far exceeding their own dimensions, providing a potential solution for large-scale construction and emergency infrastructure deployment [22], [23]. Similarly, gantry robotic AM systems are being employed for oversized metal and polymer printing in sectors such as shipbuilding and automotive manufacturing.
- Aerial and Autonomous Additive Manufacturing: The application of AM to aerial robotics has opened new possibilities for in-situ repair and maintenance in remote or hazardous environments. Autonomous drones equipped with AM tools can deposit material mid-flight, facilitating repairs on high-rise structures, wind turbine

blades, and offshore platforms [24], [25]. Such systems leverage real-time sensing and AI-driven path planning to adapt to complex geometries and environmental conditions.

- Multi-Robot Cooperative AM: Swarm robotics has been explored as a method to enhance AM scalability and efficiency. By coordinating multiple robotic arms or autonomous agents, cooperative AM systems can achieve parallelized manufacturing, reducing build times and increasing resilience against single-point-of-failures. This approach is particularly relevant in space applications, where autonomous robotic systems could be deployed for in-orbit fabrication and repair [6].
- In-Situ Repair and Maintenance Applications: In highly specialized engineering sectors such as aerospace, nuclear fusion, and energy production, robotic AM is being integrated with inspection and repair technologies to extend the operational life of critical components. 6-DOF robotic arms equipped with AM tools have been used for directed energy deposition and cold spray techniques to restore worn or damaged surfaces with micron level accuracy [20], [21]. In the context of fusion reactors, such systems are being developed to autonomously navigate the tight spaces of a tokamak vessel, detect and assess damage, and perform localized material deposition for repair.

These advancements illustrate the transformative impact of robotics-integrated AM, expanding its applicability from controlled laboratory environments to industrial manufacturing, construction, and repair scenarios. By leveraging AI, advanced sensing, and adaptive control, the next generation of robotic AM systems is poised to revolutionize fabrication with high precision, autonomous repair, and development of major infrastructures.

D. Motivation for In-Situ Repair

The motivation for developing automated in-situ repair systems lies in improving the economic feasibility and operational efficiency of fusion reactors. For example, studies on the European DEMO fusion power plant estimate that replacing blankets and divertor cassettes in a single sector could take approximately $1000\,\mathrm{h}$ [26]. Such extensive maintenance periods can substantially impact reactor availability and increase operational costs. In-situ repairs eliminate the need to remove and replace damaged components, reducing reactor downtime and minimizing human exposure to hazardous environments. The integration of AM with robotic systems allows for precise, targeted repairs on complex components such as plasma-facing components and service pipes. In this work, fused filament fabrication has been adopted as a proof-of-concept AM technology due to its low cost, ease of integration, and suitability for prototyping. The proposed system incorporates multi-sensor integration for surface preparation, defect identification, and repair execution, providing a foundation for future advancements in material deposition and automation.

III. SPECIFICATIONS AND REQUIREMENTS

The proposed in-situ repair system focuses on two distinct use cases involving scaled mock-ups of tokamak components. These scenarios aim to demonstrate the feasibility and effectiveness of automated additive manufacturing (AM) repair processes.

A. Use Case 1: Plasma-Facing Components (Tiles)

This use case involves the in-situ repair of scaled polylactic acid (PLA) mock-up tiles for Lower Hybrid Current Drive (LHCD) antennas, as illustrated in Fig. 2(a). The original LHCD tiles, depicted in Fig. 2(b), align along a vertical jig with gradually varying curvature. Assembly and disassembly require precise alignment with the jig's supporting raster, making the existing maintenance approach demanding considerable time and effort, highlighting the necessity of automation. The proposed repair focuses on tiles with previously identified cracks resulting from heat flux exposure. These cracks will be assessed, deburred, and flattened prior to the additive manufacturing process, which will restore the components to their original geometric integrity.

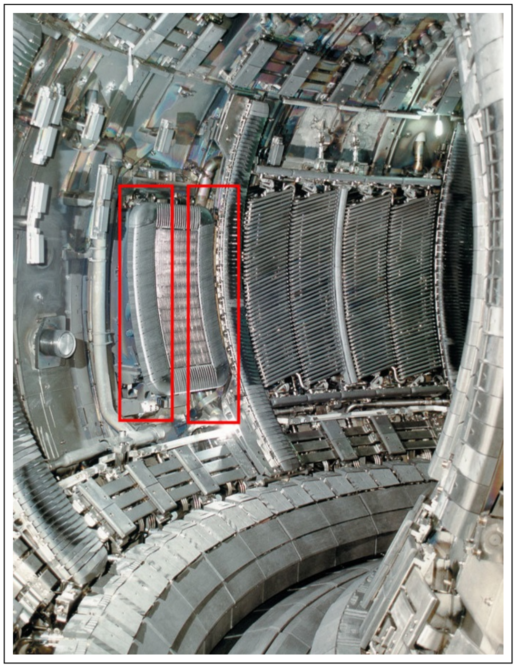
B. Use Case 2: Service Pipes (Pipes)

The second use case targets the repair of tokamak service pipes, which require frequent maintenance involving disconnection and reconnection of cooling and fueling systems. The repair process compensates for surface irregularities or material loss—such as those resulting from uneven laser cutting or wear—by additively introducing sufficient material. The primary objective is to restore the functional integrity of the pipes while ensuring precise alignment, minimizing downtime, and maintaining operational efficiency.

Fig. 3 illustrates the concept design of the proposed approach. The ultimate objective is to perform automatic in-situ repairs in all directions within the tokamak. Although this work implements only 1G deposition (horizontal components), future iterations will explore out-of-position deposition (e.g., vertical or 4G deposition). To achieve this goal, a delta robot with three degrees of freedom has been introduced at the end-effector of the primary 6-DOF robotic arm. The delta robot enhances precision and dynamic response, enabling more accurate control of the additive manufacturing process, while the 6-DOF robot provides essential reach, stability, and positioning within the complex internal geometry of the tokamak. This combined robotic configuration facilitates precise, stable deposition even in challenging orientations and constrained spaces.

Assumptions and Process Workflow:

1) Pre-Identification of Defects: Defects on components will be identified, evaluated, and deburred before the repair process, as shown in Fig. 4.
2) 1G Deposition: Horizontal deposition is chosen to optimize material deposition while minimizing the effects of gravity [27], [28].
3) Component Identification: MEM sensors will automatically detect and classify components to be repaired.



(a)

(b)

Fig. 2: (a) Hybrid Current Drive antennas, (b) an LHCD tile.

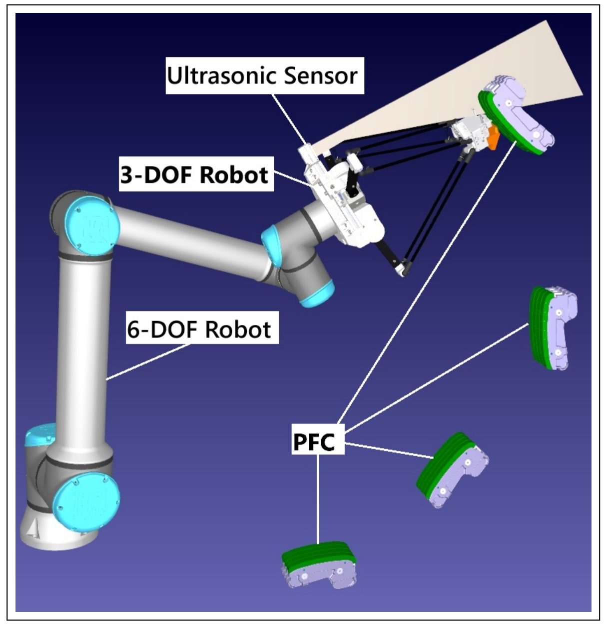


Fig. 3: In-situ repair concept.

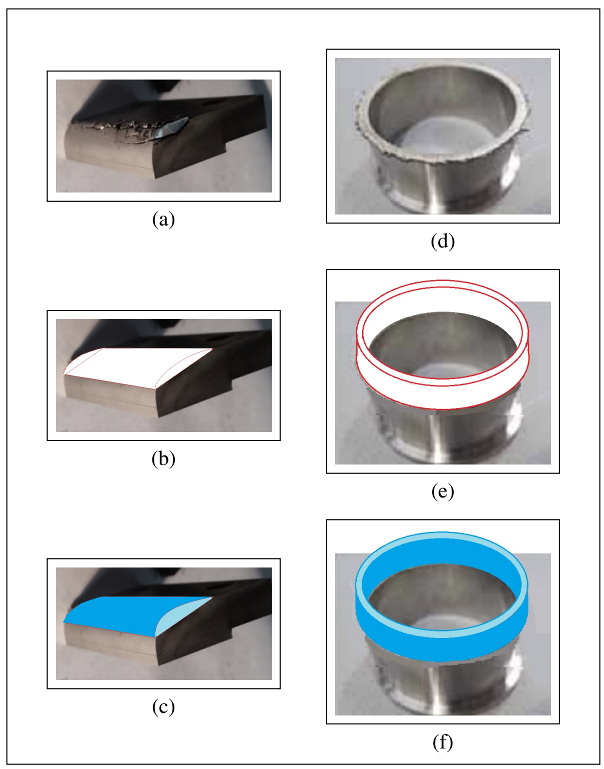


Fig. 4: Component evaluation and preparation: (a to c) Preparation steps of Plasma-facing component, (d to f) Preparation steps of Pipe edge.

The process involves generating 3D printing G-code to calculate the required material volume and the specific deposition locations [29], [30]. An auxiliary robotic arm preheats the component surface using a heat gun while an ultrasonic sensor monitors the surface temperature. Once the surface reaches an optimal temperature of approximately $60\,^{\circ}\mathrm{C}$, the delta robot positions itself over the component, and another MEM sensor calibrates the distance between the heat bed and extruder for precise material deposition. Upon completion, the robotic arms return to their initial positions.

Non-Functional Requirements:

- Performance: The linear stage travel speed is limited to $100\,\mathrm{mm\,s^{-1}}$, with an acceleration of $50\,\mathrm{mm\,s^{-2}}$, to minimize vibration.
- Safety: The robots' joint speed is capped at $60\,^{\circ}\,\mathrm{s^{-1}}$, with a joint acceleration of $80\,^{\circ}\,\mathrm{s^{-2}}$. The delta robot

tool speed is $80\,\mathrm{mm\,s^{-1}}$, while the heat gun tool speed is increased to $250\,\mathrm{mm\,s^{-1}}$ during preheating.
- Precision: The delta robot's layer height is fixed at $30\,\mathrm{\mu m}$ to minimize inaccuracies caused by payload limitations.

IV. SYSTEM ARCHITECTURE

The experimental setup integrates multiple robotic components and tools to achieve an automated, multi-DOF additive manufacturing system. The primary components are a Delta X2 robot and two UR10 collaborative robotic arms from Universal Robots.

One UR10 arm holds a heat gun with a Robotiq 2-Finger gripper to preheat the surface of components, while the delta robot is attached to the end-effector of the second UR10 arm for material deposition. The collaborative configuration is shown in Fig. 5.

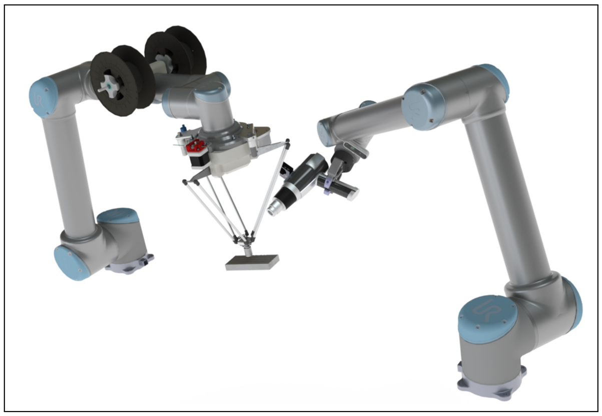


Fig. 5: Collaborative system design with Delta X2 robot and UR10 robotic arms.

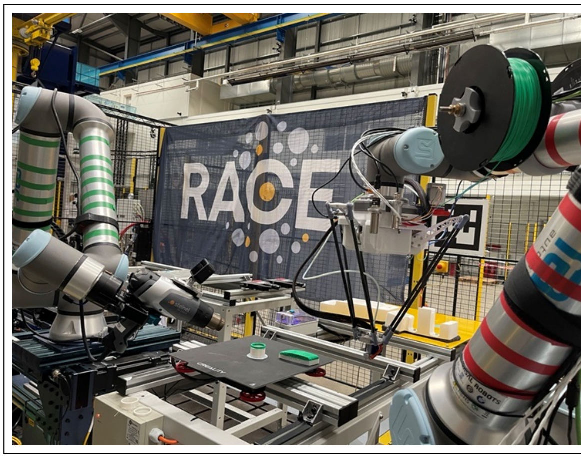


Fig. 6: AIM-TU platform: 6-DOF robot (green marking) holding a heat gun and a vision camera. 6-DOF Robot (red marking) with a 3-DOF robot holding a extruder.

Fig. 6 illustrates the robotic cell known as the AIM-TU platform, located at the UKAEA Culham Campus, where the AM trials were conducted. This platform features fixed-mounted UR10 robots positioned on automated linear stages, and includes a heated bed measuring 200 cm × 200 cm within the workspace reachable by the two 6-DOF robots. All repair trials were performed using FFF with PLA material.

Initial studies in the development process focused on the limitations of each component, particularly the UR10 collaborative robotic arms, their linear positioners, and the heat bed. The workspace layout allowed both robots to operate within a 200 cm by 200 cm area, with a platform height optimized for surface preheating and material deposition tasks.

Two approaches were evaluated for the material extrusion process: direct extrusion using a collaborative UR10 robot arm or extrusion via a lightweight delta robot mounted as an end-effector on the UR10 arm. The latter was selected primarily because directly mounting an extrusion head on the collaborative robot would constrain the printable volume and complicate the extrusion path, as all robot arm joints would need to continuously move during material deposition. Conversely, employing a lightweight Delta X2 robot [31] mounted on the UR10 allowed the arm to maintain a fixed position, while the delta robot, benefiting from fewer degrees of freedom and a reduced payload, efficiently handled the extrusion process. Additionally, a Bowden extrusion system was chosen to further minimize payload weight at the end-effector of Delta X2 robot.

Key Components:

- Delta X2 Robot: Performs precise material deposition with a maximum end-effector payload of 700 grams.
- UR10 Collaborative Robots: One UR10 manipulates the delta robot for additive manufacturing, while the other handles the heat gun for surface preparation.
- Auxiliary Sensors: Include a non-contact infrared temperature sensor, an ultrasonic distance sensor, and a vision-based component system.

Custom brackets were designed and 3D-printed to securely attach sensors and robotic components. These brackets met structural requirements to withstand dynamic loads while maintaining ease of assembly and flexibility for rapid prototyping.

Fig. 7 shows the power and interface configuration, which integrates a Raspberry Pi and Arduino microcontroller to coordinate sensor input and robot control. This configuration ensures robust and synchronized operation of all subsystems.

Implementation Challenges and Solutions: The exclusion of lasers due to safety concerns necessitated alternative sensing technologies. Ultrasonic sensors replaced laser profilers for distance measurement, and machine vision was used for component shape recognition. These adjustments maintained the system's effectiveness while ensuring safety compliance.

The testing process was divided into stages for each sensor module:

- Temperature and Humidity Measurement: The DHT 11 sensor provided accurate readings within a $3\,\%$ margin of error, confirming environmental stability during trials.
- Ultrasonic Distance Sensor: The URM14 sensor was calibrated to measure component distances with $1\,\mathrm{mm}$

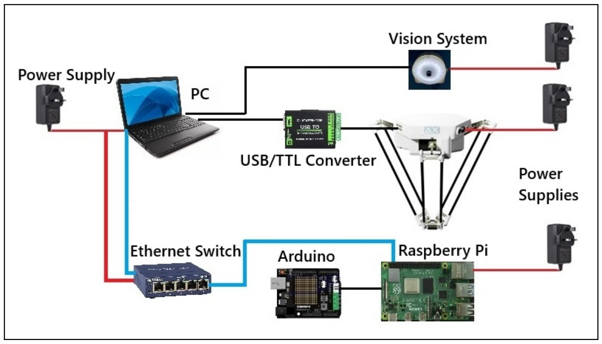


Fig. 7: A Windows PC manages the vision system and controls the Delta X2 robot. A Raspberry Pi oversees communication with the infrared and ultrasonic sensors, while an Arduino board handles data acquisition from the temperature and humidity sensors.

accuracy. Tests verified its precision over a range of 100–1500 mm.
- Infrared Temperature Sensor: Positioned $40\,\mathrm{cm}$ from components, this sensor achieved an accuracy of $\pm 0.5\,^{\circ}\mathrm{C}$ within its 5° field of view, effectively monitoring surface temperatures.

Sensor performance demonstrated sufficient accuracy for the identified use cases. However, improvements are recommended in the following areas:

- Distance Measurement: Replace ultrasonic sensors with laser profilers for enhanced precision in positioning the 3D printing nozzle.
- Temperature Monitoring: Use higher-resolution sensors for more accurate edge temperature measurements, particularly for cylindrical components.

Future iterations will incorporate these improvements to address the limitations identified during validation.

V. RESULTS AND DISCUSSION

The results demonstrate the feasibility of automated in-situ repair using additive manufacturing techniques and highlight specific areas for improvement. Later in this sections comparative laser profiling results for selected use cases are presented, clearly illustrating the geometric differences between components repaired using the proposed in-situ approach and those without defects. This comparison underscores the effectiveness of the repair methodology and identifies opportunities for further optimization.

Fig. 8 illustrates the successful implementation of AM repairs for the two use cases: plasma-facing components and service pipes. Additionally, Fig. 9 shows the components before and after the repair process, emphasizing the practical outcomes achieved.

Key process parameters were defined and controlled using Creality Slicer, including a layer height of $0.3\,\mathrm{mm}$, an infill density of $100\,\%$, and a printing temperature of $200\,^{\circ}\mathrm{C}$. The heat bed was maintained at $60\,^{\circ}\mathrm{C}$ to ensure optimal adhesion of the first layer. The components' positions were identified using machine vision, with an ultrasonic sensor measuring the distance between the nozzle and the surface.

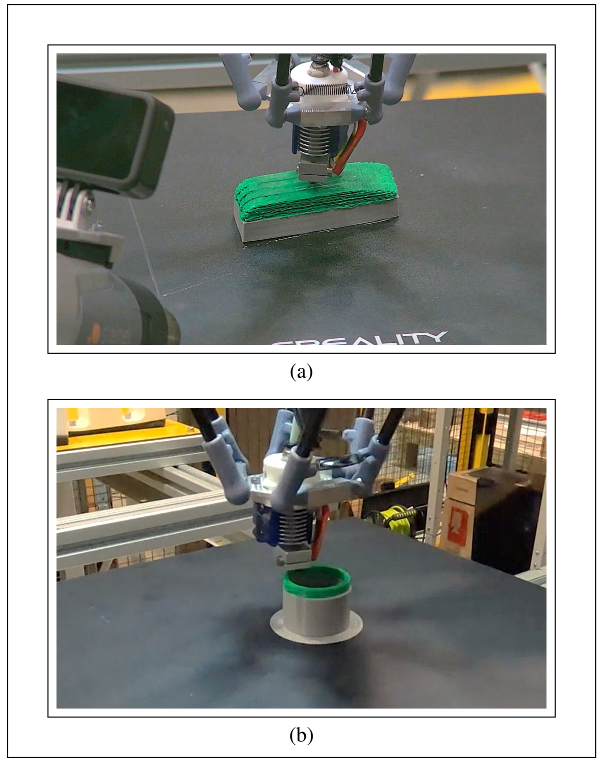


Fig. 8: Demonstrations of in-situ additive repair: (a) Plasma-facing component, (b) Tokamak pipe.

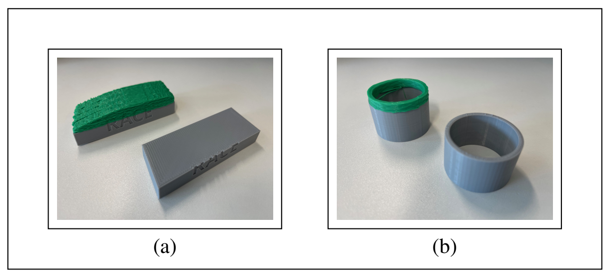


Fig. 9: AM In-Situ Repair: (a) Use case: Tiles, (b) Use case: Pipes.

These parameters collectively supported accurate and efficient material deposition.

The system exhibited consistent repair quality across both use cases. However, certain challenges were identified:

- Vibrations induced by the delta robot's mechanics and end-effector attachment reduced the accuracy of material deposition.
- The ultrasonic distance sensor's precision was insufficient for fine alignment, necessitating more advanced sensing solutions.
- The infrared temperature sensor struggled to accurately measure edge temperatures on cylindrical components, impacting the overall quality control of pipe repairs.

Fig. 10 illustrates the susceptibility of the extruder nozzle to vibrations when the initial gap distance is not adequately calibrated. The red envelopes represent the upper and lower limits of the Euler angles, depicting the nozzle's orientation relative to the world frame under improper calibration. Conversely, the blue envelopes demonstrate a significant improvement, indicated by a reduced range between the upper and lower limits, achieved when the nozzle is positioned at an appropriately calibrated distance from the components. This highlights the critical role of precise gap calibration in minimizing vibrational effects and ensuring stable extrusion performance.

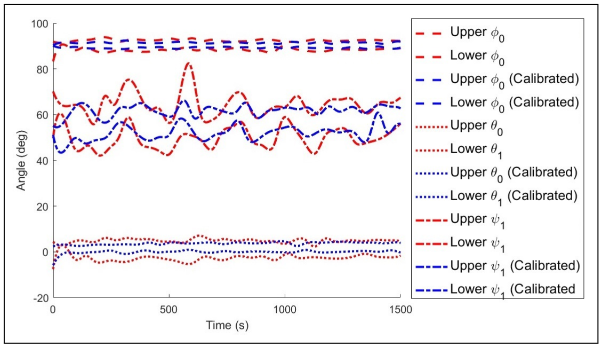


Fig. 10: Envelop of IMU Euler angles

Fig. 11 and 12 provide comparative laser profiling data, demonstrating the geometric differences between repaired and components free of defects. The results show that height variations between repaired components and reference samples without defects are within approximately 3 %. Additionally, volume and weight measurements are nearly identical. These findings validate the system's capability to successfully perform accurate in-situ repairs, while also highlighting specific areas that could benefit from further refinement.

VI. CONCLUSIONS

This study introduced an innovative approach to automating in-situ repair processes for plasma-facing components in tokamak reactors. The developed system supports the feasibility of additive manufacturing for repairing mock-up components using a 3-DOF delta robot and auxiliary robotic arms equipped with surface preparation tools.

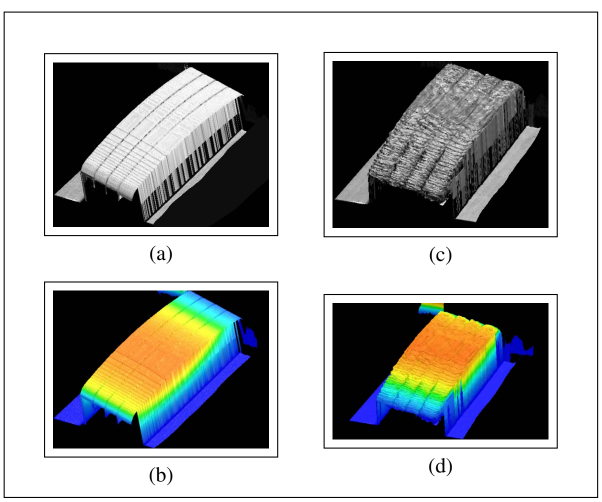


Fig. 11: 3D Laser Profiling: (a) Reference Tile, (b) Reference Tile's 3D profile, (c) Repaired Tile, (b) Repaired Tile's 3D profile.

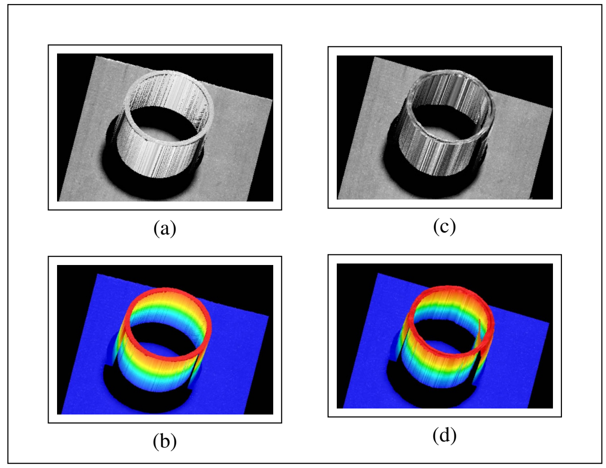


Fig. 12: 3D Laser Profiling: (a) Reference Pipe, (b) Reference Pipe's 3D profile, (a) Repaired Pipe, (b) Repaired Pipe's 3D profile.

Two use cases were evaluated, involving the repair of tiles and pipes with predetermined defects. The system effectively automated tasks such as component identification, surface preheating, and material deposition.

The findings underscore the need for advanced sensing technologies, improved robotic hardware, and expanded material capabilities to address these challenges. By implementing the proposed recommendations, future iterations of the system can achieve higher precision, reliability, and adaptability for complex repair tasks in fusion energy systems.

Based on the findings, a couple of recommendations are proposed to enhance the system's performance and extend its capabilities:

- Surface Preparation: Automated and material-specific surface preparation processes must be integrated. For instance, preheating and surface smoothing tailored for materials with superior mechanical strength like tungsten are crucial for achieving reliable repairs under extreme conditions.
- Enhanced Sensors: Replacing MEM sensors with industrial-grade alternatives will improve measurement precision. Similarly, advanced laser profilers and high-speed thermal sensors are recommended for accurate defect detection and in-process monitoring of repairs under extreme temperature conditions [32].

In conclusion, this research marks a step toward economically viable, reliable, and autonomous maintenance solutions for tokamak reactors which are crucial for advancing fusion energy. While feasibility has been demonstrated through in-situ additive repairs, current results are based on preliminary trials. Future work will focus on repeatability studies, benchmarking against manual methods, and assessing system suitability under extreme in-vessel conditions, including radiation, vacuum, and thermal constraints. These efforts will support the development of a robust, deployable platform for fusion maintenance.

References

[1] M. Barbarino, "A brief history of nuclear fusion," *Nature Phys.*, vol. 16, no. 9, pp. 890–893, Jun. 2020.

[2] R. Skilton, N. Hamilton, R. Howell, C. Lamb, and J. Rodriguez, "MASCOT 6: Achieving high dexterity tele-manipulation with a modern architectural design for fusion remote maintenance," *Fusion Eng. Des.*, vol. 136, pp. 575–578, Nov. 2018.

[3] T. Özel, H. Shokri, and R. Loizeau, "A Review on Wire-Fed Directed Energy Deposition Based Metal Additive Manufacturing," *J. Manuf. Mater. Process.*, vol. 7, no. 1, p. 45, Feb. 2023.

[4] TWI, "What is Directed Energy Deposition (DED)?," www.twi-global.com. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/directed-energy-deposition (accessed Sep. 26, 2024).

[5] L. Danielsen Evjemo, S. Moe, J. T. Gravdahl, O. Roulet-Dubonnet, L. T. Gellein and V. Brøtan, "Additive manufacturing by robot manipulator: An overview of the state-of-the-art and proof-of-concept results," *Proc. IEEE Int. Conf. Emerg. Technol. Factory Autom.* (ETFA), Limassol, Cyprus, 2017, pp. 1-8.

[6] D. Zhu et al., "Characterization of the in situ leading-edge-induced melting on the ITER-like tungsten divertor in EAST," *Nucl. Fusion*, vol. 60, no. 1, p. 016036, Dec. 2019.

[7] I. Jepu et al., "Beryllium melting and erosion on the upper dump plates in JET during three ITER-like wall campaigns," *Nucl. Fusion*, vol. 59, no. 8, pp. 086009–086009, Jun. 2019.

[8] A. Durif et al., "Edge cracking of WEST tungsten actively cooled plasma facing components after plasma operation," *Fusion Eng. Des.*, vol. 188, pp. 113441–113441, Mar. 2023.

[9] B. Gao et al., "Plasma-facing components damage and its effects on plasma performance in EAST tokamak," *Fusion Eng. Des.*, vol. 156, pp. 111616–111616, Jul. 2020.

[10] C. Li et al., "Characterization on the melting failure of CuCrZr cooling tube of W/Cu monoblocks during plasma operations in EAST," *Nucl. Mater. Energy*, vol. 25, pp. 100847–100847, Dec. 2020.

[11] M. Diez et al., "In situ observation of tungsten plasma-facing components after the first phase of operation of the WEST tokamak," *Nucl. Fusion*, vol. 61, no. 10, pp. 106011–106011, Sep. 2021.

[12] P. Urhal, A. Weightman, C. Diver, and P. Bartolo, "Robot assisted additive manufacturing: A review," *Rob. Comput.-Integr. Manuf.*, vol. 59, pp. 335–345, Oct. 2019.

[13] "What is Material Extrusion? (A Complete Guide)." www.twi-global.com. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-material-extrusion/ (accessed Aug. 30, 2024).

[14] TWI, "What is Material Extrusion? (A Complete Guide)," www.twi-global.com. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-material-extrusion (accessed Sep. 26, 2024).

[15] K. M. Taminger and C. S. Domack, "Challenges in Metal Additive Manufacturing for Large-Scale Aerospace Applications," in *Women in Aerospace Materials: Advancements and Perspectives of Emerging Technologies*, M. E. Kinsella, Ed. Cham, Switzerland: Springer, 2020, pp. 105-124.

[16] D.-G. Ahn, "Directed Energy Deposition (DED) Process: State of the Art," *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 8, no. 2, pp. 703–742, Feb. 2021.

[17] R. French, M. Benakis, and H. Marin-Reyes, "Intelligent sensing for robotic re-manufacturing in aerospace — An industry 4.0 design based prototype," *Proc. IEEE Int. Symp. Robot. Intell. Sens.* (IRIS), Oct. 2017.

[18] R. French, H. Marin-Reyes, and A. Rendell-Read, "A robotic re-manufacturing system for high-value aerospace repair and overhaul," in *Transactions on Intelligent Welding Manufacturing*, S. Chen, Y. Zhang, and Z. Feng, Eds. Singapore: Springer, 2017, pp. 36-47.

[19] J. Norberto Pires, A. S. Azar, F. Nogueira, Carlos Ye Zhu, R. Branco, and Trayana Tankova, "The role of robotics in additive manufacturing: review of the AM processes and introduction of an intelligent system," *Ind. Robot*, vol. 49, no. 2, pp. 311–331, Dec. 2021.

[20] Y. Li, J. Park, G. Manogharan, F. Ju, and I. Kovalenko, "A Mobile Additive Manufacturing Robot Framework for Smart Manufacturing Systems," arXiv.org, Sep. 04, 2024. [Online]. Available: https://arxiv.org/abs/2404.13034

[21] Gabriel Consoni Zutin, Eduardo Costa Pulquerio, Arthur Vallim Pasotti, Gustavo Franco Barbosa, and Sidney Bruce Shiki, "Application of robotic manipulator technology and its relation to additive manufacturing process — a review," *Int. J. Adv. Manuf. Technol.*, vol. 133, no. 1–2, pp. 257–271, May 2024.

[22] B. Clark, "Sea Drones in the Russia-Ukraine War Inspire New Tactics," spectrum.ieee.org, July 10, 2024. [Online]. Available: https://spectrum.ieee.org/sea-drone (accessed July 10, 2024).

[23] "Mobile Robot for Large Scale 3D Printing at Construction Sites," innovate.ieee.org, June 3, 2020. [Online]. Available: https://innovate.ieee.org/innovation-spotlight/large-scale-3d-printer/ (accessed Sep. 04, 2024).

[24] C. Q. Choi, "Flying Robots 3D-Print Structures in Flight," spectrum.ieee.org, Sept. 25, 2022. [Online]. Available: https://spectrum.ieee.org/drone-3dprint (accessed Sep. 04, 2024).

[25] K. Zhang et al., "Aerial additive manufacturing with multiple autonomous robots," *Nature*, vol. 609, no. 7928, pp. 709–717, Sep. 2022.

[26] O. Crofts and J. Harman, "Maintenance duration estimate for a DEMO fusion power plant, based on the EFDA WP12 pre-conceptual studies," *Fusion Eng. Des.*, vol. 89, no. 9–10, pp. 2383–2387, Oct. 2014.

[27] E. Kerber et al., "Variable Layer Heights in Wire Arc Additive Manufacturing and WAAM Information Models," *Machines*, vol. 12, no. 7, pp. 432–432, Jun. 2024.

[28] E. Aldalur, F. Veiga, A. Suárez, J. Bilbao, and A. Lamikiz, "High deposition wire arc additive manufacturing of mild steel: Strategies and heat input effect on microstructure and mechanical properties," *J. Manuf. Process.*, vol. 58, pp. 615–626, Oct. 2020.

[29] TWI, "What is 3D Printing? - Technology Definition and Types," www.twi-global.com. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing (accessed Sep. 26, 2024).

[30] 3DSourced, "The Complete History of 3D Printing: From 1980 to 2023 - 3DSourced," www.3dsourced.com, Jul. 17, 2023. [Online]. Available: https://www.3dsourced.com/guides/history-of-3d-printing/ (accessed Sep. 26, 2024).

[31] "Delta X Robot Kits," deltaxstore.com. [Online]. Available: https://deltaxstore.com/collections/delta-x-robot-kits (accessed Sep. 27, 2024).

[32] C. Xia et al., "A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system," *J. Manuf. Syst.*, vol. 57, pp. 31–45, Oct. 2020.