Digital Twin-Enabled Multi-Robot Systems for Safe and Efficient Nuclear Decommissioning*

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Abstract

Nuclear decommissioning remains a difficult problem to solve, particularly in structures not intended for dismantling. This article discusses two integrated projects, XS-ABILITY and DORADO, which are funded by the EU strategically towards improving the multi-robot systems integration and digital twin technologies towards nuclear decommissioning more robotic and safe. XS-Ability is centered on multi-robot systems as mobile radiation sensing platforms for advanced in situ characterization, while DORADO works on an ecosystem framework plan that integrates AI, BIM, and ontology tools for planning and optimization. These developments contribute to a broader initiative defined by a lower cued, more reliable, data-dependent framework toward nuclear decommissioning, risk reduction, and agile regulatory advancements where innovation is welcomed.

Keywords

Nuclear Decommissioning, Digital Twin; Multi-Robot Systems, In-situ Characterization, Artificial Intelligence (AI), Building Information Modeling (BIM), Radiation Safety, Ontology, Autonomous Robotics, Remote Operations

1. Introduction

Europe is facing a critical phase in the lifecycle of its nuclear infrastructure, as a growing number of facilities approach or exceed their operational lifetimes [1]. Decommissioning these complex installations presents not only technical and logistical hurdles but also significant safety challenges, especially considering that most were never designed with dismantling in mind [2]. Harsh, unstructured environments, radiation exposure risks, and limited accessibility all contribute to the high complexity of nuclear decommissioning tasks [3].

In this context, autonomous robotic systems have emerged as key enablers for safer and more efficient operations [4]. By reducing human intervention in hazardous zones, these technologies provide new capabilities for inspection, characterization, material handling, and waste management. However, their successful deployment hinges on solving fundamental challenges, including robust autonomy in GPS-denied areas, radiation resilience, regulatory compliance, and integration into existing safety frameworks.

To address these challenges holistically, the HADRON (Hazard-Aware Digitalization and Robotics in Nuclear & Other Domains) concept was introduced by the Institute for Energy Technology (IFE) [5]. HADRON embodies a strategic shift toward hazard-aware digitalization by combining robotic systems with real-time data acquisition, 3D modeling, and radiation-aware planning through digital twins. The HADRON Laboratory, equipped with ground and aerial robotic platforms, enables the testing and validation of such integrated solutions under controlled yet realistic conditions.

Building on this foundation, the RoboDecom project [5] further explored the deployment of robotic platforms for representative decommissioning tasks. It emphasized performance assessment, safety-centered design, and knowledge transfer using digital twin architectures. These efforts laid the ground-

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work for more advanced and interconnected systems that can respond to operational demands in the nuclear back-end.

This article presents two complementary EU-funded research projects — DORADO (Digital Twins and Ontology for Robot Assisted Decommissioning Operations) [6] and XS-ABILITY (Accessing hard-to-reach areas with Advanced and Breakthrough Innovation for reLiable In-situ characterization of a facilitTY) [7] — which collectively aim to transform the landscape of nuclear decommissioning.

XS-ABILITY focuses on the development and real-world deployment of multi-robot systems for in situ radiological characterization in hazardous and hard-to-access environments. The project emphasizes advanced sensing, sensor fusion, and collaborative autonomy to improve remote operations and minimize human exposure.

In parallel, DORADO seeks to establish a unified digital ecosystem that integrates artificial intelligence (AI), Building Information Modeling (BIM), and a domain-specific ontology within a digital twin framework. This approach supports planning, optimization, and knowledge management, while enhancing safety and efficiency through data-driven decision-making.

Together, these initiatives demonstrate how the convergence of robotic systems and digital twin technologies can significantly reduce operational risks, increase precision, and streamline waste handling and documentation. The following sections provide an in-depth exploration of each project, highlighting how their integrated solutions are shaping the future of nuclear decommissioning.

2. Challenges in Nuclear Decommissioning

Nuclear decommissioning poses multifaceted challenges rooted in the complexity of dismantling aged infrastructure within highly regulated, hazardous environments. Most legacy facilities were not designed with deconstruction in mind, making dismantling operations particularly risky and technically complex. The principal challenges can be categorized as follows.

- **Environmental Hazards** [8]: Decommissioning sites often contain high radiation fields, contaminated materials, and structurally unstable environments. Robots deployed in these settings must operate autonomously and reliably in GPS-denied, cluttered, and communication-limited spaces.
- **Material and System Resilience** [9]: Robotic components must withstand high radiation doses without degradation. Material selection and radiation-hardened design are crucial to maintaining operational integrity in extended missions.
- **Safety and Regulation** [10] [11]: Compliance with stringent safety standards requires advanced safety cases and verification protocols. Robotic systems must be integrated into regulatory frameworks and validated for safe operation in nuclear environments.
- **Operational Constraints** [12] [13]: Access points are often narrow or blocked, limiting the size and type of robotic systems that can be deployed. Airborne and underwater operations require specialized capabilities to manage risks related to contamination dispersion and visibility.

These challenges necessitate the convergence of robotics, digital simulation, and intelligent decision-making to create resilient, adaptable systems capable of safe and efficient decommissioning.

3. The HADRON Concept and Laboratory

The HADRON initiative [5], developed by IFE, represents a novel paradigm in hazard-aware robotics and digitalization. The concept integrates robotic systems with digital twins and radiological simulation tools to optimize planning, monitoring, and operation of decommissioning tasks.

The HADRON Lab serves as a testbed where ground and aerial robots perform advanced functions such as 3D scanning, SLAM-based mapping, radiation detection, and environmental modeling. These tasks are aligned with digital twin representations that simulate the physical environment and radiological conditions, enabling proactive planning and improved safety analysis. HADRON's core value lies in enabling real-time feedback loops between the robot's sensors and its digital twin, supporting adaptive decision-making and mission optimization.

3.1. RoboDecom: Field-Oriented Validation

As a precursor to larger-scale EU projects, RoboDecom focused on applying digital twin-based robotics to real-world decommissioning tasks. Conducted in collaboration with the OECD NEA and funded by the Research Council of Norway, RoboDecom emphasized safety-centered architecture, performance assessment, and remote task execution.

Robots such as **Boston Dynamics' Spot**, **Clearpath's Jackal**, and the **nLink platform** (see **Figure 1**) were deployed in realistic test scenarios to perform contamination mapping, swab sampling, material handling, and area scanning. The project demonstrated the feasibility of integrating semi-autonomous systems with digital twins for mission rehearsal, risk assessment, and operational planning, laying a technical and conceptual foundation for subsequent projects like DORADO and XS-ABILITY.

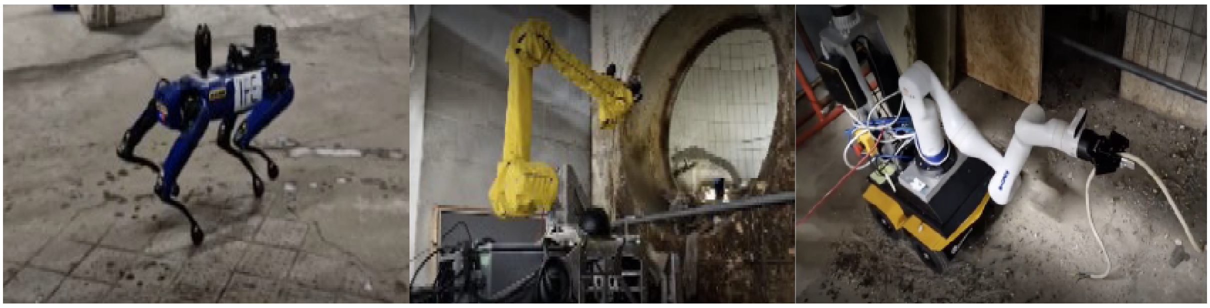

Figure 1: Deployment of the HADRON Laboratory Robotic Fleet in the RoboDecom project.

3.2. XS-ABILITY: Autonomous Multi-Robot Systems for In-Situ Radiation Characterization

XS-ABILITY is a Horizon Europe EURATOM-funded project (2024–2027) that aims to develop and demonstrate a new generation of advanced robotic systems for in-situ characterization of complex and hazardous nuclear environments [7]. The project targets key decommissioning challenges such as remote inspection of inaccessible zones and the identification of difficult-to-measure radionuclides.

To address these goals, XS-ABILITY integrates a heterogeneous fleet of robots (see **Figure 2**), including ground-based platforms like **Boston Dynamics' Spot**, **Clearpath's Jackal**, and the **SIGMA INGEGNERIA ROver**, along with three aerial **Elios** drones developed by **Flyability**. These robots are equipped with compact, high-precision 3D LiDARs and radiation sensors, and are designed to collaboratively navigate unknown environments using advanced SLAM algorithms. The robotic fleet operates in coordination to autonomously and efficiently explore nuclear sites, minimizing mission duration while maximizing spatial coverage.

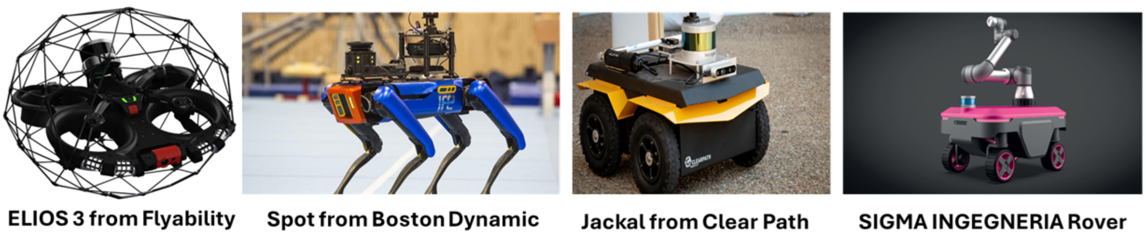

Figure 2: Robotic platforms involved in the XS-ABILITY project.

Following exploration, point cloud data from the various platforms is shared with a central server, enabling the generation of a highly detailed 3D digital representation of the environment. This collaborative data fusion approach enhances both mission planning and post-operation analysis, reinforcing the role of digital twins in improving accuracy, safety, and decision-making.

The consortium behind XS-ABILITY brings together 8 partners across 7 European countries, combining expertise in nuclear instrumentation, robotics, AI, and end-user needs. The project also aims to produce harmonized best practices and protocols for the deployment of multi-robot systems in indoor nuclear facilities, with strong potential for application in other sectors including nuclear maintenance, sensor technology, and CBRN-E defense.

4. DORADO: Digital Ecosystem for Decommissioning

DORADO builds a comprehensive digital platform to support a wide range of decommissioning activities [6]. At the core of the DORADO project lies a sophisticated data-driven architecture that integrates AI, BIM, and ontology-based knowledge representation. This integration facilitates the creation of dynamic digital twin environments, which are virtual replicas of the physical site that continuously update with real-time data. The DORADO platform is designed to ingest data from robots equipped with various radiation sensors, enabling the creation of detailed radiation maps and visualizations within the digital twin. Furthermore, the project incorporates the use of point cloud data, which is then processed and converted into comprehensive BIM models, providing an accurate and up-to-date representation of the site's physical structure. The ontology-based knowledge representation ensures that information is structured and easily accessible, enabling intelligent reasoning and informed decision-making throughout the decommissioning process.

The data-driven architecture of the DORADO platform supports a range of critical functionalities essential for nuclear decommissioning. The platform enables efficient remote operation planning by simulating tasks and optimizing robot trajectories. Furthermore, it facilitates intelligent robot task allocation, ensuring that the right robot is assigned to the right job at the right time. Crucially, the system incorporates risk identification and ALARA (As Low As Reasonably Achievable)-based dose estimation, allowing for proactive safety management. Finally, the platform features a user-friendly human-system interaction through smart voice assistants, simplifying operator control and enhancing overall efficiency and safety through hands-free report generation.

5. Synergies and Complementarities

While XS-ABILITY and DORADO pursue distinct objectives, they are strategically complementary. XS-ABILITY emphasizes on-site robotic capability and sensor integration, while DORADO provides the digital infrastructure and semantic context to plan, optimize, and document these operations. When combined, the two projects demonstrate how tightly coupled physical and digital layers can transform nuclear decommissioning into a more autonomous, efficient, and safe process.

HADRON and RoboDecom serve as bridging initiatives that validate concepts and technologies at different scales. Together, the ecosystem formed by these initiatives advances the vision of a digital twin-enabled, robot-assisted decommissioning paradigm that is both technologically robust and aligned with regulatory and industrial needs.

6. Conclusion

As Europe intensifies its efforts to safely decommission nuclear facilities, the integration of digital twin-enabled robotic systems marks a decisive step toward a more intelligent and secure operational model. HADRON has laid the conceptual and technical foundation, while RoboDecom demonstrated feasibility in operational contexts. XS-ABILITY and DORADO now push the frontiers further, developing and integrating multi-robot systems within intelligent digital ecosystems. Collectively, these initiatives offer a transformative roadmap for the nuclear sector, where digital intelligence and robotics converge to ensure safety, efficiency, and sustainability in dismantling the nuclear legacy.

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Declaration on Generative AI

During the preparation of this work, the authors used *Perplexity* in order to Grammar and spelling check. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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