

Radiation-Resilient AI: Next-Generation Robotic Systems with Adaptive Machine Learning for Nuclear Facility Management

K.V.V. Subba Rao^{1*}, Manas Kumar Yogi²

Abstract

The increasing complexity of nuclear facility operations, decommissioning activities, and emergency response scenarios necessitate the development of advanced autonomous systems capable of functioning in highly radioactive environments. This paper presents a comprehensive review of radiation-resilient artificial intelligence systems integrated with next-generation robotic platforms, specifically designed for nuclear facility management applications. We examine the convergence of adaptive machine learning algorithms, radiation-hardened hardware architectures, and intelligent robotic systems that can operate autonomously in contaminated environments where human presence is either impossible or extremely hazardous. The review encompasses current technological capabilities, emerging trends in AI-robotics integration, hardware resilience strategies, and the transformative potential of these systems for nuclear industry applications. Key focus areas include real-time environmental assessment, autonomous navigation in dynamic contaminated spaces, predictive maintenance of nuclear infrastructure, and emergency response coordination. The analysis reveals significant progress in developing robust AI systems that can adapt to radiation-induced hardware degradation while maintaining operational effectiveness, though challenges remain in achieving full autonomous operation in the most extreme nuclear environments.

Keywords: Radiation, nuclear, fusion, fission, machine learning, predictive

INTRODUCTION

The nuclear industry faces unprecedented challenges in managing the aging infrastructure, complex decommissioning projects, and potential emergency scenarios that require intervention in highly radioactive environments. Traditional remote handling systems, while effective for specific tasks, lack the intelligence and adaptability necessary for complex unstructured operations in nuclear facilities. The emergence of artificial intelligence and advanced robotics has presented transformative opportunities to address these challenges through the development of truly autonomous systems capable of operating in extreme radiation environments [1].

*Author for Correspondence

K.V.V. Subba Rao
E-mail: subbu1223@gmail.com

^{1,2}Assistant Professor, Department of Computer Science and Engineering, Pragati Engineering College (A), Surampalem, Andhra Pradesh, India

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The concept of radiation-resilient AI represents a paradigm shift from conventional remote-operated systems to fully autonomous platforms that can make intelligent decisions, adapt to changing conditions, and learn from operational experiences while withstanding the harsh effects of ionizing radiation. These systems integrate sophisticated machine-learning algorithms with radiation-hardened hardware platforms, creating robotic solutions that can function independently for extended periods in contaminated environments. The motivation for developing such systems extends beyond mere technological advancements.

Current nuclear facility operations often require extensive human resources for monitoring, maintenance, and emergency response activities that expose workers to radiation. Aging nuclear infrastructure worldwide, coupled with the growing need for decommissioning activities, has created an urgent demand for autonomous systems that can reduce human exposure while improving operational efficiency and safety outcomes [2].

This comprehensive review examines state-of-the-art radiation-resilient AI systems, analyzing the technical challenges, current solutions, and prospects for intelligent robotic platforms in nuclear facility management. This study explores the intersection of machine learning, robotics, and radiation-hardened electronics, providing insights into how these technologies are being integrated to create next-generation nuclear automation systems.

FUNDAMENTALS OF RADIATION EFFECTS ON AI SYSTEMS

Understanding the effect of ionizing radiation on electronic systems is crucial for developing effective radiation-resilient AI platforms. Nuclear environments present unique challenges that distinguish them from other hazardous operational contexts, requiring specialized approaches to system design and implementation.

Radiation-Induced Hardware Degradation

Ionizing radiation affects electronic components through several mechanisms that can compromise the AI system performance. The total ionizing dose effects accumulate over time, causing the gradual degradation of semiconductor devices, particularly affecting the precision of analog components critical for sensor interfaces and power management systems [3]. Single-event effects, caused by individual high-energy particles, can trigger temporary malfunctions or permanent damage in digital circuits, potentially corrupting data, or causing system resets at critical operational moments.

The sensitivity of modern AI processors, which rely heavily on advanced semiconductor technologies with smaller feature sizes, presents a particular challenge in nuclear environments. Graphics processing units and specialized AI accelerators commonly used for machine learning inference exhibit varying degrees of radiation tolerance that must be carefully characterized and managed [4]. Memory systems, including both volatile and non-volatile storage used for AI model parameters and operational data, can experience bit flips and degradation that directly impact the learning algorithm performance.

Adaptive Strategies for Radiation Resilience

Developing truly radiation-resilient AI systems requires implementing multiple layers of protection and adaptation mechanisms. Hardware-level resilience involves selecting radiation-tolerant components, implementing error detection and correction systems, and designing redundant architectures that can maintain functionality despite component failure. Software-level resilience focuses on developing algorithms that can detect and compensate for radiation-induced errors, including techniques for validating sensor data, detecting anomalous system behaviors, and maintaining operational continuity despite temporary hardware malfunctions.

Machine-learning algorithms can be designed with inherent resilience to hardware-induced errors. Ensemble methods, which combine multiple models to make decisions, provide a natural redundancy that can mask individual model failures. Online learning approaches allow systems to continuously adapt their behavior based on the current performance, potentially compensating for gradual hardware degradation over time. Uncertainty quantification techniques enable AI systems to assess the reliability of their own decisions, allowing for graceful degradation in performance rather than catastrophic failure.

NEXT-GENERATION ROBOTIC PLATFORMS FOR NUCLEAR APPLICATIONS

The development of robotic platforms specifically designed for nuclear environments requires careful consideration of mechanical design, actuation systems, sensing capabilities, and overall system

architecture. These platforms must balance the competing requirements of radiation tolerance, operational capability, and cost-effectiveness while providing a foundation for intelligent autonomous operation.

Mechanical Design and Materials

Nuclear robotic platforms face unique mechanical challenges related to radiation exposure, contamination control, and the need for extended autonomous operation. Material selection is critical, as traditional plastics and organic compounds can degrade rapidly under radiation exposure, leading to mechanical failure and potential contamination spread. Advanced ceramics, radiation-resistant metals, and specially formulated composite materials provide improved durability in nuclear environments, while maintaining the mechanical properties necessary for robotic operation [5].

Mechanical design must also consider decontamination requirements, as robots operating in contaminated environments may need to undergo extensive cleaning procedures or, in extreme cases, may be considered consumable items. Modular designs that allow for component replacement and simplified geometries that facilitate decontamination are essential for practical nuclear robotics applications.

Actuation systems present challenges in nuclear environments, where traditional electric motors may be susceptible to radiation damage, and hydraulic systems may suffer from seal degradation and fluid breakdown. Emerging actuation technologies, including shape memory alloy actuators and novel electromagnetic systems, offer potential solutions for high-radiation applications, while providing the precision and reliability necessary for complex manipulation tasks [6].

Advanced Sensing and Perception Systems

Intelligent operation in nuclear environments requires sophisticated sensing capabilities that can function reliably, despite radiation exposure and potentially hostile conditions. Traditional optical sensors may suffer from radiation-induced noise and degradation, requiring the development of specialized imaging systems with radiation-hardened components and advanced image-processing algorithms that can compensate for sensor artifacts.

Multimodal sensing approaches combine various sensor technologies to provide robust environmental perception. LiDAR systems, which are potentially susceptible to radiation effects, can provide the precise spatial mapping capabilities essential for autonomous navigation [7]. Radar-based sensors offer penetration capabilities for detecting objects through barriers and may exhibit better radiation tolerance than optical systems. Acoustic sensors can provide additional environmental information and may be less susceptible to direct radiation.

Radiation detection and measurement represent critical sensing capabilities in nuclear robotics applications. Advanced spectrometric systems integrated with AI-driven analysis can provide real-time assessments of contamination levels, isotopic identification, and radiation field mapping. These capabilities enable robots to make intelligent decisions regarding operational strategies, route planning, and task prioritization based on current radiological conditions.

Communication and Data Management

Maintaining reliable communication and data management capabilities in nuclear environments presents a significant technical challenge. High radiation levels can interfere with wireless communication systems, whereas the massive amounts of data generated by intelligent robotic systems require robust storage and processing capabilities that must function reliably under harsh conditions.

Advanced communication protocols specifically designed for nuclear environments incorporate error correction, adaptive power management, and multipath redundancy to ensure reliable data transmissions. Mesh-networking approaches allow multiple robotic platforms to maintain connectivity,

even when individual communication links are compromised. Local data processing capabilities reduce dependence on external communication systems, while enabling a rapid response to changing conditions.

Edge computing architectures integrated into robotic platforms provide local AI processing capabilities that can function independently of external systems [8]. These architectures must balance processing power with radiation tolerance, often requiring specialized computing hardware designed specifically for nuclear applications.

ADAPTIVE MACHINE LEARNING ALGORITHMS FOR NUCLEAR ENVIRONMENTS

The development of machine learning algorithms specifically tailored for nuclear applications requires addressing unique challenges related to data quality, environmental variability, and the need for reliable operation in safety-critical scenarios [9]. These algorithms must demonstrate robustness to sensor noise, adaptability to changing conditions, and the ability to maintain performance despite hardware degradation.

Robust Learning under Uncertainty

Nuclear environments present significant challenges for traditional machine-learning approaches owing to high levels of sensor noise, dynamic environmental conditions, and the potential for hardware-induced errors. Robust learning algorithms must function effectively despite these challenges while maintaining the accuracy necessary for safety-critical operations [10].

Probabilistic machine-learning approaches provide a natural framework for handling uncertainties in nuclear applications. Bayesian neural networks can quantify the uncertainty in their predictions, allowing robotic systems to make informed decisions about when to request human intervention or adopt more conservative operational strategies. Gaussian process models offer similar uncertainty quantification capabilities while providing theoretical guarantees regarding their behavior, which may be important for safety-critical applications.

Online learning algorithms enable robotic systems to continuously adapt their behavior based on operational experience, potentially compensating for gradual changes in the sensor characteristics or environmental conditions. These algorithms must be designed to distinguish between legitimate environmental changes and hardware-induced anomalies and require sophisticated anomaly detection capabilities and robust model-updating strategies.

Multi-Agent Learning and Coordination

Nuclear facility management often requires coordination among multiple robotic platforms, each with specialized capabilities and operational constraints. Multiagent learning algorithms enable teams of robots to collaborate effectively while adapting their coordination strategies based on experience and changing operational requirements.

Distributed learning approaches allow multiple robots to share information and improve their performance without requiring centralized coordination. These approaches must be robust to communication failures and varying levels of individual robot reliability, particularly in nuclear environments, where individual platforms may experience temporary malfunctions or degraded performance.

Hierarchical learning architecture can provide effective coordination between different levels of decision making, from individual robot actions to facility-wide operational strategies. These architectures enable the integration of human oversight with autonomous operations, allowing for graduated levels of autonomy based on task complexity and risk assessment.

Transfer Learning and Domain Adaptation

The unique characteristics of nuclear environments, combined with limited opportunities for extensive real-world training, render transfer learning and domain adaptation critical capabilities for nuclear robotics applications. These techniques enable AI systems to leverage the knowledge gained in simulated or less hazardous environments and effectively apply them to real nuclear facility operations.

Simulation-to-reality transfer represents a particularly important application area because comprehensive simulation environments can provide extensive training opportunities without the costs and risks associated with real nuclear facility testing. Advanced domain adaptation techniques can help bridge the gap between simulated and real environments by accounting for factors such as sensor noise, environmental variability, and hardware limitations that may not be fully captured in the simulation.

Few-shot learning approaches enable AI systems to quickly adapt to new situations with minimal training data, which is particularly important for emergency response scenarios in which rapid adaptation to novel conditions may be critical. These approaches must be combined with safety constraints to ensure that learning from limited data does not compromise the operational safety [11].

APPLICATIONS IN NUCLEAR FACILITY MANAGEMENT

The integration of radiation-resilient AI with advanced robotic platforms creates opportunities for transformative applications across the spectrum of nuclear-facility management activities. These applications range from routine maintenance and monitoring tasks to complex decommissioning projects and emergency-response scenarios.

Autonomous Inspection and Monitoring

Regular inspection and monitoring of nuclear facilities are essential for maintaining safety and operational efficiency. Traditional approaches require extensive human involvement and may not provide the comprehensive, continuous monitoring necessary for optimal facility management. Intelligent robotic systems can provide automated inspection capabilities that significantly enhance the scope and quality of monitoring activities.

Advanced computer vision algorithms integrated with robotic platforms can perform detailed visual inspections of nuclear facility components and automatically detect anomalies, corrosion, mechanical wear, and other indicators of potential problems [12]. Machine learning algorithms trained on historical inspection data can identify subtle patterns that may not be apparent to human inspectors, potentially enabling the earlier detection of developing issues.

Continuous monitoring capabilities enabled by persistent robotic platforms can provide real-time assessment of facility conditions, enabling an immediate response to developing problems, rather than waiting for scheduled inspection intervals. These systems can integrate multiple sensor modalities to provide comprehensive environmental assessments, including radiation levels, spread of contamination, structural integrity, and equipment performance.

Predictive maintenance algorithms can analyze monitoring data to forecast equipment failures and optimize maintenance scheduling, thereby reducing both operational costs and radiation exposure for maintenance personnel. These algorithms must account for the unique operational constraints of nuclear facilities, including radiation exposure limits, contamination control requirements, and the critical nature of the safety systems.

Decommissioning and Remediation Operations

Nuclear facility decommissioning is one of the most challenging applications of robotic systems, requiring complex manipulation capabilities, adaptability to changing conditions, and the ability to operate in highly contaminated environments for extended periods. The scale and complexity of decommissioning projects make them ideal candidates for intelligent automation technologies [13].

Autonomous dismantling operations require sophisticated manipulation capabilities, combined with intelligent planning algorithms that can adapt to unexpected conditions and obstacles. Machine learning algorithms can optimize cutting sequences, tool selection, and handling strategies based on real-time assessment of material properties and contamination levels. These systems must balance efficiency with safety requirements, ensuring that dismantling operations do not create unacceptable risks or the spread of contamination.

Waste characterization and sorting represent critical capabilities for decommissioning operations, requiring accurate identification of material types, contamination levels, and appropriate disposal pathways. AI-driven spectroscopic analysis can provide rapid and accurate characterization of materials while minimizing human exposure to potentially contaminated items.

Remediation planning algorithms can optimize the sequence of decommissioning activities to minimize radiation exposure, reduce waste generation, and ensure compliance with regulatory requirements. These algorithms must consider the complex interdependencies between different activities while adapting to changing conditions and unexpected discoveries during the decommissioning process.

Emergency Response and Crisis Management

Nuclear emergency scenarios present some of the most demanding requirements for autonomous robotic systems, which require rapid deployment, adaptation to unknown conditions, and reliable operation in extreme environments. The development of AI-enabled emergency response capabilities represents a critical application area in radiation-resilient robotics.

Rapid environmental assessment capabilities enable emergency response teams to quickly understand the scope and nature of nuclear incidents and provide critical information for decision-making and response planning. Autonomous robots equipped with advanced sensing capabilities can provide real-time assessments of radiation levels, contamination spread, structural damage, and other critical factors while minimizing human exposure to hazardous conditions.

Search and rescue operations in nuclear emergency scenarios require sophisticated navigation capabilities, obstacle avoidance, and the ability to locate and assist human casualties in highly contaminated environments [14]. AI-driven path-planning algorithms can optimize search patterns while considering the radiation exposure limits and structural hazards.

Crisis coordination capabilities enabled by multiagent AI systems can provide intelligent coordination between multiple response assets, optimize resource allocation, and ensure effective communication between human and robotic response elements. These systems must be designed to function reliably, despite potential communication disruptions and infrastructure damage.

INTEGRATION CHALLENGES AND SOLUTIONS

Successful deployment of radiation-resilient AI systems in nuclear facility management requires addressing numerous technical and operational challenges related to system integration, validation, and regulatory compliance. These challenges span hardware and software domains while encompassing broader considerations related to human-machine interaction and organizational adoption.

Hardware-Software Integration

Achieving effective integration between radiation-hardened hardware platforms and sophisticated AI software requires careful consideration of the computational constraints, power limitations, and thermal management in nuclear environments. The specialized hardware necessary for radiation tolerance may not provide computational performance typically assumed by modern AI algorithms, which require optimization and adaptation of software systems.

Real-time performance requirements for nuclear robotics applications create additional constraints on system design, as safety-critical operations cannot tolerate unpredictable execution times that may be acceptable for other AI applications. Deterministic scheduling algorithms and bounded execution time AI approaches are essential for ensuring predictable system behavior.

Power management represents a critical challenge for autonomous nuclear robots, as radiation exposure may limit the effectiveness of traditional battery technologies, whereas nuclear environments may not provide convenient access to external power sources. Energy-efficient AI algorithms and adaptive power management strategies are essential for extended autonomous operation [15].

Validation and Verification

Ensuring the reliability and safety of AI-enabled nuclear robotics systems requires comprehensive validation and verification approaches that address the unique challenges of machine-learning systems in safety-critical applications. Traditional verification methods developed for deterministic systems may not be adequate for AI systems that exhibit adaptive behavior and learning capabilities.

Formal verification techniques adapted for machine learning systems can provide mathematical guarantees of system behavior under specified operating conditions. These techniques must account for the probabilistic nature of AI systems, while providing the level of assurance necessary for nuclear applications.

Extensive testing protocols must address the full range of operational scenarios, including normal operation, degraded conditions, and emergency situations. Testing in actual nuclear environments presents significant challenges and costs, making high-fidelity simulation environments essential for a comprehensive system validation.

Continuous monitoring and validation during operational deployment enable an ongoing assessment of system performance and the detection of potential degradation or anomalous behavior [16]. These capabilities are particularly important for learning systems that may change their behavior over time based on operational experience.

Regulatory and Standards Compliance

The deployment of AI-enabled robotic systems in nuclear facilities must comply with extensive regulatory requirements and industry standards, which may not have been developed with autonomous systems in mind. Developing appropriate regulatory frameworks for intelligent nuclear robotics is a significant challenge for both developers and regulatory agencies.

Safety case development for AI systems requires the demonstration that intelligent robotic platforms can maintain safety requirements despite their adaptive behavior and the potential for unexpected responses to novel situations. This demonstration must account for the full range of possible system behaviors while providing adequate assurance for regulatory approval.

Standard development for nuclear AI systems must address unique requirements related to radiation tolerance, safety system integration, and human-machine interaction in nuclear environments. These standards must balance innovation with safety requirements, while providing clear guidance for system developers and operators.

FUTURE PERSPECTIVES AND EMERGING TECHNOLOGIES

The field of radiation-resilient AI for nuclear applications continues to evolve rapidly, driven by advances in AI technology and nuclear engineering requirements. Several emerging trends and technologies promise to further enhance the capabilities and applicability of intelligent robotic systems in nuclear environments.

Advanced AI Architectures

Neuromorphic computing architectures inspired by biological neural networks offer potential advantages for nuclear applications owing to their inherent fault tolerance and energy efficiency. These architectures may provide better radiation tolerance than traditional digital computing systems while enabling more efficient implementation of AI algorithms.

Quantum computing technologies, while still in early development, can eventually provide significant advantages for certain nuclear applications, particularly in areas such as optimization and simulation. However, the extreme sensitivity of quantum systems to environmental interference presents a significant challenge for nuclear applications [17].

Edge AI architectures optimized for harsh environments are becoming increasingly sophisticated, enabling more complex AI processing capabilities to be directly deployed on robotic platforms. These architectures must balance computational capability with radiation tolerance and power efficiency.

Enhanced Human-Machine Collaboration

The future of nuclear robotics lies not in the complete replacement of human operators but in sophisticated collaboration between human expertise and AI capabilities. Advanced human-machine interfaces can leverage the strengths of both human judgment and AI processing power while ensuring appropriate human oversight of autonomous operations.

Augmented reality systems can provide human operators with enhanced situational awareness when supervising autonomous robotic operations, overlaying AI-generated insights and recommendations on the real-world views of nuclear facilities. These systems can enable more effective remote operation and supervision of robotic platforms.

Adaptive automation strategies can dynamically adjust the level of autonomy based on the task complexity, environmental conditions, and operator availability. These strategies enable optimal allocation of human and AI resources while maintaining appropriate safety oversight.

Integrated Facility Management Systems

The evolution toward comprehensive digital twins of nuclear facilities provides opportunities for a more sophisticated integration of AI-enabled robotic systems with overall facility management. These digital twins can provide detailed models of facility conditions, equipment status, and operational requirements that enable more intelligent deployment and coordination of robotic resources.

Predictive analytics integrated across facility systems can optimize the deployment of robotic platforms based on anticipated maintenance needs, operational requirements, and regulatory obligations [18]. These systems can facilitate facility-wide optimization of human and robotic resources while maintaining safety and regulatory compliance.

Autonomous facility optimization algorithms can continuously adjust operational parameters, maintenance schedules, and resource allocation to optimize facility performance while minimizing human radiation exposure and operational costs.

CONCLUSION

The development of radiation-resilient AI systems integrated with next-generation robotic platforms represents a transformative opportunity for nuclear-facility management. These systems promise to address critical challenges related to human safety, operational efficiency, and the management of aging nuclear infrastructure, while enabling new capabilities that were previously impossible. The technical challenges associated with developing truly radiation-resilient AI systems are significant and require advances in hardware design, algorithm development, and system integration.

However, recent progress in areas such as radiation-hardened computing, robust machine-learning algorithms, and intelligent robotics has suggested that many of these challenges can be effectively addressed. The successful deployment of these systems will require continued collaboration among AI researchers, robotics engineers, nuclear technologists, and regulatory agencies to ensure that new capabilities are developed and deployed safely and effectively. The potential benefits, including reduced human radiation exposure, improved operational efficiency, and enhanced emergency response capabilities justify the significant investment required to develop these advanced systems. As the nuclear industry continues to evolve with new reactor designs, decommissioning challenges, and safety requirements, the role of intelligent autonomous systems will likely become increasingly important. The foundation established today through research and development in radiation-resilient AI will enable the nuclear industry to meet these challenges.

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