

Application of Robotics in Hazardous Environment Inspection

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Abstract: Inspection of hazardous environments such as nuclear facilities, chemical plants, underground mines, disaster-struck buildings, and offshore infrastructure poses severe risks to human operators. Robotics has emerged as a reliable and increasingly indispensable solution for minimizing human exposure while enhancing inspection accuracy, repeatability, and operational efficiency. This paper presents a comprehensive, journal-ready analysis of the application of robotic systems in hazardous environment inspection. It examines the evolution of inspection robotics, including ground robots, aerial drones, underwater vehicles, and hybrid platforms, with a focus on sensing technologies, autonomy levels, communication architectures, and human-robot interaction. The study integrates findings from recent experimental deployments and simulation-based research to evaluate system performance under adverse conditions such as low visibility, radiation exposure, toxic gases, and unstable terrain. Particular emphasis is placed on shared autonomy frameworks that balance human decision-making with machine intelligence to ensure safety and reliability. Challenges related to perception degradation, power limitations, communication failures, and regulatory certification are critically discussed. The paper concludes by identifying future research directions, including resilient multi-robot systems, AI-driven anomaly detection, and standardized benchmarking protocols, which are essential for transitioning inspection robotics from experimental deployments to routine industrial use.

Keywords: Inspection Robotics, Hazardous Environments, Autonomous Systems, Sensor Fusion, Human-Robot Interaction

1. Introduction

Industrial development and urban expansion have increased the frequency and complexity of hazardous environments requiring inspection and monitoring. Facilities such as nuclear reactors, petrochemical plants, high-rise infrastructure, and underground tunnels demand regular inspection to ensure structural integrity and operational safety. Traditionally, these tasks have relied heavily on human inspectors equipped with protective gear, yet even with safeguards, such operations remain dangerous, time-consuming, and costly [1]. Robotics offers a transformative alternative by enabling remote or autonomous inspection in environments that are inaccessible or unsafe for humans. Advances in sensing, computation, and control have made it possible to deploy robots capable of navigating complex terrains, collecting high-fidelity data, and performing limited manipulation tasks under extreme conditions. As a result, robotic inspection has transitioned from conceptual prototypes to field-tested systems across multiple sectors. This paper provides a detailed exploration of robotic technologies used for hazardous environment inspection. By examining system architectures, sensing modalities, autonomy strategies, and operational challenges, the study aims to present a holistic understanding of the current state of the field and the pathways toward widespread adoption.

2. Hazardous Environments and Inspection Requirements

The Hazardous environments are characterized by conditions that pose physical, chemical, or radiological risks to humans. These include high radiation zones in nuclear facilities, explosive atmospheres in chemical plants, confined spaces with toxic gases, underwater structures exposed to high pressure, and disaster sites with unstable

debris. Each environment imposes unique constraints on robotic design and operation [2]. Inspection requirements typically involve visual assessment, structural integrity evaluation, detection of leaks or anomalies, and data logging for regulatory compliance. In many cases, inspections must be performed repeatedly over long periods, necessitating robust and reliable robotic systems. Environmental factors such as dust, smoke, electromagnetic interference, and temperature extremes further complicate sensing and communication. Robots designed for hazardous inspection must therefore exhibit high mobility, resilient perception, and fault tolerance. They must also support safe human oversight, particularly in critical decision-making scenarios. These requirements have shaped the development of specialized robotic platforms tailored to specific hazard profiles.

3. Robotic Platforms for Hazardous Inspection

Ground-based robots are among the most widely deployed systems for hazardous inspection. Tracked and wheeled robots are commonly used in nuclear decommissioning, mining, and disaster response due to their stability and payload capacity. These robots can carry multiple sensors, including cameras, radiation detectors, gas sensors, and ultrasonic probes, enabling comprehensive inspection [3]. Aerial robots, particularly unmanned aerial vehicles (UAVs), have gained prominence for inspecting tall structures, confined indoor spaces, and post-disaster environments. UAVs offer rapid deployment and flexible access but are limited by flight time, payload capacity, and susceptibility to environmental disturbances. Recent developments in aerial manipulation have extended their capabilities to include contact-based inspection and sample collection [4]. Underwater robots, such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), are essential for inspecting offshore platforms, pipelines, and submerged infrastructure. These systems rely heavily on sonar, acoustic communication, and pressure-resistant designs. Hybrid robots capable of operating across multiple environments are emerging as versatile solutions for complex inspection tasks [5].

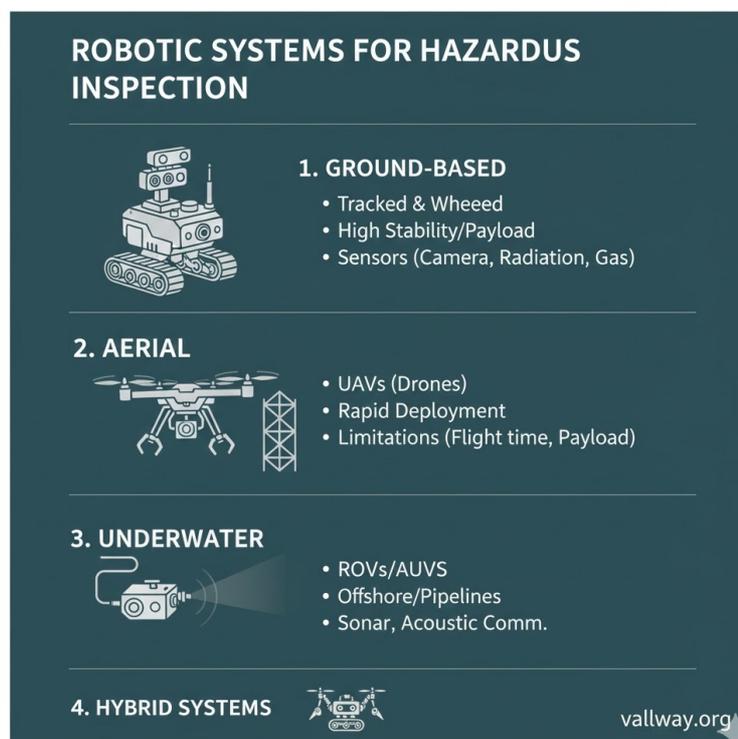


Fig. 1 Robotic Systems

4. Sensing and Perception in Adverse Conditions

Effective inspection relies on accurate perception, which is particularly challenging in hazardous environments. Vision-based sensing is often impaired by low light, smoke, dust, or turbidity. To address these limitations, robotic systems increasingly employ multimodal sensing, combining visual, thermal, LiDAR, radar, and chemical sensors to achieve robust situational awareness [6]. Sensor fusion techniques integrate data from multiple sources to compensate for individual sensor weaknesses. For example, LiDAR can provide reliable spatial mapping in low-light conditions, while thermal imaging can detect heat anomalies indicative of faults or leaks. Gas sensors and radiation detectors add contextual information essential for safety assessment. Advances in onboard processing and machine learning have enabled real-time interpretation of sensor data, allowing robots

to detect anomalies, classify hazards, and prioritize inspection targets. However, perception algorithms must be robust to noise and uncertainty, which remain significant challenges in real-world deployments.

5. Autonomy and Human–Robot Interaction

Autonomy in inspection robotics spans a spectrum from fully teleoperated systems to highly autonomous platforms capable of independent navigation and decision-making. In hazardous environments, complete autonomy is often impractical due to uncertainty and the high consequences of failure. As a result, shared autonomy has emerged as a preferred paradigm [7]. Shared autonomy combines human oversight with autonomous low-level control, allowing robots to handle routine navigation and sensing while operators intervene during complex or critical situations. This approach reduces operator workload and cognitive burden while maintaining safety and accountability. Human–robot interaction interfaces, including haptic feedback, augmented reality displays, and intuitive control schemes, play a crucial role in effective teleoperation. Latency and communication disruptions pose additional challenges, particularly in underground or shielded environments, necessitating predictive control and local autonomy.

6. Fabrication Techniques and Scalability

Reliable communication is a cornerstone of robotic inspection in hazardous environments. Wireless communication is often constrained by obstacles, interference, and signal attenuation. To mitigate these issues, systems employ a combination of wireless relays, tethered connections, and adaptive networking protocols [8]. Fault tolerance and redundancy are critical design considerations. Robots must be capable of handling sensor failures, actuator malfunctions, and partial communication loss without catastrophic outcomes. Redundant sensing, modular hardware design, and fail-safe control strategies enhance system reliability. Energy management is another limiting factor, particularly for mobile and aerial platforms. Efficient power utilization and energy-aware mission planning are essential for extending operational duration and ensuring mission completion.

7. Case Studies and Applications

Robotic inspection has demonstrated tangible benefits across multiple domains. In nuclear facilities, robots have been deployed to inspect reactor vessels and contaminated areas, significantly reducing radiation exposure to personnel [9]. In the oil and gas industry, robotic crawlers and drones perform routine inspections of pipelines and storage tanks, improving detection of corrosion and leaks. Disaster response scenarios highlight the value of rapid robotic deployment for search and assessment. Robots equipped with cameras and sensors can navigate rubble and confined spaces, providing critical information to rescue teams. These applications underscore the versatility and impact of inspection robotics when tailored to specific operational needs.

8. Challenges and Future Research Directions

Despite substantial progress, several challenges hinder the widespread adoption of robotic inspection systems. Standardization and certification remain significant barriers, particularly in regulated industries where safety and reliability requirements are stringent. Robust testing and validation frameworks are needed to build trust in autonomous systems [10]. Future research should focus on resilient multi-robot systems capable of collaborative inspection, advanced AI techniques for anomaly detection, and improved energy storage solutions. The development of open datasets and benchmarking environments will facilitate comparative evaluation and accelerate innovation.

9. Conclusion

Robotics has fundamentally transformed the inspection of hazardous environments by reducing human risk and enhancing operational efficiency. Through advances in platform design, sensing, autonomy, and human–robot interaction, inspection robots have moved closer to routine deployment across industrial and emergency response contexts. Continued interdisciplinary research and collaboration between academia, industry, and regulators will be essential to fully realize the potential of robotic inspection technologies in safeguarding infrastructure and human lives.

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