ROBOTIC PROCESS AUTOMATION FOR NUCLEAR POWER PLANTS

Evaluation of Near-Term Opportunities

June 2022

Introduction

Increasing economic challenges have created pressure on nuclear power plants (NPPs) to reduce costs closer to other types of power generation. Operations and maintenance (O&M) activities are a key driver for the cost of generation at NPPs in all phases of their service life: newly built, in-service for many years, and decommissioning.

One potential approach for decreasing cost is through expanding applications for drones, robotics, and accompanying software solutions to automate operations and maintenance tasks. In addition to cost savings, advanced robotic platforms also offer opportunities to:

- Decrease calendar time and labor hours to complete certain tasks
- Decrease the exposure of personnel to a variety of industrial and radiological hazards
- Gather information and perform work while equipment is online (rather than necessitate an outage or downpower)
- Increase the quality of data collected from an inspection
- Increase scheduling flexibility among personnel (for example, by reducing the need to coordinate between maintenance and health physics when the robot is used in an elevated radiation area instead of a human)
- Decrease administrative burden to perform certain maintenance activities that require significant oversight when performed manually

Approach

Gathering Input

Information for this report was gathered through interviews with utility personnel who are actively implementing drone and robotic solutions, industry subject matter experts (including former operators), review of published literature, EPRI's work order database, and engagement with other ongoing EPRI projects pertaining to automation and modernization. The review of publicly available literature and EPRI research products was performed to explore the current use of automating technologies in NPPs and to identify use cases. The utilities selected for the interviews had familiarity with using drones and robots in NPPs and provided insight on plant priorities for current modernization efforts. Industry subject matter experts (SMEs) and stakeholders from adjacent modernization efforts contributed additional insights on capabilities and potential limitations for certain use cases.

Selecting Top Use Cases

Of the use cases for robotic automation identified from the literature review, the top use cases discussed in this report were chosen using the following criteria:

1. Technical feasibility of automation
2. Interest of the interviewed utilities
3. Applicability to multiple utilities
4. Advantage provided by using a robotic solution, rather than other methods (e.g., instrumentation)

Additionally, the use cases selected for detailed review in this report are intended to provide a representative cross section of potential applications. To provide the diversity needed to meet this objective, multiple similar use cases were not selected, even if potential benefits were high.

Characterizing Use Cases

Characteristics for each use case are included in this report to provide a high-level overview of the selected robotics applications. The following details are provided for each use case:

- The scope of the use case and how it is traditionally performed
- Potential benefits from using robotic platforms and/or increased automation
- The current state of robotic platforms
- Desired expanded capabilities to capture the full benefits of robotic automation
- Task frequency and labor hours (where applicable)
- Key considerations that may be useful in the development and selection of robotic platforms

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Robotic Automation Use Cases

This section describes a representative set of use cases that provide the valuable potential benefits to utilities. The discussion of each use case includes potential capabilities and key considerations to help define a path for developing robotic platforms that meet utility needs.

Role for Robotic Automation

In general, the use cases selected as the best applications for robotic automation over traditional methods or other technologies (namely instrumentation or visual monitoring by fixed cameras) have one or more of the following characteristics:

- Is typically performed in the presence of challenging conditions, including radiation, heat, elevated heights, confined spaces, or submerged areas
- Is performed in locations that are remote or challenging to access
- Is traditionally performed by a human while a system is secured (or during an outage) but may be performed while the system is operating using robotic platforms
- Is performed in an area where permanent or semi-permanent equipment (cameras, instrumentation) cannot be installed
- Requires a high number of labor hours to address personnel safety or other substantial administrative, logistical, and/or technical support from site personnel that is not necessary for a robot
- Is highly structured and well-suited for repeated, automated performance that does not require creative thinking or complex judgment

Current Usage of Robots at NPPs

As discussed in interviews and reported in published literature, multiple utilities have already realized significant economic benefits from using drones and robots for certain infrequent activities, such as inspections that are on the critical path in outages or in circumstances where a remote technology can gather information more readily than a human. Implementation of robotics and automation for higher frequency use cases, such as to support operator rounds activities, has been exploratory.

Examples of current implementation of robots and drones include inspecting reactor internals, heat exchanger tubes, turbine stators, containment structures, intake structures, isophase bus ducts, and piping. Using robotic platforms to accomplish these activities has resulted in reduced dose to personnel and reduced need for O&M cost drivers such as scaffolding, dive teams, and excavation. Robots have realized benefits in dose savings through performing cleaning activities, including the decontamination of a turbine hall after a spill, and performing maintenance activities, including the welding of spent fuel pool walls and dry casks (References 1 and 2). There is clear interest in identifying more opportunities for adoption of these systems, which begins with identifying the most beneficial use cases for automated robotic platforms, and better understanding their capabilities and limitations.

Robotic automation may be implemented by utilities through vendor contracting and/or through an internal program where the utility owns the robotic equipment and is responsible for its maintenance and operation. A variety of robot types are applicable, including land-based crawlers and rovers, aerial drones, submersible robots, and static designed-for-task platforms commonly seen in factories. Robots have been used with a variety of sensors including eddy current probes, ultrasonic sensors, visual imaging cameras, hyperspectral imaging cameras, electromagnetic sensors, and thermographic sensors.

General Limitations and Gaps

While adoption of these technologies is expanding, in interviews our utility members cited a variety of barriers as limiting widespread and systematic implementation of robotic automation in NPPs:

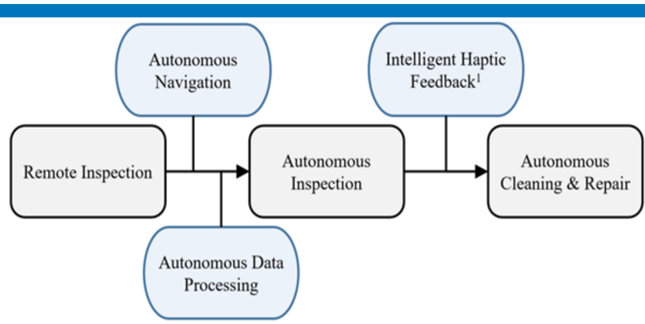
- Capability to perform the task at a level comparable to the manual approach (e.g., evaluating whether a force being applied is causing damage or is insufficient)
- Software limitations (e.g., deviations between current and baseline for video recordings)
- Storage limitations (e.g., management of large data archives for model training and record keeping)
- Hardware barriers (e.g., operation in high temperature environments, restrictive battery life, and physical size limitations)
- Regulatory barriers (e.g., line-of-sight flight path requirements for aerial drones)
- Security concerns (e.g., management of visual data gathered in-containment)

In addition to these technical and regulatory limitations, utilities also identified the following implementation barriers:

- Time and resources required to develop a robotics program in-house
- Concerns that staff optimization may ultimately result in reduced staffing needs for various functions
- Difficulty evaluating capabilities and limitations of current automating solutions and how they compare to requirements for implementation in NPPs
- Identifying and mitigating risks associated with implementation in environments with low risk tolerance, such as near critical components

There are many tasks that current robotic solutions can perform, but typically these tasks will require remote operation of the platform. The hardware and software are several step changes away from full automation, but once that automation is realized, the potential benefits of implementation can increase. An example path to full implementation of robotic automation for buried pipe inspections is depicted in Figure 1, where the grey blocks represent capabilities, and the blue blocks represent features that need to be developed to implement those capabilities.

Current remote inspection robots are capable of being controlled while taking in quality data that human experts will analyze. This is by definition a remote inspection. The next step towards full automation would be the automation of the inspection, which would require the robot be capable of navigating within (and ideally to and from) the pipe being inspected, while processing the data itself rather than providing it to a human expert off-site. The final step towards full automation would be the addition of task execution capabilities to allow the inspection robot (or another dispatchable robot) to navigate to areas noted in the inspection, and then clean or repair as needed. Better feedback controls from the mechanical interface with the pipe would be needed to safely allow a robot to perform this final task. Once the navigation, processing, and haptic feedback technologies are robust, the end result would be a robot capable of deploying to a pipe, inspecting, evaluating, cleaning, and repairing without the need for human oversight. Note that this is descriptive of the concept; other technologies would need to be considered, such as cybersecurity for the navigation and data transmission systems, battery life based on the length of pipes, and so on.



1) The ability to determine whether an action is appropriate in real-time (i.e., whether the force applied is damaging an object and whether it is sufficient to perform the intended function).

Figure 1. Example path to full implementation of robotic automation for buried pipe inspections

While full evaluation of the technology gaps and definition of a path towards full automation of every task discussed are beyond the scope of this report, future work is planned to develop this topic.

Top Tasks for Automation

Inspect and Maintain Buried Service Water Piping

Service water piping is often exposed to a harsh environment that leads to degradation. This poses a challenge to utilities that have extended the life of their plants. Corrosion allowances designed into these systems to avoid inspections, repair, or replacement were typically based on an expected life of 25 to 40 years, so license extension requires aging management through inspections [1]. Using robots equipped with various sensors (e.g., electromagnetic and ultrasonic) allows for buried piping inspections to be performed internally, which avoids the need for excavation. This significantly reduces cost, time, and risk of performing the inspections, and allows more challenging locations to be inspected with less effort [2].

While current robots have the ability to support inspections of service water piping, the autonomy and capability of robots in NPPs could be expanded to realize greater economic benefits. Capabilities that would be useful to develop or improve include increased autonomy for navigation, automated data processing and management, and the ability to perform preventative and corrective maintenance activities with a degree of autonomy.

Examples of cleaning and maintenance actions that may be useful for this application include [2]:

- Jetting water, air, or abrasive particles, and/or rubbing the pipe surface
- Collecting samples at the pipe surface

- Treating surfaces with biocides
- Welding inlays and cladding material to a section of pipe
- Applying protective coatings

For such cleaning and maintenance activities, the robot must be able to navigate elbows or other complex geometries (depending on the piping configuration and the area of interest) and identify what the appropriate course of action is based on sensory inputs (e.g., corrosion requires coating whereas the accumulation of debris requires an application of force for cleaning).

These advances would have implications for other systems as well. Examples of other piping systems that could potentially benefit from these developments include auxiliary feedwater, fire protection, spray pond systems, and circulating water systems, fuel and oil systems for emergency diesel generators, sewage and drainage systems, off-gas systems, and radioactive waste systems.

Table 1 provides a summary of information for this use case and lists key design and capability considerations for using a robotic platform to autonomously perform the tasks as described above. The considerations listed are not exhaustive. This is consistent for all tables in this report.

Table 1. Inspect and Maintain Buried Service Water Piping

Task Frequency	Beginning 10 years before design life is reached, inspections are typically performed as frequently as every three to five years, then adapted to reflect insights gained on pipe condition, with directed inspection performed every 10 years [1].
Labor Hours	For both buried and above ground service water piping systems, an analysis of EPRI's work order database indicates that approximately 5,000-10,000 man-hours are spent performing activities per unit per year.
Benefits	Cost: • Reduction in labor costs. • Reduction or elimination of the need to excavate. • May eliminate the need to drain the pipe. • May eliminate the need to remove and reapply coatings. Time: • Reduction in time to inspect the length of the pipe. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in personnel exposure to industrial risks, including confined spaces. • Reduction in risk of damaging the system by reducing excavation needs. Quality: • Increased confidence in system health by allowing for the inspection of previously inaccessible areas. Flexibility: • Increased scheduling flexibility by reducing the need to coordinate between various personnel providing support for work in confined spaces.
Key Considerations and Needs	General: • Designed for environments with significant amounts of moisture and debris. • Can navigate elbows in the pipe and is compatible with a broad range of pipe sizes. • Able to access the pipe system from existing infrastructure (i.e., no special installations needed to start inspection). • Can navigate and communicate in areas obstructed by buried concrete and metal structures Inspection: • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and baseline state to be flagged. • Able to detect wall thinning (e.g., using ultrasonic or electromagnetic sensors). Maintenance: • Is able to support maintenance activities, potentially requiring the ability to clean, cut, weld, and collect samples. • Employs feedback mechanisms to prevent damage to a surface.

Inspect and Maintain Component Supports in Containment

Component supports are important for protecting safety-related piping systems, pressure vessels, and pumps from various static and transient loads, depending on the type of support. In-service inspection and maintenance of dynamic restraints is important to maintaining the safety and operability of NPPs [3]. For component supports located in containment, these inspection and maintenance activities are currently performed manually during outages due to the elevated radiation and heat hazards present during operating conditions. Using drones or robots to perform in-service inspections and to support in-service testing (when applicable) allows for some of the work to be performed outside of the outage window. This application would increase flexibility in maintenance planning and execution. Additionally, usage of a robot would reduce the burden on operations and maintenance and reduce the dose received by personnel.

Utilities have already performed visual inspections of welds on simple component supports remotely using robots. Based on the input gathered for this report, no utility has introduced significant automation into these inspection activities or used robots to perform activities that require physical interaction with the supports (i.e., repair). It would be beneficial to expand the capabilities of supporting software to automate the identification of issues. This would eliminate the need for a human to spend time reviewing all video footage and other data collected during the remote inspection. In interviews, utilities identified the following examples as advantageous inspection and maintenance activities:

- Recording and reporting physical damage, missing or loosened items, misalignment, leaks, corrosion, deposits, and other degradation
- Torquing or replacing fasteners
- Replacing seals, fluid, and/or lubricants
- Cutting and welding to repair or replace existing supports

To enable the inspection and maintenance of support components while the reactor is in-service, a robotics platform would need to be designed for operation in conditions of elevated temperature and radiation. The robot would also have to be able to navigate complex spaces without interfering with other equipment, which requires robust obstacle avoidance and a compatible physical design (size, agility). One utility suggested that a drone with a diameter of less than 10” would be helpful to avoid obstacles typically found in containment while collecting inspection data. To reduce the burden of data processing, the robot would benefit from software or artificial intelligence capable of automating the comparison of visual data with the relevant requirements. For maintenance activities, the robot would need the motor skills necessary to wield hand tools (or a mechanically connected equivalent) and obtain sensory inputs to monitor and regulate the application of torque. Additionally, the robot would need to be capable of either carrying the tool-based payload to the location of interest or accessing the tools itself at the location.

This use case is relevant for coolant pumps, steam generators, piping systems, and other major components present in containment that are supported by snubbers, hangers, anchors, and other types of supports. The technology would be relevant for component supports in low radiation areas of the site as well and would likely be useful for the inspection and maintenance of valves.

Table 2. Inspect and Maintain Component Supports in Containment

Task Frequency	For snubbers, in-service inspection and examination is typically required at approximately three-to-four-year intervals while in-service testing is typically required every fuel cycle [4]. Inspections of other supports are typically less frequent.
Benefits	Cost: • Reduction in labor costs. • Reduction in scaffolding costs. • Potential to decrease down-time by collecting data and assessing condition while online. Time: • Reduction in time to inspect the supports. • Reduction in time to build, certify, and disassemble scaffolding. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in personnel exposure to radiation hazards and industrial risks, including elevated heights. Quality: • Images can be obtained using high-definition cameras, and a detailed visual record of the condition of supports can be stored and referenced for trending purposes. Flexibility: • Allows for issues to be identified and planned for before an outage. • Increased scheduling flexibility among personnel by reducing the need to coordinate between maintenance and health physics.
Key Considerations and Needs	General: • Can withstand temperatures and radiation exposure that is commensurate with conditions inside containment. For one example plant, these conditions were reported to be 120°F and 60 mR/hr [5]. • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. • Robust obstacle avoidance. • Size and agility that are compatible with accessing all locations of interest in containment. Inspection: • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and base-line state to be flagged. • Able to detect cracking, corrosion, and misalignment between components. Maintenance: • Able to wield hand and power tools (or replicate their function). • May need to cut or weld material.

Inspect and Maintain Cooling Water Intake and Discharge Structures

The intake structure and its supporting equipment (underwater supports, pumps, valves, and travelling screens and strainers) require regular inspection and maintenance, as well as occasional emergent work such as removing foreign material or debris. Traditional methods of ensuring the availability and integrity of intake and discharge structures require a variety of equipment, diving teams, and extensive oversight and administrative support. Furthermore, conducting underwater diving operations in intake and discharge structures is hazardous and time consuming. The use of robots to perform inspections and maintenance activities reduces the amount of time divers are needed to be underwater and reduces oversight and administrative burden. In addition to improving safety and inspection efficiency, robots also allow for improved data collection during inspections through increased access to low-clearance and other difficult-to-access areas.

Inspections of intake structures and supporting equipment have been performed using remotely operated submersibles at NPPs, but significant potential remains for adding automation and capabilities for maintenance and repair activities. Manually controlling the movement of the robot through the water can be challenging, so the use of autonomous navigation would reduce the need for training and reduce the time necessary to complete the task. Inefficiencies related to cleaning marine growth may be partially attributed to the vast difference in size between available robotic platforms and the structure itself. One route to address this particular limitation could include developing separate platforms that are task specific: for example, a robot that is small to allow for inspection of difficult to access areas and another that is large for cleaning activities.

During utility interviews, the following maintenance and repair activities were identified as potentially beneficial for robotic automation:

- Debris removal and marine growth cleaning
- Underwater cutting, grinding, and welding to repair or replace supports
- Tool usage and material handling for repair or replacement activities
- Silt and sediment mapping for condition monitoring and trending

For autonomous use in physical maintenance of structure surfaces, a robot would need to be able to evaluate whether an action (e.g., abrasive act to remove marine growth) would damage an area (e.g., if the area shows signs of erosion) or whether an alternative action should be used.

Capabilities developed for this use case may translate to other activities including inspection of other underwater valves and pumps, cooling tower basins, refueling cavities, spent fuel pools, and condensate tanks.

Table 3. Inspect and Maintain Cooling Water Intake and Discharge Structures

Task Frequency	Inspection frequency may be between every year and every five years. Frequency is typically dependent on the observed condition of the structure over time.
Labor Hours	An analysis of EPRI's work order database indicates between 50 and 1,500 man hours are spent on this use case per unit per year and that the spread of this range is driven primarily by water quality.
Benefits	Cost: • Reduction in dive team costs. • Reduction in labor costs. Time: • Reduction in time to gather inspection data. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. • Reduction in time to navigate underwater since alternate methods of informing navigation are possible (e.g., using sonar in low visibility conditions). Safety: • Reduction in personnel exposure to industrial risks, including confined spaces and being underwater. Quality: • Images can be obtained using high-definition cameras, and a detailed visual record of the condition of the structure can be stored and referenced for trending purposes. • Increased confidence in system health by allowing for the inspection of previously inaccessible areas. Flexibility: • Reduced planning and administrative time allowing for expedited response to emergent issues. This benefit may not be realized if implementation of submersible platforms is contracted through a vendor.
Key Considerations and Needs	General: • Designed for use underwater in fresh, salt, or brackish water. • Sustained operation for the time necessary to perform the activity. • Size and agility that are comparable with accessing all locations of interest. • Able to navigate underwater in poor visibility conditions (for example, by using sonar). Inspection: • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and baseline state to be flagged. • Able to detect corrosion and map silt and sediment accumulation. • Able to illuminate the intended surface when necessary. Maintenance: • Can clean marine growth from the structure surface efficiently. • Employs feedback mechanisms to prevent damage to a surface. • Able to transport foreign objects. • Able to wield hand and power tools (or replicate their function). • May need to cut or weld material.

Inspect and Maintain Isophase Bus Duct

The isophase bus system in nuclear power plants transfers power between the generator and transformers, providing an important function for power distribution. Failures of the system, although infrequent, can have significant consequences for the connected equipment and may result in a forced outage, at significant cost to the plant. Inspections of the bus duct typically look for loose hardware, cracking in welds, breakdown of insulation, localized heating, dirt or dust buildup, foreign objects and water intrusion, and signs of arcing. This inspection is currently performed using scaffolding built along the length of the duct to allow personnel to enter it using numerous inspection hatches. Using a robot to perform the inspection would result in reduced cost, time, and risk (including personnel safety hazards) due to a reduction in scaffolding to locations that need further maintenance. It would further have the potential to reduce or eliminate the need to send personnel inside.

The interviewed utilities reported that robots are only used for inspection activities and are operated remotely by trained personnel. Visual inspection footage is reviewed manually. Greater economic benefit may be realized through development of autonomous navigation and automated data processing and management.

Additional capabilities that would be useful to support maintenance of the isophase bus system include [6]:

- Testing resistances of insulators and joints
- Removing hardware covers
- Checking hardware torque and replacing damaged or missing hardware
- Cleaning dust, debris, moisture, and insulators
- Removing foreign objects

For this use case, utilities noted that a small footprint, profile, and low mass may be valuable characteristics for a robotic platform. The reduced size would allow the robot to be maneuvered more effectively in the confined space while the reduced mass would decrease the load of the robot on the duct. Additionally, since this system is typically outdoors, the robot should be designed for an environment containing dust, debris, and moisture. To achieve the run time necessary to perform the inspection without needing to be recharged, current robotic platforms are tethered. This increases the risk that the robot may get tangled. Thus, an advantageous improvement would be the capability to operate for the duration of the inspection without an umbilical power source.

Table 4. Inspect and Maintain Isophase Bus Duct

Task Frequency	Typically, isophase bus duct inspections are performed every 10 years.
Labor Hours	An analysis of EPRI's work order database indicates between 50 and 1,500 man hours are spent on this use case per unit per year and that the spread of this range is driven primarily by water quality.
Benefits	Cost: • Reduction in labor costs. • Reduction in scaffolding costs. Time: • Reduction in time to inspect the duct. • Reduction in time to set up, certify, and breakdown scaffolding. • Reduction in number of access points required. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in personnel exposure to industrial risks, including elevated heights and confined spaces. • Reduction in risk of damaging the duct by reducing personnel entry. Quality: • Images can be obtained using high-definition cameras, and a detailed visual record of the duct condition can be stored and referenced for trending purposes. • Flexibility • Increased scheduling flexibility by reducing the need to coordinate between various personnel providing support for work in confined spaces.
Key Considerations and Needs	General: • Can operate continuously in an environment with significant dust, dirt, debris, and moisture for 2+ hours. • Is able to efficiently maneuver within the duct. • Can travel the distance of the duct. • Size and agility that are compatible with accessing all locations of interest. Inspection: • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and base-line state to be flagged. • Can illuminate the intended surface when necessary. • Can detect moisture and surface damage. Maintenance: • Able to wield hand tools (or replicate their function). • Validates torque requirements. • Able to transport foreign objects. • Able to clean duct surfaces and employs feedback mechanisms to prevent damage to the surface. • Able to test resistances.

Survey to Develop and Maintain a 3D Radiation Map

Protecting personnel in NPPs from radiation requires a baseline understanding of levels of radiation throughout the plant, as well as the ability to evaluate emergent conditions. Radiation levels must be evaluated prior to and while performing work in certain areas of the plant. Using a robot to perform many of these functions enables gathering data on radiation levels without necessitating personnel exposure while increasing flexibility with respect to scheduling and resource management [7]. Ultimately, the robot and associated software could autonomously perform certain monitoring activities and produce a 3-dimensional radiation map to support other plant activities.

To perform the functions of this task, a robot should be able to measure radiation level, surface contamination, and airborne reactivity data [8]. Robots currently deployed in NPPs for this use case require a dedicated operator to manually direct the robot to the area of interest or assign waypoints and have had challenges in maneuvering into all locations of interest [9,10]. Reporting of the data requires detailed human review, creating a burden to manage the quantity of data that is produced by a surveying effort. To realize greater economic benefit, robots developed for this task should be able to:

- Autonomously avoid obstacles, given that the task may be performed in environments with high levels of human traffic and near sensitive or safety-related equipment
- Automate the population of data into an easy-to-use interface
- Transmit data in real-time while in-containment (i.e., while surrounded by thick concrete and steel) or store data onboard
- Collect samples to support leak tests of radioactive sources

The robot should be able to interface with existing methods at the plant currently used for monitoring radiation and contamination. This capability will allow the robot to build onto the existing infrastructure. To enable real time data transfer, it may be desirable for the robot to transmit a signal across containment boundaries. Similar to the use case for inspecting component supports, a robot for this use case would also have to be able to navigate complex spaces without interfering with other equipment, which requires robust obstacle avoidance and a compatible physical design (size, agility). One utility suggested that a drone with a diameter of less than 10" would be helpful to avoid obstacles typically found in containment.

This use case has potential applicability for other land-based or aerial use inspection and data collection tasks, as a robot may be able to collect radiation data while performing a different activity.

Table 5. Survey to Develop and Maintain a 3D Radiation Map

Task Frequency	Baseline survey typically performed every 10 years. Measuring radiation levels in specific locations is required more frequently.
Labor Hours	EPRI's work order database reports approximately 250–750 man hours are spent performing emergent work for this use case per unit per year. Collecting baseline measurements requires additional time.
Benefits	Cost: • Reduction in labor costs. • Reduction in scaffolding costs. Time: • Reduction in time to gather and process data through automation. • Reduction from time to set up, certify, and breakdown scaffolding. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in dose to personnel (e.g., eliminating the need to have a person survey for radiation levels in containment). Quality: • A 3D map of radiation levels may be developed and maintained in addition to the discrete measurements traditionally taken. Flexibility: • Increased scheduling flexibility among personnel by reducing the need to coordinate between maintenance and health physics.
Key Considerations and Needs	General: • Radiation hardened equipment and materials. • Ability to operate for a duration appropriate for the specific task. • Can navigate to all relevant areas, including those only accessible by stairs and ladders. • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. • Robust obstacle avoidance. • Size and agility that are compatible with accessing all locations of interest in containment. Inspection: • Autonomous data processing to populate a map with radiation levels. • Compatible with existing methods for radiation surveys. Maintenance: • Able to collect samples.

Survey to Detect Leaks in Containment

Leaks in NPP fluid systems can have a variety of consequences, including impacts to plant performance (e.g., reducing thermal efficiency or ability of a cooling system to perform its function) and effort required to control radiological material (if the leak is contaminated). Traditional methods of identifying a leak in containment may require down powering or necessitate increased risk to personnel safety due to high temperatures, elevated heights, and/or exposure to radiological hazards. During interviews, utilities shared that the use of an aerial or land-based robot to quickly access the area of interest, locate the leak, and gather data (e.g., visual or thermographic data) needed to disposition suspected leaks enables them to assess the circumstances without personnel exposure to radiological and industrial hazards and more promptly inform operations and maintenance decisions.

Robots have already been used to locate and verify suspected leaks but require significant human effort for direction and gathering the desired information [9]. Through automation, this task may be performed to greater economic benefit. Examples of autonomous capabilities discussed by utilities that are relevant to this use case include:

- Real-time reporting and data processing such that data (e.g., visual or thermal) can be rapidly interpreted by a remote human counterpart
- Autonomous navigation in containment, including stairs and ladders
- Robust obstacle avoidance

Autonomous operation would simplify usage of the robot and allow for more flexibility in distributing site resources. To evaluate areas of particular interest, including valves, pumps, welds, expansion joints, and sleeves, a robot should be able to navigate crowded spaces with obstacles. Additionally, the robot must be capable of working near sources of contamination and high heat (e.g., at the condenser bay ceiling). For real time data transfer, the robot may benefit from being able to transmit signal across containment boundaries.

In the future, a robot that can perform basic repair activities or replace components would expand options for supporting maintenance activities. This may include developing capabilities of the robot to operate valves, wield hand tools, inject sealant, cut pipe, and weld overlays and patches [11]. Such capabilities would further improve reduction in personnel exposure to radiation and industrial hazards. Similar to the previous use case, a robot for this use case would also have to be able to navigate complex spaces without interfering with other equipment, which requires robust obstacle avoidance and a compatible physical design (size, agility). It is beneficial to reiterate that a drone with a diameter of less than 10” would be helpful to avoid obstacles typically found in containment.

It is noted that development of the technology for this use case is also relevant for other applications, such as monitoring for leakage containing boric acid. For this application, a hyperspectral camera may be used instead of a temperature or moisture sensor [12].

Table 6. Survey to Detect Leaks in Containment

Task Frequency	Emergent issues can occur at any time and are expected to increase in frequency as a plant ages. One plant with decades of operation reported that leaks requiring investigation have occurred several times in the span of three to four years.
Labor Hours	According to EPRI's work order database, approximately 50 man-hours are spent on this use case per unit per year.
Benefits	Cost: • Reduction in labor costs. • Reduction in scaffolding costs. • Potential to decrease down-time by collecting data and assessing condition while online. Time: • Reduction in time to gather and process data through automation. • Reduction from time to set up, certify, and breakdown scaffolding. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduces personnel exposure to radiation and industrial risks, including elevated heights and high temperatures. Quality: • A 3D map of typical operating temperatures near components may be developed and maintained to enable quick evaluations against an expected state. Flexibility: • Increased scheduling flexibility among personnel by reducing the need to coordinate between maintenance and health physics. • May allow issues to be identified and planned for before an outage, which would improve scheduling.
Key Considerations and Needs	General: • Designed for exposure to radiation, moisture, and high temperatures. One utility recommended the robot be operational up to 300°F since many steam leaks can increase the surrounding temperature. • Logical decision making so upon detection, robot will signal operators • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. • Robust obstacle avoidance. • Size and agility that are compatible with accessing all locations of interest in containment. Inspection: • Able to detect and measure leaks (e.g., through temperature sensors or visual monitoring). • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and baseline state to be flagged. Maintenance: • Able to wield hand tools, cut and weld material, and collect samples.

Inspect and Maintain Reactor Head Studs and Stud Holes

During operation of the reactor pressure vessel, the studs which secure the reactor vessel head to the vessel are subject to high temperatures, pressure, and load which may cause them to seize. One way this risk is mitigated is through the application of nuclear grade anti-seize lubrication, which reduces maintenance down time and replacement costs. During each refueling outage the studs are cleaned, examined, and re-lubricated, and the stud hole is cleaned of excess lubricant. These activities are typically performed manually using a variety of hand tools (i.e., a brushed tool that can be rotated inside the stud hole), requiring several personnel to work in close proximity to the reactor vessel. The cleaning of excess lubricant from the stud holes is typically performed after the fuel moves have taken place to limit impact on other refueling activities. Further, stud elongation is measured before and after tensioning using depth micrometers, which involves manually inserting the tool into the stud. These activities in close proximity to the reactor vessel incur significant radiation exposure to personnel [13].

Increased automation for this process may result in significant dose savings to personnel, and automation of stud hole cleaning may allow for the activity to be performed in parallel with fuel moves. A robot intended to clean stud holes has been researched and prototyped in limited capacity [14]. If commercialized options were to be made widely available, time to perform the stud hole cleaning and the associated radiological hazards may be decreased.

Further benefit for utilities may be gained through the introduction of robotics, remote operation, and/or increased automation of current robotic technology in the following ways, which were identified through discussions with an SME:

- Automation of the process to position and secure the tensioning device to the studs
- Remote operation of the tensioning device
- Automated measurement of stud elongation

Robotic solutions for these activities could be approached through adding new functionality to existing technology or developing a new robot. Further options for automation may include allowing for some or all other stud maintenance activities to be performed without human input (i.e., develop a robot to clean, gather inspection data, and reapply lubrication on the studs).

Table 7. Inspect and Maintain Reactor Head Studs and Stud Holes

Task Frequency	Approximately each outage.
Labor Hours	Analysis of EPRI's work order database indicates this use case requires approximately 150+ man-hours per outage.
Benefits	Cost: • Reduction in labor costs. Time: • Reduction in time to position and secure the equipment. • Reduction in time to measure and report stud elongation data. • Reduction in calendar time to perform stud hole cleaning, particularly if it is performed in parallel with other maintenance activities. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in personnel exposure to radiological hazards and industrial risks, including operator fatigue from moving heavy objects and operating hand tools. Quality: • Images can be obtained using high-definition cameras, and a detailed visual record of the condition of the stud can be stored and referenced for trending purposes. • May increase consistency in taking stud elongation measurements.
Key Considerations and Needs	General: • Radiation hardened equipment and materials. • Has protections to keep it from introducing damage to the stud, stud hole, or reactor surface. • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. Inspection: • Can take measurements of stud elongation. • Able to detect cracking on studs or in stud holes. • Can illuminate the intended surface when necessary. Maintenance: • Able to wield hand tools (or replicate their function). • Can apply and remove anti-seize lubricant. • Can determine when excess lubricant has been sufficiently removed. • Can determine when a stud has been sufficiently coated in lubricant.

Inspect Water Storage Tanks

As storage tanks age, their condition (sediment buildup, corrosion, leaks, welds) must be managed to ensure the tank is able to perform its intended function of supplying water to the plant and does not pose a risk to the associated downstream systems or environment. The interior of an above-ground tank is typically inspected manually using sensors to monitor inaccessible areas, allowing for material loss on the bottom of the tank to be detected through measurements of wall thickness [15]. The inspection is typically performed by sending in a diver, which introduces risks related to diving in confined spaces and potentially diving in contaminated water. Alternatively, a manned inspection can be performed by taking the tank offline and draining it, restricting its ability to support operation in the event it is needed [16].

Performing interior storage tank inspections using robots saves cost and time, eliminates a personnel safety hazard (diving), and can allow for inspections to be performed while the tank remains in service to inform whether further actions are necessary. Additionally, using a robot affords the opportunity to gather more detailed data since it can be equipped with higher resolution cameras, improving data quality. Additional capabilities for increased economic benefit include the ability to autonomously navigate, analyze data, and report findings. More specifically, developing software that is able to identify abnormal conditions from the data gathered would allow plant personnel to focus on areas of importance. Currently, robots are remotely operated and can support inspections and sample collection, but capabilities could be expanded to include cleaning activities. One such activity would be to clean microbial growth, silt, and sediment from the tank [17].

A robot intended for use in water storage tanks would need to be able to operate in a submerged environment. For activities performed in contaminated water, such as inspections of condensate tanks in BWRs, robotic platforms would need to be radiation hardened. Robots used in contaminated water would likely be limited to further usage only in other contaminated environments.

Technology developed for this use case would be relevant for inspection of refueling water storage tanks, fire water storage tanks, safety injection tanks, and potentially other applications than water storage tanks such as spent fuel pools, diesel fuel oil tanks, and cooling tower basins [15].

Table 8. Inspect Water Storage Tanks

Task Frequency	Full inspections are typically performed during each 10-year period starting with the ten years prior to entering a period of extended operation [15].
Labor Hours	An analysis of EPRI's work order database indicates between 50 and 500 man-hours per unit per year are spent inspecting condensate water storage tanks.
Benefits	Cost: • Reduction in dive team costs. • Reduction in labor costs. Time: • Potential to eliminate the need to drain and fill the tank. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. • Reduction in time to navigate underwater since alternate methods of informing navigation are possible (e.g., using sonar in low visibility conditions). Safety: • Reduction in personnel exposure to industrial risks, including diving or working in a confined space. • Reduction in dose when water is contaminated. Quality: • Images can be obtained using high-definition cameras, and a detailed visual record of the condition of the structure can be stored and referenced for trending purposes. Flexibility: • Potential to increase tank availability. • Increased scheduling flexibility by reducing the need to coordinate between various personnel providing support for work in confined spaces.
Key Considerations and Needs	General: • Can fit through the tank manway. • May require radiation hardened equipment and materials. • Can perform the desired tasks underwater at the operating temperature of the tank. • Able to navigate underwater in poor visibility conditions (for example, by using sonar). Inspection: • Autonomous data processing either onboard or removed from the robot to allow for differences between the current and baseline state to be flagged. • Able to detect wall thinning. • Can illuminate the intended surface when necessary. Maintenance: • Can clean microbial growth without damage to the tank surface efficiently. • Able to transport foreign material.

Load Dry Fuel Casks with Spent Fuel

Dry fuel casks are used to store spent fuel after several years of radioactive decay in a spent fuel pool. However, the loading of dry fuel casks requires significant exposure of personnel to industrial and radiological hazards. First, the cask is loaded with spent fuel while in the spent fuel pool and the lid is placed on top. Then, it typically needs to be decontaminated, welded and/or bolted, drained, dried, and backfilled with an inert gas for it to be safely stored. Additional activities that are required include pressure and leak tests, gas purity sample collection and testing, as well as a full volumetric examination, surface examination, and either a hydrostatic or pneumatic test of welds when applicable [18].

Currently, this process requires significant human input and involves direct and/or remote operation of a variety of equipment (e.g., lifting yokes, transporter equipment, welding and cutting equipment, and vacuum drying equipment) [18]. Because this task typically requires multiple personnel to be at or near the cask and is highly structured, it may be advantageous for utilities to use automated robotic solutions. Using a robot instead of plant personnel would reduce personnel exposure to radiological and industrial hazards, improve efficiency, and decrease man-hours required.

There are some existing robotic solutions for the specific activities that comprise this use case. For example, multiple robotic technologies exist for welding dry casks shut, including both fixed and portable robotic welding systems [19, 20]. Robots designed to weld dry casks shut have demonstrated increased industrial safety and reduced radiation dose to workers [20]. Robots have also been used to perform visual, ultrasonic, and many other inspection activities for dry casks [21].

Capabilities of interest for expanded autonomous execution of the overall task activities include:

- Remote and/or automated operation of all equipment used in-containment (e.g., to move fuel assemblies into the cask and to place the lid)
- Autonomous positioning and securing of equipment
- Automating rinsing of the cask before loading and decontamination of the cask after it has been loaded (technique is selected based on cask, contamination level, and waste processing capabilities)
- Increased automation for cask draining and drying activities (i.e., robot to monitor during drying to ensure ice does not form)
- Autonomous bolting and welding of the cask

Robotic automation for this use case will likely require both increased automation and remote operation capabilities in existing equipment as well as the development of current/new robots. Technology developed for decontamination activities for this use case may be useful for decontaminating equipment pits and reactor cavity pools during fuel moves as well.

Table 9. Load Dry Fuel Casks with Spent Fuel

Task Frequency	Loading campaign frequency depends on site specific factors including the number of units at a site and the amount of fuel in the spent fuel pool. While performed infrequently, each campaign scope typically covers the loading of multiple casks in series [22].
Calendar Time	Approximately one week to load each cask
Benefits	Cost: • Reduction in labor costs. Time: • Automation of equipment positioning and securing may decrease calendar time required to load the cask. • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. Safety: • Reduction in personnel exposure to radiological hazards and industrial risks, (e.g., hazards associated with working on bridges above the spent fuel pool). Quality: • May increase consistency of repeated tasks and reduces the impact of shift change for different workers performing those tasks.
Key Considerations and Needs	General: • Radiation hardened equipment and materials. • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. Inspection: • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and base-line state to be flagged. • Can overcome glare when collecting gauge readings. Maintenance: • Able to wield hand tools (or replicate their function). • May need to cut or weld material.

Support Operator Rounds

Operator rounds are conducted to monitor plant systems and components and identify conditions that could affect plant operations. They include numerous activities such as inspecting the status of components, recording different parameters from analog gauges, and communicating when observed conditions do not meet the expected state. Currently, operator rounds activities are performed manually by personnel. Robots offer an alternative approach for supporting certain tasks that require visual (e.g., checking a sight gauge) and physical actions (e.g., opening a valve to check for moisture). Using a robot to perform operator round activities would provide a safety benefit by reducing exposure to industrial and radiation hazards. Furthermore, usage of a robot would provide greater availability of plant resources, allowing personnel to focus on complex activities that require judgment and creativity and/or fine motor skills, and would allow for more extensive data collection since detailed visual data could be recorded for all activities.

Several utilities reported efforts to identify and evaluate the capabilities and limitations of multipurpose robots for performing this task. These efforts are in progress, as no utilities reported using robots to perform activities that support operator rounds autonomously. Additionally, utilities have expressed that developments in simple mechanics will be important to enable the robot to perform the activities (e.g., to check a light on a control panel, the robot would need to be able to open the cabinet that contains the panel).

To support operator activities, utilities are interested in expanding robotic capabilities to include:

- Operation of ball and butterfly valves
- Operation of breakers
- Opening control cabinets and panels
- Autonomous navigation
- Autonomous processing of visual data to identify abnormalities to operators
- The ability to overcome glare on the face of a gauge or poor lighting conditions

It may also be beneficial for compatible software to be developed that can automate condition reports and work orders based on sensor input from the robot. In addition, designing the robot to support year-round operation in a variety of geographical locations and environmental conditions would allow for consistency and sharing of resources across sites.

This use case would benefit plants that are planned to be built or approaching decommissioning since robots can be incorporated to allow a plant to operate with less on-site support.

Table 10. Support Operator Rounds

Task Frequency	Operator rounds occur approximately daily. Specific activities (e.g., valve operation) are performed on an as-needed basis.
Labor Hours	EPRI work order database analysis indicates roughly 1400 hours are spent performing this task per unit per year which is approximately 4 hours per unit per day. One utility estimated that 20-30 man-hours were required daily for their multi-unit site.
Benefits	Cost: • Reduction in labor costs. • May reduce maintenance cost by allowing for more information to be gathered, informing condition-based maintenance. Time: • Reduction in time to gather and process data through automation. • Automating work orders and condition reports may result in a reduction in administrative time to complete the activities and more promptly inform maintenance activities. Safety: • Reduction in personnel exposure to industrial hazards associated with plant entry. Quality: • May increase consistency by reducing the impact of having different people perform the same task. • A detailed visual record of the condition of equipment and instrumentation can be stored and referenced for trending purposes. Flexibility: • Greater availability of site resources by automating routine activities.
Key Considerations and Needs	General: • Battery life of 2+ hours and autonomous charging capabilities. • Robust obstacle avoidance as the robot may be operating in well-traveled areas. • Can navigate to all relevant areas, including those only accessible by pressurized doors, stairs, and/or ladders. • Can navigate changes in path width (i.e., sharp corner where path goes from narrow to wide or wide to narrow). • Autonomous data processing (either local to the robot, or remotely) to allow for differences between current and baseline state to be flagged. • Can fill out and submit work orders as issues are identified. Inspection: • Can overcome glare when taking readings visually. • Can visually detect objects that are similar to their background (i.e., light on light or dark on dark). • Can detect moisture in valves. Maintenance: • Able to wield hand tools, operate a variety of valves, replace filters, remove covers, and open cabinets and panels.

Support Fire Protection Activities

Protecting personnel, resources, and equipment from fire encompasses a wide variety of monitoring and maintenance activities at NPPs and are a source of significant labor hour consumption to utilities. Currently, most of these functions are manually accomplished by personnel on-site. Activities include checking that exit paths are free of objects, fire doors are closed, and various pieces of support equipment are in good condition including seals that separate fire compartments, emergency lighting, alarms, fire detectors, fire sprinklers, standpipes, and hoses [23]. Additional responsibilities include surveillance during hot work (e.g., welding or flame cutting) or of vulnerable equipment (e.g., large batteries) when fire protection systems are unable to perform their functions [24]. Utilities are interested in using robots to support these activities to improve safety by reducing the need to send personnel into unknown situations and reduce resource needs for fire watch surveillance. This would provide utilities greater flexibility in allocating plant resources to other tasks.

During interviews, utilities shared that their focus is on investigating the limits of general-purpose robots to perform supporting activities including inspection and surveillance (rather than firefighting, as has been investigated in other industries).

To support these efforts, utilities are interested in developing capabilities including:

- Autonomous navigation
- Inspecting and monitoring boundaries, areas, and components that have been identified as being at an elevated risk level
- Operating pressurized doors to verify whether they are closed
- Verifying sensor readings (e.g., smoke detector or carbon monoxide alarm)
- Supplying oxygen tanks to first responders

Table 11. Support Fire Protection Activities

Task Frequency	Some surveillance activities may be continuous. Inspections may be performed with a variety of frequencies, including, weekly, monthly, quarterly, annually, or greater than annually [24].
Labor Hours	An analysis of EPRI's work order database indicates that the time required for fire watch activities varies significantly but may be between 500 and 1,500 man-hours per unit per year.
Benefits	Cost: • Reduction in labor costs. Time: • Reduction in administrative time to manage surveillance work in hazardous environments or for dangerous activities (e.g., hot work). Safety: • Reduction in hazards from entering unknown conditions by sending in a robot to gather information and verify sensor readings prior to personnel entry. • Reduction in personnel exposure to industrial risks associated with hot work. Quality: • Increased consistency in verification activities due to reduced risk of operator fatigue and reduced impact from shift change for surveillance activities. • Flexibility: • Increased availability of site resources to respond to emergent conditions by automating surveillance activities.
Key Considerations and Needs	General: • Battery life of 2+ hours and autonomous charging capabilities • Robust obstacle avoidance as the robot may be operating in well-traveled areas. • Able to verify whether a door has been closed. • Can navigate to all relevant areas, including those only accessible by pressurized doors, stairs, and ladders. • On-board lighting for use in emergencies. • Autonomous data processing (either local to the robot, or remotely) to allow for differences between the current and baseline state to be flagged. • Can navigate in poor visibility conditions. • Can transfer data in real time while in low signal areas. Inspection: • Able to detect flashpoints before ignition (e.g., using thermal imaging). • Able to detect smoke. Maintenance: • Able to transport and use fire extinguishers.

Inspect and Repair Steam Generator Tubing

Steam generator tubing serves as the boundary between primary and secondary coolant systems in PWRs. To ensure tube integrity, the tubes are regularly inspected for cracking, denting, wear, thinning, pitting, and foreign object intrusion. Additionally, water chemistry and leaks are monitored and tube plugging and repairs are performed [25]. Work performed near the steam generator involves significant radiation exposure. For this reason, robotics currently play a major role in steam generator tube maintenance activities. The robots used for this activity can be classified as either manipulators or tube crawlers. Manipulators are mounted to the steam generator manway, and tube crawlers are mounted directly to the tubesheet [26]. Both types may offer a variety of capabilities, including eddy current, ultrasonic, pressure, and/or profilometry testing; tube plugging and plug removal; tube extraction; sleeving of tubes; and tube stabilization [27].

Recent advances in probe technology to reduce the number of probes required for the inspection have allowed for a reduction in personnel exposure to radiation, preparation and inspection time, and the amount of waste generated [28]. Further development of robots could support additional dose reduction for personnel supporting the inspection. Potential autonomous capabilities to develop include:

- Swapping out probes or attachments autonomously (i.e., switching from a bobbin probe to a supplemental probe for transition region inspections)
- Autonomous calibration to ensure accuracy when positioning probes inside the steam generator

One utility identified the tubesheet transition region as a source of significant challenge for traditional means of inspection. Through the recent advances in probe technology in addition to the automation of changing between standard and supplemental probes discussed above, the burden of inspection for this region may be decreased.

Table 12. Inspect and Repair Steam Generator Tubing

Task Frequency	Inspection may be performed as frequently as every outage or as infrequently as every other outage. Inspection of all tubes is required at a maximum of every 60 months of operation [30].
Labor Hours	Using data from EPRI's work order database, labor hours required are approximately 50 man-hours for steam generator tubing inspection with existing technology
Benefits	Time: • Reduction in preparation, administrative, and oversight time for managing manned access to hazardous spaces. • Reduction in time to change probes through automation Safety: • Reduction in dose from automating probe changes and calibration. Quality: • Increased consistency in positioning through automated calibration.
Key Considerations and Needs	General: • Radiation hardened equipment and materials. • Can fit through steam generator manway. • Can position probes and map data to locations accurately. • Does not require personnel to be in the immediate surroundings during the inspection. • Can transfer data in real time in low signal areas (i.e., in containment) or store data onboard. Inspection: • Can detect flaw with the depth necessary. • Can change probes without human assistance. Inspection: • Able to plug, unplug, and extract tubes. • May need to cut or weld material.

Conclusions and Future Work

There are a variety of early stage automating technologies currently undergoing ad hoc adoption by utilities around the world. Commonly these take the form of sensors, drones, robotics, and submersibles. While all of these technologies have the potential capacity to support automation of operation and maintenance tasks at nuclear power plants, they are being applied as remote technologies, operated by trained staff due to technical, regulatory, and safety reasons.

Early adoption of these technologies for remote task execution has created economic, risk reduction, and scheduling value while typically improving the quality of data generated. Further adoption with the goal of automation, however, is unlikely at the current technologic maturity of several of these platforms.

While not every end-user applies these technologies the same way, their needs greatly overlap. Of these, some of the most prominent areas in need of research include:

- Improved machine vision and onboard analysis for image difference recognition
- Improved battery life to support longer or multiple shorter tasks on a single charge
- Improved autonomous navigation capabilities to support missions around safety related equipment
- Improved manipulators and haptic response to support missions requiring human-like dexterity or the use of tools
- Improved radiation hardening of sensitive equipment to support missions in containment

Many of these areas are actively undergoing development, both by robotic platform developers and by authorized third-party vendors. While the maturation of proprietary robotic technology is beyond the scope of EPRI's mission, we have work underway to support several of these objectives. Among them is the application of the Digital Assistant app developed by EPRI to assist in the collection of degradation images. These images will be analyzed with the goal of creating and training artificial intelligence models to recognize degradation modes.

There is demonstrated value in the near-term adoption of remote inspection technologies that can help build capability with platforms as they mature towards the remote execution and eventual automation of operation and maintenance tasks for nuclear power plants.

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