Robotic Demonstrations Conducted at DOE Portsmouth Facility

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Abstract: The U.S. Department of Energy's (DOE) next major decommissioning project is at its Portsmouth Facility in Piketon, Ohio. This plant was one of three large gaseous diffusion plants in the United States that was initially constructed to produce enriched uranium, a source used by commercial nuclear reactors from all around the world. The DOE Science of Safety (SOS) program is chartered with the smart infusion and integration of scientific and technological advancements into the routines of workers to enhance worker health and safety and to reduce the federal government's liability of its nuclear legacy cleanup. The specific purpose for the SOS Robotics Challenge in 2016 at the Portsmouth Gaseous Diffusion Plant was to have workers and operators demonstrate EM-Mission relevant, novel, adequately mature, robotic and related enabling technologies onsite and to increase awareness and garner support of EM stakeholders, appropriators, and Congress on opportunities of mission-relevant robotic technologies.

In August of 2016, we conducted a week of demonstrations at Portsmouth with a goal of connecting the user community with a wide range of robots/robot technologies, and earn the support of the many stakeholders involved. This demonstration was able to showcase the selected technologies in a realistic environment. The twelve demonstrations were used to train future operators, and thus gaining valuable lessons learned. The knowledge and information gathered that week enabled future planning and development, leading to improved operations for upcoming DOE tasks. Each demonstration was evaluated to understand its known risks using the DOE Technology Readiness Levels. And the range of different types of demonstrations were very broad and representative of robotic technologies in general. Some demonstrations would require further development while demonstrations that featured inspection tasks with a teleoperated platform performed very well, as expected based on the maturity of these types of robots. The technology was primarily off the shelf from leading universities from around the country.

At DOE, robots as *tools* to be used by *trained* operators to do their jobs better, safer, and more efficiently. The users were representative of the local steel workers union whose future job is the decontamination and decommissioning (D&D) of the Portsmouth site. The common issues with robots in a nuclear environment are communication (whether tethered versus wireless), and command and control with respect to human operators (referred to this as teleoperation, and is one end of a continuous spectrum up to robot systems that are automatic and autonomous). In this paper, we expand on each of the twelve demonstrations, and relate them to the needs of the Portsmouth site. This technology represented a baseline of general robotic capabilities that would feed into a technology roadmap that is currently in development at DOE.

Keyword: Robotics, Remote Operations, Technology Testbeds

1 Introduction

The goal of the Portsmouth Robotic demonstrations, held in August of 2016, was to connect the user community with a wide range of robots/robot technologies and to earn the support of the many stakeholders involved. This demonstration showcased the technologies in a realistic decontamination and decommissioning (D&D) environment. The twelve individual demonstrations were used to train future operators; thus gaining valuable lessons learned. The knowledge and information that was gathered during the Portsmouth demonstrations will enable future planning and development, leading to operations for upcoming U.S. Department of Energy (DOE) tasks.

2 Goals

The purpose for this Science of Safety Robotics Challenge at the Portsmouth Gaseous Diffusion Plant (GDP) is to:

- Have workers and operators demonstrate EM-Mission relevant, novel, adequately mature, robotic and related enabling technologies onsite.
- Increase awareness and garner support of Environmental Management (EM) stakeholders, appropriators, and Congress on opportunities of mission-relevant robotic technologies.

EM Science of Safety (SOS) is the smart infusion and integration of scientific and technological advancements into the routines of work planning and execution for the benefit of enhancing worker health and safety, and reducing federal liability of nuclear legacy cleanup. Currently, robotics and semi-autonomous systems are needed for remote access in nuclear, chemical, and other high-hazard facilities in EM that are inaccessible, restricted to human entry by size and configuration, or otherwise preclude the safe and direct entry by human workers. Federal interagency, university, and private industry collaborations with DOE implement several of the recommendations provided by the Oct 2014 Secretary of Energy Advisory Board Task Force Report on EM Technical Directive (TD). These initiatives/projects also support the National Robotics Initiative, which was chartered by the President to accelerate the development and use of robots in the U.S.

3 Demonstrations

The participants for the Portsmouth Demonstration were a combination of leading robotic researchers from academia and from several of the DOE national laboratories. There were twelve separate and distinct demonstrations selected. The maturity of each technology demonstrated (based on DOE TRL levels) varied, and the breadth of the technologies was wide ranging. This was done on purpose, in order to evaluate the applicability and suitability of each technology. This early testing was done to put the technology into the hands of the user, gathering feedback for those that are ready for early insertion, and for selected technologies needing further development.

3.1 Twelve Demonstrations

The DOE EM Technology Development Office solicited potential nuclear robotic demonstrations from academia for the purpose of informing the DOE workforce of new technologies, and of potential opportunities to deploy those technologies as they become mature to address some or all of EM challenges. Here is a summary of those twelve demonstrations[1].

3.1.1 Machine Learning Pipe Crawler

Visual inspection of multiple long piping runs (hundreds of feet each) in Portsmouth nuclear facilities is needed to gather data to make Criticality Incredible (CI) determinations, with the goal of achieving nuclear facility Cold & Dark status prior to demolition operations. Visual inspection requires slow and meticulous attention from human workers over miles and miles of piping.

The demonstration was the inspection of the inside of a pipe or circular structure, typical of those found at DOE sites. A small mobile robot was driven inside a horizontal culvert structure, taking photos as it traveled along the pipe. A commercial, 360 degree camera was mounted on a forward extension pole and the robot was controlled by a simple remote controller as shown in Figure 1a. This robot had no other sensors, such as the typical Inertial Navigation System, to localize itself for dead-reckoning purposes. The imagery and machine learning capability was not shown directly, since it was to be saved to memory or could be transmitted back to the operator for post-processing. The demonstrators discussed how a neural network could be used to determine areas of concern inside a pipe.

Fig. 1 Machine Learning & Prosthetic Limbs

3.1.2 Modular Prosthetic Limbs

There are many tasks and DOE areas that would benefit from removing human workers out of the radiation environment and replace those workers with human surrogates such as robots with arms. And there are many instances that require a dual-arm manipulation capability, and will also have some form of mobility to get to those hard to reach places.

This system in Figure 1b, known as Robo Sally, is an articulated human-like surrogate 'armed' with current prototype manipulators from the Revolutionizing Prosthetics Program, an APL-led effort to create a prosthetic arm for DARPA that looks, feels, and operates like a human limb. Sally is a robot designed with human-sized arms and fingers that are so agile, they can be used to perform any task a human would do. Both arms can be rotated at the shoulders, elbows, and wrists, and they end in two fully dexterous hands. However, all of this control is designed to permit the effective use of Sally's most important tool, the prosthetic arms in a master-slave control mode.

3.1.3 Virtual Reality Immersive Teleoperation

Immersive teleoperation in simulation can support multiple aspects of the DOE-EM mission. When planning a complex step in a D&D process for a given facility such as Portsmouth, the facility can be modeled in simulation (Figure 2a), as can the robots and tools to be used. Then one can ask "what if'" questions, by exploring different sequences and techniques for achieving the task. Simulation also allows for comparing and contrasting the characteristics of different candidate vehicles and tools. It is far more cost-effective to test a new vehicle in software simulation than testing in the real world. Finally, with the vehicles, tools, and approved plan, the simulation can be used as a training tool for operators. For all of these use cases, the key to effective teleoperation is that it be immersive for the operator, which requires high-fidelity visualization.

Platforms and tools used in industrial workplaces continue to advance in sophistication and capability. In many respects, the tools are essentially becoming robots with significant on-board control and autonomy to assist the operator. While there are many narrowly-focused simulation tools for various vehicles and industrial equipment, a general-purpose robot simulator offers many compelling advantages. Specifically, Gazebo simulation provides a novel capability in that: (1) it is flexible enough to model a wide range of systems, from articulated arms to mobile robots to drones; (2) it allows for the addition of sensors, control loops, and thus autonomy; and (3) it is open source, which dramatically lowers the barriers to entry for accessing, using, and extending the system.

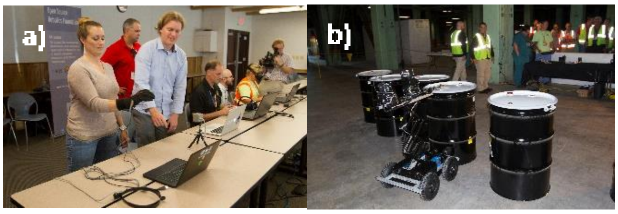


Fig. 2 Virtual Reality & Robot Rabbit

3.1.4 Radiation Robotic Rabbit

The Radiation (or Rad) Rabbit can be used in multiple *Locked High Radiation Areas* and station security, and will incorporate contingency into any response plans. The robot is a light-weight vehicle, so it can easily be picked up, carried, and transported by two people. The platform is radio controlled; it can be operated by line of sight or beyond line-of-sight by a video screen located on the controller. It is a maneuverable 4-wheel-drive unit, which allows for the robot to turn on its own axis (Figure 2b).

The radiation robotic rabbit is a teleoperated mobile robot having a Go-Pro camera, a scissors mast, and a secondary camera. The robot was designed to have simple and quick remote eyes on site for an operator, who does not have to suit up to accomplish a quick evaluation of a potentially radioactive site of interest. The original purchased robotic base did not operate as advertised, and had to be re-designed by students at SUNY-Oswego and rebuilt by Exelon. Being intuitive to control with minimal training required at its simple operator console, a DOE worker was able to instantaneously drive the robot around and do a visual inspection with its camera.

3.1.5 Serpentine and Modular Robotics

The same visual inspection of long piping runs from 5.1.1 except from the outside of small diameter pipes in Portsmouth nuclear facilities is needed to gather data to make the same Criticality Incredible (CI) determinations, with the goal of achieving nuclear facility Cold & Dark status prior to demolition operations.

Carnegie Mellon University (CMU) has developed multiple ground-based mobile robots to use in uncertain environments, including a robust snake robot and a hexapod robot. The snake robots are used for locomotion on uncertain and rough terrain, including a sand and granular material hill. The robot is equipped with a camera for surveying the scene. It has numerous standard locomotion modes, including planar locomotion using side-winder and undulating gaits, as well as special gaits for climbing trees, moving inside and outside of pipes, and several other specialized motions. The snake modules can be assembled in a variety of ways. Not only do these robots form serpentine snakes, but they can also be configured in various multi-legged layouts (Figure 3a). For example, the hexapod robot has six serpentine-like legs on which to walk and is able to step over obstacles and to traverse irregular terrain.

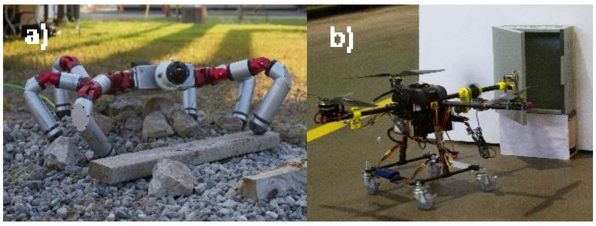


Fig. 3 Serpentine Walker & Swabbing UAV

3.1.6 Swabbing Unmanned Aerial Vehicles

Visual inspection and surface swabbing of large warehouses in Portsmouth nuclear facilities is needed to gather data to make Criticality Incredible (CI) determinations. There are a lot of two story or higher buildings that require periodic monitoring and inspection. Again, visual inspection requires slow and meticulous attention. Unmanned Aerial Vehicles (UAVs) are capable of robust physical interaction with the environment is a key capability to have in the D&D toolbox, as well as the ability to address very large structures such as buildings X-330 and X-326 at the Gaseous Diffusion Plant and the exhaust shaft of the Waste Isolation Pilot Plant. Physical interaction might be necessary when contamination levels are below the sensitivity of non-contact sensing, when doors or panels need to be opened or closed for inspection, or to apply sealants or other remediation acts in dangerous or difficult-to-access areas. But most UAVs are intrinsically unsuited for controlled physical interaction with the environment in a safe manner until now.

For very large structures, like building X-330, more efficient modes of horizontal travel are required to cover the long distances needed to get into position for physical interaction. The Boom Copter is another custom UAV with a horizontal propeller that is capable of efficient, long-distance horizontal flight, while also being designed explicitly for physical interaction. In free flight, the Boom Copter demonstrated its ability to transition from hover to high-speed horizontal transit. While constrained to a planar surface for safety, the boom copter (unmanned rotorcraft) can open closed enclosures, like an electrical cabinet door as shown in Figure 3b or apply sealants. A second rotorcraft from Purdue University, the precision hexrotor, is used for agile interaction with its environment for sampling, adding sealants, or swabbing. A third vehicle is a hybrid fixed-wing aircraft that can cover long distances and still hover in flight. All these aircraft are one-of-a-kind prototypes that were designed and developed at Purdue University.

3.1.7 Forklift Automated Safety System

Southwest Research Institute (SwRI) conducted a live demonstration of indoor automated navigation with a forklift platform that highlights two featured technologies – computer vision-based object detection and a camera-based, high-precision localization system called Ranger. These technologies hold the potential to significantly enhance the safety of mobile automated systems (e.g., material transport systems) and facilitate significant advances in situational awareness for industrial applications. SwRI has developed an extensive library of core technologies and tools for mobile robotics and autonomous vehicles. For example, incorporating the ability to detect and track people around moving equipment is critical for ensuring a safe environment.

The object-detection framework demonstrated is a flexible, modular system for detecting objects in monocular and stereo imagery. The framework includes a library of state-of-the-art, configurable feature-extraction and machine-learning plugins, which function within a framework which includes tools for training the system and executing the automatic detection. The detections from the system can have multiple uses in industrial environments, ranging from vehicle safety (obstacle avoidance) to floor environmental awareness (creating a map of where workers are located or ensuring areas are clear of people).

Ranger is a high-precision, map-based localization system that has numerous applications for automation and safety. Ranger utilizes a ground-facing camera with artificial illumination to provide precise measurements of absolute position, relative to a pre-recorded map of ground images. Ranger was originally designed for use on roads, but it is equally applicable to indoor applications, as it provides absolute measurements without the need for GPS. Moreover, by localizing with respect to the floor, Ranger is not affected by changes to the surrounding environment, such as removing or adding 'landmarks,' which can affect other indoor localization techniques. Ranger allows for precision driving in sensitive areas; reporting vehicle positions to coordinators, and/or allowing operators to enforce no-go zones for vehicles for safety. SwRI visualizes the output of object detection and Ranger running on a forklift (Figure 4a), in order to demonstrate the benefits of highly-accurate localization and perception. SwRI created intuitive displays (both in the vehicle and outside of the vehicle) using Mapviz, a modular visualization tool, to show the sensed objects and the precise location of the vehicle on a map of the environment.

Fig. 4 Automated Forklift & Robot Teams

3.1.8 Human-Centered Robot-Robot Teams

The Texas A&M Engineering Experiment Station with industry partners Endeavor Robotics (formerly iRobot), Fotokite, and AdventGX, featured two demonstrations of how human-centered robotics, sensors, and communications can increase worker safety by reducing exposure for routine tasks, eliminating 'surprises' that prolong planned exposures to radiation, and preventing worker injury from lifting or handling heavy materials and tools. This demonstration shown in Figure 4b reflects technology transfer from the active collaboration among Texas A&M University faculty members in the Nuclear Science Security and Policy Institute and the Center for Robot-Assisted Search and Rescue.

This demonstration showed how advances in ground/air robot teams can enable workers to more rapidly, completely, and reliably perform demanding visual tasks, such as conducting radiation surveys, localizing spills behind equipment and up in pipe racks, or manipulating valves, sensors, and tools. These capabilities will minimize worker exposure, because the more comprehensive views will allow detailed planning and preparation for efficient mitigation, along with eliminating surprises.

3.1.9 Mobile Systems for Inspection

University of Texas (UT) Austin has formed the Nuclear & Applied Robotics Group (NRG), whose goal is to reduce dosage or the potential of dosage to EM workers, particularly in the area of Pu sustainment. Under this program, the NRG is currently developing two mobile robot systems to perform routine contamination tests in areas where Special Nuclear Material (SNM) is stored. These systems are selected to be either autonomous or telerobotic, allowing for the inspection for alpha or other forms of radioactive contamination in areas where SNM is (or was) stored. Other sensor modalities, including gas detection and thermal sensors, are possible.

The side-by-side demonstrations were well coordinated and demonstrated using a variety of robotic and artificial intelligence technologies. The dual-manipulator robot on a Clearpath platform showed several different coordination (arm-to-arm and wheels-to-arm) modes. The operator used gesture control to plan a path that the robot could then follow to an area of interest. The robot moved autonomously, including the utilization of obstacle avoidance. Integration was professional on both robots, with wiring in the design were well routed. The second robot (Figure 5a) was an Adept Pioneer Mobile robot with sensors, a zip mast, and software for mapping and searching autonomously. This demonstration incorporated AR Tags, a legacy of AR Toolkit used in augmented reality. All operations were performed seamlessly.

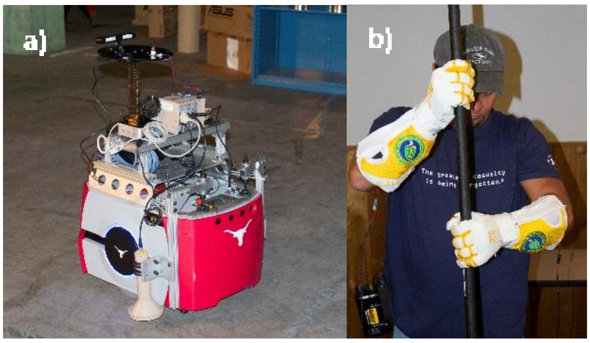


Fig. 5 Autonomous Inspection & RoboGlove

3.1.10 RoboGlove

The wearable RoboGlove (shown in Figure 5b) augments grip strength with embedded electric actuators and artificial tendons connected to each finger that retract in response to sensed forces of the user. With the glove holding their hand closed, the DOE steelworker can maintain a grip on tools, panels, etc. without straining their hands. The glove itself has both right and left side versions, and can be used in multiple, user-selectable behaviors.

Researchers at the NASA Johnson Space Center (JSC) and General Motors (GM) have designed and developed RoboGlove, a human-wearable grasp-assist device. This wearable robot was created to augment grasp forces in an effort to reduce fatigue when operating tools for an extended period of time, or when performing tasks with repetitive motion.

3.1.11 Virtual and Augmented Reality Modeling

D&D of the Portsmouth facility requires extensive planning due to the complexity and size of the facility, and with a lack of clear technical drawings of the various locations. The facilities are old with little operational/ construction knowledge by the current general workforce. Virtual Reality (VR) will enable more rapid facility understanding for worker planning and training. Augmented Reality (AR) can assist in safer work execution by providing full scope understanding and guidance throughout execution of a particular activity.

In this demonstration, Fluor-BWXT Portsmouth (FBP) provided equipment drawings and photographs for one 8-stage processing cell, and Savanah River National Lab (SRNL) engineers modeled the cell in CAD engineering and imported the model into VR to provide a proven method for understanding facility and planning work, and created a combined VR/AR training scenario to demonstrate capabilities to improve safety and efficiency of work execution (Figure 6a). The significance of the Demonstration was to feature the effectiveness of VR in understanding complex facilities, and how AR can assist in safer work execution.

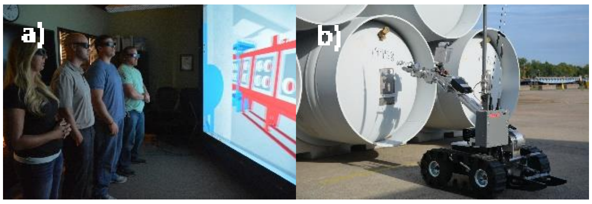


Fig. 6 Virtual Reality & Cylinder Inspection

3.1.12 Robotic Inspection of Cylinders

The purpose of using a Commercial-off-the-Shelf (COTS) mobile robot was to reduce worker radiation dosage by performing remote robotic cylinder inspections. This will become increasingly more important when performing inspections of thousands of cylinders with both automation and remote control operations. Moreover, tens of thousands of cylinders throughout the DOE worldwide complex require periodic inspection. Workers performing manual cylinder inspections receive more dosage, on average, than other non-inspector workers. Inspections include visual inspection and physical sampling (smears) that are performed within arm's length of each cylinder. The Sandia National Laboratory's DataShare application tool will be integrated to automatically store cylinder inspection information and photographs.

The Remotec HD-1, shown in Figure 6b, was used for this remote cylinder inspection demonstration. The robot has multiple cameras that can be used for inspection and the compact camera system can display live video or captured digital stills. Commercial robot cameras or the custom SNL camera system could be mounted on the robot and used for performing inspections of valves or for reading inventory numbers on cylinder boilerplates. Machine-vision software can augment the robot's camera system by reading the boilerplates, using Optical Character Recognition (OCR) to parse the text for processing and saving into a cylinder inspection database, including information and photos for each cylinder inspection task. Hand-held inspection tools were held in the robot gripper of the robotic manipulator. Force-compliant inspection tools are required to prevent damage to cylinders during physical contact operations (smears, ultrasonic wall thickness measurements, etc.).

4 Discussion

Each demonstration was evaluated and assessed an overall TRL level for its technology. Table 1 provides a quick overview of the EM Portsmouth demonstrations and its technology readiness. If there were issues stemming from the overall demonstration or a particular technology was still in development, then the TRL level reflects a less mature score. The ratings are still subjective, and can be improved or reduced by a single level, without any major controversy.

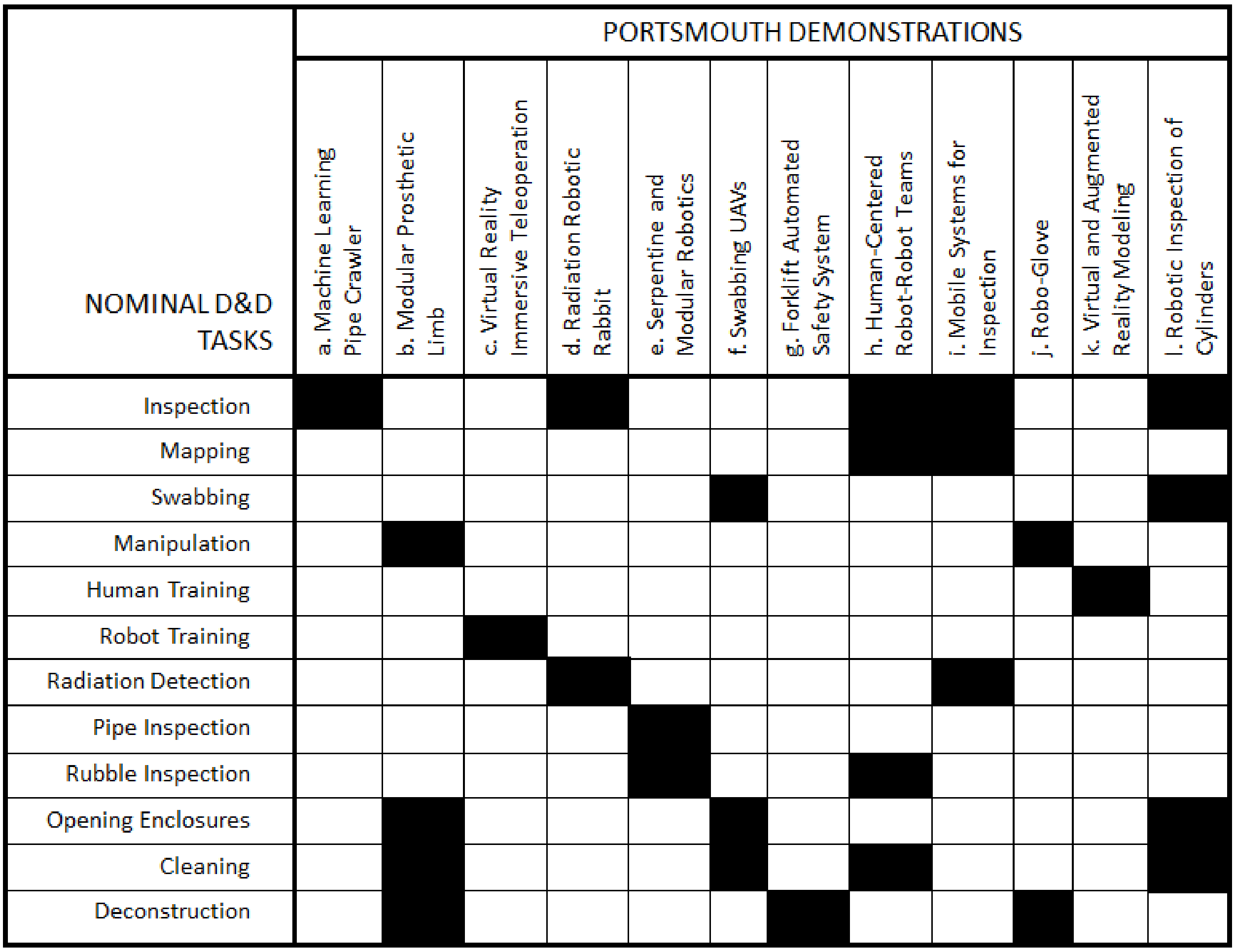
Table 1. TRL Level of Each Demonstration

DEMON - STRATION	OVERALL TRL LEVEL
1. Machine Learning Pipe Crawler	TRL 2 - Applied Research: Robot is TRL 3, but machine learning was not demonstrated but the potential is there to detect radiation on the inner surfaces
2. Modular Prosthetic Limb	TRL 5 - Laboratory Testing of Integrated System (and going on TRL 6): This robot has undergone testing of platform and manipulators, and results provide evidence that performance targets may be attainable.
3. Virtual Reality Immersive Teleoperation	TRL 4 - Lab Testing/Validation of Alpha Prototype Component/Process: Virtual reality simulation shows a manipulator at a workstation.
4. Radiation Robotic Rabbit	TRL 6 - Prototype System Verified: Robot prototype demonstrated in an operational environment where a radiation sensor was dropped into a barrel.
5. Serpentine and Modular Robotics	TRL 3 - Critical Function or Proof of Concept Established: Early stage development of a hexapod and serpentine that validate analytical predictions for walking or climbing.
6. Swabbing UAVs	TRL 2 - Applied Research: Initial practical applications to open electrical enclosure door and swabbing of tall locations. Hybrid, fixed-wing rotorcraft is in the conceptual phase or still TRL 1.
7. Forklift Automated Safety System	TRL 3 - Critical Function or Proof of Concept Established: Early stage development detects people and localizes robot, but forklift was never integrated or shown to be drive-by-wire for future automation.
8. Human-Centered Robot-Robot Teams	TRL 3/TRL 4 - Critical Function Established/ Alpha Prototype Validate Process: Early stage operations of Packbot, Fotokite, and FirstLook 110 are commercially available, but integration still in process.
9. Mobile Systems for Inspection	TRL 5 - Laboratory Testing of Integrated System: Both Robot Systems are validated in a relevant environment. Autonomy is a difficult research project.
10. RoboGlove	TRL 7 - Integrated Pilot System Demonstrated: Prototype glove demonstrated in an operational environment (integrated pilot system level at GM).
11. Virtual and Augmented Reality Modeling	TRL 6 - Prototype System Verified: System prototype demonstration in a Virtual Model based on actual Portsmouth CAD drawings.
12. Robotic Inspection of Cylinders	TRL 6 - Prototype System Verified: Mobile robot system and inspection process demonstrated in an operational cylinder yard environment.

The lower-scored TRL demonstrations can be attributed to their not being fully prepared and/or still in a further development phase. In order to achieve higher TRLs, the requirement is to show an integrated system operating within a variety of environments.

The technologies demonstrated span a wide spectrum, and their value to EM cleanup is depicted in Figure 7. The selections were by design to demonstrate as much as possible in a short window with the understanding it would not be perfect. The goal was to get robots as tools into the hands of the user in working on near-term and realistic tasks.

The demonstrations exhibited a balance of capabilities that can accomplish a number of future dismantling and decommissioning missions. The tasks listed here are representative of a menu of capabilities that could support a wide number of initiatives within EM. The availability of the technology is based on its DOE Technology Readiness Level (TRL). High TRL technologies are candidates for immediate insertion into D&D



NOMINAL D&D TASKS	PORTSMOUTH DEMONSTRATIONS											
	a. Machine Learning Pipe Crawler	b. Modular Prosthetic Limb	c. Virtual Reality Immersive Teleoperation	d. Radiation Robotic Rabbit	e. Serpentine and Modular Robotics	f. Swabbing UAVs	g. Forklift Automated Safety System	h. Human-Centered Robot-Robot Teams	i. Mobile Systems for Inspection	j. Robo-Glove	k. Virtual and Augmented Reality Modeling	l. Robotic Inspection of Cylinders
Inspection	■			■				■	■			■
Mapping								■	■			
Swabbing						■						■
Manipulation		■								■		
Human Training											■	
Robot Training			■									
Radiation Detection				■					■			
Pipe Inspection					■							
Rubble Inspection					■			■				
Opening Enclosures		■				■						■
Cleaning		■				■		■				■
Deconstruction		■					■			■		

Figure 7. Relationship of Portsmouth Demonstration Compared to DOE D&D Tasks.

tasks, while lower TRL technologies are candidates for technology maturation in order to impact EM tasks in the future.

5 Summary

Based upon the successful week of technology demonstrations, the Fluor-BWXT Portsmouth (FBP) coordination team at the Portsmouth facility shared feedback and lessons learned from each of the demonstrations with DOE-EM. After the DOE out-brief session (dated: 8-29-16), deployment readiness and priorities were also discussed in a separate FBP meeting. This information was used as input to the EM Research and Technology Roadmaps[2]. During the binning session, the FBP team felt that there were three categories of technologies: Categories A, B, and C. Category A is robotic technologies that can be implemented today. Category B is technologies than could be implemented in the near future. Category C is technologies that could be implemented in the longer term. DOE used these categories to understand what can be demonstrated and when, with an eye on readiness and impact to cleanup for Portsmouth and the rest of the EM Enterprise.

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References

[1] *Robotics Test Bed at Portsmouth Gaseous Diffusion Plant*, Final Report, Office of Environmental Management, March 1, 2017.

[2] *DOE EM Research and Technology Roadmaps: Robotics and Remote Systems for Nuclear Cleanup*, Office of Environmental Management, 2017.