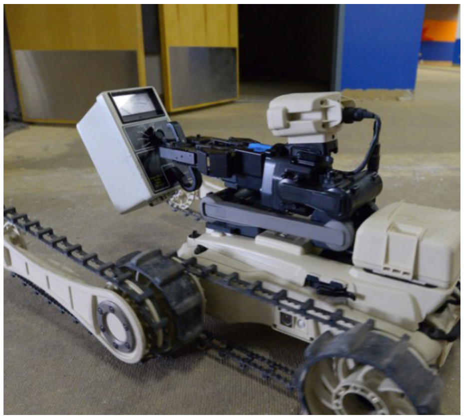
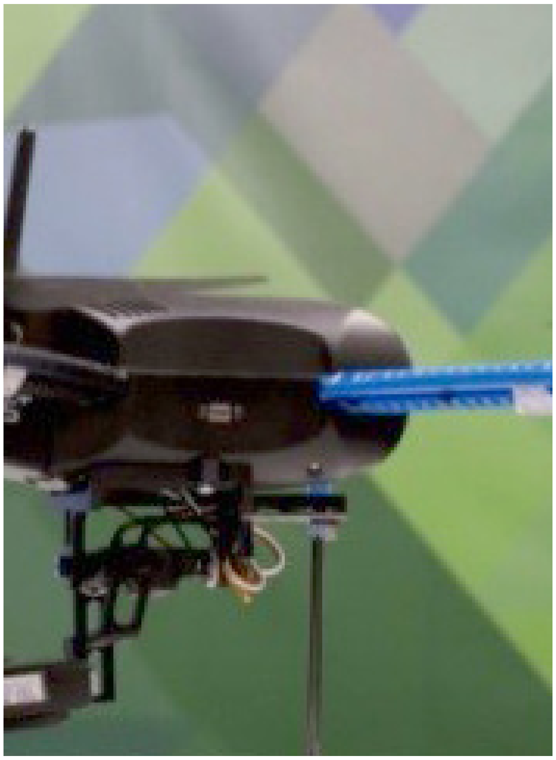
DOE EM

RESEARCH AND TECHNOLOGY ROADMAP

ROBOTICS AND REMOTE SYSTEMS FOR NUCLEAR CLEANUP





2018

U.S. DEPARTMENT OF ENERGY
Environmental Management

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1. EXECUTIVE SUMMARY

The Department of Energy's (DOE) Office of Environmental Management (EM) is responsible for the waste legacy of the nation's nuclear facilities. EM's mission includes long-term storage of nuclear waste products, as well as the assessment and remediation of several obsolete or aging nuclear facilities. This mission is projected to span many decades and cost hundreds of billions of dollars, with the most challenging sites and tasks still on the horizon. Many current and projected EM tasks present unique hazards to the workforce, including chemical, biological, and radiological contamination, as well as ergonomic issues. Because of these hazards, DOE-EM's Technology Development Office (TDO) is actively pursuing the use of robotic tools to increase the safety and efficiency of workforce personnel. Robotics and remote systems provide the potential to augment the abilities of workforce personnel, reduce acute and chronic injury rates, reduce radiation exposure, and remove workers from the immediate proximity of the most hazardous materials and areas. While EM's challenges contain many unique elements, there is substantial overlap between EM's robotic needs and the needs of other government and industrial domains, both domestically and internationally. Other agencies and industries will benefit from DOE's robotic developments as DOE continues to leverage developments from other domains. The purpose of this roadmap is to provide direction to accelerate the integration of robotic and remote systems into EM environments. The goals behind this initiative are described in more detail in Chapter 2.

The DOE-EM Robotics and Remote Systems Roadmap is motivated by specific mission needs at EM sites. Before proposing or assessing any specific technologies, the roadmap team solicited feedback from all the EM sites and visited several of the sites to better understand their needs and challenges. The roadmap team identified and aggregated the needs across the EM complex that could potentially be addressed through the use of robotics and remote systems. These needs include both assessment and remediation tasks in a variety of environments that experience challenges with the use of existing tools and methods. A summary of these needs is provided in Chapter 3. These needs should be used as a resource to technology developers as they consider potential solutions.

Based on the EM needs identified in Chapter 3, the roadmap team identified several key robotic and remote systems technologies with the potential to enable these challenging tasks to be completed more safely and effectively. These technologies include a number of traditional robotic capabilities, such as mobility, manipulation, and perception, as well as challenges that are more unique to DOE-EM's environments, such as radiation tolerance and contamination control. Each key technology is briefly described and assessed in three areas—readiness, ease of integration, and uniqueness to EM—in Chapter 4. Based on these assessments, the roadmap team specified technologies of particular interest for DOE development. These technologies include those that are unique to EM's missions, such as radiation tolerant and de-contaminable robots, as well as technologies that are anticipated to address the most pressing short-term EM site needs, such as environmental sensors and autonomous perception and mapping. Considerations of long-term remediation challenges suggest technologies that should be considered for long-term strategic research and development, including advanced manipulation and mobility platforms and autonomous navigation.

A notional path forward for research and development is provided in Chapter 5. Considerations for EM leadership, EM

sites, and the broader technology development community are also provided. These considerations are intended to lay the groundwork for an accelerated effort to develop and integrate robotics and remote systems at EM sites. The conclusions of this effort are summarized as follows:

- DOE should pursue a balanced portfolio of short-, medium-, and long-term development efforts, in order to achieve a higher impact and return on technology development investments.
  - » Short-term deployment efforts can be managed by EM sites, target specific needs, and focus on high-readiness technologies, such as robotically-deployed sensor platforms or modeling and simulation. These technologies may be available commercially or from DOE national laboratories.
  - » Medium-term development efforts can be managed by TDO, target cross cutting needs, and focus on technologies in need of applied research or advanced development, such as decontaminable systems, environmental sensing or autonomous perception and mapping. DOE national laboratories are uniquely suited to contribute to this phase of development. Universities and industries may also participate in these activities.
  - » Long-term research and development efforts can be managed by the DOE Office of Science or TDO in collaboration with other federal agencies, such as the National Science Foundation. This research is not as tightly connected to a specific need and involves increased risk and potential reward. Technologies that need substantial development to meet long-term remediation challenges at the most complex EM sites, such as advanced autonomous manipulation, mobility, and navigation should be considered.
- DOE should focus technology development investments on unique technologies, such as radiation tolerant or de-contaminable robotics, while actively leveraging development in other areas. Some custom integration to EM missions will be required for most leveraged technologies.
- EM sites should consider appropriate procurement methods when integrating new technologies and collaborate with TDO and the national laboratories for consulting and technical review.
- Technology developers should seek to understand EM's unique needs and challenges as they construct research plans and portfolios, and before proposing solutions. This roadmap provides a summary of these needs and challenges. More information is available from TDO and DOE's national laboratories.
- Practical considerations, such as workforce training and contract incentives for site contractors who integrate new technologies, should not be neglected.
- Tight collaboration between developers and workforce personnel is essential to successful integration of robotics and remote systems. This collaboration provides critical feedback to developers while acclimating workforce personnel to the technology. TDO and DOE's national laboratories can facilitate these interactions.

This roadmap in intended to receive updates periodically as EM challenges and robotic technologies evolve in coming years.

2. INTRODUCTION

The Department of Energy's (DOE) Office of Environmental Management (EM) is responsible for managing the cleanup and waste legacy of the nation's nuclear facilities. The work required to complete this mission is uniquely challenging due to the hazards associated with the nation's nuclear facilities, coupled with the complex nature and environment of much of the work involved. Appropriate technology insertion is necessary to accomplish EM's mission safely and efficiently. Robotics and remote systems present a particularly compelling set of technologies due to their potential capability to augment, protect, or remove workforce personnel from the immediate proximity of many of the most dangerous hazards. This roadmap introduces the EM mission and specifically identifies EM needs for which robotics and remote system may provide benefits. Based on these EM needs, key technologies are identified and assessed to provide specific recommendations to EM stakeholders, including EM leadership, the EM sites, and the technology development community. While challenges facing DOE-EM are the specific focus of this roadmap, substantial overlap with other application areas of interest to government agencies (e.g., the Department of Defense, National Institute for Occupational Safety and Health, National Aeronautics and Space Administration [NASA]), international stakeholders, and industry are also relevant.

Mission Challenge

Since 1989, EM has addressed the environmental cleanup and radioactive waste legacy left by the nuclear weapons complex. This legacy includes the following:

- Many first-of-a-kind research facilities, testing and proving grounds, and infrastructure used for the development of the atomic bomb under the Manhattan Project (1942 to 1946)
- A large industrial complex built across the United States (U.S.) to support the Cold War nuclear arms race (1947–1991)
- A nationwide network of government-sponsored facilities used for nuclear science research and technology development (1953–1990s)

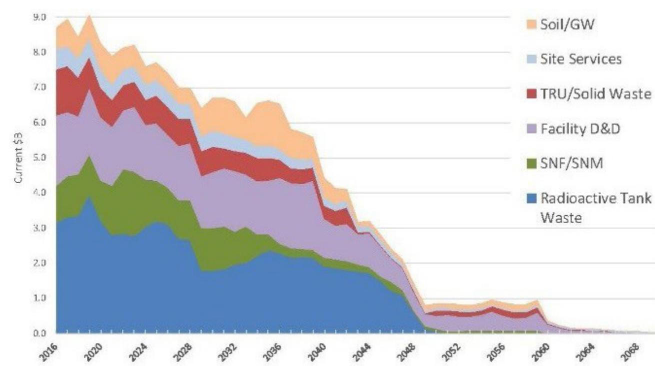


Figure 1: DOE-EM liabilities over several coming decades

"As the largest environmental cleanup program in the world, EM has been charged with the responsibility of cleaning up 107 sites across the country whose area is equal to the combined area of Rhode Island and Delaware. To date, EM has made substantial progress in nearly every area of nuclear waste cleanup and completed cleanup at 91 of these sites."

This legacy is the largest and most technically complex cleanup in the world. Many of the more straightforward remediations were completed or are currently underway. The remaining nuclear cleanup involves technically complex, high-hazard, high-risk, and high consequence work, and remains one of the U.S. government's largest liabilities. Much progress has been made over the last 29 years; however, the remaining cleanup cost is estimated at more than $250 billion over at least 50 years (Figure 1).

The Environmental Legacy of Defense Nuclear Weapons Production

The DOE (formerly Atomic Energy Commission) produced weapons-grade uranium and plutonium. The associated legacy poses environmental cleanup and waste management challenges that are technically complex and unique to EM.

Naturally occurring uranium is composed of uranium-238 (U-238) and uranium-235 (U-235) at 99.284% and 0.711% of its weight, respectively. U-235 is the only fissile (easily split with neutrons) isotope found in significant quantities in nature. The separation of U-238 and U-235 was accomplished by the process of gaseous diffusion whereby chemically-produced uranium hexafluoride (UF6) gas is forced through semi-permeable membranes. To accomplish uranium isotope separation, DOE constructed the Oak Ridge Gaseous Diffusion Plant (GDP), designated as the K-25 building, on the Oak Ridge Reservation (ORR) in Tennessee. Four other GDPs, K-27, K-29, K-31, and K-33 were later built at ORR, followed by the Portsmouth GDP in Piketon, Ohio and the Paducah GDP in Paducah, Kentucky. These GDPs no longer produce U-235, and are in various states of decommissioning.

Plutonium-239 (Pu-239) is made from U-238—when a neutron is absorbed by the nucleus of U-238, U-239 is formed, which then rapidly decays to Pu-239. Pu-239 can be separated from the uranium in nuclear reprocessing plants. The ability to produce large amounts of Pu-239 more economically than weapons-grade U-235 led to its use in nuclear weapons. By 1963, nine plutonium production reactors and five reprocessing plants were built at the Hanford Site in Richland, Washington and five production reactors and two reprocessing plants were built at the Savannah River Site (SRS) in Aiken, South Carolina.

In addition to the U-235 and Pu-239 the DOE produced for the U.S. defense program, many other radioactive and byproduct materials were generated. Radioactive isotopes of primary concern to DOE-EM include, but are not limited to: medium-lived fission products such as cesium-137 (Cs-137) and strontium-90 (Sr-90); long-lived fission products such as technetium-99 (Tc-99) and iodine-129 (I-129); and actinides such as uranium-235 (U-235), plutonium-239 (Pu-239), plutonium-240 (Pu-240), americium-241 (Am-241), and americium-243 (Am-243). Other radioisotopes of concern, include hydrogen-3 (tritium) and the irradiated corrosion wear products of iron-55 (Fe-55), cobalt-60 (Co-60), and nickel-59 (Ni-59).

U.S. Army anti-aircraft artillery gun emplacements at Savannah River Site

Many chemical processes were used in the production of these nuclear materials. For example, to accomplish the separation of plutonium and uranium from fission products in irradiated nuclear target material and spent nuclear fuel, several chemical reprocessing methods were investigated and utilized. These include the Bismuth Phosphate Precipitation Process for recovering macroscopic quantities of plutonium and the REDuction-OXidation (REDOX) solvent extraction process to recover both uranium and plutonium, which was further refined into the Plutonium and URanium EXtraction (PUREX) process. The Uranium Recovery Process was used to extract and decontaminate uranium from the metal waste produced in the Bismuth Phosphate Precipitation Process.

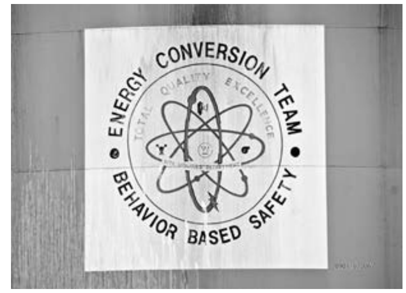
Heavy metals were widely used throughout the nuclear weapons complex. Chromium, arsenic, cadmium, mercury, and lead present the greatest risk to human health due to their prevalence and toxicity. The bioavailability of heavy metals is influenced by many complex physical, chemical, and biological factors, which makes them extremely difficult to remediate when comingled with radionuclides.

The historical use of organic chemical compounds also poses mission challenges because of the potential for: (1) uncontrolled, dangerous heat-generating reactions to occur; (2) generating ignitable gases and vapors; and (3) exposing workers to harmful gases and vapors. Many organics can undergo unexpected, undetected, and even unexplainable interactions and transformations in ecological and waste processing systems, which can complicate cleanup efforts.

Releases from DOE facilities and accidental spills of radioactive materials and chemicals to the environment have occurred. DOE's initial cleanup response has been to remediate the contaminated soils and water bodies and mitigate further environmental and human health impacts. These efforts remain an important part of DOE-EM's mission.

In the current era of EM's mission, the emphasis is on dispositioning radioactive liquid tank waste, high-level waste

(HLW), and transuranic (TRU) waste. Over the last several years, over one-third of EM's annual budget (nominally, $6 billion) has been dedicated to radioactive tank waste stabilization and disposition. In other cleanup activities, such as remediation of the contaminant plumes in deep subsurface vadose zones, the decommissioning of nuclear facilities, and the management of special nuclear materials and used/spent nuclear fuel, many technical uncertainties remain that must be addressed. Similarly, there are inherent uncertainties and risks associated with EM's aging nuclear facilities and associated infrastructure.



Tank-side banner at Savanna River Site

EM Innovation and Technology Development

DOE-EM Innovation and Technology Development provides the opportunity to reduce the aggregate cleanup cost and duration and more importantly, to perform work and operate facilities in a manner that assures public, worker, and environmental safely. Novel technologies and innovative solutions are needed to address the significant challenges associated with the remaining nuclear cleanup work that will span the next five decades. EM's technology development program encompasses the entire maturation lifecycle of technology, including leveraging technologies from other nuclear and non-nuclear industries. The program addresses issues related to: (1) radioactive liquid and solid waste treatment, storage, and disposal, (2) soil and groundwater remediation, (3) nuclear materials and spent fuel management and disposition, (4) facility deactivation and decommissioning, and (5) public, worker, facility/asset, and environmental safety and security.

EM Innovation and Technology Development addresses the strategic need to invest in fundamental research and seek game-changing solutions that positively impact EM's lifecycle by: (1) reducing costs; (2) accelerating schedules; (3) mitigating mission uncertainties, vulnerabilities, and risks; and (4) minimizing the mortgage associated with long-term, post-closure, and post-completion stewardship. High-payoff technologies are aimed at major mission needs that are outside of the day-to-day EM program, and could result in breakthroughs in execution. EM supports mission-enabling and mission-enhancing technologies, which allow work to be performed safer, more effectively, and more efficiently. These mission-enabling and mission-enhancing technologies are not intended to simply address a core mission challenge; instead, they serve to equip EM with advanced tooling and solutions that will improve quality, enhance environmental and facility operations, and reduce the environmental liability of legacy nuclear cleanup. As the state-of-the-art in many relevant technology areas continues to advance, alternatives or improvements to current baseline technologies will become available. Technology transfer from other nuclear sectors and the use of non-nuclear, commercially available technologies will also efficiently enable mission completion. Mission-enabling and mission-enhancing technologies can provide incremental or revolutionary improvements to existing capabilities and processes. Their impact can be significant, particularly when EM's safety and defense-in-depth posture is enhanced, gains are made in performance and productivity, and emergency response and preparedness capabilities are improved.

Working Safer and Smarter

Preserving and improving the safety of the workforce is essential to EM's mission. Scientific and technological advancements will be infused and integrated into planning and execution of work in a manner that improves safety. EM will collaborate with the workforce in the development and deployment of technological advancements to improve worker safety. To address high-hazard, high-consequence work, EM is actively promoting the use of advanced robotics as a key mission-enabling technology.

EM's mission cleanup challenges intersect with many robotics and remote systems domains including underwater, over ground, below ground, aerial, and access-restricted remote operations. Robotics and remote systems are needed for access to nuclear, chemical, and other high-hazard facilities that are inaccessible, restricted to human entry by size and configuration, or otherwise preclude safe entry by workers. These systems are anticipated to dramatically improve worker safety. EM has placed emphasis on the application of robotics for: (1) handling of high-hazard, high-consequence materials and waste; (2) performing worker/operator tasks that are dirty (expose workers to chemical, biological, radiological, nuclear, and physical contaminants and pollutants), dull (routine, labor-intensive, repetitive, mundane), dangerous (pose significant occupational hazards), and difficult (require significant engineering effort to accomplish); (3) easing the burden of worker/operator tasks that are physically demanding, stressful to the human body, or are otherwise ergonomically challenging; (4) performing tasks that are beyond human abilities; (5) improving the ability to respond to and recover from unplanned events or operational emergencies; and (6) improving the safety, quality, efficiency, and productivity of facility operations.

Risks to the DOE-EM Workforce

EM accounts for 54% of DOE's total dose (380.7 of 709.4 person-rem).

DOE continues to work diligently to keep occupation exposure to ionizing radiation and other workplace hazards as low as reasonably achievable; however, the nature of nuclear cleanup and radioactive waste management exposes the atomic energy workforce to ionizing radiation. As such, EM remains the DOE program retaining the highest workforce personnel radiation dose. Table 1 includes data excerpted from DOE's 2016 report on occupational radiation exposure. The data included shows the number of individuals with measurable total effective dose (TED), collective TED, and average measurable TED from each DOE program office that handles radioactive materials.

Table 1. DOE 2016 report on occupational radiation exposure

Program Office	Total Monitored	Collective TED (person-rem)	Percent Change from 2015	Number With Meas. Dose	Percent Change from 2015	Avg. Meas. TED (rem)	Percent Change from 2015
Office of Energy Efficiency and Renewable Energy	11	0.034	-	7	-	0.005	-
Office of Environmental Management	22,866*	380.672	-8% ↓	6,819	41% ↑	0.056	-35% ↓
National Nuclear Security Administration	33,209*	208.691	7% ↑	3,138	6% ↑	0.067	0%
Office of Nuclear Energy, Science and Technology	4,307*	36.541	-24% ↓	640	-11% ↓	0.057	-14% ↓
Office of Science	17,307*	83.459	-4% ↓	1,401	-8% ↓	0.060	4% ↑

- The percentage change from the previous year is not shown because it is not meaningful when the site collective dose is less than 1 person-rem (10 person-mSv)

* Individuals who worked at more than one program office are represented within each grouping; therefore, the total monitored values will not match the annual number of workers monitored.

The top three workplace injuries—contact with objects and equipment, falls, and bodily reaction exertion—are preventable.

In the 2016 edition of the National Safety Council's annual statistical report on unintentional injuries and associated characteristics and costs, the Council reported that 35.1% of U.S. injury cases in 2013 were caused by overexertion and bodily reaction. The other two top causes of injuries were contact with objects and equipment at 25.4% and falls, slips, and trips at 25.0%, with the total percentage of injuries caused by the actions and behaviors of workforce personnel, at 85.5% [1].

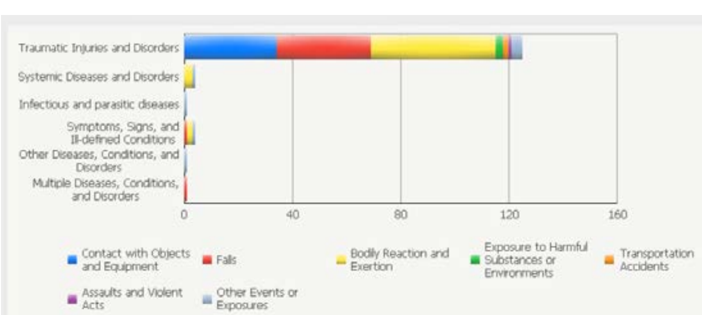


Figure 2. Data of EM personnel injuries as shown on DOE's Computerized Accident Incident Reporting System

There is a similar distribution of causes and incident rates of workplace injuries in EM. According to DOE's Computerized Accident Incident Reporting System, Injury and Illness Dashboard (Figure 2) queried on March 6, 2018, the top three injuries at EM sites involve: (1) contact with objects/equipment [ ] at 23%, (2) falls [ ] at 26% and, (3) bodily reaction exertion [ ] at 38%. Additionally, the EM workforce is rapidly aging, potentially increasing the frequency and impact of musculoskeletal injuries.

EM's work spaces are often challenging and require remote access. Remote entry is needed for access into areas and spaces that prohibit direct access or are otherwise inaccessible to personnel due to the following:

- Unsafe, unstable, or unknown physical or structural conditions
- Configurations that are difficult or impossible to reach without taking extraordinary mechanical measures
- The presence or potential presence of radiological, chemical, biological, or physical hazards that will or may result in unacceptable occupational exposure or increased health or safety risk
- Other conditions that preclude safe entry or are otherwise uninhabitable, such as areas or spaces that contain or potentially contain:
  - » oxygen-deprived environments or other conditions of poor air quality
  - » explosive gases, materials or devices
  - » extreme temperatures
  - » extreme pressures
  - » poor or no visibility or direct line of sight due to lack of lighting or obstructions
  - » submerged or substantially liquid-covered surfaces.

A majority of the most challenging EM areas have yet to be addressed and will require novel approaches and solutions to assess and remediate the challenges.

Responding to off-normal events and emergencies, particularly in compromised areas and spaces, requires first-responders and workforce personnel to don bulky and heavy personal protective and life-support equipment. Response times are increased by the potential presence of chemical, radiological, and/or nuclear hazards. Emergency robots and remote technologies in these settings remain largely custom-built or custom-configured. These technologies are also single-use, expensive, and require specialized training.

Robotics and Remote Systems to Reduce Risks to the Workforce

Many of the risks and challenges described above can be mitigated by the use of advanced technology. Providing better tools to the workforce can allow work to be completed in a safer and more efficient manner. Robotics and remote systems are particularly compelling tools because they can provide advanced capabilities while removing workforce personnel from direct proximity of hazards. For this effort, EM's robotics thrust includes the use of robotic tools to accomplish the following tasks:

- Reducing the occupational exposure to ionizing radiation, toxic chemicals, and other work-related health hazards.
- Reducing workplace injuries that result from poor ergonomic conditions or from the nature of the physical work environment.
- Handling high-hazard, high-energy, or high-consequence materials and waste.
- Performing tasks that are physically demanding on, stressful to, or uncomfortable to the human body or are otherwise ergonomically challenging.
- Performing tasks that are beyond human abilities or reasonable human comfort.
- Performing tasks that are routine, repetitive, or mundane that may cause workers to lose focus of attention or concentration.
- Performing tasks that require extraordinary engineered solutions.
- Improving the ability to respond to and recover from off-normal events, unplanned incidents, operational emergencies, and disasters.
- Improving the safety, quality, efficiency, and productivity of facility operations.

- Reducing the government liability associated with legacy nuclear cleanup.

In accomplishing the above tasks, EM seeks solutions to mitigate the involvement of workforce personnel in dull, dirty, dangerous, and/or difficult tasks.

Key Collaborations and Partnerships

EM collaborates and partners with technologists in other U.S. executive departments and independent agencies to leverage highly specialized expertise, government assets and facilities, and publicly-funded programs. Access to non-DOE national laboratories and technology centers, non-DOE federally funded research and development centers, non-DOE testing facilities and proving grounds, as well as university affiliated research centers greatly increases opportunities for cleanup innovation and enhances cleanup capabilities. Collaborating with technologists in other federal and international agencies, participating on other federal technology programs and initiatives, and leveraging investments of public funds by other federal agencies are cornerstones of the EM mission innovation and technology. EM continues to enter into agreements and arrangements for interagency cooperation and collaboration.

EM leverages and harnesses the expertise, resources, and capabilities of U.S. universities and colleges. Academia will continue to support EM in four distinct roles: (1) as an expert-based resource for conducting early-stage and applied scientific research and for providing engineering solutions; (2) as a pool of recognized subject matter experts to support technical peer reviews and independent technical assessments; (3) as incubators and pipelines for EM's future workforce; and (4) as a source of independent testing, verification, and confirmatory evaluation. EM will work to improve the technical training of the American workforce through Science, Technology, Engineering, and Math (STEM) education, experiential learning, and apprenticeships. Emerging technologies will present tremendous opportunities for job creation, but will also require a technically skilled and capable workforce to meet the demands of legacy cleanup. In addition, new technologies provide for advanced, modernized tooling and create the need for retraining of a highly qualified but aging atomic energy workforce.

Purpose and Plan

The purpose of this roadmap is to, in part, provide strategic direction by establishing an actionable framework to infuse and use robotics, remote systems, and related technologies to lower occupational risks and exposure and enhance the productivity of workforce personnel. The program will leverage technology that currently exists or is under development within DOE national laboratories, other government agencies, U.S. colleges and universities, and the commercial sector to the maximum extent practical. The unique EM mission needs and environments will require tailoring and adapting existing technology and novel technology development. While technology development will focus on needs within EM, results are expected to include relevance to other DOE missions, U.S. and international government agencies, and the commercial sector.

The development and implementation of technological advancements to enhance safety, improve productivity, improve the quality of work, and level the playing field between workforce personnel of different ages, physical abilities, and genders is inherent to EM's mission. EM is actively promoting the use of advanced robotics and remote systems as a key enabling technology for accomplishing this mission. EM advocates modernizing its workforce by identifying, developing, and deploying robotic assist devices to enhance safety, reduce hazards, and increase operational efficiency for workforce personnel.

Rather than requiring the workforce to adapt to technology, new technologies will be adapted to the workforce. Tight integration and extensive interaction between workforce personnel and technology developers will ensure that useful and effective technologies are developed to solve pressing, real-world problems.

EM envisions an evolutionary technology development process. Candidate technologies will be identified and placed in the hands of the workforce to provide a preliminary evaluation of effectiveness and usefulness, as well as to solicit feedback for improvements. If a technology is deemed effective and useful, any identified improvements will be implemented and a long-term field test will be performed by workforce personnel. Results of the long-term field tests will identify any additional required system improvements prior to production implementation of the technology.

Extensive collaboration between workforce personnel and technology developers is essential to this process. Currently, EM is focused on developing a strategy for concept development of needed technologies as a means to mature the technologies. This strategy also includes a plan to test, demonstrate, and deploy the technologies with industry partners. This strategy includes a time horizon that encompasses the decades that are required to complete the cleanup mission. Near-term needs and opportunities will be clearly prioritized, while longer term needs and new capabilities enabled by emerging technologies will be tracked and leveraged appropriately.

ROADMAP TEAM

EM's Technology Development Office (TDO) sponsors development of this roadmap. The TDO Director has assembled a Robotics Advisory Team to assist with program development and execution. This team consists of the following members:

Rod Rimando, Chair	DOE-EM Technology Development Office
Paul Dixon	Los Alamos National Laboratory
Philip Heermann	Sandia National Laboratories
Tom Nance	Savannah River National Laboratory
Josh Mehling	NASA

The Robotics Advisory Team utilizes resources from Savannah River, Los Alamos, and Sandia to execute the robotics program. The advisory team consists of subject matter experts (SMEs) in universities, other federal agencies, and industry to inform and execute the program. This roadmap was developed by the DOE Robotics Roadmap Core Team, which consists of the following members:

Jason Wheeler	Sandia National Laboratories
Troy Harden	Los Alamos National Laboratory
John Lee	DOE-EM Technology Development Office
Richard Minichan	Savannah River National Laboratory
Eric Kriikku	Savannah River National Laboratory
Wendell Chun	University of Colorado, Denver
Bill Hamel	University of Tennessee
Richard Voyles	Purdue University

To form an initial foundation, TDO conducted the following information gathering activities:

1. A small group of expert roboticists was assembled to understand the relevancy and utility of robotics in the EM mission. This group visited several EM sites—Waste Isolation Pilot Plant (WIPP, May 2015), Hanford (August 2015), Idaho National Laboratory (August 2015), Savannah River Site (SRS, December 2015), and H-Canyon (March 2017)—and several U.S. universities (July 2016). TDO also facilitated interactions with nuclear clean-up efforts internationally, visiting the United Kingdom (April 2015), Japan (April 2016), and South Korea (November 2017) to share knowledge and technology. More details about these interactions is included in Appendix F.

2. A series of robotics demonstrations were conducted at the Portsmouth Gaseous Diffusion Plant in August 2016 to connect the user community with the wide range of robotic technologies and to obtain support from the stakeholders involved. This demonstration showcased the technologies in a realistic decontamination and decommissioning environment. More details about these demonstrations is included in Appendix E.

3. The DOE field offices were consulted to identify program and personnel risks that may be reduced with robotics. Clean-up schedules and needs/challenges that do not currently have a solution were also identified. A primary roadmap goal is to benefit ongoing and upcoming clean-up operations; therefore, ongoing interactions at the sites will be necessary. To sustain relevance, the roadmap must be updated on a regular basis. Clean-up site interactions will continue to provide feedback on the effectiveness of existing activities and guide planning for the future. Technology pull from the workforce is also important. Regular interactions with the workforce at each of the sites will assure that practical operations experience motivates the technologies pursued.

ROBOTICS DEVELOPMENT AND DEPLOYMENT STRATEGY

This roadmap will provide a high-level description of needs at EM sites, identify and assess key technologies, and provide recommendations for technology development and deployment. This roadmap is the technological vision that underlies TDO's existing development and deployment strategy. This strategy is based on the following elements:

1. ***Leverage technology and best practices.***
   Applicable technology is already available and being developed by DOE national laboratories, universities, industry, other federal agencies, and internationally. TDO will maintain a continuous outreach to facilitate communication and establish teaming relationships that support the clean-up effort. This effort will include technology from other federal programs, such as the National Robotics Initiative (NRI) and the National Networks for Manufacturing Innovation program.

2. ***Develop technology to address unique needs.***
   The legacy waste clean-up mission presents unique chemical and radiological challenges, as well as access challenges to aging facilities with varying levels of contamination. Existing technology will be adapted for use where practical, but some targeted development is anticipated. This development will occur, for example, through TDO requests for proposals, use of existing site funds, or targeted funding to sites, national labs or partners.

3. ***Prepare for future needs.***
   The scope of the clean-up effort, with decades of work and hundreds of billions of dollars of liability, requires a phased approach with near- to long-term perspectives. With many difficult challenges involved with multi-year technology development cycles, technology development must begin ahead of time to ensure that solutions exist when needed. Since base technologies associated with robotics and remote systems are continuously changing, diligent efforts will be necessary to track and adequately communicate the relevance and potential impacts of future developments on the coming decades of clean-up efforts.

4. ***Facilitate Technology pull.***
   Far too often, technology is developed only to sit on the shelf unused. This issue is two-fold; personnel are not aware of the usefulness of the technology and the technology may contain limitations that make it impractical. Due to the complexity of the EM mission, the DOE workforce and technology developers must collaborate on technology development. Collaboration must consist of the workforce educating technology developers on subtleties of the work and the developers educating the workforce on what the technology can do. Close collaboration will ensure successful development and deployment of systems that will make a true impact in clean-up projects.

5. ***Support site deployment.***
   The clean-up contractors are staffed to conduct the clean-up work. The contracting mechanisms and workforce must be considered in evaluating the risks and rewards of technology insertion. The contractor must be incentivized to deploy technology that can support and improve the DOE mission, even in the face of risks. The workforce will require training on how to best use the new technology and ensure its maintenance so that it can remain effective over time.

6. ***Transfer Technology.***
   Historically, DOE research and development has impacted many different domains. For example, the Argonne National Laboratory's Remote Control Division created the first robotic manipulators two decades before the introduction of industrial robots. Similarly, the unique needs and environments of the DOE legacy clean-up are likely to foster the development of technology capable of broader application to not only other parts of DOE, but also to other agencies and the civilian chemical and nuclear power industries, as well as potentially heavy industry. Transferring the technology to industry can leverage economies of scale to reduce the cost of the technology to DOE-EM. There is also potential for the technology to increase U.S. workforce competitiveness.

7. ***Facilitate International Common Interest Collaboration.***
   There are other chemical/radiological clean- up efforts conducted worldwide, and TDO will facilitate information sharing within this community. This facilitation benefits the U.S. by leveraging technology and best practices for application to DOE-EM's clean-up mission. The nation also benefits by sharing information with international partners to minimize risk to U.S. interests.

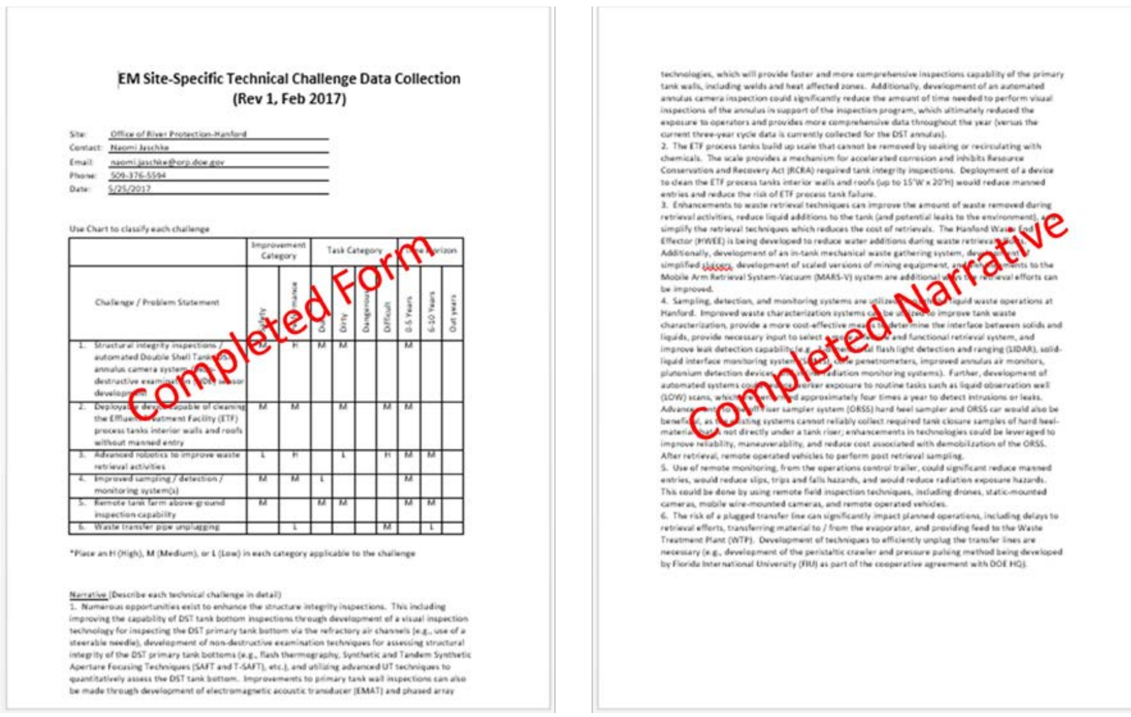
ROADMAP DESCRIPTION

The remainder of this roadmap will discuss specific needs, technologies, and plans related to robotics and remote systems that address the challenges and goals described above. Some of the relevant EM site needs where robotics may provide benefits are described in Chapter 3. Key robotic and remote systems technologies that are likely to provide the most impact are identified, described, and assessed in Chapter 4. Key conclusions, considerations, and plans for DOE-EM stakeholders are summarized in Chapter 5.

3. EM SITE NEEDS

The DOE-EM Robotics Roadmap will enable successful program execution only if it addresses the site needs where robotics and remote systems technologies can impact worker safety, enable new capabilities, reduce cost, and decrease the time required to complete this important work. The roadmap team performed the following steps to comprehensively identify needs across the DOE EM complex:

1. TDO and members of the roadmap team visited several sites over two years and learned about the needs of the sites.
2. TDO submitted feedback forms to all the EM sites, requesting identification of site needs.
3. TDO received completed forms (Figure 3) from EM sites identifying and describing their needs.



EM Site-Specific Technical Challenge Data Collection
(Rev 1, Feb 2017)

Site: Office of River Protection-Hanford
Contact: Naomi Jaschke
Email: naomi.jaschke@orp.doe.gov
Phone: 509-376-5594
Date: 5/25/2017

Use Chart to classify each challenge

	Improvement Category		Task Category				Time Horizon		
Challenge / Problem Statement	Safety	Performance	Dull	Dirty	Dangerous	Difficult	0-5 Years	6-10 Years	Out years
1. Structural integrity inspections / automated Double Shell Tank (DST) annulus camera system / non-destructive examination (NDE) sensor development	M	H	M	M			M		
2. Deployable device capable of cleaning the Effluent Treatment Facility (ETF) process tanks interior walls and roofs without manned entry	M	M		M		M	M		
3. Advanced robotics to improve waste retrieval activities	L	H		L		H	M	M	
4. Improved sampling / detection / monitoring system(s)	M	M	L				M		
5. Remote tank farm above-ground inspection capability	M		M	M			M	M	
6. Waste transfer pipe unplugging		L				M		L	

*Place an H (High), M (Medium), or L (Low) in each category applicable to the challenge

Narrative (Describe each technical challenge in detail)
1. Numerous opportunities exist to enhance the structure integrity inspections. This including improving the capability of DST tank bottom inspections through development of a visual inspection technology for inspecting the DST primary tank bottom via the refractory air channels (e.g., use of a steerable needle), development of non-destructive examination techniques for assessing structural integrity of the DST primary tank bottoms (e.g., flash thermography, Synthetic and Tandem Synthetic Aperture Focusing Techniques (SAFT and T-SAFT), etc.), and utilizing advanced UT techniques to quantitatively assess the DST tank bottom. Improvements to primary tank wall inspections can also be made through development of electromagnetic acoustic transducer (EMAT) and phased array technologies, which will provide faster and more comprehensive inspections capability of the primary tank walls, including welds and heat affected zones. Additionally, development of an automated annulus camera inspection could significantly reduce the amount of time needed to perform visual inspections of the annulus in support of the inspection program, which ultimately reduced the exposure to operators and provides more comprehensive data throughout the year (versus the current three-year cycle data is currently collected for the DST annulus).
2. The ETF process tanks build up scale that cannot be removed by soaking or recirculating with chemicals. The scale provides a mechanism for accelerated corrosion and inhibits Resource Conservation and Recovery Act (RCRA) required tank integrity inspections. Deployment of a device to clean the ETF process tanks interior walls and roofs (up to 15'W x 20'H) would reduce manned entries and reduce the risk of ETF process tank failure.
3. Enhancements to waste retrieval techniques can improve the amount of waste removed during retrieval activities, reduce liquid additions to the tank (and potential leaks to the environment), and simplify the retrieval techniques which reduces the cost of retrievals. The Hanford Waste End Effector (HWEE) is being developed to reduce water additions during waste retrieval efforts. Additionally, development of an in-tank mechanical waste gathering system, development of simplified sluicers, development of scaled versions of mining equipment, and enhancements to the Mobile Arm Retrieval System-Vacuum (MARS-V) system are additional ways the retrieval efforts can be improved.
4. Sampling, detection, and monitoring systems are utilized throughout liquid waste operations at Hanford. Improved waste characterization systems can be utilized to improve tank waste characterization, provide a more cost-effective means to determine the interface between solids and liquids, provide necessary input to select a more reliable and functional retrieval system, and improve leak detection capability (e.g., 3-dimensional flash light detection and ranging (LIDAR), solid-liquid interface monitoring system (SLIMS), cone penetrometers, improved annulus air monitors, plutonium detection devices, and in-line radiation monitoring systems). Further, development of automated systems could reduce worker exposure to routine tasks such as liquid observation well (LOW) scans, which are performed approximately four times a year to detect intrusions or leaks. Advancements to the off-riser sampler system (ORSS) hard heel sampler and ORSS car would also be beneficial, as the existing systems cannot reliably collect required tank closure samples of hard heel-material that is not directly under a tank riser; enhancements in technologies could be leveraged to improve reliability, maneuverability, and reduce cost associated with demobilization of the ORSS. After retrieval, remote operated vehicles to perform post retrieval sampling.
5. Use of remote monitoring, from the operations control trailer, could significant reduce manned entries, would reduce slips, trips and falls hazards, and would reduce radiation exposure hazards. This could be done by using remote field inspection techniques, including drones, static-mounted cameras, mobile wire-mounted cameras, and remote operated vehicles.
6. The risk of a plugged transfer line can significantly impact planned operations, including delays to retrieval efforts, transferring material to / from the evaporator, and providing feed to the Waste Treatment Plant (WTP). Development of techniques to efficiently unplug the transfer lines are necessary (e.g., development of the peristaltic crawler and pressure pulsing method being developed by Florida International University (FIU) as part of the cooperative agreement with DOE HQ).

Figure 3. Sample roadmap feedback form

4. The roadmap team identified additional needs by conducting conversations and site visits, as well as from documents and presentations prepared by site representatives.
5. The roadmap team aggregated the needs relevant to robotics and remote systems into general categories that affect multiple sites and missions.

A total of 12 sites provided feedback for the roadmap. Table 2 shows the seventeen aggregated EM needs and the number of sites that identified each need. The top two needs identified were Need 12 (Remote Remediation of Contaminated, Physically Challenging Spaces), identified by 11 sites, and Need 15 (Waste Material and Landfill Operations), identified by seven sites. Other needs that were identified by five and six sites each were considered high priority and significant to the complex.

Table 2. Aggregated site needs and the number of sites with each need

No.	Need Title	Sites with This Need
1	Nondestructive Assay (NDA) of Process Equipment and Piping	5
2	Remote Structural Evaluation	3
3	Site Modeling, Work Planning, and Training	2
4	Hazardous Material Handling	5
5	Fluid and Liquid Waste Processing and Removal	4
6	Process Equipment Removal	3
7	Visual Inspections and Inventory Control	6
8	Hazardous, Reactive, and Explosive Gas Monitoring and Removal	2
9	Access and Assessment of Confined, Physically Challenging Spaces	6
10	Mapping and Assessment of Underwater Radiation Environments	3
11	Material Handling and Manipulation in Glove Boxes and Hot Cells	1
12	Remote Remediation of Contaminated, Physically Challenging Spaces	11
13	Emergency Response	1
14	Worker Enhancement and Injury Reduction	6
15	Waste Material and Landfill Operations	7
16	Soil Characterization and Handling	3
17	Remote Equipment Maintenance and Repair	4

The following paragraphs summarize the aggregated EM needs and form the basis for technology identification and road-mapping. A description is provided for each EM need, with some examples of more specific embodiments of that need.

NONDESTRUCTIVE ASSAY (NDA) OF PROCESS EQUIPMENT AND PIPING

Before the Deactivation and Decommissioning (D&D) of many EM sites can be conducted in earnest, facilities and equipment must be assayed to determine the amount of contamination, which informs the amount of rigor required during the execution of the project. For example, process equipment components must be assayed before they can be segmented for size reduction and prior to recovery of nickel from converters. Existing methods for NDA in these environments are expensive, time-consuming and ergonomically challenging for personnel. NDA of large components is challenging because personnel must hold detectors in place for prescribed dwell times, often in difficult-to-reach positions while wearing substantial personal protective equipment (PPE). Long sections of piping must also be inspected for internal uranium contamination. Waste must be classified to determine appropriate processing and storage.

REMOTE STRUCTURAL EVALUATION

Many sites in the EM complex consist of aging structures, a number of which have not been used for many years. The structural integrity of tunnels, buildings, and other structures needs to be assessed before personnel can safely enter and to ensure stored materials are secure. Other areas are accessible to personnel, but structural issues may not be observable to them or detectable with existing methods (e.g., striking walls with a rod and listening to the acoustic response). Even structures not intended for personnel need to be evaluated for integrity of operations. There is a need across multiple sites to remotely assess the structural integrity of rooms, walls, tunnels, and other structures.

SITE MODELING, WORK PLANNING, AND TRAINING

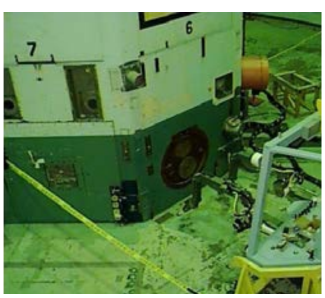
Site personnel use drawings and schematics, which are sometimes outdated, to plan work in new workspaces. In addition, separate drawings for each construction element (electrical, plumbing, ventilation, etc.) exist for most areas; therefore, no comprehensive representations are available. Furthermore, sites are currently generating a rapidly increasing volume of data. Personnel have limited spatial awareness of a workspace before entering, and it is challenging for personnel to manage the data and represent it in a seamless, easily comprehensible format. Personnel also face health issues when training in process-intensive buildings (full PPE and respirators in a hot, humid environment). Models could allow improved planning and realistic virtual training for workforce personnel. These models can also be used in real time to enhance remote operations and to improve situational awareness for complex tasks in physically challenging spaces. Changes to sites due to man-made or other factors (e.g., ground creep at WIPP) also need to be considered in site models.

HAZARDOUS MATERIAL HANDLING

At most DOE-EM sites, workforce personnel are required to handle materials that present at least one type of health hazard (e.g., ergonomic hazards due to size/weight, radiological, biological, or chemical contamination). Substantial PPE may be required to protect against radiological, biological, or chemical hazards; however, PPE can potentially increase ergonomic or physiological hazards. In most cases, personnel must only transport material over short distances—to sort and load it into trucks for long-range transport in D&D activities, for example.

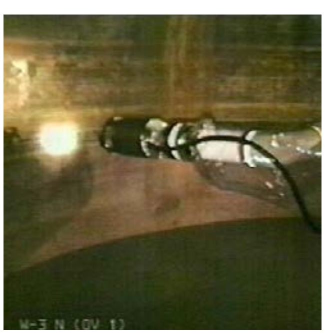
FLUID AND LIQUID WASTE PROCESSING AND REMOVAL

At most DOE-EM sites, fluids—many of which are hazardous (e.g., lubricating oils, fuels, and liquid chemicals from equipment and tanks)—must be drained, drummed, and re-located to an off-site disposal facility. Currently, the transfer of hazardous fluid is manually performed by workforce personnel in PPE. These tasks also involve repetitive heavy lifting, often requiring the efforts of two workers.



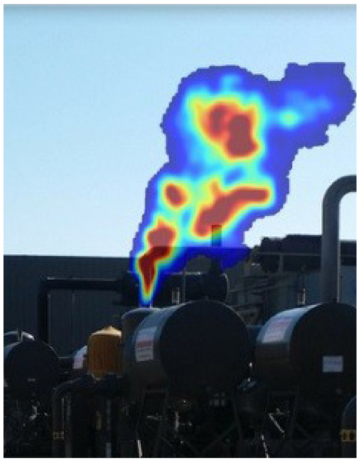
PROCESS EQUIPMENT REMOVAL

Large process equipment must be assayed and segmented for size reduction and recovery of any desirable materials. This work involves substantial physical hazards due to the size and contamination of the equipment. In many cases, workforce personnel must operate large equipment, including cutters, on lifts, ladders, or scaffolding. The presence of heavy objects, at risk of collapsing, around work areas also poses dangers for workforce personnel.



VISUAL INSPECTION AND INVENTORY OPERATIONS

Valuable and/or potentially hazardous items requiring regular inventories and/or safety inspections are stored in many DOE-EM sites. Waste containers, such as uranium hexafluoride (UF6) cylinders, and other items may produce low to moderate levels of radiation, increasing the risk of exposure to workforce personnel performing the inspections. In addition to the radiation dose challenges, it is challenging for workforce personnel to accurately inspect large numbers of items (in many cases thousands) without making mistakes.



HAZARDOUS, REACTIVE AND EXPLOSIVE GAS MONITORING AND REMOVAL

Measurements of reactive gases (e.g., surface ozone, carbon monoxide [CO], volatile organic compounds, oxidized nitrogen compounds, and sulphur dioxide), mercury vapor, and explosive gases (e.g., benzene, furan, hydrogen, hydrogen sulfide, methane, etc.) are critical for nuclear storage facilities, in order to determine which areas are safe for personnel to enter, protect against catastrophic loss, and to ensure ventilation systems are working as intended. Currently, monitoring of the amount of ventilation and/or hazardous gas concentration across the site is completed almost exclusively by human personnel, often while wearing substantial PPE, causing inefficiencies and potential dangers. The ability to remotely remove these gases would also prove beneficial for workforce personnel.

ACCESS AND ASSESSMENT OF CONFINED, PHYSICALLY CHALLENGING SPACES

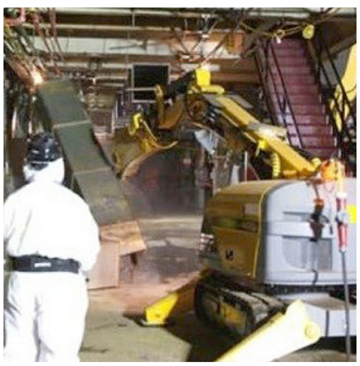
Multiple facilities across the complex include confined spaces of unknown physical condition and contamination. Often, these spaces are inaccessible to workers and may not have been explored for years or even decades. These spaces also may include limited physical access and/or lighting, wetted or pooled surfaces, and high levels of radiation. As a first step toward ultimate remediation, physical and radiation maps must be used to gain understanding on the condition of these spaces. For example, several underground areas of WIPP, as well as an exhaust shaft, are currently off-limits to workforce personnel due to uncertain contamination levels. Similar concerns exist in some areas slated for D&D. Other examples across the complex include the SRS H-Canyon Air Exhaust Tunnel and the Hanford Site PUREX Plant Tunnels. Furthermore, mapping is needed in smaller areas within nuclear facilities with limited access, including underground tanks at Hanford and SRS.

MAPPING AND ASSESSMENT OF UNDERWATER RADIATION ENVIRONMENTS

Multiple DOE-EM facilities include high-radiation nuclear waste products in underwater environments. Technology is required to inspect the contents in order to assess the radiological state of the stored materials, the structural integrity of storage containers, and the condition of the storage environment. These underwater spaces may have poor visibility and high levels of radiation, creating an unsafe environment for human inspection. A nuclear facility of particular interest is the Hanford Waste Encapsulation and Storage Facility, which has more than 1900 cesium-137 and strontium-90 capsules in underwater storage. Another nuclear facility of interest is the SRS L-Basin, which includes more than 18,400 fuel assemblies in underwater storage. Tank farms at Hanford and other sites require assessment of tank conditions, as well as chemical composition and precipitate volumes.

MATERIAL HANDLING AND MANIPULATION IN GLOVE BOXES AND HOT CELLS

Gloveboxes are widely used across the complex for handling radioactive and nuclear materials within an enclosed, hermetically-sealed, and controlled environment. Operators view the interior through clear walls or windows while manipulating the contents through long-sleeved attached gloves. The heavy glove material and negative air pressure within the boxes cause difficulties manipulating the gloves, reducing operator effectiveness and inducing fatigue. Furthermore, glove ports are at a fixed separation and height, creating ergonomic challenges and reach limitations for operators of different sizes. Maintenance can also become costly as gloves routinely require replacement. Similarly, work in higher radiation hot cells is conducted through outdated and heavy tele-operated manipulators with limited dexterity, particularly for grasping, causing challenges to personnel.



REMOTE REMEDIATION OF CONTAMINATED, PHYSICALLY CHALLENGING SPACES

Across the complex, significant amounts of waste and contaminated equipment reside in physically challenging spaces that are unsafe, difficult, or impossible for human personnel to access. Site examples include the Hanford PUREX Plant Tunnels, the underground tanks at Hanford, SRS, and others. Terrain at these sites may include substantial rubble, water, and other obstacles that will likely prevent conventional wheeled-vehicle access. Significant material movement, decontamination operations, and waste processing must be initiated before personnel can enter.

EMERGENCY RESPONSE

The unique hazards associated with DOE-EM missions present challenging emergency response requirements. Spills, fires, or other incidents, coupled with the unique work environments at the facilities of interest, cause human emergency response to be exceptionally dangerous and sometimes impossible. Remotely operated tools capable of quickly responding to these incidents, while performing more routine tasks during normal work operations, would provide a new response capability that is safer, more effective, and more efficient. By promoting dual-use of these remotely-operated tools across a variety of purposes, workforce personnel will become more familiar and more proficient in their use, and the equipment will receive a higher level of maintenance.

WORKER ENHANCEMENT AND INJURY REDUCTION

Many of the tasks required of DOE-EM facility personnel include challenging physical tasks, often to be completed with substantial PPE. These physically taxing tasks can only be completed by a small subset of the workforce and present substantial risks of musculoskeletal and ergonomic injuries. Examples of such tasks include the removal of transite panels at Portsmouth, as well as tasks requiring the use of heavy tools for extended periods. Assisting workers in these tasks could reduce injury risk and level the playing field to allow a broader number of personnel to perform these tasks.

WASTE MATERIAL AND LANDFILL OPERATIONS

DOE-EM's D&D facilities include contaminated and uncontaminated landfills for long-term waste storage. It is often difficult to classify materials as uncontaminated; therefore, materials are required to be transported to limited contaminated landfills. The loading of materials in trucks for transport to landfills is inefficient and dangerous, and human-operated bulldozers and other equipment in contaminated landfills expose personnel to radiation and other hazards. In addition to reducing and eliminating the risks to personnel, methods to classify the type of waste could increase longevity of contaminated landfills. There is also a general need to reduce the amount of contaminated waste that is generated and stored.

SOIL CHARACTERIZATION AND HANDLING

Sites, such as Y-12, contain mercury-contaminated soil that is expensive to treat. It is difficult to remotely characterize the amount of contaminated soil present, causing uncertain cost and time projections. Some remediation methods involve mixing the contaminated soil with specific chemicals to produce a stable product, a method which will be difficult to perform manually.

REMOTE EQUIPMENT MAINTENANCE AND REPAIR

Maintenance and repair of infrastructure or machinery can prove challenging at many DOE-EM facilities due to the challenging environments. Personnel access may be limited or impossible. In some cases, piping or other mechanical infrastructure may also need to be manipulated or repaired. Static or mobile machinery and other equipment (e.g., cranes, excavators, etc.) also require occasional maintenance. Even in cases where personnel can access the equipment, PPE requirements may limit their effectiveness in performing the required tasks.

Evolution of EM Site Needs

The above-list of aggregated site needs is a snapshot and is expected to evolve over the decades in order to effectively complete the EM mission. As such, this roadmap is expected to be updated periodically to capture changes in the site needs and priorities and to ensure the EM Robotics Roadmap is focused on current state-of-the-art technologies. For example, as more robotic and remote equipment is deployed at the sites, it is assumed more sites will identify EM Need 17, Remote Equipment Maintenance and Repair. It is important to note that not all of the aggregated needs have an identical impact on the overall EM mission. Additionally, it is important to consider the timing of the needs. Some needs are immediate while others will emerge over time. While there are some active remediation and D&D activities, many of the more challenging sites are currently undergoing an assessment phase, with remediation to follow in the coming years and decades.

4. KEY TECHNOLOGIES

Several corresponding key robotic and remote systems technologies have been identified based on the needs described in Chapter 3. The technology identification and roadmapping processes included the following steps:

1. ***Developing a list of technologies to meet the identified aggregated EM needs –*** The roadmap team compiled a list of robotic technologies that are required to meet the site needs. The team performed this process by listing up to 10 capabilities required to meet each of the aggregated EM needs. The team then identified up to 10 technologies required to provide the listed capabilities. The required technologies were then aggregated across all of the needs to obtain an initial list of technologies to discuss in the roadmap.
2. ***Engaging a broad set of robotics SMEs –***The roadmap team engaged robotics SMEs via a WebEx meeting and provided them a survey to assist in assessing the state of each of the technologies. SMEs were also asked to assess whether the technologies identified were adequate or if additional technologies were necessary. Some key technologies were added following the assessment.
3. ***Creating a short assessment of each technology area –*** The roadmap team wrote a short description for each technology identified and assessed its readiness and availability.
4. ***Completing a roadmap for each technology –*** The roadmap team assessed each technology in detail. Specific items considered for each technology included readiness, availability, and uniqueness to DOE-EM missions.
5. ***Developing conclusions and recommendations –*** The roadmap team crafted conclusions and recommendations for roadmap stakeholders, based on the analysis.

Each technology identified using the steps described above will be briefly described and assessed in this chapter. More detailed technology descriptions can be found in the supporting documentation that accompanies this roadmap. Each technology is assessed in three areas: readiness, ease of integration, and uniqueness to EM needs. The first two criteria are related but not identical. Some technologies may be mature enough for implementation but require significant effort to integrate into a DOE-EM facility due to lack of commercially available systems, extensive workforce training, or other reasons. For each criterion, the technologies are categorized as low, medium, or high. Because there is substantial breadth in both technology areas and EM needs, only broad categorical assessments are appropriate, since some technologies may be ready for implementation for certain applications but require additional development before broad application. A brief description of each criterion is as follows:

Readiness: Readiness assesses how close a technology is to being ready for implementation in relevant DOE-EM environments and is closely related to Technology Readiness Level (TRL). See the supporting documentation for a detailed description of DOE TRLs.

- Low – The technology requires fundamental scientific or engineering developments before it could be considered for EM implementation. Approximate DOE TRL 1–4.
- Medium – The technology may be applicable for some EM needs but will require development and/or engineering or integration efforts before deployment. Approximate DOE TRL 4–7.
- High – The technology is at or near the state that would allow it to be deployed in EM environments. Approximate DOE TRL 7–9.

Ease of Integration: Ease of integration assesses the relative amount of effort required to integrate a technology area into an EM site. Implementation of robotic and remote systems at EM sites will generally require integration efforts. These efforts may include tailoring to EM environments, testing/qualification, and workforce training. In some cases, even mature technologies may not be readily available for purchase due to the lack of a strong market driver.

- Low – Substantial planning and time (months or years) will be required to integrate the technology at EM sites. Substantial adaptation, market development, testing etc. are required.
- Medium – Some planning and time (weeks or months) will be required to integrate the technology at EM sites. Some customization, qualification, and training may be required.
- High – Technology is readily available and can be straightforwardly integrated at EM facilities (in days to weeks).

Uniqueness to EM Needs: Uniqueness to EM needs assesses how uniquely a technology applies to EM needs. Many of the technologies discussed in this roadmap are applicable to a variety of government and industrial problems. These technologies are also likely to be independently developed by other agencies or companies. Integration of these technologies to EM sites may be required; however, focused development may be unnecessary. A few other technologies are more uniquely suited to EM needs and are likely to require focused development if they are to reach maturity.

- Low – The technology has broad applicability in industry or other large markets.
- Medium – The technology applies to other industries but EM needs present some unique nuances that require consideration and adaptation.
- High – The technology does not have another obvious application market and is primarily suited to EM environments and challenges.

Key Technology Discussions

Each key technology will be briefly described and assessed, based on the criteria described above, in this section.

EXOSKELETONS FOR INJURY PREVENTION AND PERFORMANCE AUGMENTATION

Systems that can be worn by workforce personnel have been developed that can support human workers as they perform ergonomically challenging tasks. These devices may be passive (no external power) or active (powered) and may support various parts of the body to reduce strains on muscles and joints. While some systems are commercially available, they are relatively new on the market and their long-term benefits are still being evaluated. Careful consideration of training and workforce integration will be required. This technology applies broadly to many EM needs, including critical concerns about worker safety. While there are other industries exploring the use of exoskeletons (military, retail, construction, and assembly), their applicability to EM is somewhat unique in that EM's unstructured environments demand PPE. The high-consequence materials handled by personnel also pose individual considerations that require careful assessment before implementation could be approved.

Readiness
Medium

Ease of Integration
Low

Uniqueness to EM Needs
Medium

HUMAN-SAFE AND COLLABORATIVE SYSTEMS METHODS INCLUDING CONTROL ALGORITHMS

Traditionally, industrial robots and workforce personnel do not share workspaces due to potential injury to personnel. Recently, robots were developed that are capable of safely collaborating with personnel; however, these robots are typically low-force and cannot complete high payload manipulation tasks. Research is being conducted that might allow high-payload robots to work collaboratively with or nearby human personnel. These robots tend to include back drivable (low friction and inertia) capabilities and contain integrated force sensing across the entire robot. Control algorithms are also under development that permit not only proximity to humans but collaborative operations. Substantial personnel training would be required to fully deploy these systems at EM sites.

Readiness
Medium

Ease of Integration
Low

Uniqueness to EM Needs
Medium

DEPLOYABLE SENSORS TO CHARACTERIZE ENVIRONMENTS, INCLUDING VIDEO, GEOMETRY, STRUCTURAL INTEGRITY AND CHEMICAL COMPOSITION

For a visual "picture," sensors are required to map an environment in two-dimensions. For a geometric map that indicates range and volume, sensors are required to map an environment in three-dimensions. Light Detection and Ranging (LIDAR), with time of flight measurements or stereo cameras, is ubiquitous for these applications. Fiber optic, ultrasonic, and other sensors are used to measure structural integrity of walls or ceilings. Chemical sensors, such as spectrometers, can be used to determine local composition. These sensors exist individually but require integration and refinement for specific deployment platforms. Similar issues exist for each sensor: resolution, field-of-view, and the need for real-time collection and analysis. Sensors are also susceptible to noise and require extensive processing. For example, stereo vision data is available but produces sparse data clouds with low resolution, as compared to a LIDAR that is an active sensor. Some of these technologies are mature but require improved algorithms for fusing data into a common environment. Availability also varies due to the special materials pertinent to each type of sensor and the sensors may not be off-the-shelf. Given the enormous scale of some of the EM sites, improved sensing techniques to characterize structural integrity of large components at range may be required.

Readiness
Medium

Ease of Integration
Medium

Uniqueness to EM Needs
High

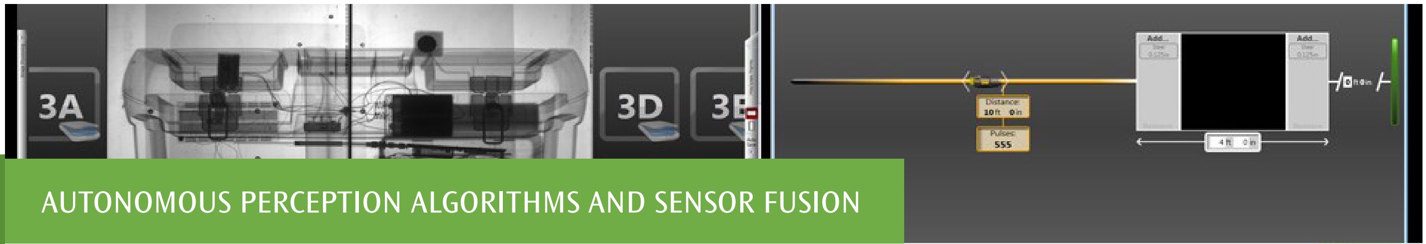
COMPACT, ROBOTICALLY-DEPLOYABLE, AND ACCURATE (α,ß,γ) RADIATION SENSING

Radiation sensors are used extensively throughout the DOE-EM complex. Most highly-accurate sensors are large and are not ideally suited to robotic deployment. Sensors for detecting ambient radiation and localizing radiation sources, as well as providing distributed radiation maps, are becoming more compact and energy efficient, as room temperature solid state detectors and digitized pulse generation and analysis circuits become more common and robust. Radiation sensor packages for gamma radiation are to include gamma energy spectroscopy for identification of radioactive isotopes. Sensor packages will also include detectors sensitive to beta and alpha radiation, available as commercial off-the-shelf components that are hand portable. While the detectors are quite mature, the size and weight characteristics of the sensing system necessary for robotic deployment remain a challenge, particularly for α and ß sensors. The most notable trade-off when integrating with robotic systems will be detection efficiency versus mass and volume. As with environmental sensors, robotic sensors exist individually but require integration with software and graphical user interfaces. This requirement is particularly true of mapping sensors that provide spatial radiation distributions.

Readiness
High

Ease of Integration
Medium

Uniqueness to EM Needs
High



AUTONOMOUS PERCEPTION ALGORITHMS AND SENSOR FUSION

Perception from sensor data applies broadly to many DOE-EM needs. Perception algorithms, which receive input from sensors, extract actionable information that can be used by higher-level controllers. This information includes recognizing and labeling objects, detecting anomalies, and detecting and locating particular signatures of interest in the presence of sensor noise. Computer vision techniques provide a baseline for object recognition from two-dimensional color imagery. Emerging techniques can also significantly improve performance by incorporating multi physics data via sensor fusion. Multi-sensor methods are also effective in detecting signals in high noise environments by assisting in reducing false positives. Many perception methods leverage machine learning, which is particularly effective at detecting anomalies without training explicitly to look for a particular anomaly types. The importance of autonomous perception will increase as DOE EM missions become more complex. Many pieces of this technology are maturing; however, broadly capable autonomous perception remains extremely challenging and substantial development will be required before these algorithms are reliably deployed. If learning techniques are used, the integration process will likely need to include training with large EM-specific data sets to enable perception in relevant environments.

Readiness
Low

Ease of Integration
Medium

Uniqueness to EM Needs
Low

REAL-TIME LOCALIZATION AND MAPPING FOR MOBILE PLATFORMS AND SENSORS

Localization refers to the process of determining the precise location (and perhaps orientation) of a robot or its sensor(s) relative to the environment. This information is important in creating maps of unknown environments, facilitating navigation, and fusing signals from multiple sensors. Mapping involves creating a geometric map of an unknown environment and may also involve overlaying other sensor information to that geometry. There is a broad need for both the localization and mapping of many site locations across the EM complex. Two technologies used for localization and mapping are Global Positioning System (GPS) and dead-reckoning. Outdoor localization can generally be obtained directly from GPS sensor readings, while dead reckoning is used to plot the trajectory of a mobile robot; however, dead-reckoning is susceptible to errors. When GPS is not available, robots use triangulation with natural or artificial landmarks and may combine this information with odometry. Inertial sensors that use GPS and dead-reckoning technology are mature and readily available. These two technologies are commercial, but triangulation technology (sensor and algorithms) is still in development due to ambiguity in locating targets. Artificial targets, such as beacons or reflective corner cubes in known patterns, can ease localization calculations. Algorithms that simultaneously localize a platform and generate a map of an unknown environment (simultaneous localization and mapping [SLAM]) have been developed but are computationally intensive and challenging to execute in realtime.

Readiness
Medium

Ease of Integration
High

Uniqueness to EM Needs
Medium

AUTONOMOUS NAVIGATION FOR VEHICLES, ROBOTIC PLATFORMS AND EQUIPMENT IN CHALLENGING AND UNSTRUCTURED ENVIRONMENTS

Autonomous navigation refers to the ability to plan an acceptable path from a starting location to a goal location while avoiding obstacles within the environment. Navigation technology applies broadly to many DOE-EM needs, especially those that involve remote operations. Inputs to the navigation process include known environment geometry, localization information, and a variety of sensing inputs. For many DOE-EM applications, the environment is poorly characterized and/or unstructured, which indicates that the final goal location may be uncertain or moving. Whole-body path planning and contact-rich path planning may be required to enable high-degree-of-freedom systems (e.g., mobile manipulators) to traverse confined spaces. The environment geometry and knowledge of that geometry may also change over the course of operations; therefore, the motion planning/ navigation system must also easily accommodate re-planning as information about the environment is updated over the course of operations. While some systems are commercially available, they are usually tied to a particular vehicle or platform and may be proprietary. The importance of autonomous (or semi-autonomous) navigation technology will continue to increase as the DOE-EM mission become more complex. Advances in automotive navigation are likely to provide an opportunity to leverage another large market; however, substantial unsolved problems in the navigation of confined and unstructured spaces remain.

Readiness
Low

Ease of Integration
Medium

Uniqueness to EM Needs
Medium

MULTI-AGENT CONTROL ALGORITHMS FOR COLLABORATIVE OPERATIONS BY MULTIPLE ROBOTIC SYSTEMS

For applications requiring remote robotic intervention, multiple coordinating robots may provide increased capabilities. Coordination could be particularly valuable for sensing problems that require distributed apertures, for the monitoring and prevention of faults in complex environments, and for completing manipulation tasks that are too force-intensive or challenging for a single platform. Looser forms of cooperation can enable faster mission completion by parallelizing tasks. A number of research demonstrations of multi-agent collaboration were conducted over the past 20 years, generally with simplified tasking and environments. Most methods require regular communication between agents and reliable localization. Substantial effort would be required to achieve robust, reliable operation for the complex, challenging environments typical of DOE-EM operations. Generating fail-safe operations of such systems will require significant advances in the cooperative monitoring, prediction, and active avoidance of fault conditions.

Readiness
Low

Ease of Integration
Medium

Uniqueness to EM Needs
Medium

MOBILITY IN CHALLENGING AND UNSTRUCTURED AIR, GROUND AND UNDERWATER ENVIRONMENTS

Mobility platforms for aerial, ground, and underwater environments are plentiful. Forward propulsion and steering capabilities to guide the motion of the platform for navigation is key to mobility. Platform options include fixed-wing and rotor-craft vehicles for aerial applications, as well as wheels, tracks, legs, or hybrid combinations for ground traversability. Thrusters or fins with tail action can be used for underwater mobility. Challenges to mobility are determined based on the difficulty of the platform to maneuver terrain or space based on potential obstacles and the complexity of the terrain. Wheeled and tracked platforms are ubiquitous. Navigation of more challenging terrain may require legged platforms, which are nascent. In general, larger ground vehicles are required to traverse larger obstacles; however, they are fundamentally more difficult to fit through small spaces. For the confined, minimally-structured environments commonly found at DOE-EM sites, mobility may introduce challenges that require customization of mobility solutions and, in some cases, the development of new mobility paradigms. Small platform mobility is readily available from the recreation and hobby market, and mid- to large-size platforms are available from specialized engineering companies that support the industrial military complex. In the most extreme environments, it may be necessary to consider robotics with less mature capabilities, such as climbing or jumping.

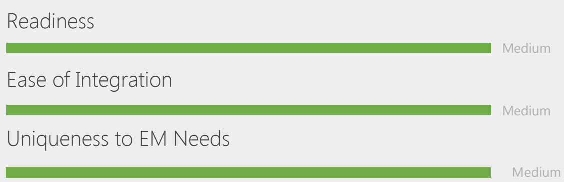
Readiness
Medium

Ease of Integration
High

Uniqueness to EM Needs
Medium

DEXTEROUS, MEDIUM TO HIGH PAYLOAD, MANIPULATION AND GRASPING

Dexterous manipulators are required in a wide range of static and mobile applications during DOE site remediation, such as handling hazardous materials that would be dangerous for workforce personnel. For some applications, the reach and payload requirements may tax readily available arms and hands. Some manipulators—for example, those pertaining to the remediation of waste underground storage tanks at the Hanford Site—must have cross sections that are compatible with the tank riser access ports, requiring a reach of up to tens of meters. Because these manipulator systems and their associated tooling will maintain mobile applications, their payload-to-weight ratios should be as low as possible. Improving much higher effective payload-to-weight ratios will require advanced control methods that exploit manipulator dynamics and kinematic singularities. These systems must be amenable to teleoperation interfaces or autonomous control. Both unilateral (position/velocity control) and bilateral systems (force, impedance control, etc.) are also required depending on the level of task complexity. A major enhancement in overall remote handling could result from effective multi-fingered end effectors that could span the payload range of interest. Improved multi-point end effectors would allow more direct use of standard tools and also enhance all remote grasping effectiveness. Manipulator arms capable of performing many easier manipulation tasks are commercially available. Considerable developments in radiation tolerance, end-effectors, dynamic control methods, and significant improvements in payload-to-weight ratio will be required for more challenging DOE-EM remediation applications.



INTUITIVE OPERATOR INTERFACES FOR TELEOPERATION, SEMI-AUTONOMOUS CONTROL AND DATA VISUALIZATION

Most robotic and remote systems use an operator interface for teleoperation and semi-autonomous control. This technology applies broadly to DOE-EM needs. Improvements in operator interfaces will also increase operational efficiency. This technology is applicable to all industries that use robotic systems and the market will expand as the use of robotics expands. Commercially available user interfaces have been used at DOE-EM sites for decades with positive results; however, use of traditional low-level teleoperation tools is generally slow and laborious. As cleanup tasks and environments become more complex, it is anticipated that a greater operational pace will be required to ensure progress is made before, for example, robot batteries run out. New technologies, such as tele-manipulation in glove boxes, will also require novel, intuitive control interfaces, as well as require integration of more advanced interfaces. Integrating a new user interface ranges from quick and simple to long and complicated, depending on the complexity of the robotic/remote system and the number of sensors and platforms used. In general, some customization and specific training is also required. More advanced interfaces, such as large touch screens, virtual/augmented reality, and haptic feedback displays are emerging that may provide further improvements to these controllers.

Readiness
High

Ease of Integration
Medium

Uniqueness to EM Needs
Medium

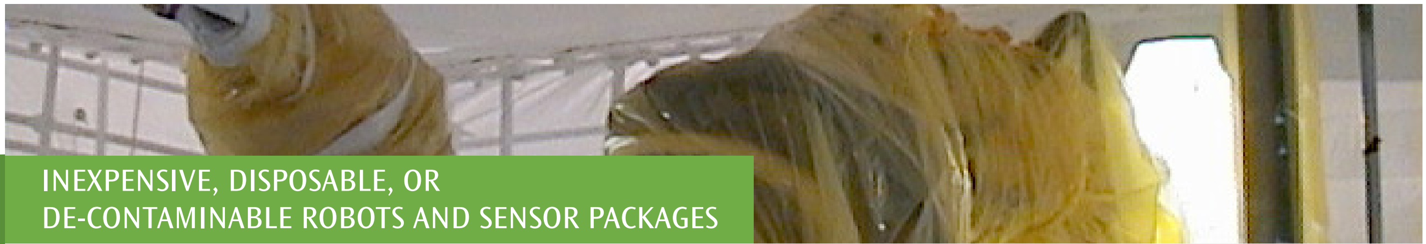
RADIATION TOLERANT ROBOTICS, MATERIALS AND SYSTEMS AND CONTAMINATION CONTROL

Deployment of robots and remote systems in DOE-EM facilities presents a unique challenge not typically considered in robotic applications. These units will be exposed to radiation, contamination, and harsh environments as they operate to accomplish their mission. As a result, systems used in these environments must be radiation tolerant or hardened depending on the expected dose rates and lifetimes. Designers must pay particular attention to electronics and plastics when designing equipment for this purpose. For equipment deployed in higher radiation areas, the design process should include a radiation tolerance evaluation. Literature and data are available to guide design, but some instances require conducting test evaluations on a certain material in order to obtain a full understanding of how a certain material will perform. Test facilities, required to perform such an evaluation, are normally found in a DOE national lab, where experienced engineering personnel familiar with the requirements for radiation tolerant systems can be consulted as a source. Contamination of equipment is also an issue, especially if equipment will be re-used or if the equipment will require repair.

Readiness
Medium

Ease of Integration
Medium

Uniqueness to EM Needs
High



INEXPENSIVE, DISPOSABLE, OR DE-CONTAMINABLE ROBOTS AND SENSOR PACKAGES

Due to the unique chemical, biological, and radiological hazards across the EM complex, robots may be contaminated in operations. It is typically costly, in terms of resources and occupational radiation exposure, to de-contaminate complex equipment for contact repair and reuse. In many cases, robots were left in place after a single use, unable to be recovered or reused. De-contaminable or disposable robotic systems would allow cost effective and rapid evaluations of scenarios that preclude human intervention. Inexpensive robots are also emerging in industry. These systems should provide a modular approach to the deployment of vision, radiation, chemical, and other sensor modalities. The mobility and manipulation packages should be modularized for different tasks so that most sensor and end-effector packages could be generalized. Disposable platforms, designed without careful attention to radiation tolerance, could be an inexpensive option with limited life expectancy. De-contaminable robots may also be developed that can be reused many times for different missions. These robots will require radiation tolerance and the ability to allow contamination to be fully and easily removed after hazardous operations. In practical terms, this maintenance implies smooth surfaces, minimal or no crevices, covers over complex components, and seals so the unit can be washed down with a spray wand. Robotic and remote systems will need to be adapted, and in some cases reconfigured, to meet these requirements. Focused development will be required for de-contaminable systems; however, this development is unlikely to be performed by other agencies or industries.

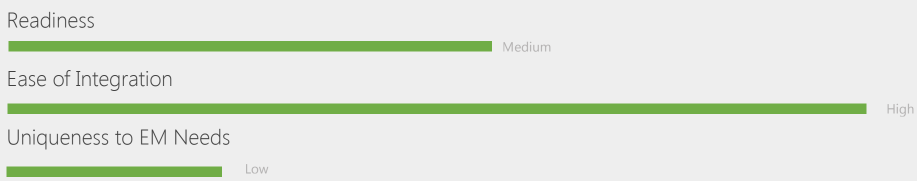
Readiness
Low

Ease of Integration
Medium

Uniqueness to EM Needs
High

COMPACT, LIGHTWEIGHT, AND EFFICIENT ENERGY STORAGE SYSTEMS WITH ELECTRICAL OUTPUT

Every robotic device, platform, manipulator, sensor, and processor requires electrical power to be received from an onboard energy storage system or through a tether. Depending on the technology selected, this design decision determines the amount of useful life available to accomplish tasks. Robot power consumption is based on its power utilization profile and whether consumables are used or if energy storage requires recharging. There is active research and development in this area, especially from adjacent markets in consumer electronics; however, improvements are always needed in power density and overall efficiency. Smaller robots are dependent on battery technologies, while larger platforms depend on internal combustion or a hybrid of solar panels, batteries for storage, and possibly fuel cells for extended operations. Rotary wing aerial platform payloads and mission durations are severely limited by battery power. For example, battery systems can account for as much as a third of the total weight of a ground robot. Lithium batteries can be susceptible to an explosion and fire, particularly in environments with unknown gas compositions. A similar safety concern also accompanies fuel burning systems. Waste-stream considerations are also relevant to the choice of energy sources, as many used batteries may be considered hazardous waste.



RELIABLE, HIGH-BANDWIDTH WIRED/WIRELESS COMMUNICATION IN CONFINED SPACES AND CHALLENGING ENVIRONMENTS WITH HIGH METALLIC CONTENT AND RESTRICTED LINES OF SIGHT

A cable tether is the most straightforward and common solution to supplying both power and signals to a remotely operated robotic system used in nuclear environments; however, the simplicity of cable tethers is offset by the challenges of effective tether management (e.g., avoiding entanglements and binding) necessary for tethers to operate across complex topologies and terrains. There are huge gains to be obtained if remotely deployed systems can be self-powered and receive/transmit signals wirelessly. There is a fundamental need to create high bandwidth (on the order of hundreds of megahertz) wireless data communication networks that can operate in EM environments. Today's wireless technologies are highly sophisticated and prevalent (e.g., IEEE 802.11), but they have not been applied to the types of environments typical in many nuclear applications, e.g., forests of metallic components and structures with high density concrete walls and limited lines of sight. These environments are notorious for signal multi pathing and other interferences. High data rate line of sight type communications have been used in the past where signal paths can be assured, but they are typically expensive. While the desired data rates are high due to imaging type sensors, the data paths are comparatively short (a few hundred meters or less). Additionally, EM environments may be dusty and contain chemical vapors, likely leading to premature damage of unprotected radio frequency (RF) components if not properly housed. A new class of wireless data networking tools are needed that are small, light, low-power, secure, and disposable. Smart (partially autonomous) and deployable repeater node concepts, capable of intelligently managing their connectivity through the available signal corridors, are required.

Readiness

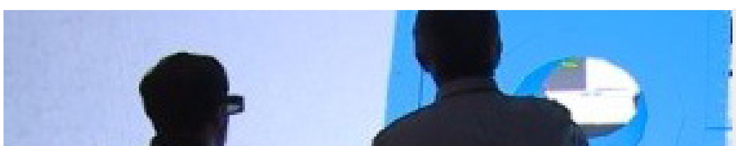
Medium

Ease of Integration

High

Uniqueness to EM Needs

Medium



HIGH PERFORMANCE COMPUTING SOFTWARE FOR DATA PROCESSING AND VISUALIZATION

The ability to quickly and efficiently process and/or display data is an essential function for large data sets to be useful. This capability allows human operators to easily identify patterns and trends which can lead to higher productivity or an alert to a possible dangerous situation. This capability is necessary as sensors or sensor suites are deployed to collect data from an increasing number of inaccessible locations in nuclear/hazardous facilities throughout the DOE complex. These sensors may include cameras (photos and videos), physical measurements, chemical characteristics, LIDAR, and other characteristics. The use of these sensors has the potential to produce extremely large amounts of data that can quickly become overwhelming. For example, LIDAR scans produce point cloud data that accumulates rapidly. High performance software tools that process large data sets and provide visual output to facilitate interpretation and recognition of trends are the key to addressing this challenge. Powerful computing hardware that is small and energy efficient continues to emerge and can be leveraged for DOE-EM challenges.

Readiness

Medium

Ease of Integration

High

Uniqueness to EM Needs

Low

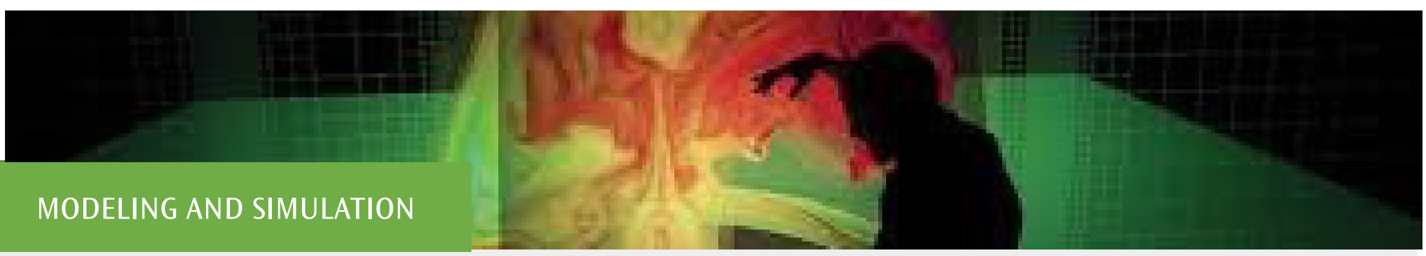
MODULAR PROTOCOLS FOR COMMUNICATION AND HARDWARE/ SOFTWARE INTERFACING TO PROMOTE INTEROPERABILITY

Modularity is a key aspect of systems design that provides a level of customizability to each unique application, a high degree of re usability across applications, and promotes interoperability between system components. For robotic systems, modular protocols and design paradigms can apply to hardware components, software components, communication interfaces, and data structures. Use of modularity within DOE-EM robotics missions will improve cost effectiveness as well as performance by maximizing levels of operator comfort when using different platforms. An example involves user interface consoles that control many types of air and ground vehicles, reducing re-training burden and improving operator competence. Another form of modularity involves data interfaces for sensor data, including video and LIDAR, that permits uniform storage and archiving for post-processing and analysis. Traditional manufacturers were slow to embrace modularity for fear of losing captivity of customers or liability concerns. For example, DOE pursued modular robotics concepts in the past, but often at elevated costs. Today, the complexity of software applications has forced many companies to embrace modularity in software and standard communications protocols as standard business practice. The robotics R&D community increasingly uses modular, open-source software for interfacing to common hardware, implementing autonomous behaviors, and other functions. Hardware modularity in robotics remains elusive, but is beginning to appear in cost-competitive form. How these open protocols can be applied to high-consequence applications is an open question that will require careful consideration.

Readiness — Medium

Ease of Integration — Medium

Uniqueness to EM Needs — Low



MODELING AND SIMULATION

It is often useful to create a virtual model of a system or task as a preliminary test of viability, prior to implementation of a physical system. Real-time simulation and “virtualized reality” can also be used as a tool during operation to improve situational awareness and to aid in fault diagnosis and reaction to unanticipated situations. Models can be physical or mathematical and are used in simulations to reduce risk, make decisions, support analysis, guide development, and initiate personnel training. Modeling and simulation assists developers in understanding a system’s behavior without actually testing the physical system or its behavior in a novel environment. The use of a robotics simulator can also save cost and time. Modeling and simulation tools are mature, with many products to choose from. These simulation tools are also available commercially. For EM, operations can be simulated within models of the actual environment, enabling evaluation of the feasibility of tasks with severe environmental constraints.

Readiness — High

Ease of Integration — High

Uniqueness to EM Needs — Low

SUMMARY AND CONCLUSIONS

Based on the descriptions and assessments provided above, some conclusions and recommendations for technology development can be made. In particular, the readiness of a particular technology and its uniqueness to DOE-EM can suggest a path forward for development and integration. Table 3 summarizes the technology assessments across these two criteria.

Table 3. Summary of technology assessments

	LOW READINESS	MEDIUM READINESS	HIGH READINESS
HIGH UNIQUENESS	Decontaminable Robots	Radiation Tolerant Systems Geometric/Environmental Sensors	Radiation Sensing
MEDIUM UNIQUENESS	Autonomous Navigation Multi-Agent Control	Exoskeletons Human-Safe Robotics Manipulation Communications Localization and Mapping Mobility	Operator Interfaces
LOW UNIQUENESS	Autonomous Perception	Modular Protocols/Interfaces Energy Storage High-Performance Computing	Modeling and Simulation

The groupings in Table 3 provide the first level of insight into potential technology development strategies for individual key technologies. Several important groupings may be categorized as follows:

- ***Broadly-applicable enabling technologies:*** As indicated near the center of Table 3 above, there is a grouping of many of the core competencies of robotics and technologies that are moderately ready for and moderately unique to EM's missions. These technologies are likely to continue maturing independent of EM's investments; however, some focused development and integration will accelerate the application of technologies to EM's challenges.
- ***High readiness technologies:*** Technologies indicated on the right side of Table 3, are ready or are almost ready for EM implementation. In fact, many of these technologies are already used in some form at EM sites. Radiation sensing is ubiquitous at EM sites; however, robotically deployable sensors will require some focused development. The highly unique applicability of these sensors to EM challenges justifies attention, despite the relative readiness of this technology.

- ***Applied R&D investments:*** Technologies indicated in the horizontal center of Table 3 are candidates for applied research and/or engineering development by universities, national laboratories, or industry.
- ***Long-term R&D:*** Technologies indicated on the left side Table 3 should be considered for long-term research and development by universities or national laboratories.
- ***Technologies unique to DOE-EM:*** The most unique technologies to EM are identified in the top row of Table 3. These technologies are generally radiation-related technologies, with the exception of environmental sensing. These areas are likely to require focused development by DOE-EM, as they are unlikely to evolve quickly for other applications, though space and commercial nuclear power have some overlapping interests.

Within each of these groupings, the development challenges/costs may be estimated via the “ease of integration” metrics. In addition, an analysis of the relevance of each technology to EM needs indicates that some technologies could result in a broader impact over others. While all of the technologies identified in this chapter have potential impact for DOE-EM missions, this analysis suggests that a subset of those are particularly well-aligned for research, development, or integration funding to accelerate that impact. Figure 4 shows a summary analysis of the key technologies applicable to the various EM needs described in Chapter 3. Some core competencies applied moderately to most or all needs. Other competencies applied strongly to a few needs and weakly or not at all to other needs. It is important to note that all needs do not have equal importance to the overall EM mission, as discussed in Chapter 3.

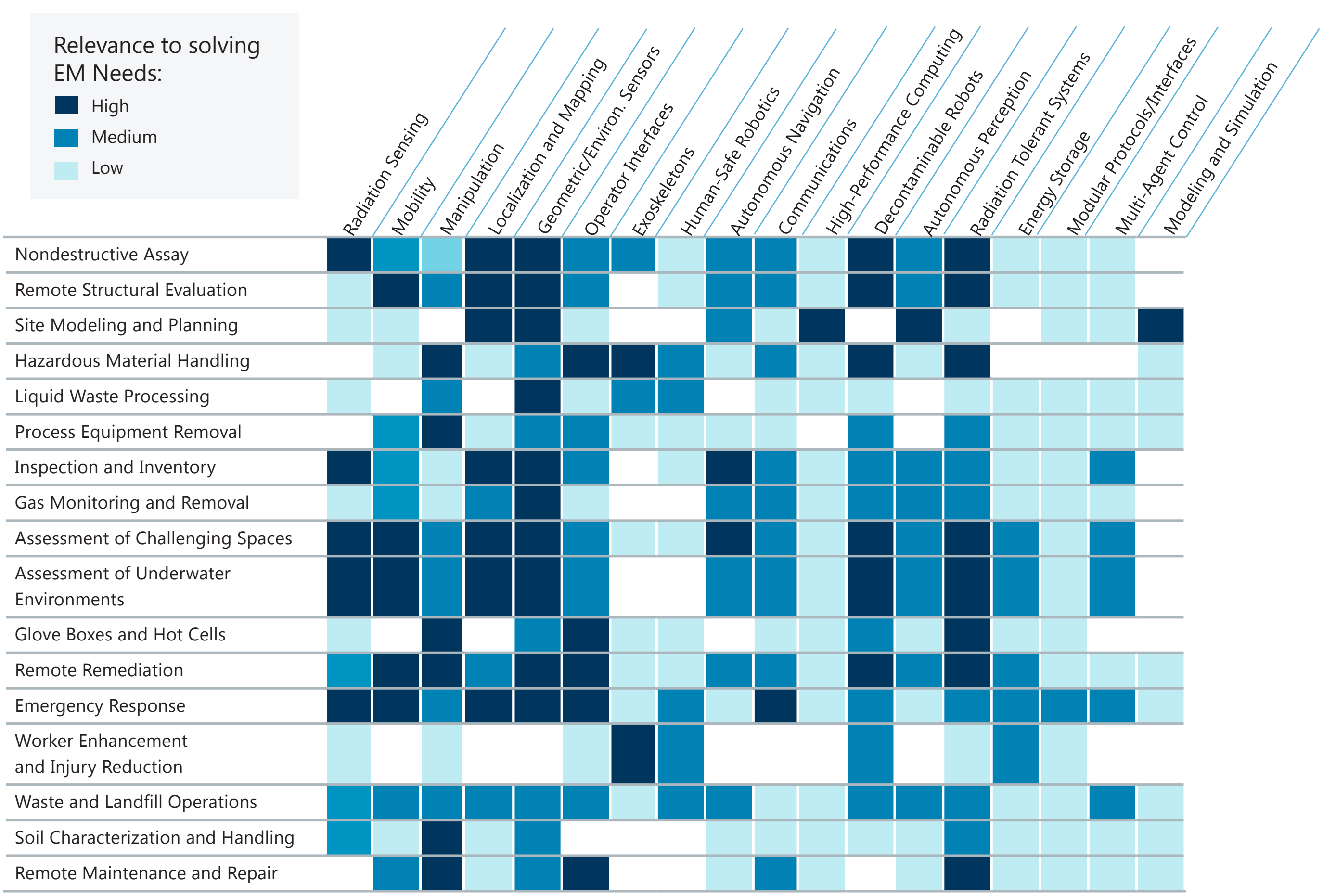


Figure 4. Relationships between aggregated EM needs and key robotic technologies

The following discussion identifies some technologies of particular interest for EM development.

Radiation sensors, radiation tolerant systems, and decontaminable/disposable robots: As previously discussed, radiation sensors and systems that are radiation tolerant and/or decontaminable are of particular interest to DOE-EM, with relatively little overlap with other emerging applications. DOE has recognized this interest and has invested some development funding in these areas in recent years. Radiation sensors require some miniaturizations and improvements to allow them to be readily deployed on robotic platforms. Additionally, these sensors are not trivial to field for some applications (e.g., NDA of process equipment) due to extensive qualification processes. Many applications, such as the assessment of unknown environments, should not require similarly extensive qualifications; however, these important factors must be considered as the sensors evolve. Radiation tolerant and decontaminable/disposable robots are less mature and warrant consideration for focused development by DOE. Technologies that are relatively mature (e.g., radiation sensors) could be developed and integrated by industry and funded by the sites themselves, with support from TDO and DOE's national laboratories as needed. Radiation tolerant and decontaminable systems are less mature; therefore, development should be overseen by TDO and performed by universities, national labs, and industry. Inexpensive/disposable robots may be developed independently for consumer applications, and these developments might be leveraged for EM use.

Environmental sensing, autonomous perception algorithms, and autonomous localization/ mapping/navigation: Many EM site needs require robotic systems to enter areas of unknown geometry, structural integrity, and contamination. In many cases, the system will need to localize itself relative to objects in its environment, map the geometry of the environment, and navigate to new locations. Video and geometric sensing have and will likely continue to evolve due to consumer applications. Structural and compositional sensors will require some focused development. The algorithms required to complete these tasks, even with advancing sensors, are in early- to mid-stage research and development. EM's environments present uniquely challenging, and as yet untested, demands on these algorithms and should be a focus of DOE's funded research and development portfolio. TDO should oversee R&D in this area and work should be executed by a combination of universities, national labs, and industry.

Exoskeletons and wearable robotics: Systems that can be worn by workforce personnel are of particular relevance to DOE-EM missions. Multiple sites indicated use of these systems as their top anticipated technology need in coming years to reduce injury, level the workforce playing field across age, gender, and physical ability, and increase worker capability/endurance. EM's work areas and tasks present particular difficulties for automation. The environments are unstructured and dynamic and the tasks are generally not overly repetitive; therefore, human personnel are likely to be heavily involved in task completion for many years to come. Teleoperated robots can provide stand-offs from hazards and may increase strength in some cases, but these systems can be slow and impractical for many applications. Augmenting workers with devices that can increase strength and reduce strains on the joints could have tremendous benefits in the future. Despite the unique hazards inherent in EM's sites, the dominant causes of injury are still related to overexertion, falls, or joint strains. Exoskeletons are now available in industry that may address some of these injuries. Other exoskeletons will emerge over time. Because these devices are intimately connected with individual personnel, careful consideration of their integration, acclimation, and training must be considered. These devices are nascent and long-term secondary effects have not been thoroughly studied. A carefully constructed integration plan is recommended that is specific to the task and environment where the system will be used. TDO is well-suited to oversee this development. Short-term solutions may be found in industry; however, universities and labs should be funded to support development of systems tailored to EM's needs and environments. To ease integration burdens on site managers, DOE's national laboratories can assist with integration plans.

Manipulation, mobility and associated control algorithms: Many of the most challenging EM remediation sites are currently in an assessment phase. Robotics with sensing capabilities may provide the most immediate benefits. Current D&D and remediation projects are complex, but the roadmap team expects the complexity of the work to increase over time. More challenging sites, such as highly contaminated and unstructured sites, that are currently under assessment will need to be remediated in the coming decades. The robotic platforms required to remediate these areas are more challenging to implement than those required for assessments, which generally only carry sensing capabilities. Highly mobile platforms with strong, dexterous manipulation will need to be developed if they are to be implemented as more challenging sites are remediated. Highly mobile platforms, high-payload dexterous manipulators, and the teleoperation and/or autonomous controllers that enable platforms are candidates for longer-term strategic R&D investments. Because of wide disparities between the most challenging facilities, advanced mobile manipulation capabilities will be needed across scales ranging from shoebox-sized to large construction equipment.

While the technologies discussed above are of particular importance to DOE-EM, developments in other key technologies described earlier in this chapter will also be needed and should be pursued independently by DOE-EM or in collaboration with other agencies. General technology development strategies will be discussed in Chapter 5.

5. CONCLUSIONS

The ultimate goal of this roadmap is to provide to DOE-EM stakeholders actionable information that can guide the development and integration of robotic and remote systems technologies, allowing EM's work to be completed in a safer and more efficient manner across the vast EM time scale. As discussed in the preceding chapters, robotics are well suited to impact several current and imminent EM challenges, particularly in increasing the health and safety of workforce personnel. The long-term impacts of robotics, as technologies mature over decades, are undeniable. Furthermore, within the time scale of the EM mission, small, targeted investments to accelerate development of key technologies of high relevance and uniqueness to DOE could have enormous cost implications over the lifetime of the effort. Due to the complexity of the environments and tasks, the Roadmap Team does not anticipate that robotics will replace a substantial fraction of the workforce at EM sites over the next decade or possibly beyond; however, the roadmap team does anticipate that advanced robotic and remote technologies will eliminate a substantial fraction of the remaining total dose and other risks workforce personnel are exposed to, increasing worker well-being and reducing DOE liabilities. The roadmap team also anticipates that many of the recommendations and outcomes of this effort will apply to other federal agencies, numerous U.S. industries and international stakeholders.

Three things seem clear, from this roadmapping effort and the survey effort reported in Appendix 2

- Robotic and remote technologies are already deeply entrenched in the DOE-EM mission and operations. There is wide acceptance of the need for robotics to keep workforce personnel safe and many successful examples of robotic applications exist that are helping to reduce risks and increase efficiency of current operations.
- DOE-EM investment in new technologies, including robotic and remote technologies, is historically low. While DOE benefits from advancements in the general scientific community, it is falling behind in technology transfer of many key technologies and is not adequately stimulating important areas of development that are unique to current and future EM applications.
- Site operators are not adequately incentivized to develop and deploy innovations to reduce the extreme scale of long-term worker exposure and remediation cost.

Figure 5 depicts an illustration of a high-level overview of a potential DOE-EM R&D strategy. Basic research, indicated on the left side of the figure, is aimed at solving high-impact, long-term challenges. While this research is inherently risky, the impact, if successful, should be high, with a multiplicative effect on long-term cost reduction. This work could be conducted by the DOE Office of Science or in collaboration with other federal agencies, such as the National Science Foundation (as DOE has been conducting as part of the recent NRI). This work is likely to be executed primarily by universities, national labs, or other research institutions.

The center portion of Figure 5 represents applied research and advanced development, including considerations about the environment where the system will be deployed. As this work is more closely tied to specific needs, it is appropriate for DOE-EM (through TDO) to shepherd this portion of the development cycle. EM sites and workers should also be engaged in this part of the process to ensure the approaches are relevant and to provide feedback on applications. The national laboratories can play a critical role in the execution of this work, as the laboratories include both the research and development expertise to evaluate and develop cutting edge technology, as well as experience deploying fieldable systems. Universities and industry may also participate in portions of this phase of development. Some technologies may be sufficiently more mature over other applications, and can directly enter applied research or advanced development.

The right portion of Figure 5 represents the final implementation of the technology at EM sites. This implementation includes testing in a relevant environment, training the workforce, and qualification. With oversight from TDO, the EM sites and their operating contractors should lead this phase of development to ensure it meets their specific needs. For situations where a moderate to high number of units are being deployed, industry is best suited to provide the technology to the sites, though national labs or other organizations may be involved in integration, testing, and/or qualification. For low-quantity applications, national labs or universities (in collaboration with labs or industry) may be able to provide deployable systems directly.

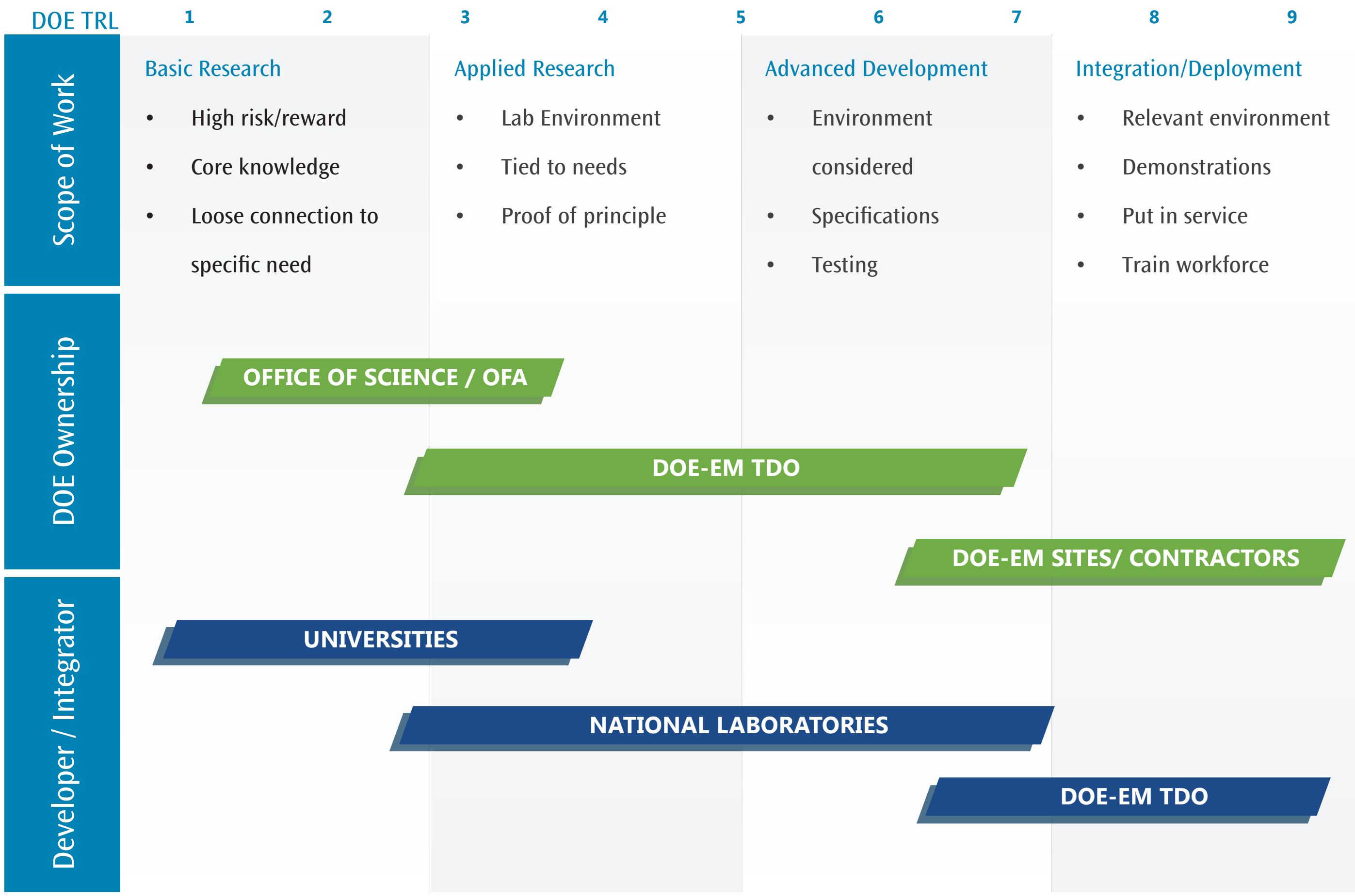


Figure 5. Potential DOE-EM robotics and remote systems technology development taxonomy

A balanced development approach that considers all phases of development is important to achieve long-term mission benefits. In recent years, DOE-EM has focused its limited development resources on relatively near-term problems, as indicated in the right portion of Figure 5, to support pressing technology needs at a few sites. While it is appropriate to focus the bulk of development on medium- to near-term solutions, the roadmap team advises that some portion of development be allocated to longer-term research challenges. While there is increased risk involved in long-term research and a longer wait in order to reap benefits, the potential impact can be significantly larger if the work is successful. The roadmap team anticipates that a technology development program focused on the next five years could yield a return on that investment of approximately 2X in terms of the overall EM budget. A more balanced, far-sighted R&D program that mixes short-, medium-, and long-term investments could yield a much higher return—perhaps 10 or 100 times higher—over 15–20 years. Depending on the size of the R&D program, this return could represent hundreds of millions of dollars or more of savings to taxpayers.

Considerations for DOE-EM Leadership

This section summarizes key conclusions and potential actions that apply specifically to DOE-EM Leadership as they consider how to develop and integrate robotic and remote systems to achieve their missions.

Prioritize research and development on technologies that are unique to DOE-EM missions and will reduce cost and workforce exposure. Even with increased investment, technology development funding is limited and must be intelligently allocated to achieve the highest impact. TDO can be empowered to make strategic, and sometimes speculative investments in technologies that have the potential to provide broad impact to EM missions. These investment decisions can be informed by the roadmap team, the broader scientific community and the DOE national labs. Some of these investments should be focused on areas that are not likely to be independently developed for other government, industrial, or consumer applications, but TDO can take a bold strategic view to provide leadership and balance the perspectives of the more conservative operational sites.

Technologies that are highly unique to EM needs are prime candidates for initial development. These were identified in Chapter 4 and include the following:

- Decontaminable/disposable robotics (low readiness, medium ease of integration)
- Radiation tolerant systems (medium readiness, medium ease of integration)
- Environmental sensors (medium readiness, medium ease of integration)
- Deployable radiation sensors (high readiness, medium ease of integration)

Of these four technologies, radiation sensors are the most mature and likely to be developed and integrated by industry and the sites. TDO should consider continuing to focus development resources on decontaminable and radiation tolerant robots and mobile sensor platforms to characterize unknown environments. This work spans the R&D spectrum and can be executed by universities, national labs, and industry.

Technologies that are not unique to EM but have potential for broad, long-term impact should also be considered. For example, developments in modular interfaces, protocols and interoperability could greatly accelerate development and deployment cycles over decades. Near-term investments in this area could reap large returns over the course of the EM mission.

Leverage developments by other offices, federal agencies, and industry. Many of the key robotic technologies will continue to be developed independently by the Department of Defense, NASA, other government agencies, and industry. EM can leverage these developments by conducting the following tasks:

- Maintaining awareness of robotics research across the government and industrial complex by attending conferences and meetings, leaning on national labs and other partners conducting work for related applications, and forming consortia with organizations with overlapping interests.
- Participating in collaborative funding mechanisms, such as NRI, to ensure DOE's interests are represented in calls for proposals.
- Advocating with the DOE Office of Science to ensure that investments are made in lower-TRL technologies that will serve EM's long-term needs.
- Actively partnering with developers to integrate maturing technology at EM sites, leveraging previous investments while ensuring EM requirements are met. Many solutions used in other sectors will not be immediately applicable to EM needs without focused integration efforts.
- Prioritizing direct funding for technology areas that do not progress sufficiently quickly to meet EM's pressing needs.

Balance short-, mid-, and long-term technology needs with operational considerations. As discussed above, a balanced R&D portfolio that addresses near-term challenges, while looking toward high-impact, long-term solutions, is appropriate for a mission that spans several decades. Near-term, low-risk solutions can be developed while research into higher-risk, higher reward solutions—with the potential to provide a more substantial impact in the long-term, if successful— is pursued. Long-term R&D can be completed in collaboration with the DOE Office of Science, the National Science Foundation, or other federal agencies. TDO should consider continuing to focus near- and mid-term development on key emerging site needs through programs such as the Nuclear Energy University Program (NEUP) while utilizing open-ended mechanisms (e.g. Broad Agency Announcements) to solicit ideas for high-impact, cross-cutting technologies. Managing a balanced portfolio will require a significant breadth of experience and expertise and the ability to work with developers from academia, labs, and industry. DOE national laboratories are uniquely suited to execute work across this spectrum and also work with non-DOE developers (e.g., as technical reviewers, advisors, testers, and/or integrators).

Specifically, short- and mid-term investments in EM environment-specific and wearable robots and mobile assessment platforms can be complemented by longer-term R&D investments in platforms that can manipulate the environment for remediation. This structure is well-aligned with the anticipated EM mission timeframe. More challenging sites will first be assessed before remediation efforts accelerate over the next 10–20 years. In parallel with these efforts, TDO should consider R&D in radiation-specific areas (radiation tolerance, de contamination capabilities, etc.).

Incentivize contractors to use emerging technologies as part of operating contracts. The contractors who oversee the EM sites generally negotiate fixed-price contracts to execute work and, by design, maintain a short-term and narrow focus in completing their scope of work. While appropriate in many ways, these contracts disincentivize risk-taking in integrating novel technologies or solutions. Modifications to contracts that motivate contractors to seek and implement novel technologies would accelerate the use of novel approaches, which may increase safety and/or efficiency. Contract provisions might include risk mitigation options for contractors who seek novel technologies or partner with TDO in implementing strategic goals.

Act as a liaison between sites and developers to get technology over the "valley of death." EM TDO can facilitate interactions between EM sites and technology developers in academia or industry to assist in sending novel solutions to workforce personnel. These interactions can ensure developers receive feedback in making solutions more applicable and also ensure the workforce is comfortable with emerging technologies. The DOE national laboratories, with R&D and deployment expertise, can act as a resource in these interactions to test and integrate these tools.

Restore technology development investments to pre-2000 levels. DOE made a conscious effort over the past 15 years to accelerate the pace of cleaning up and shutting down a large number of aging, highly contaminated facilities. This effort has been highly successful, both in objective measures of progress and in subjective measures of community citizenship. However, the remaining difficulties are complex and long-term (multiple generations of engineers and technologists) and demand technological solutions that do not currently exist. Current EM stakeholders must devise a long-term plan to realize these solutions.

Figure 6, shows the percent of DOE-EM's budget that was allocated to technology development from the 1990's to today. Technology development represented about 5.5% of the budget in the 1990's, while the current rate is below 0.25%. Technology development is by nature speculative. Some technologies advance rapidly, while others stagnate, never finding practical applications. Other technologies mature slowly for years, or even decades, before impacting real-world problems. Slowly developing technologies often provide the largest long-term impact. The acceleration of immediate clean-up efforts over the past fifteen years appears to have been a good investment, but the current investment in technology development is no longer adequate for future needs. It is time to restore a mix of speculative technology development and operational investments to meet the decades-long, technologically challenging EM mission that lies ahead.

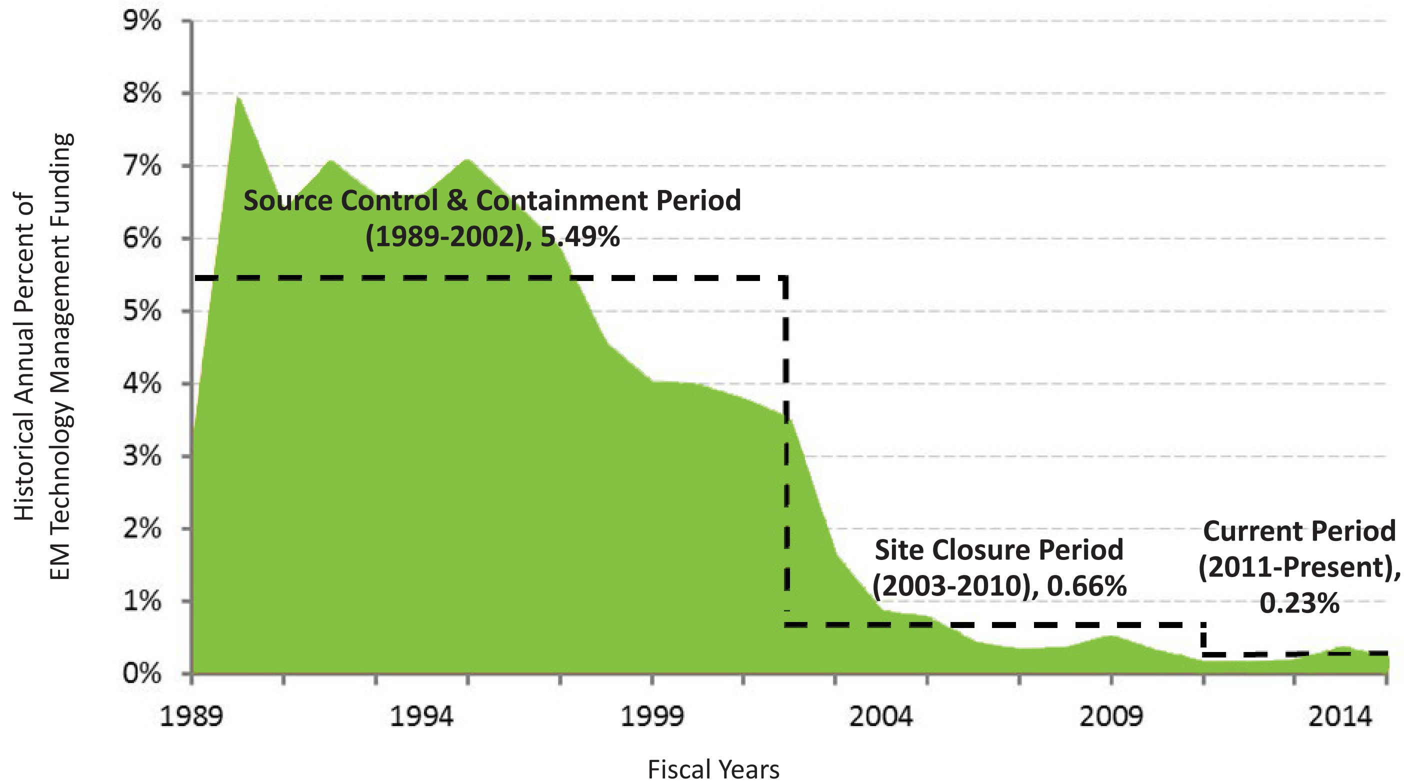


Figure 6. Historical technology funding of DOE-EM

Considerations for DOE-EM Sites and Contractors

This section summarizes key conclusions and potential actions that apply specifically to DOE-EM sites and their operating contractors as they consider how to integrate and deploy robotic and remote systems to complete their work.

Search for high-readiness technologies for near-term implementation. EEM sites should develop awareness of and search for appropriate opportunities to procure mature technologies that can impact their missions. As identified in Chapter 4, those technologies may include the following:

- Robotically-deployable radiation sensors (high uniqueness, high ease of integration)
- Intuitive operator interfaces (medium uniqueness, medium ease of integration)
- Modeling and simulation (low uniqueness, high ease of integration)

For many applications, these technologies can be rapidly procured and integrated to meet EM needs.

Search for applications where medium-readiness technologies can be applied rapidly. Due to the relatively broad technology areas used in this roadmap, there is a spectrum of readiness that depends on the specific application requirements. Many technologies that were assessed as having medium readiness contain available systems that will meet some of the needs at EM sites currently. For instance, exoskeleton systems are commercially available that may be appropriate for some EM tasks, whereas more generally applicable systems will require further development.

Robotic mobility and manipulation platforms that can be teleoperated are available and can address needs in some less challenging EM environments.

Lean on DOE-EM TDO, the national laboratories, and the roadmap team for advice on potential solutions and partnering opportunities. The TDO robotics team, including those on the roadmap team, are available to consult on potential technologies and solutions to guide decisions regarding if and how to implement new tools. Sites may be generally aware of a technology; however, they may be uncertain if it applies to their needs. Sites may also be approached by developers from universities/industry with potential solutions. TDO and the roadmap team can provide objective technical reviews of proposals and targeted developments/integrations if desired, since the technology discussions in this roadmap are brief by necessity. A roadmap team member may be contacted for more detail on any robotic technology, whether specifically addressed in the present document or not..

Consider workforce training aspects of robotic systems. Most robotic systems require some training for them to be operated safely and effectively. As robotic tools become more prevalent at EM sites, site managers should consider providing general robotic safety courses, in addition to system specific training. Dual-use applications, such as inspection robots that can double as emergency response tools, can increase the efficiency of training. In addition to training the workforce, site managers can actively solicit feedback from the workforce to ensure that the systems are meeting their needs and that potential improvements can be identified and fed back to TDO and developers. Proper training and preparation will help avoid the misuse of technology which can cause skepticism among the workforce and reduce openness to new capabilities.

Develop and refine technology acquisition and deployment mechanisms. Some robotic systems may be readily available commercially and can simply be purchased, with training and support provided by the supplier; however, some customization of the technology will be required in most situations. In these cases, careful consideration of procurement methods can ensure viability and sustainability of the solutions. When technology development and/or customization is required, the first step is often to define or refine the system requirements. A design can then be developed and/or refined to meet these requirements and a prototype system can be developed and tested. This testing may indicate that design iterations are required. When design refinements are complete, a small-scale pilot deployment may be appropriate to increase confidence in personnel and determine long-term viability before the solutions are deployed more broadly at all relevant sites.

Other technology acquisition-related principles should be considered during this process, such as the following:

- The technology acquisition strategy must consider acceptance by the contractors operating the sites.
- Sites should share solutions and lessons learned—both positive and negative—with one another to benefit the entire EM complex. A general knowledge of needs across the complex may facilitate more broadly-applicable solutions. TDO can facilitate this information exchange if desired.
- Sites should also consider maintenance, supply-chain, and intellectual property (IP) issues, which could increase cost or prohibit availability in the future, in order to ensure sustainable and robust technology solutions. During technology development and/or deployment, considerations should be made regarding how the technology will be procured and maintained over many years. Ideally, these resources will not be limited to a single company. DOE's national laboratories can act as a resource to provide sustainable technology for some applications, ensuring that DOE's interests are fully considered.

Ultimately, technology procurement methods must enable broad DOE mission success by assuring worker safety, environmental stewardship, and value to the taxpayer.

Cultivate relationships with technology developers. Relationships between several sites and certain national labs exist, which are healthy and bi-directional. It is evident, however, that the current reduced budgetary emphasis on technology development has created a culture where research and development is not perceived to be part of the site's mission, which may inhibit creative technological solutions. The EM sites and site contractors have a foundational role in R&D because they have the deepest insights into current and future problems. Sites can actively participate in R&D, both strategically and operationally. This involvement may involve information exchange with TDO and relationships with corporate developers, university researchers, and the DOE national labs.

Recommendations to Technology Developers

This section summarizes key conclusions and recommendations that apply specifically to the broader technology development community, including academic researchers, laboratories, international stakeholders, and industry as they consider ways to tailor their work to better apply to EM challenges.

Develop an understanding of EM problems before proposing solutions. Technology providers should seek an in-depth understanding of the EM site needs and challenges and carefully consider the implications of that knowledge on any proposed solution. This roadmap provides an overview of these needs and challenges, which are perhaps sufficient as a starting point for academic researchers proposing solutions that are not specifically tied to one need or site. Shorter-term, specific solutions will require more detailed knowledge of the nuances of the environment, tasks, and worker interactions. More detailed information can be found in specific DOE solicitations (e.g., NEUP), presentations, and publications. Developers are also encouraged to contact TDO, the roadmap team, and DOE's national laboratories for more information.

Engage workforce personnel throughout the development process. Because workforce personnel will interact closely with most of the robotic systems relevant to EM needs in the next several years, personnel should be engaged early in the development process in order for them to provide feedback on usability and to allow them to become comfortable with the technology. Workforce personnel can be engaged through TDO, DOE's national laboratories, labor unions, or EM sites directly. Acceptance by workforce personnel early in the process can increase the likelihood of successful technology transfer.

Develop an awareness of technologies of particular interest to DOE-EM. Until recently, DOE's robotics needs and interests have not been widely publicized. Researchers were perhaps less aware of DOE's priorities than they were of other, more prevalent applications. Independent of any specific funding mechanism, researchers may want to consider EM's challenges as they construct research plans and portfolios, as this emerging application maintains a strong potential for growth and aligns with other domestic and international material handling challenges. As previously discussed, many core robotics technologies, such as mobility, manipulation, localization/mapping, and navigation, are relevant to EM; however, other technologies are of specific interest due to high relevance and/or lack of overlapping applications in other areas. These technologies include the following:

- Radiation tolerant robotics and systems
- Decontaminable or disposable robotics
- Robotically deployable radiation, geometric, structural, and environmental sensors, along with associated perception, localization and mapping algorithms.
- Exoskeletons and wearable robotics that improve workforce personnel safety and/or effectiveness

A Notional Research and Development Path Forward

While investigating the above considerations, the roadmap team outlined a potential research and development path forward for meeting EM needs in both the short- and long-term. Due to budget and other limitations, most, if not all, of the technologies discussed in the present roadmap cannot be simultaneously developed; therefore, TDO must prioritize the most important technology development tasks. This prioritization should account for the readiness of the technologies, the relevance/uniqueness to EM missions, and the anticipated timing of EM site tasks. Figure 7 shows a notional balanced research program spanning approximately one decade. Technologies that are mature enough to be considered for short-term deployment at the EM sites are labeled on the right column. The sites themselves can lead this integration, with support from TDO and the roadmap team. Moderately mature technologies requiring some applied research or advanced development (by DOE's national laboratories, universities, or industry) are listed in the middle column. TDO is best suited to lead the development of these technologies. Technologies that require fundamental advances in capabilities before they can be considered for EM implementation are listed in the left column. The research can be conducted by universities and DOE's national laboratories, and can be overseen by the DOE Office of Science, in collaboration with TDO and other government agencies. As these sets of technologies advance over time, the technologies will shift to more applied development and ultimately preparation for site deployment. As initial technologies mature, additional fundamental technologies will enter the technology development pipeline (mid and lower left). It is important to note that DOE does not need to independently develop each of these technologies, as many of them will be concurrently developed for other applications. DOE can and should leverage these developments, as other agencies and industries will similarly leverage DOE's investments.

	Strategic, long-term R&D	Applied Research & Advanced Development	Information, Testing and Deployment
Years 1-3	• Advanced manipulation and mobility platforms • Multi-robot and human-robot collaboration	• Modular Protocols and Interfaces • Robotic environmental characterization/mapping • Exoskeletons for high-priority EM tasks • Radiation tolerant and decontaminable systems	• Robotically-deployed radiation and environmental sensors • Modeling and Simulation • Exoskeletons for targeted tasks
Years 4-6	• Full-body exoskeletons for task-agnostic worker augmentation • Autonomous navigation in unstructured environments	• Advanced manipulation and mobility platforms • Multi-robot and human-robot collaboration	• Modular Protocols and Interfaces • Robotic environmental characterization/mapping • Exoskeletons for high-priority EM tasks • Radiation tolerant and decontaminable systems
Years 7-9	• Humanoid robots and/or avatars	• Full-body exoskeletons for task-agnostic worker augmentation • Autonomous navigation in unstructured environments	• Advanced manipulation and mobility platforms • Multi-robot and human-robot collaboration

Figure 7. A notional balanced set of robotic and remote systems investments.

As an immediate path forward, the roadmap team identified a non-exhaustive set of steps that can be considered to accelerate the development and integration of robotics and remote systems at EM sites.

Integrate 2–3 robotic systems at EM sites to address acute personnel health and safety challenges. TDO and the EM sites have already started exploring novel robotic deployments that can address current site needs primarily focused on health and safety. This research should remain a priority, as pilot deployments can acclimate personnel to the technologies and provide essential feedback to developers in order to increase utility. Care must be taken not to over-emphasize the anticipated short-term benefits of the technologies to avoid disillusion of the workforce, which could proliferate to robotics in general.

TIMEFRAME: Currently underway and anticipated to continue for several years.

ROLES AND RESPONSIBILITIES:

- EM Sites:
    - Actively collaborate with TDO and technology providers to identify appropriate needs and solutions.
    - Provide developers access to the workforce for acclimation and feedback.
    - Use appropriate procurement methods depending on the specific solution being sought.
- TDO:
    - Facilitate interactions between sites and developers.
    - Provide technical guidance on potential technological solutions.
    - Clarify capabilities and limitations of technologies to calibrate site worker expectations.
    - Potentially provide funding for cross-cutting implementations.
- Technology Developers:
    - Learn the needs of EM sites prior to proposing solutions.
    - Clearly communicate proposed solutions and associated risks/benefits.
    - Involve workers in the development process.

Independently develop robotic solutions for the most challenging EM needs anticipated in the next 3–5 years. DOE-EM should identify a few pressing needs and associated technologies for focused development over the next few years. As discussed in Chapter 4, radiation tolerant or decontaminable robotics and systems that can map and assess unknown environments are prime candidates for this research. This development can be sought through BAAs or more task-specific RFPs.

TIMEFRAME: Currently partially underway via NEUP; consider expanding to other funding mechanisms in FY18 and beyond.

ROLES AND RESPONSIBILITIES:

- EM Sites:
    - Provide information to EM TDO regarding evolving mission challenges.
    - Support TDO and technology developers as work is completed to ensure relevance.
- TDO:
    - Develop solicitations for technology solutions.
    - Oversee development and facilitate interactions with sites.
- Technology Developers:
    - Adapt research priorities in consideration of EM’s needs.
    - Provide detailed responses to solicitations.

   » Develop proposals which are highly cognizant of EM challenges, as opposed to simply pushing new technology. Universities and industry should consider collaborations with EM sites and DOE national laboratories.

Actively leverage concurrent robotic developments in government and industry. EM should continue to monitor and search for opportunities to leverage developments in robotics for other applications. Other application areas of particular interest include military, space, mine safety, commercial nuclear power, and construction. Additionally, several international agencies are actively pursuing solutions to problems very similar to EM's. These collaborations can be accomplished via formal or informal consortia, attending conferences and meetings, and maintaining a network of robotics experts across the DOE complex, including the national laboratories.

TIMEFRAME: Currently underway and anticipated to continue for the duration of the program.

ROLES AND RESPONSIBILITIES:

- EM Sites:
   - » Search for robotic deployments in adjacent industries that may be applicable to EM needs.
   - » Consult TDO and the roadmap team for technical reviews.
- TDO:
   - » Provide support for DOE personnel and contractors to participate in robotics meetings and conferences.
   - » Plan targeted technical exchange opportunities for leaders in various sectors and internationally.
   - » Develop internal DOE expertise by supporting DOE national laboratories' efforts in robotics technology development
- Technology Developers:
   - » Participate in technical interchange opportunities.
   - » Consider EM applications as research and development portfolios are developed.

Independently pursue basic research and development for the most challenging long-term EM problems. In order to reap the largest possible return on R&D investments over many decades, DOE should fund fundamental research into technologies that are of particular import to their long-term needs. Based on the discussions above, robotic systems that can be used for the more challenging remediation efforts should be considered. Potential research areas may include novel mobility and manipulation capabilities that are contamination and radiation tolerant, as well as systems that include more autonomy. These considerations are not required to represent the majority of the EM R&D budget but should represent a non-negligible portion of it.

TIMEFRAME: Beginning in FY18 and continuing for the duration of the program.

ROLES AND RESPONSIBILITIES:

- EM Sites:
   - » Actively collaborate with TDO and technology providers to identify appropriate needs and solutions.
   - » Provide developers access to the workforce for acclimation and feedback.
- TDO:
   - » Identify the most pressing technological needs over the next 10–20 years.
   - » Collaborate with the DOE Office of Science and other federal agencies to solicit ideas.
   - » Ensure DOE's interests are represented in broad government research efforts.
   - » Utilize DOE's national laboratories to maintain internal DOE robotics R&D expertise.
- Technology Developers:
   - » Tailor research portfolios to include aspects relevant to EM missions.
   - » Respond to call for novel R&D.

Train the current and future workforce to use robotic systems. Most of the current EM workforce has not been trained to safely and effectively use robotic systems. As these systems become more ubiquitous at DOE sites, consideration of how to train not only current personnel but future personnel is important. In the coming decades, workforce personnel who are not only comfortable working with robots but are able to perform maintenance and repair will be necessary.

TIMEFRAME: Beginning in FY18 and continuing for several years.

ROLES AND RESPONSIBILITIES:

- EM Sites:
  - » Provide both system-specific and general robotics safety and operation training.
- TDO:
  - » Assist sites in developing training materials, with support from DOE's national laboratories and the roadmap team.
  - » Facilitate interactions between robotics SMEs and site workers.
- Universities:
  - » Provide courses and research programs that allow students to become familiar with robotics in general and radiation issues specifically.
  - » Consider providing vocational programs involving robotics, as they may be necessary as these systems become more common in many industrial settings.

Many of these tasks are already underway under TDO's leadership. The groundwork has been laid in recent years as TDO, DOE's national laboratories, EM sites, and other stakeholders have undertaken a focused initiative to provide better robotic tools to the workforce. This roadmap leverages that initial work and recommends some novel aspects and foci that the roadmap team anticipates will accelerate the integration of these systems, improving the safety and effectiveness of the workforce, EM's most precious resource.

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DOE-EM and the roadmap team would like to acknowledge contributions to this roadmap from several individuals representing the EM sites, DOE's national laboratories, other government agencies and the broader robotics community.

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Acronyms

ALARA	As low as reasonably achievable
BAA	Broad Agency Announcement
CO	Carbon Monoxide
D&D	Deactivation and Decommissioning
DOE	Department of Energy
EM	Environmental Management
GPS	Global Positioning System
LIDAR	Light Detection and Ranging
Mrem	Milli-Roentgen Equivalent Man
NDA	Non-destructive Assay
NDE	Non-destructive Examination
NEUP	Nuclear Energy University Program
NRI	National Robotics Initiative
OFA	Other Federal Agencies
PPE	Personal Protective Equipment
RF	Radio Frequency
RFP	Request for Proposal
SLAM	Simultaneous Localization and Management
SME	Subject Matter Expert(s)
SRS	Savannah River Site
TDO	Technology Development Office
TED	Total Effective Dose
TRL	Technology Readiness Level
WIPP	Waste Isolation Pilot Plant

SUPPORTING DOCUMENTATION

Contents

APPENDIX A ROBOTICS GLOSSARY OF TERMS

Algorithm – A systematic method for solving a certain kind of problem. Sometimes used more generally to mean any well-defined, systematic method of doing something.

Augmented Reality – A technology that superimposes computer-generated images on a user's view of the real world, providing an intuitive way to display simulated or enhanced information.

Automation – The automatically controlled operation of an apparatus, a process, or a system by mechanical or electronic devices that take the place of human organs of observation, decision, and effort

Autonomous Robot – A robot that operates in real-time with no human interaction

Closed-Loop – Control achieved by a robot manipulator by means of feedback information. As a manipulator or mobile robot is in action, its sensors continually feed-back information to the robot's controller which are used to further guide the manipulator/platform within the given task. Many sensors are used to feed-back information about the manipulator's placement, speed, torque, applied forces, as well as the placement of a targeted moving object, etc.

Control Mode – The means by which instructions are communicated to the robot.

Controller System – The robot control mechanism is usually a computer of some type, which is used to store data (about both the robot and work environment), and store and execute programs, which operate the robot. The controller system contains the programs, data, algorithms; logic analysis, and various other processing activities, which enable it to perform.

Degrees Of Freedom – The number of independent directions or joints of the robot, which would allow the robot to move its end effector through the required sequence of motions. For arbitrary positioning, 6 degrees of freedom are needed: 3 for position (left-right, forward-backward, and up- down) and 3 for orientation (yaw, pitch and roll).

End-Effector – An accessory device or tool specifically designed for attachment to a robot wrist or tool mounting plate to enable the robot to perform its intended task. (Examples may include gripper, spot weld gun, arc weld gun, spray point gun, or any other application tools.)

Environment – Of or pertaining to one's surrounding, sometimes the natural or real world around us, and sometimes the area in which the robot will be operating.

Force Feedback – A sensing technique using electrical signals to control a robot end-effector during a task. Information is fed from the force sensors of the end-effector to the robot control unit during the particular task to enable enhanced operation of the end-effector.

Intelligent Robot – An autonomous robot that may incorporate all or some of the following: exploits large amounts of knowledge; receives unexpected, and possibly unknown inputs; uses symbols and abstractions; communicates using some form of natural language; learns from its environment; exhibits adaptive goal-oriented behavior; and makes decisions.

Kinematics – The relationship between the motion of the endpoint of a robot and the motion of the joints. For a

Cartesian robot this is a set of simple linear functions (linear tracks that may be arranged in X, Y, Z directions), for a revolute topology (joints that rotate) however, the kinematics are much more complicated involving complicated combinations of trigonometric functions. The kinematics of an arm are normally split into forward and inverse solutions.

LIDAR – An acronym standing for LIght Detection And Ranging. An optical remote sensing technology which measures properties of light to find range and/or other information of a distant target. The most common method is to send laser pulses into the environment, and determine the distance to various objects by measuring the amount of time they take to reflect back. Other methods, like measuring the frequency of the reflected light, are also used.

Manipulator – An interconnected set of links and powered joints comprising a robot that supports and/or moves a wrist and hand or end-effector through space.

Mapping –The ability of a robot to enter an area, navigate, sense, and record information in such a way to allow an accurate map of the area to be constructed.

Navigation – The ability to direct a vehicle from one place to another.

Obstacle Avoidance – The ability of a robot to detect an obstacle or object in its environment and navigate without colliding with the object.

Payload – The maximum mass that the robot can manipulate at a specified speed, acceleration/deceleration, center of gravity location (offset), and repeatability under continuous operation over a specified working space.

Sensor – A device that detects some important physical quality or quantity about the surrounding environment, and conveys the information to a robot or processor in electronic form.

Supervisory Control – One or more human operators periodically programming and receiving information from a computer that interconnects through artificial effectors and sensors to the controlled process or task environment

Teleoperation – A means to use a machine that extends a person's sensing and/or manipulating capability to a location remote from that person.

Telepresence – The operator receives sufficient information from the robot and its task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site

Touch Sensor – A sensing device, sometimes used with the robot's hand or gripper, which senses physical contact with an object, thus giving the robot an artificial sense of touch. The sensors respond to contact locations and/or forces that arise between themselves and objects.

Virtual Reality – Experienced by a person when sensory information generated only by and within a computer compels a feeling of being there in an environment other than the one the person is actually in.

World Model – A three dimensional representation of the robot's work environment, including objects and their position and orientation in this environment, which is stored in robot memory. As objects are sensed within the environment the robot's controller system continually updates the world model. Robots use this world model to aid in determining its actions in order to complete given tasks

APPENDIX B TECHNOLOGY READINESS LEVELS

Technology Readiness Level (TRL) indicates the maturity of a given technology, as defined in the following table. The TRL scale ranges from 1 (basic principles observed) through 9 (total system used successfully in project operations). TRL is a widely used indicator of the degree of development of a technology toward deployment; on a scale of 1-9, with 9 being full deployment.

DOE TECHNOLOGY READINESS LEVEL □ DEFINITIONS
TRL 1 - Basic Research: Initial scientific research has been conducted. Principles are qualitatively postulated and observed. Focus is on new discovery rather than applications.
TRL 2 - Applied Research: Initial practical applications are identified. Potential of material or process to solve a problem, satisfy a need, or find application is the focus.
TRL 3 - Critical Function or Proof of Concept Established: Applied research advances and early stage development begins. Studies and laboratory measurements validate analytical predictions of separate elements of the technology.
TRL 4 - Lab Testing/Validation of Alpha Prototype Component /Process: Design, development and lab testing of components/processes. Results provide evidence that performance targets may be attainable based on projected or modeled systems.
TRL 5 - Laboratory Testing of Integrated/Semi-Integrated System: System component and/or process validation is achieved in a relevant environment.
TRL 6 - Prototype System Verified: System/process prototype demonstration in an operational environment (beta prototype system level).
TRL 7 - Integrated Pilot System Demonstrated: System/process prototype demonstration in an operational environment (integrated pilot system level).
TRL 8 - System Incorporated in Commercial Design: Actual system/process completed and qualified through test and demonstration (pre-commercial demonstration).
TRL 9 - System Proven and Ready for Full Commercial Deployment: Actual system proven through successful operations in operating environment, and ready for full commercial deployment.

The DOE TRL levels are similar to the DOD TRL levels as described in the Department of Defense's Technology Readiness Assessment (TRA) Guidance document dated April 2011 as prepared by the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)). The DOD TRL scale is shown here.

TRL	Definition	Description	Supporting Information
1	Basic Principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underline this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsytems. References to who, where, and when these tests and comparisons were performed.
4	Component and/ or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System components that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/ or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test resulta compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents then end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

The DOD Table has more definition than the DOE Table. Starting at TRL 5 on the DOE scale, the department transitions quicker towards an integrated system (or partially integrated system) where DOD is still focusing on components with an eye towards breadboard testing. Both TRL 6 levels are similar with prototype testing in relevant environments. TRL 7-9 are the same in both scales, but with slightly different language such as "Pilot Systems" and "Commercial Design".

Technical risks are a common denominator to assess project development costs and schedule potential overruns. Effective technical risk assessment is a necessity for program management. To be effective, technical risk assessment must be performed in advance so that DOE decision makers can clearly weight the risk/reward of continuing with a project. The technology risk assessment is based on lessons learned from previous projects, the experience of team members and advisors, and historical data from similar products developed.

The future success of the DOE project depends on the maturity of the underlying hardware, software, and integrated system (as measured by its TRL Level). First developed by NASA and as illustrated below, the TRL provides a means to assess the maturity of the building blocks, and in this case the underlying technologies.

This original NASA TRL Diagram lists the original 9 levels, but shows the overlap of levels of readiness. In NASA's TRL scale, component validation continues up to level 5, where a prototype or model starts at Level 6, and is still a part of technology development. The DOE Roadmap uses the same DOE TRL scale and also has this overlap. To accommodate for this overlap, the Roadmap team initially evaluated each technology on a three-level scale: high – medium – low, but also evaluated the technologies based on the important criteria of ease of integration and uniqueness to DOE-EM needs.

APPENDIX C KEY TECHNOLOGY DATA SHEETS

EXOSKELETONS FOR INJURY PREVENTION AND PERFORMANCE AUGMENTATION

Description: Robotics systems have been and are being developed that workers can wear to help them perform tasks more safely and effectively. Exoskeleton systems may support or assist one or more joints or may transfer the weight of the person or a tool to the ground, offloading some limbs and joints. Some of these systems are passive, requiring no external power supply, while others provide actuation. Actuated systems require an energy source to be carried or a tether to provide power. Because these wearable systems are intimately integrated with the worker, careful consideration to fit, comfort, adjustability, hygiene and donning/doffing must be carefully considered. Additionally, the mechanical impedance (mass, friction and stiffness) must also be minimized so the system minimally impedes the wearer's movements.

Maturity Assessment: Exoskeleton development began decades ago but practical system development has only been underway for 15-20 years. Full-body powered and passive backpack unloading exoskeletons were originally developed for the Department of Defense with low- to moderate levels of current integration into military environments. More recently, passive upper-body and soft assistive devices have been developed. Lower-body active devices have been developed and are currently in use for rehabilitation applications. In recent years, commercial exoskeletons have become available for industrial applications, primarily for upper-body joint support or tool offloading. Despite many companies marketing wearable systems, relatively little industrial adoption has occurred. However, automotive, aerospace and retail companies are now purchasing and integrating these devices into their workplaces. Initial feedback has been mixed. Many users find the devices helpful in reducing joint strain. Others are discouraged by the lack of comfort and obtrusive ergonomics of the devices. Academic and government research continues to explore more advanced systems, particularly soft systems.

Availability: Several exoskeleton systems for industrial applications are commercially available that apply to common manufacturing or construction tasks. These can be purchased in a few sizes with short lead times. For more unique tasks and applications, custom development by a company, university or national laboratory may be required. Before applying commercial systems to new application areas, careful consideration should be given to testing and workforce training and acclimation. Because these systems are more intimately connected to the workers, workforce buy-in is uniquely important.

References:

1. Exoskeltonreport.com
2. WearRA.org

HUMAN-SAFE AND COLLABORATIVE SYSTEMS METHODS INCLUDING CONTROL ALGORITHMS

Description: Traditional industrial robots were not designed to operate with or in proximity to human workers. Safety protocols require humans to not enter a robot's workspace when it could be operational. In recent years, efforts have been made to develop robots and control systems that can operate both in proximity to and with human workers. These robots generally include some combination of low-force capacity, backdriveability (i.e. low friction and inertia), distributed force sensing and intelligent control algorithms. Advanced concepts for human-safe robotics are also being considered, including soft robots.

Maturity Assessment: Relative to industrial automation, human-safe robots are immature. However, they are emerging in forms that can and are being implemented in some industrial settings, particularly for low-payload applications where the robot's strength is limited. It is generally assumed that control systems alone cannot be relied upon for safety but consideration of the robot hardware is also important. Low-impedance actuators with integrated force sensing have been developed that are appropriate for these applications. Robotic skins with distributed contact sensing are also under development. Control systems that work in concert with these hardware developments have been implemented. More advanced approaches to human-safe robotics, such as soft robots, are active fields of research, primarily in academia. These may become viable at some point but not for many years. While additional work is needed before robots and humans can work safely side-by-side while performing high-payload tasks, the field of human-safe robotics is advancing quickly and should reach maturity in timeframes relevant to the DOE-EM mission.

Availability: Most of the core components required for human-safe robotics are commercially available in some form. Low-impedance actuators and joint force sensors are readily available. Robotic skins that measure contract location and pressure are not commercially available in an integrated system but the core components of such a skin are available. A few human-safe robots are being actively marketed. These are for low-payload applications such as assembly and packing. High-payload robots that can operated near humans are not readily available. The control algorithms for these systems have been developed and tested in the research community and could be integrated into a full system in time.

References:

1. "Next Generation Robotics", Christensen et al., A Computing Community Consortium White Paper, arXiv:1606.09205, 2016

DEPLOYABLE SENSORS TO CHARACTERIZE ENVIRONMENTS INCLUDING VIDEO, GEOMETRY, STRUCTURAL INTEGRITY AND CHEMICAL COMPOSITION

Description: Deployable sensors can be either mobile (deployed on a mobile robot) or stationary (to be placed by a mobile robot). These sensors or sensor suites can be deployed strategically (e.g. in a line) or in specific locations such as the center of a room, depending on the application. These units can be self-contained (networked to data and power infrastructure) or integrated into a larger infrastructure of the environment. Characterization of the environment typically includes a 2D or 3D map. These maps are usually visual interpretations of measurements made by sensors. For example, sensors can be used to model an as-built structure to compare with architectural drawings or to track changes over time. Potential sensors to characterize an environment include, but are not limited to: 1) photographs and video, 2) geometric measurements, 3) testing and analyses for structural integrity, and 4) chemical or compositional analysis. A camera for still photography or a video camera is used to document a visual space. Depending on the conditions, the visual sensor may require additional lights and potentially a gimbal to expand the field of view of the sensor or a manipulator to both locate and position the visual sensor. Cameras are also available that image in non-visible (e.g. infrared) spectra. To measure geometry, there are several options such as LIDAR (scanning, flash, or nodding), or stereopsis (processing using a Gaussian pyramid) system. The result is a point cloud that could be fitted with surfaces that can eventually be labelled as objects (based on shape, color, texture, etc.). The environment can be reconstructed by understanding the kinematics of the sensor.

To get a complete picture of the integrity of a structure, measurement of strains, stresses, temperatures, and deflections may be required. There are fiber optic sensing instruments, including Bragg gratings that are packaged to gather such information. These can be arrayed into a network of sensors that is suitable for physically contacting the structure. Lastly, chemical analysis techniques are used to measure composition with potentially deployable instruments such as spectrometers, mass spectrometers, radiometers, and bolometers. Chemical analysis equipment can be used to characterize and quantify chemical components in gas, liquid and solid samples. This technique requires samples to be taken. For mass spectrometry, chemical species are ionized and the spectrometer sorts the ions based on their mass-to-charge ratio, thus determining content from a sample. To enhance spectrometry, this device can be combined with chromatographic separation techniques. This method produces a mass spectrum and/or three-dimensional contour map.

Maturity Assessment: Cameras and LIDAR are mature technologies, but may have to be hardened for the radiation environment. Similarly, there are several established manufacturers for fiber optic sensing instruments for structural analysis, as well as chemical analyzers, spectrometers, and radiation sensors. Individually, the majority of these sensors are mature but integration will be required.

Availability: Several sensors, LIDAR, fiber optics, chemical analyzers, spectrometers, and radiation sensors for industrial applications are commercially available that could perform the environmental measurements. There may be a level of integration required, as well as adaptation to the nuclear cleanup environment. Lead-time could be an issue if a part is not common or requires customization.

References:

1. Durrant-Whyte, H. and Henderson, T., “Chapter 35 Multisensor Data Fusion”, Springer Handbook of Robotics, Rev.2, Springer Publishing, ISBN 978-3-540-23957-4, September 2016

COMPACT, ROBOTICALLY-DEPLOYABLE, AND ACCURATE (α,ß,γ) RADIATION SENSING

Description: Sensors for detecting ambient radiation, localizing radiation sources and providing distributed radiation maps are becoming more compact and energy efficient as room temperature solid state detectors and digitized pulse generation and analysis circuits become more common and robust. Radiation sensor packages for gamma radiation, to include gamma energy spectroscopy for identification of radioactive isotopes, as well as detectors sensitive to beta and alpha radiation are available as commercial-off-the-shelf (COTS) components that are hand portable. Accurate quantification of α and ß radiation remains challenging for robotically deployed sensors. The detector, power supply, and associated electronics can be combined into a single package, or the processing signals can be sent via data cables (coaxial or digital) to allow the electronics and power supplies to be separated from the radiation exposure. These sensors can be used to measure environmental radiation levels, identify gamma emitting isotopes, and detect and identify alpha or beta emitting contamination. For contamination measurements, it is standard to take a "swipe" sample wherein a piece of filter paper is wiped across the surface of interest and then taken to a detector for the radiation measurements. This process is typically performed manually, but could be teleoperated or automated.

Maturity Assessment: The radiation detectors themselves are a very mature and reliable technology that has been used for 50-100 years in the radiation sciences field. Newer, digital, and more compact systems have been developed and put into COTS packages for many years, with each succeeding generation showing improved operation (battery life, on-board analysis capability, sensitivity to the radiation) and reduced form factor. These systems are now often digitally controlled and so are open to automated control by a remote operator. The operation of portable systems is limited only by size, weight, and battery life, and COTS systems with multi-hour power supplies are common. The most notable trade-off when integrating with robotic systems will be detection efficiency vs. mass and volume. A larger active volume will have a higher radiation detection efficiency and be able to provide useable data on a shorter time-scale. Systems for automating the collection and analysis of the radiation data have been offered by vendors, but integrated and easy to use automated data collection is less mature than the necessary hardware. The key challenge in this area is adaptation of radiation sensors to the size and power constraints for smaller robotic deployment.

Availability: Several radiation sensors for industrial applications are commercially available that could perform the gamma, beta, and alpha detection needed for radiation measurements. These systems are typically designed for handheld operations by health physicists or wall-mounted for area surveillance. Note that unless the only needed measurement is simple radiation exposure levels, a different radiation sensor, with its associated electronics and analysis components, is typically needed for each type of radiation to be measured. In the case of only gross counts of total radiation activity for alpha and beta radiation, which is typical of contamination surveys, then a single detector system will often suffice for both. The COTS systems have typical lead times of up to 90 days, but solid state detectors for gamma energy spectroscopy often have greater lead times due to the necessity of very high quality crystals as the active volume.

References:

1. Knoll, Glenn F. Radiation detection and measurement. John Wiley & Sons, 2010.
2. RAJAN, GOVINDA, and JOANNA IZEWSKA. "Radiation Monitoring Instruments." IAEA publication (ISBN 92-0-107304-6) (2005).

AUTONOMOUS PERCEPTION ALGORITHMS AND SENSOR FUSION

Description: Robotic sensor platforms with various sensors require sophisticated perception algorithms to make sense of the large volume of incoming data. The algorithms convert sensor data into actionable commands and output those commands to actuators in the predominant sense-plan-act robot paradigm. Autonomous sensor data processing algorithms are designed to provide the ability to easily utilize sensor data. Automatic algorithms based on finite state machines have been demonstrated for many years, but autonomous software relies on modern "artificial intelligence" algorithms. These algorithms include computer vision, which allows a system to recognize known objects and then automatically interact with them in some way, and machine learning, which in the context of anomaly detection entails developing systems to automatically detect anomalies without needing to explicitly train the system for a particular type of anomaly. Sensor fusion techniques are another process in the software architecture, and use tools and algorithms during the integration cycle, including relational databases or a Kalman filter, to combine sensor inputs in order to reduce system uncertainty. When a human needs to interact with the data, sensor fusion can also refer to combining the sensor data in a way that allows an individual to better see system status. In the processor, the higher-level algorithms typically used in artificial intelligence are hot topics of development, while low-level algorithms for control, reactive behaviors, and general signal conditioning have been around since digital control was introduced.

Maturity Assessment: Data processing algorithms require an appropriate hardware architecture that takes advantage of multiple GPU/CPU combinations, especially when machine learning techniques are implemented. Computer vision is a promising capability but requires extensive training time and data for the algorithms to classify objects with high accuracy while avoiding false alarms. The training data must be relevant to the intended domain, which is a challenge for EM applications. Machine learning algorithms are becoming common, but are still a developmental technology and are nascent for real-world applications. Sensor fusion is also a research topic with much work needed to have a fielded system. Fielded systems are still largely done on an ad hoc basis for a particular (usually quite structured) application. Fusing of large sensor data sets for general applications is still a relatively immature technology that will require additional research.

Availability: Individual algorithms are available, but integration with a software architecture is still required. Computer vision algorithms are abundant in universities as well as with a number of commercial vendors. Some cutting edge machine learning algorithms are embedded in private companies and may not be available for general use. However, there are 62 different autonomous architectures as reported by the Army Research Lab, and many ad hoc algorithms still require some degree of integration.

References:

1. Tom Mitchell, Machine Learning, McGraw Hill Publishing, ISBN-13: 978-0070428072, Copyright 1997
2. Durrant-Whyte, H. and Henderson, T., "Chapter 35 Multisensor Data Fusion", Springer Handbook of Robotics, Rev.2, Springer Publishing, ISBN 978-3-540-23957-4, September 2016
3. Berthoud Horn, Robot Vision, MIT Press, ISBN: 9780262081597, Copyright 1986.

REAL-TIME LOCALIZATION AND MAPPING FOR MOBILE PLATFORMS AND SENSORS

Description: Localization is associated with the location and potentially the orientation of a mobile robot, which in 3D space can be described with six degrees of freedom but this description can be reduced for a ground robot to 2.5 D problem. Localization is defined as either an absolute position (e.g. GPS defined location in world coordinates) or a local position. It is this reference coordinate frame of the robot that is used to register and locate sensory data about the environment surrounding the robot. What makes localization difficult is that the robot could be constantly moving, potentially introducing navigational errors if incremental sensors are being used (e.g. odometry). A common navigational technique is to dead-reckon with inertial sensors, and employ absolute localization to correct and reset incremental errors. Localization is important in navigation, which requires realtime updates as the robot follows a planned trajectory. For building a 2D or 3D map, localization is required to register sensory or payload data. For this application, localization may be accomplished in post-processing within some acknowledged error. For outdoor robots, GPS is available for absolute localization to determine the location and trajectory of the robot. For indoor, underground or other GPS-denied situations, the robot can localize by triangulating on both natural and artificial landmarks (e.g. employing beacons or planned targets). In a special situation if the robot is traveling in a straight line and is tethered, it is may be possible to measure the tether's reeled-out length to estimate the distance traveled. As stated previously, localization is critical to making sure that the robot is on its planned trajectory, but is also used to update the positions of the robot in a map. However, if there is no "a priori" map, then the robot can only wander or explore. More recently, there has been a large body of work on the "lost robot problem" where a mobile robot is dropped into a new and unknown environment. As the robot wanders, it builds a map about its travel and this technology is known as Simultaneous Localization and Mapping (SLAM). SLAM is an established algorithm with several variants having been demonstrated but most are computationally intensive and challenging to execute in realtime.

Maturity Assessment: GPS technology is very mature and is found everywhere. If the GPS accuracy is not good enough for mobile robot navigation, there are other options such as using the P-code (precision code) as opposed to the C/A code (civilian code), or implementing a relative GPS system. Unfortunately, robots in tunnels, caves, tanks, or indoors are considered GPS-denied environments. There has been some effort in psuedolites, but this would take special improvements to the infrastructure. Dead-reckoning is also very mature, but is prone to accumulated errors due to a variety of symptoms such as wheel slip. Triangulation on artificial landmarks is easier than using natural landmarks, but this assumes that the landmarks are in place prior to navigation. Like psuedolites, this would assume changes or improvements to the infrastructure. Measuring the amount of tether used is also a very mature technology, but only provides a rough estimate if there are no kinks and there is no slack in the tether. SLAM technology is in the research stage. Depending on its selected navigation sensor, the results vary from dense to very sparse maps. For example, multi-laser LIDARs can be real-time, but camera based systems require higher computations and for the most part can be near real-time or processed off-board the robot.

Availability: Robot inertial navigation systems (INS), GPS, and integrated INS/GPS systems are readily available commercially. Both INS and GPS have benefitted from the mobile phone market, leading to miniaturized and cheap components. Integrated INS/GPS system are used by the military, but tend to be larger ruggedized units. Due to the military market, these units are typically more expensive and include other military-type features such as encryption. Triangulation system performance is dependent on the software and processing platform. There are commercial optical systems made for inspection and registration in the aerospace industry, but they are not specifically used for triangulation of robots. Landmark detection and triangulation software are known to exist in research laboratories. Similarly, SLAM hardware is readily available, but system performance is poor based on the sensor/processing package utilized. SLAM software are also not commercial but various algorithms are available that could be adapted for EM use.

References:

1. Dudek, G. and Jenkin, M., "Chapter 29 Inertial Sensing, GPS, and Odometry", Springer Handbook of Robotics, Rev.2, Springer Publishing, ISBN 978-3-540-23957-4, September 2016
2. Stachniss, C., Leonard, J., and Thrun, S., "Chapter 46 Simultaneous Localization and Mapping", Springer Handbook of Robotics, Rev.2, Springer Publishing, ISBN 978-3-540-23957-4, September 2016

AUTONOMOUS NAVIGATION FOR VEHICLES, ROBOTIC PLATFORMS AND EQUIPMENT IN CHALLENGING AND UNSTRUCTURED ENVIRONMENTS

Description: For vehicles, robotic platforms, and equipment, the term autonomous navigation refers to the ability to plan an acceptable path from a starting location to a goal location while avoiding obstacles (including other equipment) within the environment. Inputs to the navigation process include known environment geometry, localization information, and a variety of sensing inputs. For many DOE-EM applications, the environment is poorly characterized and/or unstructured which means that the final goal location may be uncertain or moving. The environment geometry and knowledge of that geometry may also change over the course of operations. Therefore, the motion planning / navigation system must also easily accommodate re-planning as information about the environment is updated over the course of operations. A variety of autonomous navigation algorithms are being actively developed for consumer applications (principally self-driving cars). Some of this development will be relevant to EM environments but the unstructured nature of those areas will require additional, focused development.

Maturity Assessment: Obstacle avoidance, motion planning, and real-time (or semi-real-time) variants of autonomous navigation algorithms have long been and continue to be active areas of research. Given the large number of motion planning algorithms, few of which are optimal for a given environment, the greatest challenge is to integrate the available tools together into a usable navigation system for a particular robot or task. In most cases, this is done on a task-by-task basis which leaves little time or money for navigation system optimization or updating. The recent explosion in the use of drones and self-driving cars has resulted in a large number of navigation algorithms for flying and driving. Most of these methods work well in a relatively open environment, but do not work well when the environment is cluttered. Many navigation systems also stop working when they cannot receive Global Positioning System (GPS) signals. Cars and drones have a large enough user base to make investments in autonomous navigation technology economically viable. The autonomous navigation tools used for self-driving cars and for drones can be leveraged for use in DOE-EM environments but will need to be tailored to the DOE-EM tasks. Other navigation tools (i.e. for manipulators and equipment) are much less mature and will need significant development. Navigation systems will need to be trained with large amounts of EM-specific sensor and environment data before they can be used in those situations.

Availability: The autonomous navigation tools used for self-driving cars are nearly ready for commercial use. However, complete autonomous navigation systems that can be used on generic vehicles are still not readily available. Drones that are capable of automatic flight are readily available, but generally do not include the necessary systems to react intelligently to environmental changes. Overall, navigation systems tend to be integrated on a platform by platform basis. They are not readily available for purchase without purchasing a particular platform. They also need significant development for use in challenging unstructured environments.

References:

1. Bonin-Font, F., Ortiz, A., Oliver, G., "Visual Navigation for Mobile Robots: A Survey" Journal of Intelligent and Robotics Systems, November 2008.

MULTI-AGENT CONTROL ALGORITHMS FOR COLLABORATIVE OPERATIONS BY MULTIPLE ROBOTIC SYSTEMS.

Description: The simultaneous use of multiple physically independent and independently controlled robotic systems ("agents") may increase mission effectiveness. This is particularly true when the agents provide different, complementary capabilities. Such operations require dedicated algorithms that coordinate and synchronize the multiple agents to achieve the desired mission outcomes – particularly when operating in environments where operator situational awareness is limited, or where reacting or responding to unexpected data in real-time is required. For DOE-EM cleanup operations, there are three classes of multi-agent behaviors that offer potential benefits: (1) By tightly synchronizing their actions, multiple agents may be able to achieve improved task outcomes vs. single agents; (2) Multiple agents may enable faster mission completion by parallelizing effort; and (3) Collaborating agents may be able to improve each other's reliability and performance by sharing information about the environment and state, e.g. to avoid faults. The first of these classes aligns well with traditional, often bio-inspired, methods for consensus or "swarm" control, in which highly scalable teams of simple, usually identical agents collaborate on simple tasks by communicating limited information with their neighbors in a network. Examples include sensing with distributed, dynamic apertures and shared load carrying. The second class lends itself to "task assignment optimization" methods in which teams of potentially heterogeneous agents are each assigned a series of individual tasks such that a set of global objectives is optimized. For example, each of several agents may be tasked with mapping or decontaminating a portion of a facility, with agents assigned to different spaces based on the geometry and their mobility capabilities. The third class requires collective monitoring and cooperative control of the multi-agent system state relative to environment conditions, with particular attention paid to threats. For example, an aerial vehicle may monitor a ground vehicle's progress through treacherous terrain, anticipating faults such as tipping over or getting stuck and suggesting corrective actions. Each of these classes requires communication between agents and knowledge of location relative to each other and to the environment. For the first and third classes, it is critical that these data be shared in near real-time.

Maturity Assessment: Numerous research demonstrations have been conducted of collaborating robotic and unmanned systems. These demonstrations are supported by a substantial body of theoretical work that can, subject to certain assumptions, provide provable guarantees of convergence / stability. However, most practical demonstrations have been conducted on very simple tasks, e.g. moving in formation, converging on the source of an emission, or optimally visiting targets, and real-world implementations rapidly violate the key assumptions that guarantee system outcomes. No unified architecture at the multi-vehicle level has yet emerged that enables the seamless comparison and rapid exchange of algorithms to evaluate and improve performance. The third class of behaviors described above is particularly immature. While existing research could readily be leveraged to tailor scripted demonstrations to DOE-EM specific scenarios, achieving a trusted capability that is robust to the challenges of typical EM environments remains a substantial challenge.

Availability: Most prominent algorithms for multi-agent control have been developed at universities and research labs, and most are published in the open literature. Many researchers develop algorithms within Matlab and implement in the Robot Operating System (ROS) Libraries are available within ROS that implement some swarm functionality. Attempts have been made to establish programming languages to ease the implementation of swarms, e.g. Buzz. Despite the best efforts of researchers to develop platform-agnostic methods, most implementations are tailored to some degree to work with particular vehicles and therefore require significant adaptation / integration to work on specific platforms. In general, the intellectual property is available to implement existing collaborative behaviors, but substantial tailoring to both tasks and platforms will be required.

References:

1. http://wiki.ros.org/micros_swarm_framework, accessed 8/21/2017
2. http://the.swarming.buzz/, accessed 8/21/2017

MOBILITY IN CHALLENGING AND UNSTRUCTURED AIR, GROUND AND UNDERWATER ENVIRONMENTS

Description: Locomotion addresses the broad issue of getting a robotic system from point A to point B, which subsumes planning and mobility. Here, “mobility” is defined as the ability to move, or to move freely and easily, in various environments including ground, aerial, surface water, underwater, and underground domains. (An underground room, such as the WIPP or H-canyon exhaust shaft, is considered an example of ground mobility, not underground mobility.) Mobility is a 2.5D problem (direction and motion) for ground and surface water vehicles and a 3D problem for aerial, underwater and underground (e.g. tunnel borer) environments. Ground vehicles typically use wheels, tracks, legs, serpentine and vibratory modes of locomotion, but hybrid mobility modes (e.g. tracks plus limbs) are becoming more common. All mobility types require a propulsive force and a method to direct vehicle progress (i.e. steering) in multiple degrees of freedom, but the degree of control is another important distinction (i.e. omni-directional or non-omni-directional). Surface water vehicles are buoyant, but still require propulsion and steering (typically a rudder or directed thrust). Ruddered and Ackerman-steered vehicles are simple, but non-omni-directional, while legged and serpentine vehicles are typically complex, yet omni-directional. Likewise, fixed-wing aerial vehicles utilize airfoils for lift and must have propulsion for forward motion, making them non-omni-directional. Rotorcraft, including both helicopters and now the popular quadcopter (or other multi-rotor), as well as blimps, are omnidirectional vehicles. For aerial vehicles, launch, landing and recovery phases must be carefully considered. Underwater vehicles use thrusters, but researchers have also used fins for propulsion and steering. In open water, there is a special class of vehicles labeled “gliders” that use changes in buoyancy to bob up and down for long-duration, non-omni-directional underwater mobility.

Maturity Assessment: Mobility in simple and/or engineered environments is very mature, but mobility in unstructured and rubble-strewn environments is much more challenging. Two mature types of ground mobility in rubble include track/limb hybrids and the rocker-bogie concept, used by Mars rovers, but even these have strict limitations. Commercial offerings abound in the “suitcase size” form factor for all modes. Wheels can be problematic in challenging environments due to their dependence on friction and need for a continuous free path. Legged and serpentine mobility works extremely well in the unstructured, biological world, but maturity is lacking in engineered versions. Vehicles that have to dynamically balance to stay upright, such as humanoids, unicycles, and platforms with two wheels are even more immature. Biomimetic robots based on fish swimming and bees flying still require additional research. “Build or buy” remains a critical issue as challenging environments almost certainly require customization for success

Availability: General mobile platforms for air, ground and water are plentiful, inexpensive and off-the-shelf, but few handle challenging environments. The key parameters for mobility are time in air or range covered for a given payload. Mobile manipulation for air/ground/water is available but provides limited capabilities for unstructured tasks and environments.

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2. Bekker, M.G., Introduction to Terrain-Vehicle Systems, University of Michigan Press, USA, 1969

DEXTEROUS, MEDIUM TO HIGH PAYLOAD MANIPULATION AND GRASPING

Description: Dexterous manipulators are needed in a wide range of applications within DOE site remediation, particularly in dismantlement and decommissioning of remote facilities and equipment. In general, these manipulators must be compatible with the harsh radiological and chemical environments associated with legacy facilities and will be used to operate tooling for disassembling and dismantling equipment/components and to perform tasks involving material and object handling, e.g., waste materials packaging. Such manipulators need payload capacities in the tens to hundreds of kg and reaches in the range of 1.5 to 3 meters. It should also be noted that there is a special class of manipulator needs pertaining to the remediation of waste underground storage tanks, particularly those at the Hanford Site. These manipulators must have cross sections that are compatible with the tank riser access ports and they will require much longer reaches on the order of ten meters and payloads in the 30 to 50 kg range. All of these manipulators will require six degrees of freedom, and kinematic redundancy may improve maneuverability in the typically complex remote task environments. Because these manipulator systems and their tooling will have to be mobile to reach remote work sites within facilities, their payload to weight ratios should be as low as possible.

In addition to the harsh environments, it is inevitable that the manipulators and effectors have routine collisions/interactions with objects, making physical robustness critically important. Electrically actuated manipulators are preferable, but it is recognized that electro-hydraulics may be required for high payloads. These systems will be deployed in remote nuclear operations, therefore they must be amenable to teleoperations though remote control interfaces in addition to being suitable for autonomous or programmed control. Both unilateral (position/velocity control) and bilateral systems (force, impedance, etc., control) are needed depending on the level of task dexterity. A critical and unique requirement for these manipulator systems is that they be designed to the maximum degree possible for remote maintenance at the modular level and decontamination for component level maintenance and repair. In many applications, even though significant radiation/contamination condition will exist, conventional and carefully selected materials and components will suffice for achieve desired life expectancies. In some cases, radiation hardening for materials and components maybe necessary to achieve acceptable time-before-failure.

The workhorse end effector in nuclear operations is the standard parallel jaw gripper which provides two points/edges of contact and normally requires special tooling grasp fixtures or very tedious/careful grasping operations. A major enhancement in overall remote handling could result from effective multi-fingered end effectors that could span the payload range of interest. Improved multi-point end effectors would allow more direct use of standard tools and also enhance all remote grasping effectiveness.

Maturity Assessment: Robotic manipulators are a generally mature technology. Manipulators that meet the specific requirements of some DOE-EM missions are available but improvements in payload-to-weight ratio and robustness to harsh environments will be needed to meet the full scope of EM needs.

Availability: There are numerous industrial robot manufacturers who have manipulator offerings that can fit with some nuclear remote applications, including some radiation “hardened” systems. This class of manipulators are highly reliable and comparatively low in cost, but they are designed for manufacturing automation type tasks and environments and do not meet many of the nuclear remote operations requirements. There are also a few manufacturers of teleoperated systems for undersea operations, and these are typically electro-hydraulically actuated and designed for subsea pressure and temperature conditions. In the past, these have been in nuclear cold prototype demonstrations with good results. In general, there are few companies that offer systems designed specifically for nuclear applications. There are no multi-fingered end effectors in the size range of interest presently available. Robust and low-cost multi-purpose robot systems that provide effective remote control in the size range of interest are not generally available.

INTUITIVE OPERATOR INTERFACES FOR TELEOPERATION, SEMI-AUTONOMOUS CONTROL AND DATA VISUALIZATION

Description: All robotic and remote systems need some form of operator interface. This can range from simple switches to control the remote system movements to virtual reality environments controlling multiple systems with tactile feedback displays. Good operator interfaces also display appropriate data to the operator. The types of data supplied to the operator can cover a range from simple camera images to complex system operating parameters. Every operator interface requires some operating instructions and practice before the operator can conduct efficient remote tasks. A good operator interface is intuitive, requires minimal operating instructions, and displays the pertinent system data at the appropriate time. Robotic and remote systems can be operated in three different manners, tele-operated, semi-autonomously, and autonomously. A tele-operated system requires the operator to control the system at all times, like driving a car. A semi-autonomous system allows an operator to control the system or the system computer to control parts of the system, like a self-parking car. An autonomous system receives high level commands from an operator; then the control system uses sensors and software to complete the desired task, like a self-driving car. For DOE environments, fully autonomous systems will be used on a very limited basis due to the unknown factors in most tasks. These include unstructured environments and changing conditions. Intuitive control interfaces with advanced feedback may be necessary to teleoperate robotic systems for the most challenging EM tasks.

Maturity Assessment: Operator interfaces for robotic and remote systems range from very mature to research and development projects. Computer programs have served as operator interfaces for decades, but there are no accepted interface standards so each manufacturer develops their own interface. As computer and graphics technologies got better over the years, the operator interfaces have also improved. Most robotic systems also have the capability to receive commands and send status to other computers. This allows for manufactures and users to develop systems with multiple remote devices and sensors. This integrated system will have its own operator interface and usually is commanding the subsystems to operate in a semi-autonomous mode. Again, without accepted standards, these integrated user interfaces can range from intuitive to complicated and hard to understand. The commercial industry has seen a rise in game controllers as user interfaces for tele-operated systems. Younger operators typically are comfortable with the game controllers, and the controllers are very cost effective. Virtual Reality (VR) and Augmented Reality (AR) are relatively new technologies that can provide an enhanced operator interface, a simulated training environment, and excellent data visualization platforms. The VR and AR systems are commercially available now and research is underway on VR/AR remote system operator interfaces and training systems. Haptic feedback controllers or wearable tactile displays are also under development that may provide more intuitive remote feedback to operators.

Availability: All robotic and remote systems are delivered with a user interface that performs the required functions. Unfortunately, an intuitive interface that provides teleoperation, semi-autonomous control, and good data visualization is rare. The reasons for this are; 1) the cost to develop and test the interface, 2) customers don't value an intuitive interface (and therefore do not want to pay for one) until after hours of using the system, and 3) no accepted standards for user interfaces, which leads to development of user interfaces on a system by system basis with little re-use of previous work.

References:

1. https://en.wikipedia.org/wiki/Human%E2%80%93robot_interaction
2. O'Hara, J. M., Brown, W.S., Lewis, P. M., Perensky, J.J. (2002). Human-System Interface Design Review Guidelines. NUREG-0700, Revision 2. Prepared for the U.S Nuclear Regulatory Commission, Washington DC.

RADIATION TOLERANT ROBOTICS, MATERIALS AND SYSTEMS

Description: Deployment of robots and remote systems in DOE-EM facilities presents a unique challenge that is not part of typical robotic applications. These units will be exposed to radiation and contamination as they operate to accomplish their mission in addition to harsh industrial environments. This exposure can limit the effectiveness and longevity of the platforms. Electronics and polymers are likely the most susceptible to the effects of radiation. The effects of radiation exposure on materials is a function of accumulated dose, therefore the dose rate and time required for a particular mission must be considered when evaluating designs for nuclear service, as well as potential exposure to chemical or other hazards. Many applications do involve exposure which humans should avoid, although, with dose rates below a level that would impact typical commercial robots and components. In this situation, the preferred method is to use standard commercial parts since they are readily available and much less expensive. Designers must pay particular attention to electronics and plastics when developing equipment for use in nuclear facilities. There are a number of plastics which hold up in radiation much better than others. In most cases, radiation tolerant plastics and electronics (e.g. processors, cameras) are of the more expensive engineered plastic variety. Being aware of materials such as Teflon which are very susceptible to radiation effects also helps the designer avoid problems. For equipment planned for higher radiation areas, the design process should include a radiation tolerance evaluation step. There is some literature and data available to help with this process, but there are times when a test program on a particular material must be conducted to understand how a material of interest will perform. In order to perform such a test, a test facility is required which likely would involve a national lab. The DOE National Labs and some universities can also be a resource for design and testing expertise. There is even specialized knowledge of facility specific requirements within the facility design authority engineers that can be very useful to designers. In addition, there are design techniques such as providing shielding around vulnerable components protecting them from the expected radiation or at least lowering the dose rate to a level that will provide a useful life.

Maturity Assessment: Robots, sensors, electronics and cameras for the applications under consideration are relatively mature technologies minimizing the risk for deploying the units in nuclear facilities. Many times the choice is to use COTS devices due to their lower cost and simply consider them disposable once they have achieved their mission. This is especially true since many robotic applications are short term by definition. In situations where a system would be permanently installed in a high radiation environment, radiation hardened components should be used. This is even more significant in scenarios where is it expensive in terms of manpower/schedule/facility down time to replace a part if it goes out. For example, radiation hardened cameras are a commercial product which should be specified where their higher cost can be justified.

Availability: There are many robotic platforms with various attachments such as manipulators, cameras and sensors are commercially available. As alluded to before, many of these systems can be used as is in low radiation areas of the DOE complex. However, there are cases when specialized radiation hardened electronics and cameras must be employed for success of the mission. Although, radiation hardened components are available, many have long lead times so one should plan ahead when they are needed. Another consideration, to meet the needs of DOE EM unique applications, it may be necessary to integrate a number of commercially available components into a system. An engineered approach like this is very achievable but will impact the schedule to ensure everything works together properly as a system.

References:

1. Design Guides for Radioactive Material Handling Facilities and Equipment, American Nuclear Society, Remote Systems Technology Division, 1988.

2. Literature Review of Environmental Qualification of Safety-Related Electric Cables, BNL-NUREG-52480, Brookhaven National Lab, 1996.

INEXPENSIVE, DISPOSABLE, OR DECONTAMINABLE ROBOTS AND SENSOR PACKAGES

Description: There is a basic need for inexpensive, disposable or de-contaminable mobile (ground, aerial, underwater) robotic platforms that could be used for surveillance, inspection, and mapping tasks in the complex and unstructured environments that occur in stages for waste remediation. It is typically costly in terms of resources and occupational radiation exposure to decontaminate complex equipment for contact repair and reuse. Hence, such robotic capabilities would allow cost effective and rapid evaluations of scenarios that preclude human intervention. These systems should be physically small and provide a modular approach to the deployment of vision, radiation, chemical, and other sensor modalities. The mobility packages should also be modularized for different types of mobility options and such that sensor packages, at least many, could be generalized for most platforms. For those that are disposable, that could be designed for limited life expectancy which should reduce costs associated with materials and radiation tolerance, e.g., many forms of plastic structural materials should be feasible. High power density batteries will be the likely power supply approach for these robots, but the battery supply systems should also be modularized such that the initial power available can be matched to the specific mission requirements. This will allow weight management tradeoffs against mission length, sensor packages, and effective mobility for specific topologies/terrains. Most likely, these types of robots would be teleoperated, but may include autonomous subtask capabilities that are achievable and useful. Generally, these robots would need to be operable over wireless connections. Contamination of equipment is an issue, especially if the desire is to reuse the device or there could be a need for repair. The equipment must be designed for decontamination so it can be cleaned to the extent it can be contact handled for repairs. What this means in practical terms is smooth surfaces, minimal or no crevices, covers over complex components, and in some cases sealed so the unit can be washed down with a spray wand.

Maturity Assessment: There is an extensive base technology in consumer electronics, robotics, and drone products that can be applied to this need, with some focused development and adaptation. Drones for example have already been used for the class of needs envisioned, for short mission lengths. Many of these products have mastered the use of low-cost injection molded plastic structures. Of course, additional design and manufacturing considerations will be necessary to properly address the requirements associated with nuclear environments. Miniature visual and infra-red camera technologies are readily available. Other sensor modalities may require development to reduce their physical sizes and power requirements. Many of the component technologies exist, but significant effort is needed to adapt, optimize, and integrate for this application.

Availability: Consumer robotics products are beginning to emerge, which has drastically driven the price of the platforms and components down. This should provide potentially disposable platforms for single use situations. Decontaminable systems are generally not available and will be needed over time to allow more capable platforms to be reused for more challenging tasks.

References:

1. Guzman, R., Navarro, R., Ferre, J., Moreno, M., "RESCUER: Development of a Modular Chemical, Biological, Radiological, and Nuclear Robot for Intervention, Sampling, and Situation Awareness," Journal of Field Robotics, 33(7), 2016.

COMPACT, LIGHTWEIGHT, AND EFFICIENT ENERGY STORAGE SYSTEMS WITH ELECTRICAL OUTPUT

Description: Power is required for sensors, processors, actuators, and the majority of accessories associated with robotic systems. Energy storage systems that are compact, lightweight, and efficient relative to the size of the robot and the robot's specific mission applications are needed. The nominal power supplies for robots are: batteries, fuel cells, generator systems, including air-breathing engines, photovoltaic cells, and hybrid systems that combine multiple options (i.e. batteries and generator systems connected in series). There are other exotic options such as flywheels, compressed gas, nuclear generators, and other lesser known power sources. Batteries may be either rechargeable or disposable. For real-world examples, small robots are generally limited to batteries (e.g. NiCad, Li, Li-Ion, Lead Acid, and Silver Cadmium) due to size constraints, while larger vehicles like cars can use dedicated generator systems, or be integrated into the vehicle's power system. Unfortunately, there are no perfect energy delivery systems and design trade-offs are required. Humanoids have a very limited operational life with rechargeable batteries, and the flight time of quadcopters are severely limited even if the platform is equipped with two battery packs. Generator systems utilize moving parts that can cause vibrations that can affect the performance of sensors and precision pointing systems. Battery – powered, fixed-wing aerial vehicles have longer flight times than multi-rotor aircraft of similar size. Military robots depend on generator systems, while some maritime systems have experimented with fuel cells (typically consuming hydrogen). If a robot can be tethered and use power through the tether, power can be virtually unlimited and there is a direct reduction in energy storage weight on the vehicle.

Maturity Assessment: Batteries, generator systems, photovoltaic cells, and hybrid systems are all mature technologies, but may have to be verified for the radiation environment. There are many established manufacturers for these power and energy storage systems. And, there are many institutions all over the world working to improve these technologies by increasing efficiencies and bringing cost down. In time, researchers will be able to improve the energy densities of all the available energy and power options.

Availability: Many of the aforementioned energy sources and energy storage systems are available from commercial sources. Lead times for different components may vary, but the majority of them are off-the-shelf. If special requirements are needed, some development may be needed that would extend availability times. Many spent batteries and other power sources may be considered hazardous waste so consideration of the waste stream is also important when choosing an energy-storage and delivery system.

References:

1. Kevin Dowling, "Power Sources for Small Robots", Carnegie Mellon University Robot Institute Technical Report, CMU-RI-TR-97-02, January 1997.

RELIABLE, HIGH-BANDWIDTH WIRED/WIRELESS COMMUNICATION IN CONFINED SPACES AND CHALLENGING ENVIRONMENTS WITH HIGH METALLIC CONTENT AND RESTRICTED LINES OF SIGHT

Description: The most straightforward and common solution to supplying both power and signals to a remotely operated robotic system used in nuclear environments is a cable tether. However, their simplicity is offset by the challenges of effective tether management that must operate across complex topologies and terrains. Tether entanglements and binding with objects in the robot's path all too often restrict or even terminate remote deployments. The cable payout/recovery subsystems become quite complex. There are huge gains to be made if remotely deployed systems can be self-powered and wireless. Hence there is a fundamental need for the capability to create high bandwidth (on the order of 100's MHz) wireless data communications networks that support the remote operation of such systems. Today's wireless technologies are indeed highly sophisticated and prevalent (e.g. IEEE 802.11), but they have not been applied to the types of environments typical in many nuclear applications. Environments where the desired network region would be deployed are essentially forests of metallic components and structures with high density concrete walls with limited lines of sight. These environments are notorious for signal multi-pathing and other interferences. High data rate line of site type communications have been used in the past where specific line of sights can be assured, but they are typically expensive. While the data rates are high due to cameras and other sensors, the data paths are comparatively short from ones to hundreds of meters. These environments may be dusty and contain chemical vapors. A new class of wireless data networking tools are needed that are small, light, low power, and disposable. Smart (partially autonomous) and deployable repeater node concepts that can intelligently manage their connectivity through the available signal corridors are needed.

Maturity Assessment: Wireless technologies are very mature in terms of functional electronics and software. Integration of multi-node networks has been established in many different types of applications. It is believed that many of the underlying technologies associated with the military's digital battlefield strategy have relevance to nuclear remote operation's needs. Additional development and integration to meet the operational and environmental constraints of the nuclear domain will be required.

Availability: Base technologies are widely available in the existing data communications industry.

References:

1. Springer Handbook of Robotics, 2nd Edition 2016, Chapter 58, Section 58.3

HIGH PERFORMANCE COMPUTING SOFTWARE FOR DATA PROCESSING AND VISUALIZATION

Description: The ability to quickly and efficiently process and display data is an essential for large data sets to be useful. This capability allows one to easily identify patterns and trends which can lead to higher productivity or an alert to a possible safety situation. The requirement for this proficiency in the world of mobile robots is a result of the desire to deploy sensors or sensor suites to collect data from inaccessible locations in nuclear/hazardous facilities throughout the DOE complex. These sensors may include cameras (photos & videos), physical measurements, chemical characteristics, LIDAR and others. Depending on the data collection rate, resolution and size of the location being investigated, this could produce extremely large amounts of data. As an example, LIDAR produces point cloud data that would result in very large files if high frame-rates are used. Ultimately, data collected through robotic deployments can quickly become overwhelming without the proper tools to process it efficiently. Proper visualization goes far beyond simple bar graphs and pie charts which allows for new information to be discovered. Enhanced visuals make for easy communication and interpretation across multiple disciplines. High performance software is necessary for large data sets which involve complex calculations. Time and money is lost as a result of not being able to process and display data properly in a timely manner. With the right data processing tools, the information collected can be translated into a form that is easily readable. The technology can even go as far as developing a virtual reality model with embedded data that a user can click on a location for local information or simply observe through visual cues in the model, the condition of each area of interest.

Maturity: High performance data processing has been under development since the late 1980s to early 1990s. The capabilities of the software have at times been limited by the hardware that they are run on. As time has gone on the speed and number of calculations that a microprocessor can handle has increased and thus data processing has increased as well. During that time research has been conducted in order to optimize solutions for end user needs. Recently the industry has been moving towards real time data display which includes large scale simulations that would require an amount of memory too large to be practical. Real time applications allow the end user to interact with the data whether this is a simple touch screen interface or more complex virtual reality solutions. Data processing is being adopted by many different industries such as health care, energy, and information technology.

Availability: There are many commercially available software platforms to choose from. These types of software range from simple to use programs such as Microsoft Office to larger and more complex programs such as the solutions offered by AVS. Many software packages are now being offered as subscriptions which require a yearly fee. This allows the end user to always use the most up to date software. It should be noted that high-performance software will allow for new methods for displaying data which will require a learning curve to use properly.

References:

1. Sagirolu, S., Sinanc, D., “Big Data: A review,” International Conference on Collaboration Technologies and Systems, 2013.

MODULAR PROTOCOLS FOR COMMUNICATION AND HARDWARE/SOFTWARE INTERFACING TO PROMOTE INTEROPERABILITY

Description: Modularity is a key aspect of systems design that provides a level of customizability to each unique application, a high degree of re-usability across applications, and promotes interoperability between system components. For robotic systems, modular protocols and design paradigms can apply to hardware components, software components, communication interfaces, and data structures. Examples of coarse modularity include user interface consoles that control many types of air and ground vehicles. The common look-and-feel reduces re-training burden and improves operator competence. Another form of coarse modularity involves interfaces for sensor data, including video and LIDAR that permits uniform storage and archiving for post-processing and analysis. These types of modularity can be implemented using open standards, such as JAUGS and DDS. Fine-grained modularity includes sensors and actuators that plug-and-play to allow different capabilities for different applications such as mapping, inspection and emergency response. Wheels or treads might swap to provide different levels of traction and dust generation for different anticipated scenarios, but also, software modularity might quicken design cycles by allowing SLAM algorithms to work with LIDAR or stereo, interchangeably. Software modularity can be achieved through efforts like the Robotic Operating System (ROS), but hardware modularity is more primitive and proprietary.

Maturity Assessment: Modularity is an important technology area that traditional manufacturers have been slow to embrace for fear of losing captivity of customers. ROS 1.0 is mature enough to have multiple adopters in the research space, including government and academic labs, but a planned migration to ROS 2.0 will disrupt interoperability for an unknown period. DDS underpins the communications upgrade to ROS 2.0, but JAUGS remains a separate standard and seems to be falling out of favor after a period of time when it was mandated by DOD. Some companies have developed standard hardware interfaces that allow tinker toy-like mechanical modularity, but generic implementations for control software are more primitive.

Availability: ROS is available and supported by the Open Software Robotics Foundation, but a long-term sustainability plan has not been developed.

References:

1. Gerkey, B., et al, Programming Robots with ROS, O’Reilly Media, 2015.
2. JAUGS specification

MODELING AND SIMULATION

Description: Models are a representation of a system such as a robot and its environment. This representation can be of hardware, software function, an entity, process or phenomenon. Models, typically mathematical and/or graphical, are used in simulations. Simulations are used to reduce risk, make decisions, support analysis, used in experimentation, and for training. Modeling and simulation help engineers and system developers to understand a system's behavior without actually testing the entire system or to test its behavior in an untested environment. Mathematical models are needed for manipulators, and to an extent mobile robots, to set coordinate frames, and understand kinematics and dynamics of the system. These same models are used for design analysis and to control these robots, whether in position, rate, or force control. Kinematic models of mobile robots include vehicle steering and potentially traversability models for rougher terrains. Physical models of robots are used in planning and navigation performance analysis. A model or simulation may also test the effects of a well-characterized system on an unknown environment. Simulations are useful to validate designs and to optimize performance and can be important for training.

Maturity Assessment: Modeling and simulation tools are very mature with many products on the market to choose from. They support most robotics configurations, and can be modified to support more custom configurations as needed, such as for crawlers or side-winding vehicles. Models of EM-relevant environments will require development. Custom software testbeds or hardware-in-the-loop systems may have to be developed from scratch.

Availability: Modeling and simulation tools for robotics are available commercially. Modeling and simulations can be ubiquitous to the entire engineering community. With proper training, there can be trained operators made available to complete any task. The more challenging task is not building the models of the robot, but the modeling of the environment.

References:

1. Spong, M., Hutchinson, S. and Vidyasagar, M., Robot Modeling and Control, John Wiley & Sons Publishing, Inc., November 2005.

APPENDIX D SELECTED EM SITE FEEDBACK

Introduction

The collection of technology needs and challenges from the Department of Energy's Environmental Management (DOE-EM) sites was a key component in the development of the EM Robotics and Remote Systems Roadmap. As described in detail in the roadmap, these needs were identified through a combination of site visits and requests for information.

To form an initial foundation, DOE-EM's Office of Technology Development (TDO) conducted the following information gathering activities:

1. A small group of expert roboticists was assembled to understand the relevance and utility of robotics in the EM mission. This group visited several EM sites—Waste Isolation Pilot Plant (WIPP, May 2015), Hanford (August 2015), Idaho National Laboratory (August 2015), Savannah River Site (SRS, December 2015), and H-Canyon (March 2017)—and several U.S. universities (July 2016). TDO also facilitated interactions with nuclear clean-up efforts internationally, visiting the United Kingdom (April 2015) and Japan (April 2016), to share knowledge and technology.
2. A series of robotics demonstrations were conducted at Portsmouth Gaseous Diffusion Plant in August 2016 to connect the user community with the wide range of robotic technologies and to obtain support from the stakeholders involved. This demonstration showcased the technologies in a realistic decontamination and decommissioning environment.
3. The DOE field offices were consulted to identify program and personnel risks that may be reduced with robotics. Clean-up schedules and needs/challenges that do not currently have a solution were also identified.

Task #3 above was executed primarily using a feedback form that was sent to representatives at each EM site, as described in Section 3 of the Roadmap. Site representatives were asked to identify needs they felt could be impacted by robotics or remote systems and to assess the relevant improvement/task categories and time horizons in a table. The needs were also described in a more detailed narrative form. As discussed in that section, a total of 12 sites responded with feedback about their needs. This appendix includes samples of the feedback provided to provide the technology development community insights into the details of some needs. The roadmap team encourages interested developers to contact sites or national laboratories directly to discuss needs in more depth.

Office of River Protection

HANFORD SITE, RICHLAND, WASHINGTON

Data Date: May 25, 2017

Table 1. Office of River Protection Survey Worksheet

Hanford Site	Improvement Category		Task Category				Time Horizon		
Statement of Challenge or Opportunity	Safety	Performance	Dull	Dirty	Dangerous	Difficult	0-5 Years	6-10 Years	Out Years
1. Structural integrity inspections / automated Double Shell Tank (DST) annulus camera system / Non-destructive examination (NDE) sensor development	M	H	M	M			M		
2. Deployable device capable of cleaning the Effluent Treatment Facility (ETF) process tanks interior walls and roofs without manned	M	M		M		M	M		
3. Advanced robotics to improve waste retrieval activities	L	H		L		H	M	M	
4. Improved sampling / detection / monitoring system(s)	M	M	L				M		
5. Remote tank farm above-ground inspection capability	M		M	M			M	M	
6. Waste transfer pipe unplugging		L				M		L	

Key: H (High), M (Medium), L(Low), X (Relevant with no specified magnitude)

DISCUSSION

1. Numerous opportunities exist to enhance the structure integrity inspections. This including improving the capability of DST tank bottom inspections through development of a visual inspection technology for inspecting the DST primary tank bottom via the refractory air channels (e.g., use of a steerable needle), development of non-destructive examination techniques for assessing structural integrity of the DST primary tank bottoms (e.g., flash thermography, Synthetic and Tandem Synthetic Aperture Focusing Techniques (SAFT and T-SAFT), etc.), and utilizing advanced UT techniques to quantitatively assess the DST tank bottom. Improvements to primary tank wall inspections can also be made through development of electromagnetic acoustic transducer (EMAT) and phased array technologies, which will provide faster and more comprehensive inspections capability of the primary tank walls, including welds and heat affected zones. Additionally, development of an automated annulus camera inspection could significantly reduce the amount of time needed to perform visual inspections of the annulus in support of the inspection program, which ultimately reduced the exposure to operators and provides more comprehensive data throughout

the year (versus the current three-year cycle data is currently collected for the DST annulus).

2. The ETF process tanks build up scale that cannot be removed by soaking or recirculating with chemicals. The scale provides a mechanism for accelerated corrosion and inhibits Resource Conservation and Recovery Act (RCRA) required tank integrity inspections. Deployment of a device to clean the ETF process tanks interior walls and roofs (up to 15'W x 20'H) would reduce manned entries and reduce the risk of ETF process tank failure.
3. Enhancements to waste retrieval techniques can improve the amount of waste removed during retrieval activities, reduce liquid additions to the tank (and potential leaks to the environment), and simplify the retrieval techniques which reduces the cost of retrievals. The Hanford Waste End Effector (HWEE) is being developed to reduce water additions during waste retrieval efforts. Additionally, development of an in-tank mechanical waste gathering system, development of simplified sluicers, development of scaled versions of mining equipment, and enhancements to the Mobile Arm Retrieval System-Vacuum (MARS-V) system are additional ways the retrieval efforts can be improved.
4. Sampling, detection, and monitoring systems are utilized through the liquid waste operations at Hanford. Improved waste characterization systems can be utilized to improve tank waste characterization, provide a more cost-effective means to determine the interface between solids and liquids, provide necessary input to select a more effective and functional retrieval system, and improve leak detection capability (e.g., 3-dimensional flash light detection and ranging (LIDAR), solid-liquid interface monitoring system (SLIMS), cone penetrometers, improved annulus air monitors, plutonium detection devices, and in-line radiation monitoring systems). Further, development of automated systems could reduce worker exposure to routine tasks such as liquid observation well (LOW) scans, which are performed approximately four times a year to detect intrusions or leaks. Advancements to the off-riser sampler system (ORSS) hard heel sampler and ORSS car would also be beneficial, as the existing systems cannot reliably collect required tank closure samples of hard heel-material that is not directly under a tank riser; enhancements in technologies could be leveraged to improve reliability, maneuverability, and reduce cost associated with demobilization of the ORSS. After retrieval, remote operated vehicles to perform post retrieval sampling.
5. Use of remote monitoring, from the operations control trailer, could significant reduce manned entries, would reduce slips, trips and falls hazards, and would reduce radiation exposure hazards. This could be done by using remote field inspection techniques, including drones, static-mounted cameras, mobile wire-mounted cameras, and remote operated vehicles.
6. The risk of a plugged transfer line can significantly impact planned operations, including delays to retrieval efforts, transferring material to / from the evaporator, and providing feed to the Waste Treatment Plant (WTP). Development of techniques to efficiently unplug the transfer lines are necessary (e.g., development of the peristaltic crawler and pressure pulsing method being developed by Florida International University (FIU) as part of the cooperative agreement with DOE HQ).

Oak Ridge Environmental Management

OAK RIDGE RESERVATION, OAK RIDGE, TENNESSEE

Data Date: April 12, 2017

Table 3. Oak Ridge Environmental Management Survey Worksheet

Oak Ridge Reservation	Improvement Category		Task Category				Time Horizon		
Statement of Challenge or Opportunity	Safety	Performance	Dull	Dirty	Dangerous	Difficult	0-5 Years	6-10 Years	Out Years
1. Protect worker from mercury vapor.	X						X	X	
2. Better soil mixing equipment.		X		X		X		X	X
3. Efficient debris removal during D&D	X	X	X			X		X	X
4. Excavation of pyrophoric material.	X				X		X	X	
5. D&D of structurally unsound buildings for human existence	X				X		X	X	X
6. For landfill operations, sorting and segregating contaminated from uncontaminated materials. Also, waste characterization techniques can be developed and applied to help identification of waste streams for the Sanitary and Construction landfills.	X	X	X	X	X	X	X	X	X
7. Automated or remotely controlled Earth moving equipment (e.g., large bulldozers) used inside the boundaries of landfills	X	X	X	X	X	X	X	X	X
8. Efficient strategies and engineering controls for working in tight spaces	X	X			X	X	X	X	X
9. Solutions to improvement in the use of EM RA Wastewater Treatment-EM facility	X	X				X	X	X	X
10. Calculation of Unknown volume of contaminated soil at Y-12 to be excavated or treated for mercury and other contaminants		X						X	
11. Contingency for Melton Valley Sludge Disposal.	X	X			X	X		X	
12. Isotek Downblending Disposal	X	X			X	X	X	X	

Key: H (High), M (Medium), L(Low), X (Relevant with no specified magnitude)

DISCUSSION

1. Protect worker from mercury vapor – As D&D occurs in buildings at Y-12, mercury vapor is released from the walls, floors and piping. Mercury vapor levels are temperature dependent and when vapor levels rise to unsafe levels, workers are unable to perform work. Systems that collect, treat and package vapor prior to D&D or systems that collect vapor during D&D will be helpful.
2. Soil mixing equipment – At Y-12 the potential remedy for soil might be an in situ stabilization by mixing the mercury-contaminated soil with sodium sulfide to create cinnabar, a stable, non-leachable material incapable of transforming into methylmercury. An efficient, automated soil mixing system might be capable of completing the job safer and faster than traditional soil mixing equipment.
3. Efficient debris removal – During D&D debris is removed slowly and loaded onto dump trucks and hauled to the landfill, which is a relatively slow process. If a more efficient, automated system is engineered to speed up the process, it would save time and money.
4. Excavation of pyrophoric material – At ORNL and Y-12 there is buried pyrophoric material that presents a challenge to excavation. A safe process to excavate this type of material and package it for transport to another burial site is necessary.
5. D&D of structurally unsound buildings – Buildings at Y-12 and ORNL are over 70 years old. As these structurally unsound buildings are prepared for D&D many unsafe conditions for human workers exist. Engineered systems and robots to test areas for structural integrity or perform work in these areas would be beneficial.
6. Landfill operations – Sanitary and Construction Landfills at Y-12 are capable of taking non-contaminated debris from D&D operations. Sorting and segregating contaminated from uncontaminated materials has the potential to expand the lifespan of the contaminated materials landfill. Advanced waste characterization techniques can be developed and applied to help identification of waste streams for the Sanitary and Construction landfills.
7. EMDF Landfill Operations – The EMDF is the new CERCLA landfill that will be located at Y-12 in Bear Creek Valley. Earth moving equipment (e.g., large bulldozers) is used inside the boundaries of landfills. If this equipment could be automated or remotely controlled, there would be less radiological and respirable exposure to human workers. In addition, engineering solutions to get the waste from ORNL and Y-12 D&D projects faster and safer than one dump truck at a time could be developed.
8. ORNL D&D near active facilities – D&D of EM buildings will be occurring right next to new, state of the art, Office of Science facilities. Lack of space for support equipment, disruption of vehicle traffic, airborne contamination, debris falling, accidental disruption of water, electric and other services, are all potential consequences to lab activities. Efficient strategies and engineering controls for working in tight spaces are needed for EM to be as non-disruptive as possible to lab operations.
9. EM RA wastewater treatment – EM has decided to utilize its existing wastewater treatment facility at ORNL to treat all wastewaters from EM remedial activities and D&D. The system is about 70 years old and requires continual maintenance. Engineering solutions to improvements in the use of this facility or additional facilities closer to the D&D at Y-12 would improve productivity.
10. Unknown volume of contaminated soil – At Y-12 there is no exact or estimated number of cubic yards of soil that must be excavated or treated for mercury and other contaminants. At ORNL there is no exact or estimated number of contaminated soil to be excavated or treated under the buildings designated for D&D. With mercury-contaminated soils requiring an ex situ treatment at ~$10,000 per cubic yard, an estimated cost for a decision on excavation, ex situ treatment, versus in situ stabilization is necessary to make a decision. An efficient method of soil characterization, of multiple contaminants, over wide areas and under buildings would increase productivity and reduce costs.
11. Melton Valley Sludge Disposal – This project presents a unique challenge because it contains a waste that has been sitting in tanks for a long time and, like the tanks in the Hanford tank farm, the waste composition has changed over time. A plan has been conceived for this project but the challenge comes if the plan does not work as designed.

12. Isotek down blending disposal – Isotek is responsible for disposition of the U-233 waste stored at ORNL. The proposed disposition is on site down blending, stabilization and offsite disposal. A well-designed plan has been conceived for this project but the challenge comes if the plan does not work as designed.

Savannah River Operations Office: H-Canyon

SAVANNAH RIVER SITE, AIKEN, SOUTH CAROLINA

Data Date: March 21, 2017

Table 4. Savannah River Operations Office Survey Worksheet

Savannah River Site: H-Canyon	Improvement Category		Task Category				Time Horizon		
Statement of Challenge or Opportunity	Safety	Performance	Dull	Dirty	Dangerous	Difficult	0-5 Years	6-10 Years	Out Years
1. Deployable device capable of handling/ carrying required instrumentation and maneuvering through and around tunnel obstacles in high wind and radiation.		M		M	H	M	X		
2. Additional sensors to (1) map tunnel inside and (2) allow in-place NDE measurements, if feasible.		M		M	H	H	X		
3. Advanced coring tools to sample concrete from tunnel inside. Retrieve and transport cones from coring location to tunnel access		L		H	H	H	X		
4. Advanced equipment to perform Canyon wall and overhead crane repair.		M		M	H	H		X	
5. Structural integrity inspections and repair of underground/embedded exhaust		H	M	H	H	M	X		
6. Exhaust stack internal visual inspection and wall thickness		X	M	H	H	H	X		
7. Cell/Sump inspection and cleaning.	X	X	H	H	H	H	X		
8. Cooling water basin inspection.									
9. Failed canyon equipment resizing and packaging for disposal.	X	X	M	M	M		X		
10. Advance device for internal inspection and repair of piping/tubing	X	X	H	H	H	H	X		

Key: H (High), M (Medium), L(Low), X (Relevant with no specified magnitude)

APPENDIX E

ROBOTICS DEMONSTRATIONS: PORTSMOUTH GASEOUS DIFFUSION PLANT, AUGUST 2016

EXECUTIVE SUMMARY

The goal of the Portsmouth Robotic demonstrations, held in August of 2016, was to connect the user community with a wide range of robotic technologies and developers. These interactions increased the workers' familiarity with the technology and built support for their long-term integration into mission activities. The demonstration showcased the technologies in a realistic decontamination and decommissioning (D&D) environment. Twelve individual demonstrations were used to train future operators and give feedback to developers. The knowledge and information gathered during the demonstrations will enable future planning and development, leading to implementations for upcoming U.S. Department of Energy Environmental Management (DOE-EM) tasks. Using DOE Technology Readiness Levels, each demonstration was evaluated to better understand its accompanying risks. The operators and managers at the Portsmouth facility prioritized each demonstration against their own near-term needs. This list formed the basis of a plan for fiscal-year 2017 funding; balancing the needs with technological maturity and skirting the proverbial technological valley of death.

The Portsmouth Robotic demonstrations were an early step to introduce robotic technologies to the D&D workforce. This activity was part of DOE Environmental Management's larger mission of reducing its environmental liability by safely executing high hazard, high consequence, and high risk work. This liability includes the clean-up of the chemical and nuclear wastes from the Manhattan Project and the Cold War. To work safer, EM is investigating the use of robots to reduce or eliminate occupational radiation exposure, as well as using robot technologies to prevent injuries and reduce stress to these same workers. EM's Science of Safety initiative is part of its broader mission and will develop and implement technological advancements that will improve safety, enhance productivity, increase worker quality of life, and level the playing field between workers of different ages, physical abilities, and genders. EM is actively promoting the use of advanced robotics as a key enabling technology for accomplishing its mission. Thus, EM advocates modernizing its workforce by identifying, developing and deploying robotic assist devices.

This document was originally created as a stand-alone report summarizing the demonstrations described above. It has been reformatted and edited to be accompany the DOE-EM Robotics and Remote Systems Roadmap as a contextual reference, providing the reader with additional information about ongoing EM robotics activities.

2016 ROBOTIC DEMONSTRATION

Goal of Demonstrations

The purpose of the 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 about opportunities related to mission-relevant robotic technologies.

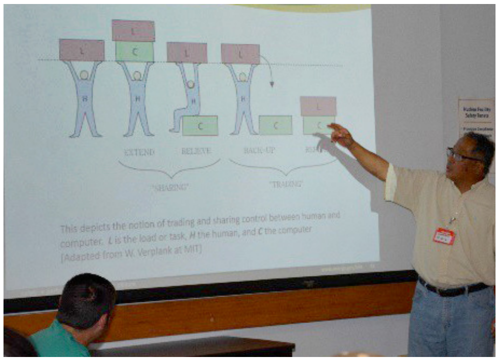
DOE-EM's Science of Safety (SOS) initiative includes the smart infusion and integration of scientific and technological advancements into the work planning and execution to enhance worker health and safety, and reduce federal liability of nuclear legacy cleanup. Currently, robotics and semi-autonomous systems are needed for remote access in nuclear, chemical, and other high-hazard facilities in EM that are inaccessible due to size and configuration, contamination, or otherwise preclude the safe and direct entry by human workers. Federal interagency, university, and private industry collaborations 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.

Science of Safety

Nuclear safety is defined by the International Atomic Energy Agency as, "The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards." Nuclear safety covers the actions taken to prevent nuclear and radiation accidents or to limit their consequences. This includes nuclear power plants, all other nuclear facilities (such as Portsmouth), the transportation of nuclear materials, and the use and storage of nuclear materials.

Portsmouth Gaseous Diffusion Plant

The Portsmouth Gaseous Diffusion Plant, at Piketon, Ohio, was built in 1952 and completed in 1956. The plant was one of three large gaseous diffusion plants in the United States that were initially constructed to produce enriched uranium to support the nation's nuclear weapons program, and later commercial nuclear reactors around the world. This plant occupies about 1,200 acres of the 3,777-acre Portsmouth Site. At the end of 2010, this facility was placed in Cold Shutdown to prepare for Deactivation and Decommissioning (D&D), which commenced in 2011. The property consists of three operational areas: the gaseous diffusion plant, the centrifuge facility, and the depleted uranium hexafluoride conversion facility (DUF). The largest of the three areas is the gaseous diffusion plant, which consists of three main process buildings (X-333, X-330, and X-326) housing the gaseous diffusion process equipment, as well as hundreds of supporting facilities. The various support facilities include those needed for feed and transfer operations, maintenance, steam generation, chemical cleaning, decontamination, process heat removal, water supply, water storage, water distribution, electrical power distribution, and administration. Most of the buildings are within an approximately 1,000-acre industrialized area.



Prepping Portsmouth

Prior to the actual demonstrations, DOE-EM provided a robotics preparatory class to Portsmouth employees who would support the demonstrations. The purpose of the class was to help workers understand basic robot terminology, and how engineers and operators complement each other. The users were representatives of the local United Steel Workers (USW) union, whose future job is the decontamination and decommissioning of the Portsmouth site. The class discussed common issues with robots in a nuclear environment, such as communication (tethered versus wireless) and command and control by human operators (teleoperation). The starting point for cleanup operations is for the operator to always be in the control loop of the robot, with artificial intelligence integrated in support of the basic mission as appropriate (such as for data signal processing and self-diagnostics).

With each new day, there is news on artificial intelligence, and how it can change the way humans approach different tasks. The baseline for cleanup is for the operator to always be in the control loop of the robot, and artificial intelligence can be integrated in support of the basic mission as appropriate (such as for data signal processing and self- diagnostics).

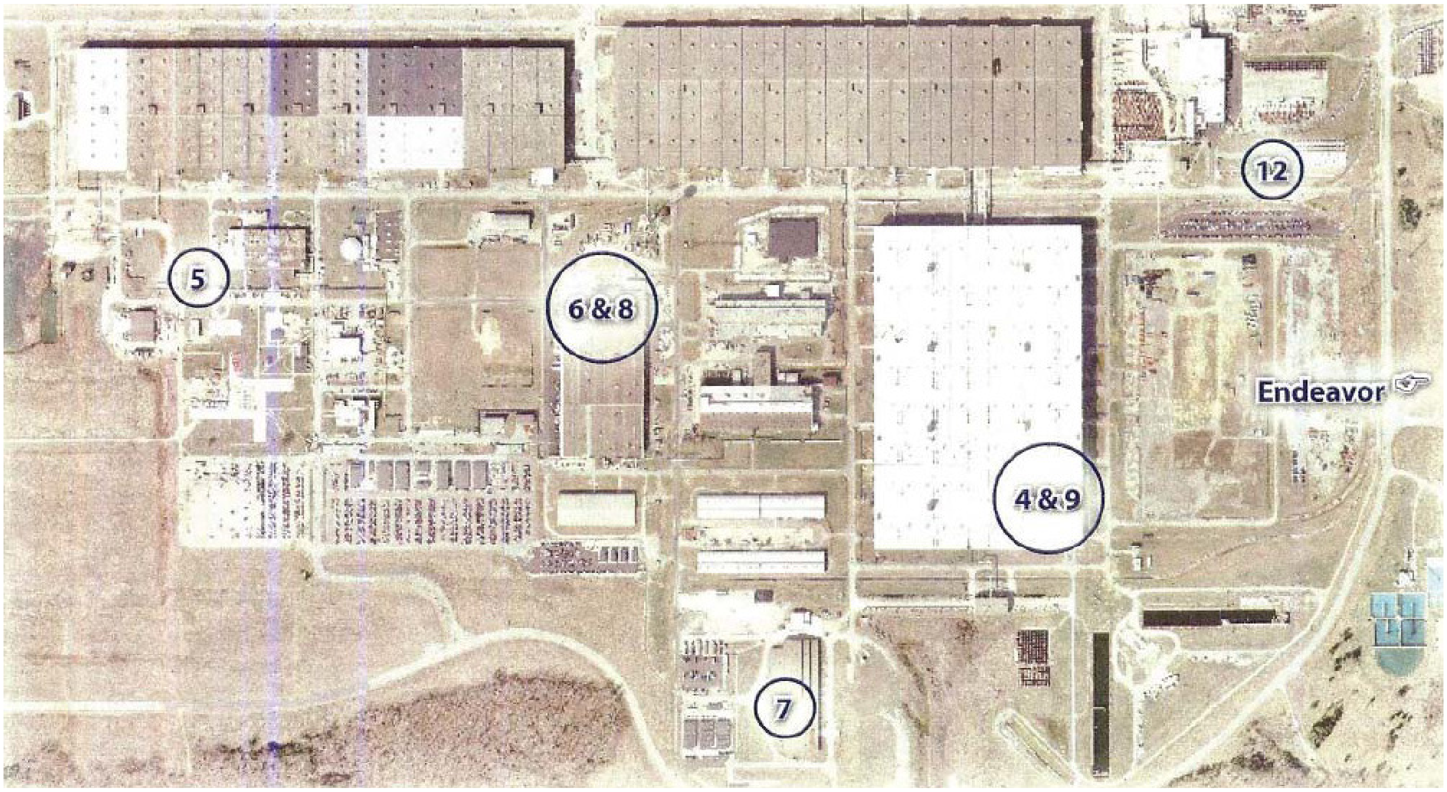
The preparatory class also introduced workers to topics in cybernetics, robot arms (manipulators), robot sensors (such as cameras, lasers, and speed sensors), different forms of mobility such as legs and wheels, and flying robots such as multi-blade rotorcrafts. The key technology for the user is the human-robot interface, such as joysticks, virtual displays, laptops, or the common control stations used by the military for controlling robots.

It should be cautioned that robots cannot do everything a human can, but robots have distinct benefits in hazardous environments or in repetitive tasks. The key challenges for introducing robotics into the DOE include utilization within radiation environments, complexity of tasks and environments, and the safety constraints necessary for both the operator and robot. The class was a primer for the operators and was not intended to be a substitute for individual, task-specific training.

Expected Results

The participants in the Portsmouth Demonstrations were a combination of leading robotic researchers from academia and from several of the DOE national laboratories. There were twelve separate and distinct demonstrations. The maturity of each technology demonstrated (based on DOE TRL levels) varied, and the breadth of the technologies was wide ranging. This diversity was deliberate, 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.

The demonstrations were scheduled for a four-day period, with an additional day for contingencies. To make the demonstrations meaningful, specific locations were chosen within the Portsmouth X-333 facility (location 4 & 9 in the above map), X-720 facility (location 6 & 8 in the above map), X-744G facility (location 7 in the above map), X-745F location (location 12 in the above map), and X-760 area (location 5 in the above map). Other laboratory-ready demonstrations



were held in the Endeavor Center, an off-site complex that is a part of The Ohio State University and adjacent to the Portsmouth Gaseous Diffusion Plant property. The Endeavor Center doubled as a daily starting point, including the location for the required safety briefings, a central point for logistics and debriefing.

The TRL levels for the various robots varied from TRL 2 to TRL 7. The majority of the technologies were Proof of Concepts (TRL 3) or a validation of an Alpha Prototype in a relevant environment (TRL 5). TRL 6 is a beta-prototype system in an operational environment. The technology closest to a relevant operational environment was the virtual reality cave and desktop systems, which modeled specific locations at Portsmouth.

TECHNOLOGY DEMONSTRATIONS

Technology Demonstration Descriptions

The twelve demonstrations are listed in the table below. In the subsequent analysis, we evaluated the strengths and weaknesses of each demonstration. The goal was to collect both positive and negative feedback (lessons-learned) for each project for the purpose of building upon each technology for the future.

Technology Demonstration	Demonstration Leader
1. Machine Learning Pipe Crawler	1. Sandia National Laboratories
2. Modular Prosthetic Limb	2. John Hopkins University Applied Physics Lab
3. Virtual Reality Immersive Teleoperation	3. Open Source Robotics Foundation (A non-profit organization)
4. Radiation Robotic Rabbit	4. Exelon/State University of New York (Oswego)
5. Serpentine and Modular Robotics	5. Carnegie Mellon University
6. Swabbing Unmanned Aerial Vehicles (UAVs)	6. Purdue University
7. Forklift Automated Safety System	7. Southwest Research Institute
8. Human-Centered Robot-Robot Teams	8. Texas A&M University and Endeavor Robotics
9. Mobile Systems for Inspection	9. University of Texas - Austin
10. RoboGlove	10. NASA Johnson Space Center
11. Virtual and Augmented Reality Modeling	11. Savanah River National Laboratory
12. Robotic Inspection of Cylinders	12. Sandia National Laboratories

Each of these demonstrations is discussed in greater detail in the subsequent sections, beginning with the EM challenge it addresses. This is followed by a description of the technology, including a highlight table that identifies key attributes. Finally, each of the demonstrations is evaluated by summarizing strengths and weaknesses.

This section is followed by an analysis of the demonstrations by taking a step back to take a broad view of the body of work at Portsmouth. The breath of technologies and tasks within each demonstration is discussed. It should be remembered that this was the first step in a series of robotic demonstrations and deployments that will train operators and allow the early insertion of key robotic tools that can enhance robotic safety in order for DOE to complete its mission.

1. MACHINE LEARNING PIPE CRAWLER

EM Challenge

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. Current methods of visual inspection require meticulous attention from workers over miles and miles of pipe.

Technology Description

Machine Learning Pipe Crawler Key Attributes
Vehicle - Simple platform
Sensor – Two 180 degree cameras attached to a forward boom and situated back-to-back
Control – Teleoperated with simple radio controller (or tethered in the future)
Environment – Long runs of circular culvert or piping
Unique Features – Machine Learning (in this case a neural network) to detect potential areas of contamination
Waste transfer pipe unplugging

Recent machine learning (ML) advancements will enable automated detection of internal pipe features and anomalies. This Sandia National Laboratories (SNL) system augments or automates the visual identification of anomalies that will make inspections more efficient and will reduce worker fatigue (workers will drive the robot while the ML model looks for anomalies). The captured video will be used to train a deep neural network to automatically detect internal features in subsequent inspections.

SNL has compact camera systems that display live video and capture digital stills at a specified rate. The camera system integrates easily with DataShare, a mature framework developed by SNL for building real-time data-sharing applications. It will be used to build the integrated system. DataShare will manage data flow between components – camera system, ML model, and DataShare's database – and will provide a dashboard that displays live and recorded inspection results.

SNL develops Machine Learning (ML) applications that identify features in digital images. These applications are trained using video and digital-still images. Portsmouth data (preferably captured by a crawler) is required to train the model to recognize features and anomalies, and to test the ML model's ability to detect features in new images. SNL used images of PORTS pipes that include real features (joints, tees, etc.) and actual anomalies (crystal deposits). SNL also needs images with no features or anomalies as a baseline. To support system testing, a piping testbed was built at SNL with analogous piping features and simulated anomalies. The system featured a modular design to facilitate integration with other pipe inspection robots. The system consists primarily of software and can be trained for other inspection tasks throughout the complex, including Uranium Hexafluoride cylinder inspections.

Demonstration Description

This demonstation focused on data acquisition and ML model development to augment the current capabilities of the pipe crawler robot. Because of the compressed timeline, the integration of the ML vision system with the crawler was not feasible. Instead, a standalone ML vision system was demonstrated. The modular ML vision system required digital video or still images to train the model and subsequently identify features in new images. Since the system is robot agnostic, it provides feature-detection capability to any robot with fixed-camera systems and is applicable to previously captured videos and images.

The demonstration involved 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. 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 was not shown, since it was to be saved to memory or transmitted back to the operator for post-processing. The demonstrators discussed how a neural network could be used to determine areas of concern inside the pipe.

Demonstration Evaluation

Demo Strengths – The mobile robot drove a short distance, taking 360-degree imagery in a temporary pipe. The seam of both 180-degree cameras were aligned horizontally for the purpose of not distorting the images further. This was done because panoramic cameras display distortion at the image edges. The demonstration highlighted the basic principles involved.

Demo Weaknesses – Due to a lack of preparation time, no machine learning processing was demonstrated, but the demonstrators described the possibilities of using a neural network to do this analysis. The robot used was not the anticipated AIT Portable Industrial Rover, but rather was a simple-platform robot (simple hobby vehicle) that was not optimized for pipe crawling. There was no way to localize the rover’s position accurately, only by counting observed rib seams as it traveled. A better method for tagging the location of photos with the location of the robot would be useful.

2. MODULAR PROSTHETIC LIMB

EM Challenge

There are many tasks and 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. There are many instances that require a dual-arm manipulation capability, and will also require some form of mobility to get to hard to reach places.

Technology Description

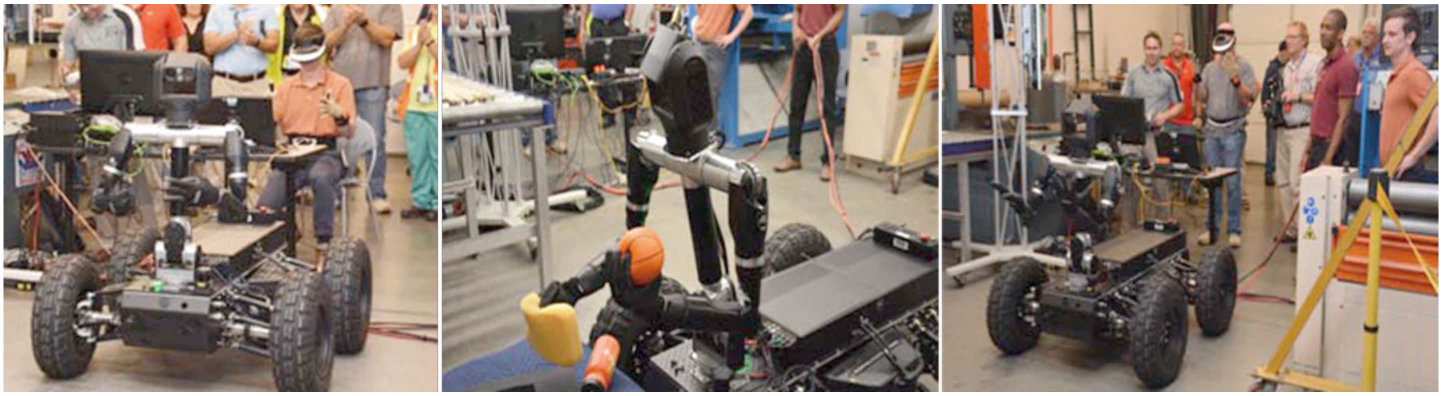
Modular Prosthetic Limb Key Attributes
Vehicle -Simple, four-wheel platform
Sensor – Stereo head on a neck gimbal
Control – Telepresence, master-slave system
Environment – Open industrial environment
Unique Features – Dual prosthetic manipulators with dexterous hands
Waste transfer pipe unplugging

This system, 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 many tasks 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.

The current robot is configured on a base of 4 rugged wheels, allowing it to move across challenging terrain. It can be steered by a video-game-type controller, a joystick, or a foot-controlled pressure sensor worn in the operator's shoe. Robo Sally's stereoscopic vision is provided to the operator in real-time via a virtual reality headset. The video feed is provided in real time to the operator, who can be located remotely anywhere in the world. The operator not only sees what Sally sees, but also when the operator moves his or her head, Sally's head follows.

To control the robot's movements, the operator wears a special Robo Sally suit, outfitted with Xsens MTw trackers on the head, upper arms, and lower arms, as well as special sensor-laden gloves. The MTw trackers allow the operator's moves to be precisely measured and wirelessly transmitted, to allow Sally to mimic the operator. To operate Sally's arms, the operator wears exoskeletal sleeves (with controllers) and gloves (CyberGlove Systems LLC) with sensors on the fingertips. The operator can control the robot's movements by simply moving her own limbs. The development of this bimanual dexterous robotic platform allows an operator, located anywhere, to step into a foreign or dangerous environment and perform any number of in-situ tasks.

Demonstration Description



The John Hopkins University Applied Physics Lab conducted three different demonstrations: Robo Sally, the next generation prosthetic arm, and a telepresence control system that could control Robo Sally. An operator donned the suit and was slaved to the mobile robot. The operator was immersed in the robot so that the operator saw through the stereo-camera head on the robot. Control of each arm was slaved to the human operator's arms. The robot was driven to a table with multiple items, picked up each item, and then passed each object to individuals in the audience. In a separate demonstration, the fixed-base prosthetic arm was used to show the dexterous manipulation of a multi-finger hand.

Demonstration Evaluation

Demo Strengths – Telepresence is one step better than teleoperation because the operator is immersed in the robot's visual and audio (hearing) system. The advanced, dual-manipulator system acts like a person's own arm. The Robo Sally robot is a good surrogate for the human, and it would be plausible to replace the existing arms with the next generation prosthetic arm and a more advanced robotic hand.

Demo Weaknesses – The telepresence is good, but the limitations in the hardware cannot fully match the performance specifications of a human operator (e.g., Field of View). As good as the arm articulation is, it is still not robust enough to handle off-nominal or dangerous tasks, such as handling a cutting torch. However, one must recognize that this was a demo of existing technologies not necessarily developed for any specific tasks. In fact, the system was designed to accommodate the 50th percentile male. With identified requirements, the system could be tailored accordingly with more human levels of performance (e.g., field of view, strength, reach, etc.).

3. VIRTUAL REALITY IMMERSIVE TELEOPERATION

EM Challenge

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, 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.

Technology Description

Virtual Reality Immersive Teleoperation Key Attributes
Environment – Simulated
Display – Monitors or heads-up
Control – Head-tracking, hand tracking, gaming controllers
Unique Features – Robot Operating System (ROS), Gazebo simulation
Unique Features – Dual, prosthetic manipulators with dexterous hands
Waste transfer pipe unplugging

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 provides a novel capability in that: (1) it is flexible enough to model a wide range of systems, from articulated arms to cars 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.

Unlike traditional animation or gaming development, software which interacts with the Gazebo simulator can be quickly re-targeted to real robot hardware through the Robot Operating System (ROS). Investments in engineering expertise, software development, and operator training can thus transfer freely between simulation and physical machinery.

In recent years, exciting progress has been made towards low-cost, easily-portable virtual reality (VR) headsets. These headsets are constructed with mass-market smartphone components, resulting in a low-cost device with high fidelity. Over the past several years, the Open Source Robotics Foundation (OSRF) has created many simulated demonstrations with low-cost VR headsets, and they have been consistently popular with visitors at public demonstrations. The OSRF has used the Oculus Rift development kit for previous projects, but thanks to recent dramatic market expansion, they will re-evaluate the available options on the market and select the best candidate for a demonstration. OSRF proposes to use low-cost VR headsets to create immersive, engaging simulations of two scenarios: robotic material handling and safe vehicle operation.

OSRF used Gazebo to demonstrate immersive teleoperation of a robotic manipulator that is handling material in a hazardous environment. The exact task is chosen and customized, based on feedback from DOE-EM management and staff. If the handling task is confined to a small area (e.g., the kind of work that might be done in a glove box), then OSRF can simulate one or more industrial robot arms, such as those from Universal Robots or Yaskawa Motoman. If the handling task requires motion over a large area (e.g., carrying objects from one location to another), then OSRF can simulate a humanoid robot (such as the Boston Dynamics Atlas or the NASA Valkyrie), or have a manipulator arm mounted on a mobile robot like Robo Sally. OSRF has extensive experience simulating these types of systems, and they have existing models from which to start the project and re-use. Whichever task and robot are chosen, OSRF will model the environment, including relevant objects, equipment, and tools.

Given the environment, task, and robot, OSRF selected an appropriate motion-tracking mechanism for user input. OSRF has experience with a wide array of such systems, from handheld gaming devices, to both optical and magnetic tracking. All of these input systems allow for natural motions of the user (i.e., moving hands around in space) to be mapped into executable control commands that are sent to the robot (i.e., torques applied to motors). If appropriate, OSRF can also offer haptic feedback to the user, via gloves that are instrumented with small motors that physically communicate information about contact with objects.

Demonstration Description



This visualization demo was provided by the Open Source Robotics Foundation, who also guide the ROS standards development. The desktop demo was based on Gazebo (simulation software originated at the University of Southern California) and demonstrated some generic process tasks. This included opening and closing containers. The models were pre-made, with no specific locations in mind.

Demonstration Evaluation

Demo Strengths – The models were good and complemented the work of the Savannah River National Laboratory (SRNL) demonstrations. The tasks were very intuitive to the users, and the system was easy to observe from various vantages.

Demo Weaknesses – Again, similar to SRNL, visualization requires good and accurate models, and the system has to be used to become useful and effective. It takes time to build good and accurate models. It would have been more powerful to use a Portsmouth site environment.

4. RADIATION ROBOTIC RABBIT

EM Challenge

State University of New York at Oswego and the Nine Mile Point Nuclear Power Plant (operated by Exelon) collaborated on a project to develop a robot that can easily be used in an operational nuclear power plant. The Rad Rabbit can be used in multiple locked high-radiation areas and station security, and will incorporate contingency in response plans. The robot is a light-weight vehicle, so it can easily be picked up, carried, and transported by 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 (skid steering).

Technology Description

Radiation Robotic Rabbit Key Attributes
Vehicle – Simple four-wheel platform, skid-steered
Sensor – Multiple cameras, gamma sensors, air sampler
Control – Teleoperated, manual
Environment – Open industrial environment
Unique Features – Simplicity, scissor-mast, modular
Waste transfer pipe unplugging

The robot has variable speeds that allow for operation as slow as a 'snail's pace' or as 'quick as a rabbit' (hence the name). If radio communication is lost, the robot will immediately stop. At its lowest height the robot stands at 20" tall and is 21" wide. On the controller, there is a toggle switch that allows for the platform to be raised to 4' in height. Attached to the extendable platform is a camera with 360-degree pan, tilt, and zoom capabilities.

Also mounted to the extendable platform is radiation detection equipment (gamma sensor) that can remotely send real-time radiological information, such as accumulated dose and dose rates, to the operator. There are also LED lights that are operated by a toggle switch on the remote control station.

For recording video, SUNY-Owego and Exelon added a second video camera attached to the main camera head. If they add another camera, they can perform 3D imaging. For dark, low-light areas, there are additional attachments for more powerful LEDs. The internal components have smooth armor on the sides and most of the top and the entire bottom. This allows for easy decontamination. The wheels are easily removable, in case there is a change-out need for radiological reasons or for specific terrain changes. The existing larger, more aggressive tires allow the robot to drive over a six-inch obstacle. There also is an attachment spot for an air sampler.

Demonstration Description



The radiation robotic rabbit from the State University of New York at Oswego and Exelon demonstrated a teleoperated mobile robot having a Go-Pro camera, scissors mast, and a secondary camera. The robot was designed to have simple and quick remote eyes for an operator, who does not have to suit up to accomplish a quick evaluation of a potential 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, an operator was able to instantaneously drive the robot around and do a visual inspection with a camera.

Demonstration Evaluation

Demo Strengths – The robot worked very well and the controls were quick to learn. The communication system worked well with better range and bandwidth than expected, receiving clear video at the operator station. Exelon had integrated a separate antenna and communication system for more challenging communication environments. This was an effective demonstration, in terms of inspecting inside the 55-gallon drums by lowering a sensor probe into a top opening.

Demo Weaknesses – With more preparation time, the Go-Pro video camera would have been integrated, which in this demonstration had to be shown on a separate monitor. Even though some intricate tasks were done with mono-vision, stereo-vision could have provided depth cues to enhance intricate tasks, such as seeing the edges of the opening for dropping the probe into a tight tolerance opening on the top surface of the drum.

5. SERPENTINE AND MODULAR ROBOTICS

EM Challenge

Visual inspection of multiple long piping runs from the outside of small diameter pipes and the inside of larger diameter pipes 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. The task of visual inspection requires meticulous attention from workers over miles and miles of pipe.

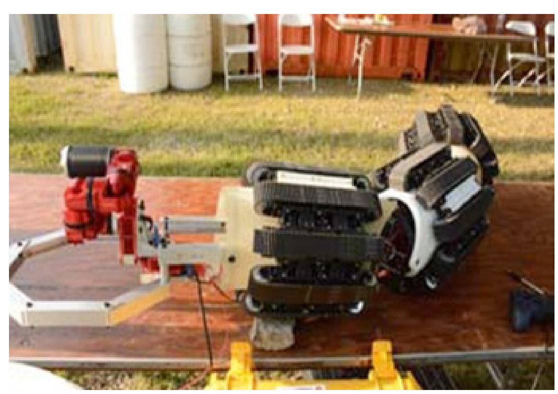
Technology Description

Serpentine and Modular Robotics Key Attributes
Mobility – Hexapod and serpentine
Sensor – Camera
Control – Shape-control, tethered or battery powered
Environment – Open terrain and vertical pipes
Unique Features – Multiple Degree-of-Freedom (DOF) mechanisms
Waste transfer pipe unplugging

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, such as sand or debris. 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. 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.

Demonstration Description





CMU delivered two robots using modular robotic technologies: a four-foot long serpentine robot (or snake robot) and a hexapod robot with six smaller serpentine legs. Both robots were tethered, so that they could concentrate on mobility and not have battery-life be an issue for the demonstrations. These demonstrations were held outdoors. The snake robot successfully spiraled its way up and down a vertical pipe, and later slithered on a grassy surface. The hexapod negotiated a rubble pile, by selectively placing its foot accurately and incrementally stepping across the surface.

Carnegie Mellon University (CMU) has multiple ground-based mobile robots to demonstrate in uncertain environments and for the Portsmouth Site, they also teamed with Purdue University to add a collaborative demo, in which CMU's snake robot was attached to Purdue's Tread/Limb/Serpentine Hybrid robot for hyper-inspection and hyper-mobility. This modular combination of robust locomotion and robust manipulation provides the ability to look around and behind obstacles in complex, uncertain environments.

Demonstration Evaluation

Demo Strengths – The serpentine robot is state-of-the-art in climbing vertical pipes and offers a different mode of mobility. The hexapod is a stable, versatile platform for walking, especially on irregular surfaces. This robot is modular and can be easily reconfigured.

Demo Weaknesses – The robots did not represent a complete system but a proof of concept for advanced mobility. The snake robot had a camera, but the main focus of this demonstration was on mobility of multi-body systems.

6. SWABBING UNMANNED AERIAL VEHICLES (UAVS)

EM Challenge

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 many two-story or taller buildings that require periodic monitoring and inspection. Unmanned Aerial Vehicles (UAVs) capable of robust physical interaction with the environment are 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 in dangerous or difficult-to-access areas. Most UAVs are intrinsically unsuited for controlled physical interaction with the environment in a safe manner.

Technology Description

Swabbing UAVs Key Attributes
Vehicle – Multi-rotor and hybrid aircraft, fixed-wing platform
Sensor – Cameras, IMU/INS
Control – Velocity control, hovering
Environment – Tall open structures
Unique Features – Swabbing, hovering fixed-wing, opening enclosure doors
Waste transfer pipe unplugging

Purdue University has developed a wide range of custom UAVs explicitly designed to safely and semi-autonomously perform physical interaction tasks, such as swabbing surfaces for mass spectrometer analysis of low-level contamination or for applying sealants. The Dexterous Hexrotor is a special multi-rotor drone that demonstrated swabbing the walls and the rails of the overhead crane in building X-720. It is capable of precise force control and can be optimized to exert complex force trajectories in six degrees-of-freedom. Semi-autonomous modes such as “swabbing” can be initiated at the push of a button once pre-positioned near a desired sampling site.

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 can open enclosures, such as an electrical cabinet door and can apply sealants. A second rotorcraft, the Dexterous Hexrotor, is used for agile interaction with its environment for sampling, adding sealants, or swabbing. A third vehicle demonstrated is a hybrid fixed-wing aircraft that can cover long distances and still hover in flight. These aircraft are one-of-a-kind prototypes that were designed and developed at Purdue University.

Demonstration Description



Purdue University introduced three flying robots. A multi-rotor robot flew inside a tall building and acquired a swab on a high surface. A second multi-rotor vehicle opened the door of an electrical cabinet. To offset any gravity loading on this Boom Copter, the platform is attached to a wheeled dolly, so that it moved only in a planar direction. Purdue has also developed a custom, hybrid, vertical take-off and landing (VTOL) prototype with two large tilting propellers built into the fixed-wing structure. This provides both the ability to hover and fly horizontally with high efficiency. As a flying research prototype, the VTOL was used for display purposes only, as its inherently unstable flight controller was still undergoing validation tests for public demonstrations. This final vehicle was a static representation of a winged vehicle that could also hover, which was not ready to fly.

Purdue and CMU performed a collaborative demo, in which CMU’s snake robot (with camera) was attached to Purdue’s hybrid robot, for the purpose of combining locomotion and manipulation with the ability to look around and behind obstacles. This robot moves around by remote control, and the snake provides images from the end of the its appendage. This provides views under, behind, and around objects. Some customization to the actual environment is possible, with appropriate direction.

Demonstration Evaluation

Demo Strength – As a capability demonstration, the multi-rotor aircraft was able to swab a high spot on a vertical wall. A second vehicle successfully opened and closed an enclosure door with a hexcopter in a planar direction.

Demo Weaknesses – These demonstrations showed capability, but much is needed to mature these technologies. The BoomCopter was confined to the plane for demonstrations of opening and closing doors. In a mature vehicle, the vehicle would open/close doors in three-dimensional space.

7. FORKLIFT AUTOMATED SAFETY SYSTEM

EM Challenge

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, which will enable the safety-related technologies to be demonstrated on top of a fully automated system. The ability to detect and track people around moving equipment is critical for ensuring a safe environment.

Technology Description

Forklift Automated Safety System Key Attributes
Vehicle – Forklift, rear-end swing
Sensor – Down facing localization camera, people detection camera, wheel speed
Control – Drive-by-wire, localization
Environment – Open industrial environment
Unique Features – People detection and tracking, image matching localization, ROS
Waste transfer pipe unplugging

The object-detection framework demonstrated is a flexible, modular system for detecting objects using monocular or 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 automatic detection. 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 environments, 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 vehicle no-go zones for safety. SwRI displayed the output of object detection and Ranger running on a forklift, in order to demonstrate the benefits of highly-accurate localization and perception. They created intuitive displays (both inside and outside of the vehicle) using Mapviz, a modular visualization tool, to show the sensed objects and the precise location of the vehicle.

Demonstration Description

The goal of this project was to show a forklift with a sensor system for determining its position and detecting people (using a camera as an obstacle avoidance system). The forklift, using a localization scheme from a downward facing camera that matches high resolution images stored in its memory would register its position to a map to aid navigation within a tight course outlined by cones. The forklift arrived late to SwRI. As a result, not all sensors for the localization system could be adequately integrated, forcing the research team to solve the problem by developing additional software. Ultimately, the system was demonstrated localizing itself against a map and detecting people, both of which were shown on a screen in the forklift cab and outside the forklift on a display table).

Demonstration Evaluation

Demo Strengths – The demonstration was not integrated, but could be shown in pieces. The person tracking algorithm using GPUs was demonstrated on a video monitor. It correctly framed a person with a box of interest on a secondary video screen. The video screen also showed a map of the ground surface with the location of the forklift; however, this system was not working properly during the demonstrations, and engineers from SwRI traveled to the site the following week to correct the problem (which was a faulty wheel encoder). With the advent of Convolutional Neural Networks, GPUs are becoming the standard hardware for running computer vision programs due to the efficiency of the parallelized architecture.

Demo Weaknesses – The technology was not ready for demonstration and required more time. Since the forklift was not outfitted with drive-by-wire actuators, the platform could not be driven remotely (though it was known that this was not going to be feasible given the limited amount of time with the forklift). Given more time, the demo could have been more integrated. The person detector worked as a technology demonstrator, but this needs more development to also be fully integrated onto the forklift. Too many items, such as wheel rotation sensors, were missing to consider this a fully developed vehicle. The sensor that was used had previously never been attempted on this platform before.

8. HUMAN-CENTERED ROBOT-ROBOT TEAMS

EM Challenge

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, and preventing worker injury from lifting or handling heavy materials and tools. The demonstrations reflect technology transfer from the active collaboration among faculty 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 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 while eliminating surprises.

Technology Description

Human-centered, robot-robot Teams Key Attributes
Vehicle – Packbot 510, Fotokite, 110 FirstLook
Sensor – Cameras, INS/IMU
Control – Teleoperation, remote control
Environment – Open industrial environment, confined spaces, areas with loss of wireless communications and GPS
Unique Features – Tethered rotorcraft, mobile-manipulation, robot teams, collaboration
Waste transfer pipe unplugging

Demonstration Description



Endeavor showcased a product demonstration of three of their 110 FirstLook robots. The 110 FirstLook is an expandable, lightweight robot that can provide immediate situational awareness, perform persistent observation, and investigate dangerous and hazardous material while the operator is in a remote, safe setting. The platform is robust, which was demonstrated by having members of the audience throw the vehicle as far and as hard as possible, without damaging it.

In a separate demonstration, the Packbot 510 robot drove around and was accompanied by a commercial tethered quadcopter (Fotokite). The Fotokite did not work, due to a bad servo electronic board. With the remote control console, the operators were able to drive the Packbot around, and a commercial nuclear radiation detector was attached to the robot's arm. The detector found controlled radiation in user-safe containers, but the mapping software did not work. The demonstration was later repeated and worked as planned.

Nuclear workers drove the Packbot 510 and deployed the Fotokite UAV carried by the Packbot 510. They monitored streaming, real-time data from nuclear sensors and cameras using a single display. The robot created maps of the physical layout of the facility, overlaid with radiation 'heat maps' in real-time (using the RadEye Spectroscopic Personal Radiation Detector (SPRD) sensor). The workers used the UAV to investigate hard-to-reach places, such as overhead pipe racks or behind equipment. The UAV can also serve as an extra set of eyes for demanding, hand-eye-coordination tasks, while navigating in confined spaces. The UAV successfully ascended into pipe racks and upper stories of the facilities.

As a separate demonstration which can be used individually, as a swarm, or to assist another robot, several 110 FirstLook robots were introduced. This small and light robot is able to be thrown to or into a specific location and serve as a wireless network repeater. It is designed for a wide range of special-operation tasks, including inspection of a room. With 4 built-in cameras, the 110 FirstLook provides multi-directional situational awareness, while keeping the operator out of harm's way. Though the robot weighs just 5 pounds, it is sturdy enough to survive 15-foot drops, overcome obstacles as high as 7 inches, and automatically 'self-rights' itself if flipped over. Future capabilities of this robot include two-way audio communication and digital mesh networking, which will allow multiple robots to relay radio communications over greater distances.

Demonstration Evaluation

Demo Strengths – The Endeavor Robotics 110 Firstlook demonstration worked as advertised, but the demonstration was more of a product demonstration from the manufacturer. This platform is robust. The concept for the Texas A&M demo was good, but complete implementation did not occur the first time due to a variety of circumstances out of the team's control. The demonstration was successfully repeated at a later time.

Demo Weaknesses – 110 FirstLook is worked for its intended purpose of having quick eyes for early responders. However, this did not easily translate to a real application for the DOE at this time. It could be envisioned that a group of 110 FirstLook robots could map an unknown area, or they could act as a communication repeater that could benefit emergency situations. The Packbot did move under remote control, but neither the air-ground collaboration nor the radiation mapping was demonstrated the first time. This indicates some of the brittleness of the technology and that adequate contingencies were not implemented. These can be overcome in the future.

9. MOBILE SYSTEMS FOR INSPECTION

EM Challenge

University of Texas (UT) Austin has formed the Nuclear & Applied Robotics Group (NRG), whose goal is to reduce radiation dosage in 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 teleoperated, allowing for the detection of 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.

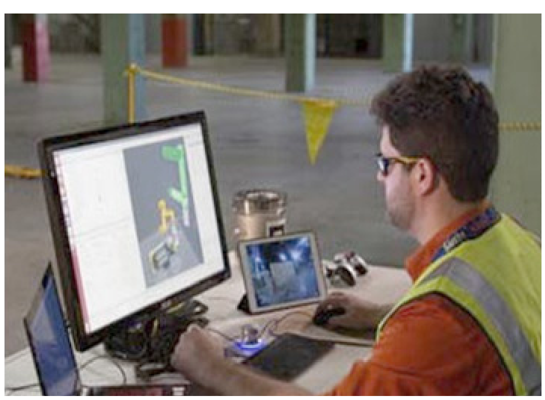
Technology Description

Mobile Systems for Inspection Key Attributes
Vehicle – Adept Pioneer indoor mobile robot, Clearpath Robotics Warthog
Sensor – Cameras, LIDAR, INS/IMU, radiation sensors
Control – Autonomous
Environment – Indoor industrial environment
Unique Features – Autonomous Navigation, computer vision, mobile dual-manipulation, zipper-mast, ROS, custom user interface

These systems can be operated from a variety of different control fidelities, as desired by the user. For example, the operator can:

- Operate remotely with a high level of operator involvement using a standard hand controller
- Command the system remotely to traverse automatically generated waypoints on a virtual fixture surrounding an item of interest
- Via high level commands, traverse a robot-generated map of the space
- Operate in an autonomous inspection mode using predefined locations selected in a map previously generated by the robotic system.

Demonstration Description



The University of Texas-Austin demonstrated two robots working in relevant nuclear environments. The two systems were demonstrated in a DOE-designated area and performed the completion of contamination testing using a combination of real or surrogate sensors under the supervision of nominally trained DOE-designated operators who were supervised by UT personnel.

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. The second robot 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.

Demonstration Evaluation

Demo Strengths – These were two well-integrated demonstrations, and performed as planned. All technologies worked with few issues. The platforms used open software architectures (ROS) which should permit interoperability. Mobile manipulation is a difficult and evolving technology.

Demo Weaknesses – This demonstration was the closest to being ready for DOE applications, though many of the technologies used were simpler or more mature than those demonstrated by other groups.

10. ROBOGLOVE

EM Challenge

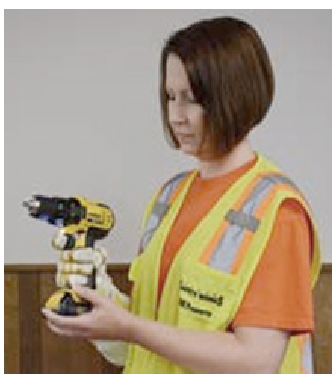
The wearable RoboGlove augments grip strength with embedded electric actuators and artificial tendons connected to each finger that activate in response to sensed forces. With the glove holding their hand closed, the DOE worker can maintain a grip on tools, panels, etc. without straining their muscles. The glove itself has both right and left hand versions, and can be used in multiple, user-selectable modes.

Technology Description

RoboGlove Key Attributes
Wearable – Glove
Sensor – Position, finger force/pressure
Control – Motion and/or force in response to direct user input or interaction with tools and the environment
Environment – Industrial or manufacturing environment
Unique Features – Adjustable gloves, left and right hand, lightweight and self-contained, built-in human safeties, programmable task specific modes across individual sensors and fingers

Researchers at the NASA Johnson Space Center (JSC) and General Motors (GM) have 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.

Demonstration Description




To allow the DOE to assess the efficacy of utilizing the RoboGlove in a diffusion plant environment, NASA developed three tasks to demonstrate the benefit of this robot-enabled technology. In preparation for the tasks and to ensure a successful demonstration at Portsmouth, cycle testing and minor modifications were performed to increase reliability and performance. In support of the demonstrations, two pairs of existing gloves were utilized for the tasks, and two spares were manufactured. One pair was medium size and one was large size. NASA has found that these two sizes accommodate the anthropometry of most people. NASA procured and fabricated all necessary spares, performed reliability testing, and completed task development. In addition, NASA provided a team to accompany the hardware during testing at the Endeavor Center at Portsmouth.

Demonstration Evaluation

Demo Strengths – The glove worked as planned, being used by various steel workers and by handling an assorted array of tools. There were multiple glove pairs of varying sizes used. If the user needs to grasp a tool or handle a piece of material for a long period of time, the glove could provide benefits.

Demo Weaknesses – A small number of prototypes exist and work is required to further mature the product. The fit was variable, depending on a person's hand geometry. Thus at times, the position of the sensors was suboptimal during operation.

11. VIRTUAL AND AUGMENTED REALITY MODELING

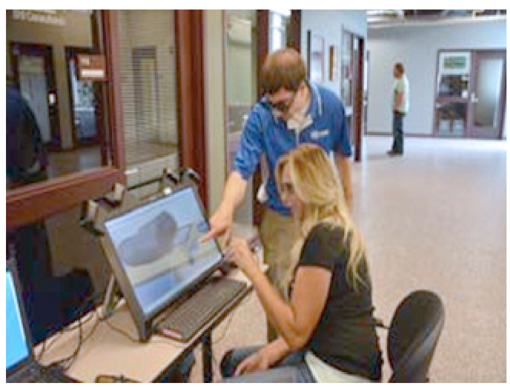
EM Challenge

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 general workforce. Virtual Reality (VR) will enable more rapid facility understanding for worker planning and training. Augmented Reality (AR) will assist in safer work execution by providing full scope understanding and guidance throughout execution.

Technology Description

Virtual and Augmented Reality Modeling Key Attributes
Environment – Simulated
Display – Monitors or heads-up
Control – Head-tracking, hand tracking
Unique Features – FBP specific CAD-models, virtual reality, augmented reality
Unique Features – Adjustable gloves, left and right hand, lightweight and self-contained, built-in human safeties, programmable task specific modes across individual sensors and fingers

Demonstration Description


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

SRNL demonstrated two visualization systems; an augmented system (based on a Google system) and a virtual reality system (using a shuttered stereoscopic system on a large screen display). The augmented reality demo was conducted via desktop, while the virtual reality demo used a larger room for a large-audience demonstration.

Demonstration Evaluation

Demo Strengths – Both demonstrations were well done and raised awareness of available technologies. The augmented reality demo used a simple model to demonstrate basic capability. The virtual reality demo used CAD drawings from the Portsmouth site to model a realistic scenario. The models may have value to the site for future modeling and planning activities. The models were generally accurate, but sometimes lacked definition.

Demo Weaknesses – The usefulness of visualization technologies is a function of the quality and accuracy of the models used. Experience has shown that either the models are often not available or too expensive to produce. Being more than a novelty, the system has to be utilized to become more effective.

12. ROBOTIC INSPECTION OF CYLINDERS

EM Challenge

The purpose of the commercial-off-the-shelf (COTS) mobile robot demonstrated was to reduce worker radiation dose by performing remote cylinder inspections. This will become increasingly important when performing inspections and inventory of thousands of cylinders. Tens of thousands of cylinders require inspection throughout the DOE complex. Workers performing manual cylinder inspections receive more dosage, on average, than other PORTS workers. Inspections include visual inspection and physical sampling (smears) that are performed within arm's length of each cylinder. The SNL DataShare (discussed previously) application will be integrated to automatically store cylinder inspection information and photographs.

Technology Description

Robotic Inspection of Cylinders Key Attributes
Vehicle – Remotec Andros Vehicle (multi-track)
Sensor – Cameras, INS/IMU, pan/tilt/zoom
Control – Teleoperated
Environment – Outdoor environment
Unique Features – Mobile manipulation, computer vision, force-compliant smear tool

Demonstration Description

A COTS mobile robot, the Remotec HD-1, was used for this remote cylinder inspection demonstration. The robot has multiple compact cameras that can be used for inspection and can display live video or captured digital stills. Commercial robot cameras and the SNL camera system were mounted on the robot and used for performing inspections of valves or for reading inventory numbers on cylinder boilerplates. Machine-vision software augments the robot's camera system by reading the boilerplates, interpreting the text, and processing and saving the results into a cylinder inspection database including data and photos for each cylinder inspection. Inspection tools were held in the robot's gripper. Force-compliant inspection tools are required to prevent damage to cylinders during physical contact operations (smears, ultrasonic wall thickness measurements, etc.).

This was an outdoor demonstration of a teleoperated track robot. The goal was to drive the Remotec Andros robot remotely, using a military-style RF communication system. Three steelworker operator teams were able to drive the robot and inspect stacked tagged pressure cylinders, which are abundant at the Portsmouth site. The auto-zoom-capable video camera provided high quality images.

For this demonstration, SNL developed a force-compliant tool for performing smear operations. They worked with operators to identify the best techniques for performing smears, using the robot arm and then assisting Portsmouth workers with a demonstration of the technique. This inspection system can be replicated at other facilities throughout the complex.

Demonstration Evaluation

Demo Strengths – The Andros Robot worked as envisioned, but the demonstration felt like a product demonstration from the manufacturer (similar to Endeavor Robotics). The operation was very realistic, in terms of having a team consisting of an operator, a procedure reader, and a safety/QA officer. The platform is robust and highly finished, and the quality of the returned video was very good (enough to read panel text).

Demo Weaknesses – The robot is another teleoperated system, but the high price of this commercial platform might be prohibitive, as the vehicle itself costs a few hundred thousand dollars. There is no autonomous capability, and it was not clear if this platform could be upgraded. Remotec alluded to some additional capability, but that is at an additional cost. With help from SNL, this could be a robust and efficient system/capability.

ANALYSIS

A wide spectrum of technologies were demonstrated, and their value to EM cleanup is depicted in the following figure. The diversity of technologies was by design to demonstrate as much as possible in a short window with the understanding that challenges and issues would arise. The goal was to get robotic tools into the hands of users in 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 number of initiatives within EM. The maturity of the technology is based on its DOE Technology Readiness Level (TRL).

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 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	X			X				X	X			X
Mapping	X							X	X			
Swabbing						X						X
Manipulation		X								X		
Human Training											X	
Robot Training			X									
Radiation Detection				X					X			
Pipe Inspection	X				X							
Rubble Inspection					X			X				
Opening Enclosures		X				X						X
Cleaning		X				X		X				X
Deconstruction		X					X			X		

DOE TRL Levels

TRL indicates the maturity of a given technology, as defined in the following table. The TRL scale ranges from 1 (basic principles observed) through 9 (total system used successfully in project operations). TRL is a widely used indicator of the degree of development of a technology toward deployment.

TECHNOLOGY READINESS LEVEL -DEFINITIONS
TRL 1 - Basic Research: Initial scientific research has been conducted. Principles are qualitatively postulated and observed. Focus is on new discovery rather than applications.
TRL 2 - Applied Research: Initial practical applications are identified. Potential of material or process to solve a problem, satisfy a need, or find application is the focus.
TRL 3 - Critical Function or Proof of Concept Established: Applied research advances and early stage development begins. Studies and laboratory measurements validate analytical predictions of separate elements of the technology.
TRL 4 - Lab Testing/Validation of Alpha Prototype Component /Process: Design, development and lab testing of components/processes. Results provide evidence that performance targets may be attainable based on projected or modeled systems.
TRL 5 - Laboratory Testing of Integrated/Semi-Integrated System: System Component and/or process validation is achieved in a relevant environment.
TRL 6 - Prototype System Verified: System/process prototype demonstration in an operational environment (beta prototype system level).
TRL 7 - Integrated Pilot System Demonstrated: System/process prototype demonstration in an operational environment (integrated pilot system level).
TRL 8 - System Incorporated in Commercial Design: Actual system/process completed and qualified through test and demonstration (pre-commercial demonstration).
TRL 9 - System Proven and Ready for Full Commercial Deployment: Actual system proven through successful operations in operating environment, and ready for full commercial deployment.

Technology Matrix

Each demonstration was evaluated and assigned an overall TRL level. The following table provides an overview of the EM Portsmouth demonstrations and the associated technology maturities. 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.

DEMONSTRATION	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.

DEMONSTRATION	OVERALL TRL LEVEL
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: Remotec System and inspection process demonstrated in an operational cylinder yard environment.

The lower-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, an integrated system operating within a variety of environments should be shown.

Role of the Operator – Teleoperated or Autonomous Operations

Due to the harsh nature of the radiation environment, many robotic tasks should be teleoperated, ensuring a human operator is always in the control loop. This approach keeps the cognitive capabilities of the worker engaged, and at the same time moves the human out of the radiation environment. In practice, a robot that is teleoperated (man-in-the-loop) may also have some automatic functions. For example, if a tool needs to be exchanged, an automatic function or process to switch a tool with a quick-change device may be available. Automatic functions are used in known environments where all aspects of the problem are observable, and its model is well established.

If the environment is dynamic or the task has some unobservable operations that require decision making, then autonomy may be an appropriate solution. Autonomy differs from automatic functions in that it requires adaptation and decision making. Autonomy operations are still in a research and development phase within the broader scientific community. An autonomous robot can learn from its experiences, and makes a choice by evaluating alternatives in order to achieve a pre-specified goal.

For clarification, robotic teleoperation vs. autonomy is not an either/or (autonomy is a trait with degree, e.g. semi-autonomous, fully autonomous, etc.). There is nuance here where autonomy is actually a very good thing (e.g. autonomous force and safety monitoring handled by a robot is far more effective than trying to accomplish the same thing through haptic feedback to a remote operator).

With teleoperation as a baseline for DOE robotic tasks, a robot that is tethered or communicates with a wireless system is implied. However, tethers can get stuck or entangled, thus immobilizing the robot. There are examples from the past that have used the tether to pull out and retrieve an immobilized robot (typically smaller vehicles). Wireless communication is an alternative option, but brings its own issues such as lower bandwidth, multi-path, and drop out issues. When communication between the operator and robot is lost, the robot should stop in place as a safety option. Radiation can also distort the signal or incur upsets/interrupts in the hardware.

Amount of Operator Training Required at Portsmouth

Many of the teleoperated interfaces demonstrated were intuitive and straightforward, similar to some of the existing computer gaming consoles and smart cellphones available today. Additional training is required when the robot becomes more complicated, for example when the robotic platform leaves the ground as with a UAV. The training of a certified operator would improve robot performance. This is where simulations and virtual reality can improve the acuity of the operator. A more rigorous training curriculum is needed to support the education of the workforce. Automation (including robots) have been working its way into a variety of industries such as self-driving cars, coal-mining, manufacturing, and logistics.

The operators used in the Portsmouth Demonstrations and the unions in general are starting to see robotics and automation permeate all facets of cleanup life, especially in the DOE. The workforce sees this paradigm shift, and many have embraced the changes. Operators in our preparatory class were enthusiastic, and this was followed by a positive change in attitudes and receptiveness that was evident after only one week of demonstrations. There is a new yearning by our workforce to learn more, get re-trained, and add new skills in preparation of future D&D efforts at Portsmouth and the rest of the DOE sites.

Active Use and Future Plans to Use ROS

The Robot Operating System (ROS) is a flexible framework for writing robot software. It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behaviors across a wide variety of robotic platforms. At the simplest level, ROS offers a message-passing interface that provides inter-process communication and is commonly referred to as middleware. A communication system is often one of the first needs to arise when implementing a new robot application. ROS's built-in and well-tested messaging system saves a developer time, by managing the details of communication between distributed nodes via the anonymous publish/subscribe mechanism. Because the publish/subscribe system is anonymous and asynchronous, the data can be easily captured and replayed without any changes to existing code. The asynchronous nature of publish/subscribe messaging works for many communication needs in robotics, but sometimes there is a desire for synchronous request/response interactions between processes.

The ROS middleware also provides a way for tasks to share configuration information through a global key-value store. In addition to the core middleware components, ROS provides common, robot-specific libraries and tools that get the robot up-and-running quickly. Here are just a few of the robot-specific capabilities that ROS provides: Standard Message Definitions for Robots, Robot Geometry Library, Robot Description Language, Pre-emptible Remote Procedure Calls, Diagnostics, Pose Estimation, Localization, Mapping, and Navigation. One of the strongest features of the ROS is its powerful development toolset. These tools support introspecting, debugging, plotting, and visualizing the state of the system being developed. ROS provides seamless integration with popular open-source projects, such as OpenCV and MoveIt!, along with a message-passing system that allows the user to easily swap out different data sources, from live sensors to log files.

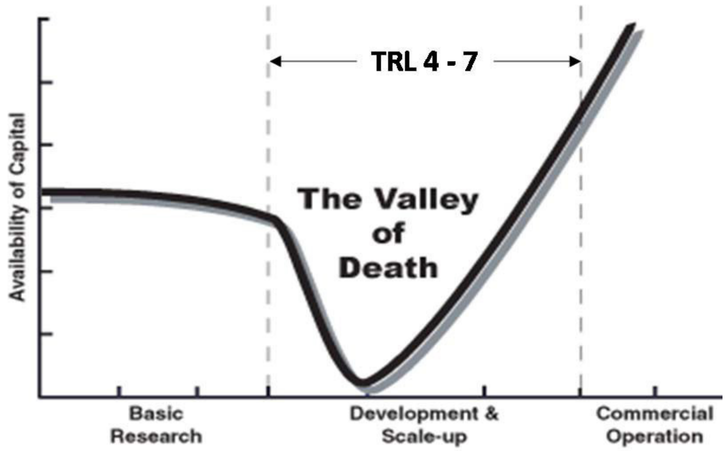
	Portsmouth Demonstrations											
Robotic Technologies	a. Machine Learning Pipe Crawler	b. Modular Prosthetic Limb	c. Virtual Reality Immersive Teleoperation	d. Radiation Robotic Rabbit	e. Serpentine Modular Robotics	f. Swabbing UAVs	g. Forklift Automated Safety System	h. Human-Centered Robot-Robot Teams	i. Mobile Systems for Inspection	j. Robo-Glove	k. Virtual and Augmented Reality Modeling	l. Robotic Inspection of Cylinders
Manipulator		X		X				X				X
Computer Vision	X											X
Robotic Hand		X										
Mobility					X			X				X
Machine Learning	X											
ROS		X	X				X		X			
Telepresence		X	X								X	
Teleoperative Control	X			X	X	X		X	X			X
Autonomous Control									X			
Modeling			X								X	
Rotorcraft						X		X				
Localization							X		X			
Robot Teams								X				
Wearable										X		

The strengths of the ROS include the fact that it is open source, the number of useful libraries available, and its message-passing scheme to integrate a diverse set of software modules and libraries. The biggest users of the ROS framework are smaller research and development groups that do not have the resources within their own organizations, and who can rely on these libraries libraries to fill niche technologies. By no means is ROS mature, and there are people all over the world developing new and key pieces. As a result, DOE is working in conjunction with the army, industrial consortiums, DARPA, and others in the government on safety and security features such as NQA-1 and for software V&V.

OUTLOOK

It was observed that many of the technologies demonstrated fall within the proverbial technological 'valley of death.'

'Valley of Death' for Technology

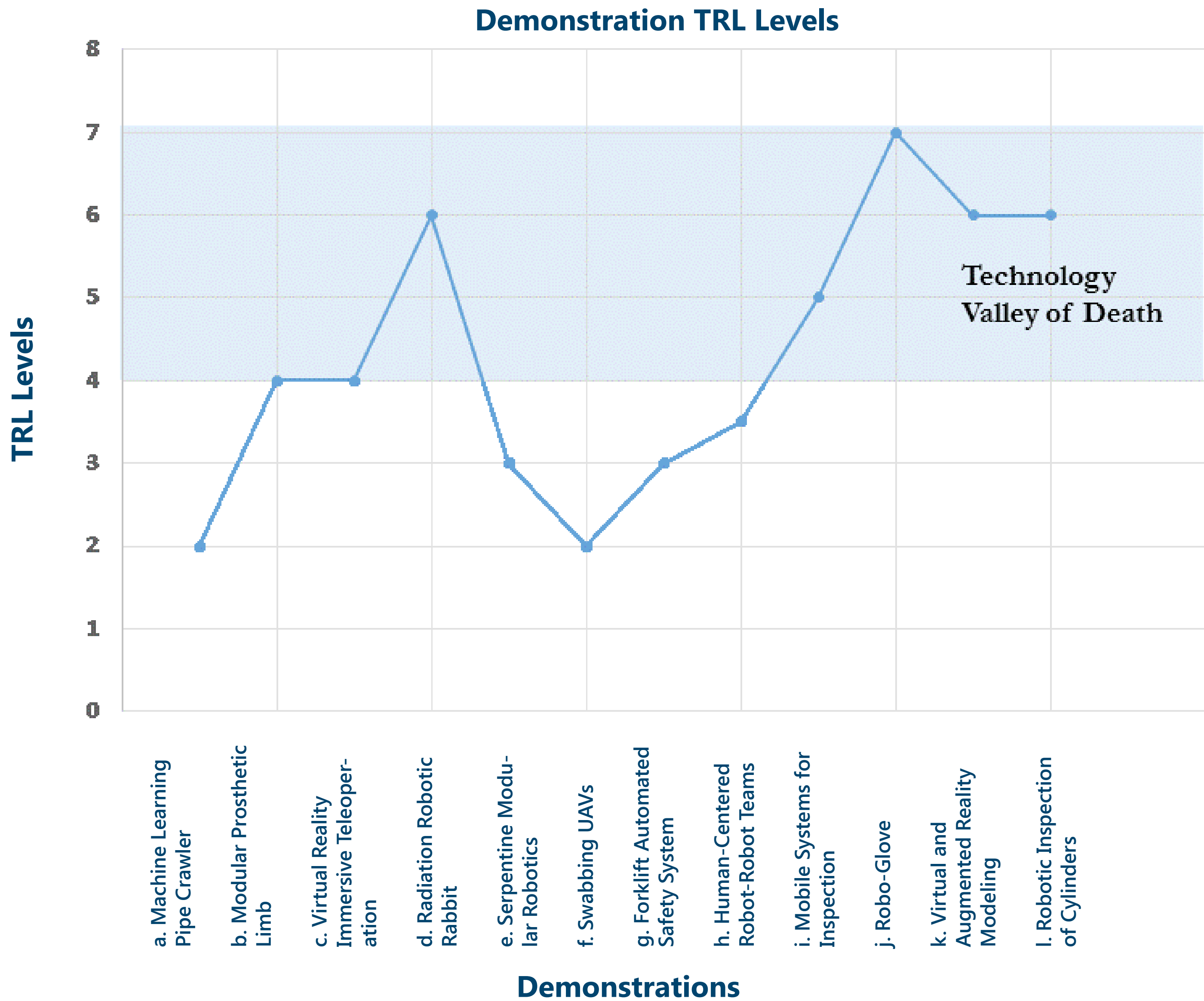


As many scientists and engineers who have discovered a promising new technology have found, it is difficult to bridge the divide between basic research and a viable product or marketable technology that is ready to use. People who study innovation refer to the gap between federally-funded research and a new commercialized technology as the 'valley of death', where new technologies go to die. Bridging that chasm is crucial for the nation's prosperity; but as some can attest, it is not easy, and many companies do not even try.

This is not to be confused with the 'uncanny valley,' termed by robotics professor Masahiro Mori. Mori postulated that the uncanny valley is the region of negative emotional response towards robots that seem almost 'human.' The notion is that human robots that appear almost, but not exactly, like real human beings elicit feelings of eeriness and revulsion among some observers.

Accelerators for America's Future, published by the DOE Office of Science, cites the valley of death as a critical challenge that results in countless lost opportunities. Difficult obstacles block the bridge between the two: complex funding mechanisms for research and development, a lack of national facilities and demonstration projects, an aversion to risk, and policies that make coordination among government entities and between government and industry extremely challenging. The high cost and high risk of robotics are the two major obstacles that leave many potential nuclear robotic solutions stranded in the valley of death. However, academia, teamed and working together with a national research laboratory, can be a natural and positive thing, as evidenced by the 2016 Portsmouth Demonstrations.

The following figure depicts the maturity of each of the individual demonstrations, and each demonstration's relationship to the valley of death (colored in blue).



There were no technologies demonstrated over TRL 7, and each demonstrated system required some further development or refinement.

Next Steps

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 has been documented here. During the binning session, the FBP team felt that there were three categories of technologies: Categories A, B, and C. Category A includes robotic technologies that can be implemented today. Category B includes technologies than could be implemented in the near future. Category C includes technologies that could be implemented in the longer term.

Category A

Technologies that are applicable now that could potentially add value in the near term with some additional incremental investment by EM are as follows.

1. Machine Learning Pipe Crawler – SNL
4. Radiation Robotic Rabbit – SUNY Oswego / Exelon
8. Human-Centered Robot-Robot Teams - Texas A&M – 110 First Looks
9. Mobile Systems for inspection - UT - Austin
11. Virtual and Augmented Reality Modeling - SRNL
12. Robotic Inspection of Cylinders - SNL

Category B

These demonstrations showed promise, but are not ready for deployment or need additional development and proof of concept demonstration.

2. Modular Prosthetic Limb - Johns Hopkins University APL
3. Virtual Reality Immersive Teleoperation - Open Source Robotics Foundation
8. Human-Centered Robot-Robot Teams - Texas A&M - Packbot/Fotokite
10. RoboGlove - NASA

Category C

These are interesting technologies, but they showed no obvious need or future application that couldn't be addressed with a different or more mature system (i.e. from Categories A or B).

5. Serpentine and Modular Robots - CMU
6. Swabbing UAVs - Purdue
7. Forklift Automated Safety System - SwRI

Continuing the DOE EM Mission

FY17 FUNDING PRIORITIES

Focusing on the Category A technologies, the team applied a prioritization process which was based on potential for near term benefits and availability of funding for investment in deployment.

Priority #1

Complete the SRNL Virtual Reality model for the X-333 process cell. The immediate benefits of having a tool for planning, alternatives analysis, and training are clear. Projected costs include the balance of the modeling task to reflect missing items and to ensure dimensional accuracy with existing conditions, as well as the hardware and software capability on site at Portsmouth to enable the system to be used effectively.

Priority #2

Acquire at least one of the SUNY Rabbit Robots and several of the Endeavor First Look Robots to have on hand for a variety of potential applications. Based on the feedback from the demonstrations, there was a clear interest and willingness to start using these systems to assist with both off-normal events and some other routine activities. The early introduction of these versatile and generic systems would help to implement a progressive technology-based culture or mindset for the deployment of new tools.

In addition, there was an interest in acquiring a UAV, primarily for activities and surveillance external to the buildings. This would start to break down barriers and paradigms, relative to existing traditional tools and techniques.

Priority #3

Continue to expand the development and implementation of the SNL pipe crawler and machine learning applications for identification of uranium deposits in pipes for X-326, and later in X-330. There is also the potential of adapting the technology beyond visual inspection, to include internal NDA measurements rather than the traditional external measurements currently being performed.

Priority #4

Implement the two application specific technologies (Floor Inspection and Cylinder Inspection), as the need arises.

- The Adept Pioneer-based floor mapping system would appear to be ready to implement, prior to the next major campaigns of floor inspections and contamination control mapping. This effort would require some additional programming by UT – Austin students, to automate the generation of floor maps and additional confirmation testing of various detectors, and the ability to interpret cracks and anomalies in the floor surfaces. A national lab or company would likely need to support integration and deployment.
- The cylinder inspection would require a cost-benefit trade study which looks at FBP cylinder quantities, as well as other potential cylinder storage locations (DUF6 plant and Paducah). The study would need to consider potential dose-reduction benefits, as well as quantifying how labor and schedule would be affected from the current approach. Likewise, there would be an additional adaptation to a later-generation Remotec robot with a narrower footprint and extended reach capability. This would include tool deployment and on-platform tool storage, as well as the implementation of the machine learning and DataShare systems to create an inventory baseline.

CONCLUSIONS

Based on the short timeframe provided (approximately two months) to complete twelve diverse scenarios with robots, there were many good demonstrations. Due to the limited preparation time, the researchers needed to have the technology already working to be successful. The range of different types of demonstrations was broad and was representative of robotic technologies in general. Some demonstrations require further development, while demonstrations that featured inspection tasks with a teleoperated platform performed well (as expected, based on the maturity of this class of robots). From what was observed, the JHU-APL demo is teleoperated and with increased robustness could be implemented, if better manipulation is required. Their manipulator is one of the best research arms currently available, but the cost is very high. The CMU serpentine robot has been proven and is mature, but it may require a few more years to become production worthy. In all, commercial vendor platforms performed as expected and are robust (having high TRL levels).

The most relevant demonstration was from the University of Texas Austin, who also included some advanced autonomous capabilities. The University of Texas - Austin systems may not be ready for immediate commercial use, but the demonstration of the robots was relatively applicable. This is due in part to their long standing relationship with Los Alamos National Lab. Finally, visualization technologies can be advantageous, if they can be used regularly and high quality models are available.

The technologies that have an immediate impact are outlined in Category A. DOE intends to pursue these technologies going forward.

APPENDIX F

ROBOTIC HANDLING OF HIGH CONSEQUENCE MATERIALS

ACRONYMS

AMWTP	Advanced Mixed Waste Treatment Project, Idaho National Lab
CAM	Continuous Air Monitor
CoE	Center of Excellence
COTS	Commercial Off-The-Shelf
CPS	Cyber-Physical Systems
DOE	Department of Energy
DST	Double-Shell Tank
DWT	Double-Wall Tank (same as DST)
HCM	High-Consequence Materials
HEPA	High Efficiency Particulate Arrestance – air filters
HLLW	High Level Liquid Waste
INL/INEL/INEEL	Idaho National Lab
IRID	International Research Institute for nuclear Decommissioning
JAEA	Japan Atomic Energy Agency
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MARS	Mobile Arm Retrieval System – robotic tank cleaning system
NASA	National Aeronautics and Space Administration
NDA	Nuclear Decommissioning Authority, United Kingdom
NDE	Non-Destructive Evaluation
NNL	National Nuclear Laboratory, United Kingdom
NSF	National Science Foundation
ORP	Office of River Protection, Hanford
OSTP	Office of Science and Technology Policy, White House
PCV	Primary Containment Vessel
PFP	Plutonium Finishing Plant
PNNL	Pacific Northwest National Laboratory
PORTS	Portsmouth Gaseous Diffusion Plant
ROV	Remotely Operated Vehicle (often underwater vehicle)
S/C	Suppression Chamber
SLAM	Simultaneous Localization And Mapping
SRNL	Savannah River National Lab
SRS	Savannah River Site
SWT	Single-Wall Tank
TRL	Technology Readiness Level
TRU	TRans-Uranics – elements with atomic weights beyond uranium
UAV	Unmanned Aerial Vehicle

INTRODUCTION

This report is part of a larger effort to explore the implications robotics can play on the handling of high-consequence materials to meet the needs of the Department of Energy, Office of Environmental Management (DOE-EM). The safe, expedient, and cost-effective handling of nuclear waste, as an example of a “high-consequence material,” is of primary interest to the DOE-EM and is the focus of this report. However, this information was gathered as part of a larger effort involving NSF, NASA, OSTP, and the DOE to look not only at specific examples, but to see what commonalities exist between the handling of various types of high-consequence materials, the possible mishaps that can occur, improved testing and estimation of low-likelihood events, and the best steps to take to avoid negative consequences of extremely rare mishandling events.

This report represents the combined opinions of a group of government and academic experts on robotics and automation based on several visits to a variety of government and academic facilities in the United States and abroad that handle nuclear materials, study the handling of nuclear materials, either in the normal course of operations or in response to emergencies. The expert group visited a hand-picked list of important sites in the United States and in foreign countries with close ties to the US nuclear materials complex. The list of sites selected was not intended to be exhaustive, but representative of some of the most difficult environmental problems created by enriched nuclear materials processed and stored in the US along with some of the most innovative solutions to handle such materials explored by developers of robotic systems.

The specific sites visited include Sellafield and its related facilities in the UK; the Waste Isolation Pilot Plant (WIPP), Idaho National Lab (INL), the Hanford Site, the Savannah River Site (SRS), the Portsmouth Gaseous Diffusion Plant (PORTS), NASA Johnson Space Center (JSC), University of Texas at Austin, Texas A&M University, and Southwest Research Institute (SwRI) in the US; Tohoku University, Toshiba Corp, University of Tokyo, International Research Institute for Nuclear Decommissioning (IRID), Mitsubishi Heavy Industries, Kyoto University, Hitachi Ltd, and the Naraha Remote Technology Development Center in Japan; and the ISOFIC Conference, Korea Atomic Energy Research Institute (KAERI), the Ministry of Science and ICT in South Korea. In addition, several members of the team attended or participated in the finals of the DARPA Robotics Challenge.

This study resulted from a pair of proposals created by Purdue University and funded by the National Science Foundation (NSF) and DOE-EM, respectively, to study various aspects of the handling of high-consequence materials and the implications to the science of safety. The lead author of this report and also the principal investigator (PI) for the two studies was responsible for the formation of the various groups of experts that took part in this study, in consultation with the project sponsors. The selection of DOE sites to visit was coordinated with DOE project sponsors. The opinions expressed represent the opinions of the expert study group participants and not the opinions of the NSF or DOE-EM.

What this document is intended to do:

- Survey efforts around the world to use robotics to handle high consequence materials and to compare the state-of-the-art in the U.S. with the state-of-the-art elsewhere
- Support internal DOE dialog concerning the use of robotics to address current and future DOE/EM needs.
- Provide conclusions that give guidance for future roadmapping efforts, but essentially culminating with a set of talking points supported by the observations made at the sites visited.
- Provide a relatively concise summary of the problems identified at the sites visited to ascertain which identified problems may (or may not) be addressed by robotics or automation.
- Propose opportunities to build on the robotics and automation efforts completed or ongoing at the labs, by identifying opportunities to integrate commercial and academic capabilities (as well as other efforts across the DOE complex) to meet future needs.

What this document is not:

- It is not a roadmap document.
- It is not a document that criticizes existing efforts.

To create this document, 45 experts in US and 10 experts from Japan, France, Korea, Sweden, UK, Spain, and Italy were variously assembled to participate in a series of site visits, workshops, and conference calls. International participation was particularly important because the unique nature and infrequent occurrence of exposure events make it desirable to gather the most pertinent experiences from around the world.

This introductory section will briefly define what we mean by High Consequence Materials (HCM) and summarize the priorities related to HCM as we understand them for each interested national agency before outlining the basic structure of this document.

2.1. High Consequence Materials: Definition

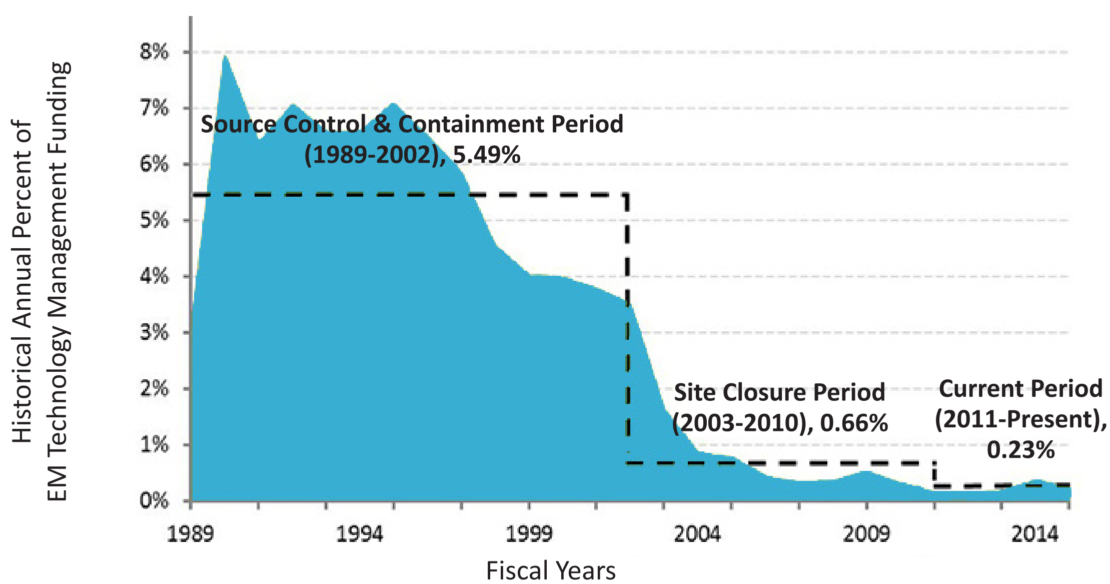
High Consequence Materials (HCM) are materials that if released into the environment in an uncontrolled manner, might cause damage or harm to people, animals, and the Earth itself. Examples of such materials include nuclear and chemical waste, biological contagions for which there is no cure (i.e. the Ebola virus), or even return samples from outer space that may harbor unknown compounds or life forms.

The chance of contamination of the general public by any of these materials is extremely small; however, there are professionals that are exposed to these types of dangers on a regular basis. Since these professionals must handle these materials, it is paramount not only for their safety, but for the safety of the general public, to take extreme measures to ensure that any and all possible mistakes are minimized and contained.

2.2. DOE History of Funding for Technology and Development

The Department of Energy had a long history of funding robotics and high-consequence materials funding in the 1980s and 1990s. Robotics for handling nuclear waste was a priority that supported work in multiple national labs (Sandia, Los Alamos, Oak Ridge, Pacific Northwest, Idaho and Lawrence Livermore) as well as some extramural funding. This work had a strong emphasis on manipulation and control and established a baseline of competence within the national labs and the R&D sector.

Around 2002, a strategic shift in funding occurred as DOE put high emphasis on closing many of the hundreds of facilities around the country that were heavily contaminated, but had long since been mothballed. During this strategic shift, many sites, such as Rocky Flats, were finally cleaned up and returned to civilian uses after languishing for decades on the EPA Superfund list. These facility clean ups were made possible by the decades of research and development on advanced technologies of the 80s and 90s, but an unfortunate result of the mission-shift was a similar funding shift that slashed funding for technology and development (see Figure below).



2.2.1. DOE-EM ROBOTICS CROSS-CUTTING TECHNOLOGY PROGRAM

As an example of the extent of technology development programs that existed prior to 2002, the Robotics Cross-cutting Technology program (RBX) was created by DOE-EM in the 1980's to support the remediation mission. The purpose of the RBX was to support DOE sites with specific projects to reduce the barriers inhibiting the use of robotics and remote systems technologies to reduce costs and hazards in the completion of long-term remediation projects. The program was organized and led by DOE national laboratory technical staff in concert with academia and industry. During its prime years, the RBX was one of the largest robotics programs in the US and produced both practical solutions to EM site projects, as well as spearheaded basic robotics research and development in key areas. To assure relevance and correct prioritization of all activities, the RBX technical agenda was crafted in concert with the EM sites.

The core technical leadership and expertise for the RBX was obtained through technical staff at specific national laboratories and sites with established capabilities in robotics and remote systems. RBX teams addressing specific EM technical focus areas (FA's) from a robotics perspective were expected to become integrated with the broader focus area teams within the Office of Science and Technology (OST). The RBX technology areas paralled the OST FA's and consisted of: buried wastes, underground storage tanks, mixed wastes, remote analytical chemistry, and basic robotics cross-cutting technologies. Each of these areas was led by a national coordinator (selected from the RBX senior team members) who was responsible for assuring that focus area/site needs/priorities were incorporated, establishing project teams across the sites, national labs, universities and industry partners.

2.3. Document Guide

This section summarizes the background and motivations for the DOE and NSF to organize site visits and workshops related to the science of safety for high consequence materials. Section 3 condenses and summarizes the key observations made from each of these sites visits which included:

- Stellafield, UK (April, 2015)
- Waste Isolation Pilot Plant (June, 2015)
- Idaho National Laboratory (August, 2015)
- Hanford Site month, (August, 2015)
- Savannah River Site, (December, 2015)
- Tohoku University, Japan (April, 2016)
- Toshiba Corp, Japan (April, 2016)
- University of Tokyo, Japan (April, 2016)
- International Research Institute for Nuclear Decommissioning, Japan (April, 2016)
- Mitsubishi Heavy Industries, Japan (April, 2016)
- Kyoto University, Japan (April, 2016)
- Hitachi Ltd, Japan (April, 2016)
- Naraha Remote Technology Development Center, Japan (April, 2016)
- NASA Johnson Space Center (July, 2016)
- University of Texas at Austin (July, 2016)
- Texas A&M University (July, 2016)
- Southwest Research Institute (July, 2016)
- Portsmouth Gaseous Diffusion Plant (August, 2016)
- ISOFIC Conference, Gyeongju, Korea (November, 2017)
- Korea Atomic Energy Research Institute (November, 2017)

- Ministry of Science and ICT, Korea (November, 2017)

Some the findings and recommendations of this report were drawn from the additional experiences of the participants from across the DOE complex, similar facilities abroad, and other national institutions who handle high-consequence materials. Participants are listed in the respective subsection for each site visit. Section 4 cannot provide a comprehensive summary of all the possible locations from which we could draw from this report, but does summarize key observations from selected sites, listed above, that are not part of the DOE complex (international sites and U.S. non-governmental facilities). In Section 5, we recognize that many external factors should be accounted for in our final analyses and any such factors are documented here. Finally, Section 6 presents the key findings and recommendations of the participants for consideration by the sponsoring agencies.

DOE SITES VISITED

Enriched nuclear materials are the largest single type of high consequence material that this team is concerned with and these are materials of high national importance. DOE has stewardship of the vast majority of these materials in the US and we chose to examine the sites of greatest importance to the DOE and with the longest term impacts on DOE goals and operations. Those sites include the Waste Isolation Pilot Plant (WIPP), the Hanford Site (Hanford), the Savannah River Site (SRS), and Idaho National Lab (INL). The WIPP was chosen because it is the only designated permanent storage facility for high-level nuclear waste in the United States and because it had a recent critical incident that resulted in an extended shut down. Hanford was chosen because it is the largest site in the DOE portfolio (40% of all the waste Curies of the US are at Hanford) and includes the largest high-level waste re-processing facility in the world. Savannah River was chosen because it is the second largest site in the DOE portfolio and includes the greatest variety of waste types and sources. Finally, INL was chosen because of its proximity to Hanford and the complexity of the calsine waste.

Figure 3.1: Geographic distribution of sites of interest to DOE for enriched nuclear materials.

It was decided that a team of robotics and nuclear experts, primarily from academia and government, but with representation from the private sector, be recruited as a complement to the national expertise that already exists at the national labs. Therefore, national lab employees were initially excluded from the DOE site visits, but team members with former national lab experience were included through a combination of targeted recruitment and open invitation. Subsequent trips to non-DOE sites in the US and abroad included current national lab employees. The primary group focused on the Savannah River Site, due to the variety of needs and opportunities it presents. A smaller subset of the team visited Hanford and INL to report back to the larger group. The WIPP was visited only by the lead PI.

In addition to the important national sites, it was deemed valuable to make occasional assessments of international sites and capabilities. The United Kingdom is an excellent candidate for such visits because they were a strategic partner in the early development of enriched nuclear materials during World War II and face many of the same types of problems that the US does, on a smaller scale. Japan is a strategic candidate because of the Fukushima Daiichi incident and the existing close collaboration the US has with the Japanese government and academic labs in response to that incident.

3.1. Summary of WIPP Visit

The Waste Isolation Pilot Plant (WIPP) is a long-term storage facility deep underground in the salt mining area near Carlsbad, New Mexico, USA. An unfortunate combination of mishaps closed the plant for investigation and clean-up after a release of radioactive material occurred in February of 2014. First, on February 5, 2014, a fire on a salt truck in the underground mine caused an accident investigation that temporarily closed the storage facility. While this was a typical industrial accident that posed no danger to persons outside the facility, less than two weeks later, airborne radiation was detected some 700 meters from the location of the salt truck fire by a continuous air monitor (CAM) in the mine. Multiple CAMs eventually indicated a plume moving through the mine, but nobody was in the mine at the time and the lack of diagnostic infrastructure or robotic tools for investigation limited options: it was known that a radiation cloud was traveling through the mine, making it unsafe for humans to enter, but no further information was available on the cause or precise location of the problem nor the risk to people or other materials in the mine. After more than a month of uncertainty, it was determined that a single canister ruptured in the deep cavern of Panel 7. It was determined that the canister had been packed with improper filler material prior to shipment to the WIPP and other canisters were subject to the same issue.

The salt truck whose brake/wheel caught fire on February 5, 2014.

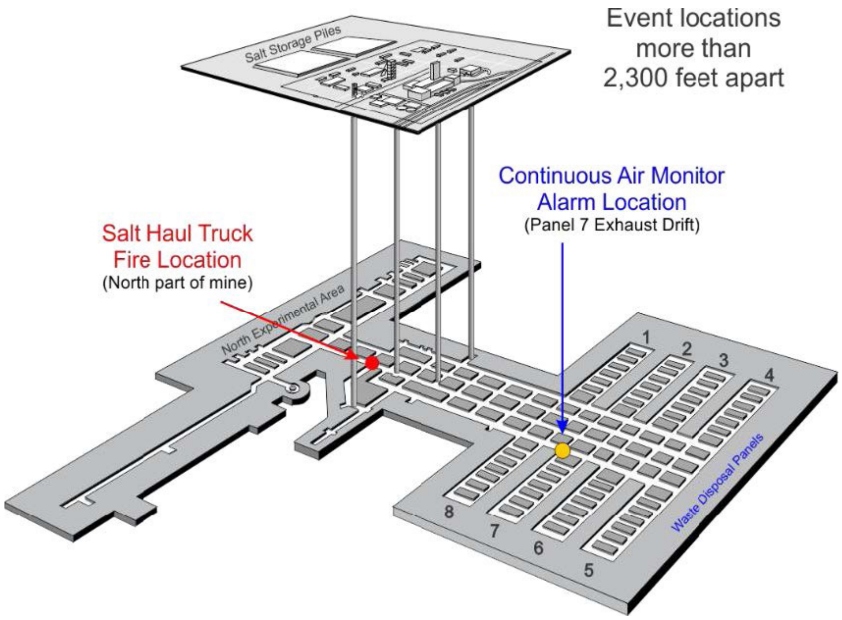
3.1.1. SALT TRUCK FIRE

The salt truck fire of February 5, 2014 is detailed in an Accident Investigation Board report issued March 13, 2014.

An image of the ruptured canister that released radiation on February 14, 2014.

3.1.2. RUPTURED STORAGE DRUM

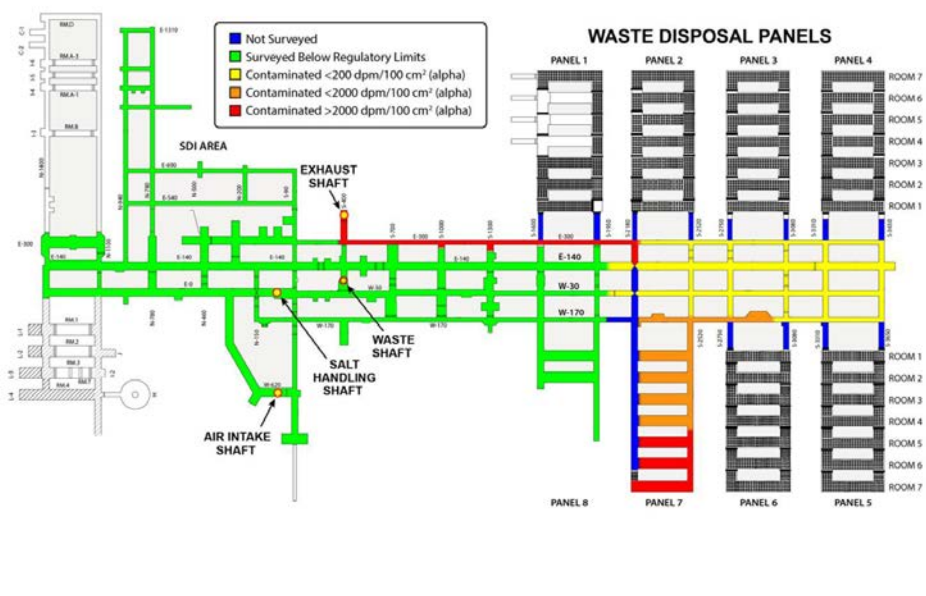
The continuous air monitor in the exhaust draft of panel 7 first detected airborne radiation on February 14, 2014. At this time, the mine was already closed for the salt truck accident investigation, so minimal information was available to interpret the incident. The WIPP's ventilation system automatically switched to filtration mode, and all exhaust air was re-directed to a bank of HEPA filters on the surface of the facility. This prevented the release of radioactive material to the surface (though a small amount was released due to tiny leaks in the exhaust shaft and dampers), but effectively cut the air circulation down to about 65,000 CFM, significantly below normal operating capacity.



Locations of the two incidents in February, 2014.

With airborne radiation floating through the facility, and virtually no information on what had happened nor what might happen in the immediate future, humans were not permitted to re-enter the mine for about a month. Exhaust air was being filtered through the HEPA filters on the surface, but no maintenance was being undertaken in the mine. Re-bolting became a key concern as the mine is constantly deteriorating without regular maintenance. The volume of air flow determines the total amount of work that can be accomplished underground, so with all the air circulating through the HEPA filters continuously, the reduced flow dramatically curtails operations in the mine.

Bolting in uncontaminated areas, a critical periodic maintenance step, resumed in November, 2014.



3.2. Summary of the Idaho National Lab Visit

The Idaho National Lab (INL) was originally a remote testing outpost of Argonne National Lab, and has undergone a number of name changes throughout its history. It was named the Idaho National Engineering Lab (INEL) in 1974, the Idaho National Engineering and Environmental Lab (INEEL) in 2007, and the INL in 2015. It is currently operated by Battelle Energy Alliance, LLC under contract. As a testing facility, it has had a total of 52 nuclear reactors of various types within its borders and now hosts four operational reactors, all of which will face decommissioning and demolition at some point.

The INL tour focused on a few specialized facilities with unique problems. These include the Underground Storage Tanks (UST) and Integrated Waste Treatment Unit (IWTU), the Calcine Solids Storage Facility, and the Advanced Mixed Waste Treatment Project.

3.2.1. UNDERGROUND STORAGE TANKS AND INTEGRATED WASTE TREATMENT UNIT

INL has a total of 11 underground storage tanks that have held waste (one additional tank has never held waste), but these are not a particularly difficult problem for INL. Unlike Hanford or Savannah River, they are constructed of stainless steel and are less susceptible to corrosion and leaking. The largest of the tanks is 300,000 gallons, but eight of the eleven tanks have already been emptied, cleaned, and closed, as of 2016.

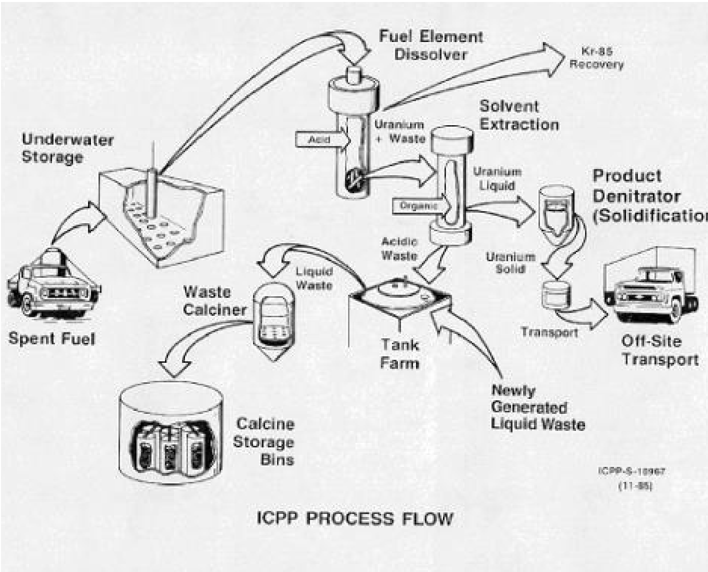
The Integrated Waste Treatment Unit (IWTU) is a relatively new facility designed to treat 900,000 gallons of radioactive liquid waste that is stored in the three remaining full tanks. It is expected to take 2-3 years to process all 900,000 gallons of waste. Only one nuclear waste treatment process in the IWTU uses robotics in the form of a teleoperated arm/gripper for inspection of processed waste. A teleoperated crane is also used for canister plugging, loading, and unloading. Each 2-foot diameter by 10-foot high stainless steel cylindrical canister is placed in a concrete-walled, above-ground vault until it can be transferred to permanent storage. Long-term storage will likely be at WIPP or a facility such as Yucca Mountain.

3.2.2. CALCINE SOLIDS STORAGE FACILITY

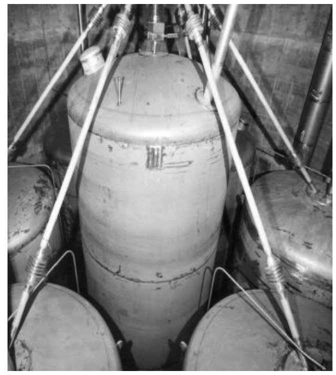
Previously at this site, 9 million gallons of high-level liquid waste were processed, with the liquid being converted into 4,400 cubic meters of calcine grains. This granular material looks like salt, includes fine debris, and is radioactive. The calcine facility is comprised of a total of six large, concrete silos, each of which is partially submerged in the ground and contains four to seven tanks. Each tank is a tall steel cylinder, approximately 20 feet in diameter and up to 60 feet tall, that is anchored to the concrete floor of its silo. Three-inch pipes enter the top decks of the silos and route to the top of each tank. Pneumatic transport was used to deliver the granular calcine material into the tanks. Tanks were filled to capacity, including the fill pipes. Temperatures inside the silos are approximately 400°C, with air convection within the silos as the only means of heat transfer. The tanks and silos “breathe” through HEPA filters on the silo top decks into the local atmosphere. Radiation levels inside the silos are beyond suited protection.

The silos and tanks were constructed and filled under the assumption that their calcine contents would never be removed. However, a settlement with the state of Idaho has changed that plan. The calcine must now be removed, and the silos must be washed and then grouted in place. DOE/EM is interested in inspecting the tanks to understand if the material is still loose or has sintered or otherwise formed a solid. A variety of potential solutions were discussed: using liquids to flood the silos and float out entire tanks, adding access pipes to the tanks and silos, and using special purpose robot arms (e.g. custom snake-like robots) to extract the calcine. The extraction of an entire tank would be challenging because the tanks were likely never designed for such handling after being filled, and would be difficult to lift and manipulate without causing structural damage. It would also be challenging to maintain acceptable containment during such large-scale operations. Options for extracting the calcine without removing entire tanks include the use of augers and vacuums to remove material through the network of pipes (new or existing).

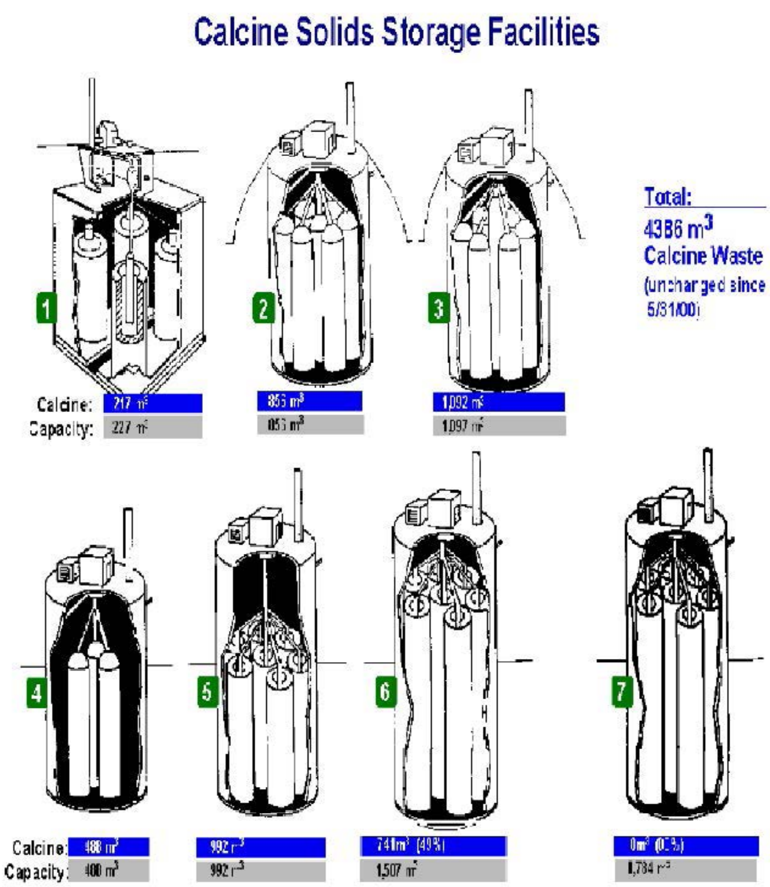
The shipment of the extracted material is not clear, as the final storage depot has not yet been selected. Therefore, the means of transport and form in which the calcine can be safely transported are not clear. Another option discussed was the building of a new onsite factory for converting the extracted calcine into vitrified logs for transport in stainless steel canisters.



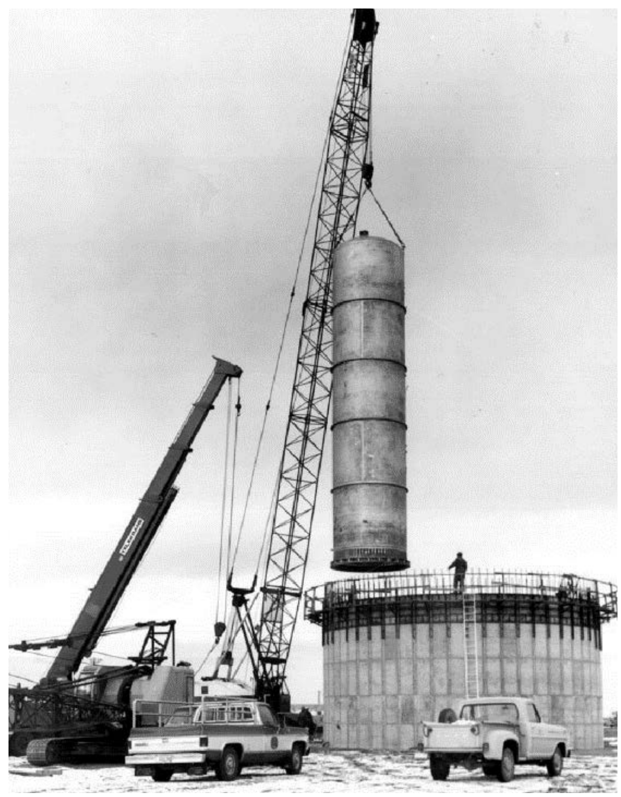
The Idaho Chemical Processing Plant (ICPP) process flow for converting high-level liquid waste into calcine grains.



The interior view of a large concrete silo illustrates the complex system of pipes used to fill each of the four to seven cylindrical tanks within each silo.



Schematics for seven concrete silos show the varied tank configurations, pipe networks, and calcine capacities of each silo.



A tall steel cylindrical tank is being carefully lowered into a concrete silo by a crane during construction of the calcine storage facility.

An unused steel cylindrical tank is shown prior to its insertion into a concrete silo. Fill pipes will be attached to the top of the tank while its base will be anchored to the floor of the concrete silo.

Table A-1. Average calcine compositions, excluding oxides, in weight percent.[1]

Component	Alumina Calcine	Zirconia Calcine	Zirconium-Sodium Blend Calcine	High-Sodium Calcine
Aluminum	87.3	11.8	6.5	53.4
Boron	0.4	1.1	1.0	0.8
Cadmium			5.5	0.2
Calcium		37.7	31.9	4.0
Chloride			0.1	0.4
Chromium		0.4	0.1	0.1
Fluoride		30.1	21.9	1.0
Iron	0.1	0.3	0.2	0.4
Mercury	5.5			0.003
Nitrate	2.6	0.1	8.1	23.0
Phosphate	1.1			0.7
Potassium	0.1	0.1	0.9	2.5
Sodium	1.4		4.1	11.4
Sulfate	1.5		3.7	1.4
Tin		0.3	0.2	
Zirconium		18.2	15.5	0.3

A blank cell indicates an insignificant quantity.

Average calcine compositions, excluding oxides, in weight percent for various chemical components.

3.2.3. ADVANCED MIXED WASTE TREATMENT PROJECT

The purpose of the Advanced Mixed Waste Treatment Project is to repackage legacy waste drums from nuclear weapons plants (primarily the Rocky Flats Plant) such that the TRU wastes are segregated more effectively from other radioactive wastes. In this process, the danger is not radioactive emissions, but rather potential exposure to TRU contaminants (primarily plutonium) and other hazardous chemicals. Consequently, the entire process is remotely operated.

The massive facility receives 55 gallon drums from storage pits onsite at INL and other storage depots around the country. The facility measures and weighs the drums, cuts them open, extracts dangerous items and other materials that are not allowed at the final storage sites (e.g. pressurized aerosol cans), crushes the material, and then stores it in newer and better sealed containers. The newer storage containers are intended to be shipped to WIPP, but are currently being stored onsite since WIPP is temporarily closed as of this visit (February 2014).

A central facility control room having control stations with PC computers and graphical interfaces enables the viewing and remote supervision of all processing cells. Handling of the mixed waste containers is done with conveyors, elevators, and electro-hydraulic manipulators (Brokk, Inc.). An incoming waste barrel is loaded via elevator into a robot cell. There are three robot arms in the cell, each with its own work station. Typically, two robots are in use at any one time, 24 hours a day, 7 days a week. The cell is also used to store many older arms and grippers that are no longer in use. A human operator remotely controls a hydraulic Brokk manipulator to rip open the steel barrel and sort out non-allowable objects. Each 6 degree-of-freedom Brokk robot arm features a spherical wrist and a large gripper/crusher, is approximately 10 feet long, has a payload capacity over 1000 lbs, and has a top speed of approximately 2 ft/sec. No force/torque sensors or cameras were observed on the arms. The arms are controlled by line of sight (approximately 15 ft) through thick windows using simple switches that control each actuator joint individually. The operator must learn to control the robot using a non-intuitive, mirrored joint space since the operator's window onto the cell provides an overhead and reversed view of the workspace (from the front of the manipulator). On average, it takes approximately one year for a new operator to become fully trained and qualified to operate the robot. A maximum of only 2.5 hours of continuous seat time is allowed for the operators.

The waste barrels contain a mix of plastic, paperwork, cardboard, tools, rags, cans, contaminated PPE, and other garbage from the last 70 years. The TRU wastes are contained in polyethylene bags inside of the drums. When a new barrel arrives, the operator must grab and open a tiny latch using a gigantic 1 degree-of-freedom robot gripper. Once the drum lid has been pulled off, the operator must grasp the plastic bag in the drum and use it to swing the drum back and forth until the drum eventually falls away from the bag. This bimanual task is especially challenging for the teleoperator of a single robot arm whose dimensions dwarf the materials to be manipulated. A simple mechanical fixture (or second robot arm) that grabs the base of the drum would make it easier for the teleoperator to pull the plastic bag out and to perform other required bimanual tasks.

Hatches in the cell floor are covered by lids, which the operator opens with the robot arm. The sorted materials are dropped into barrels below the cell. The old barrel is crushed with the robot arm and dropped down one of these hatches. Below the cell, the new barrels receive the sorted material and move on conveyor belts into lid sealer, washer, and crusher operations. The conveyors move within long glovebox tunnels, with glove portals every 2 ft (vertical and horizontal) for cleaning and equipment repair by human hands. New aluminum, 55 gallon barrels containing the sorted waste are crushed down to "pucks" that are 4 to 10 inches in height.

A teleoperated puck picker is used to carefully transfer the pucks to a box for transport and storage using a simple gripper and friction. In one incident, a puck was dropped, which shattered the adjacent glass and resulted in contamination outside of the robot enclosure. Since then, precautionary measures have been implemented, such as the requirement of a 600 lbs "push test" in order to ensure a good grip of the puck by the robot gripper. The inherent challenges of teleoperation, especially with limited sensing and dexterity, make the addition of such safety checks a requirement for any teleoperated system used for the remote handling of high consequence materials.

In discussions with the INL plant operations manager, he indicated that one of the biggest issues is maintenance and repair of the hydraulic Brokk manipulators. The manipulators break regularly, and require 2-3 human entries into the cell per week for repairs, mainly for the repair of hydraulic lines. Due to the TRU present in the cell, maintenance personnel must wear a positive pressure PPE suit with five layers of gloves, which degrades dexterity. Each PPE suit requires extra personnel for donning and doffing, and weighs approximately 31 lbs, which greatly reduces stamina. Each cell entry is limited to 1 hour in a PPE suit due to thermal and radiation exposure limits. Additionally, medical health scans are required prior to and after work in the cells. When repairs are required in the conveyor, crushing, and processing work areas, personnel must perform the repairs via glovebox portals.

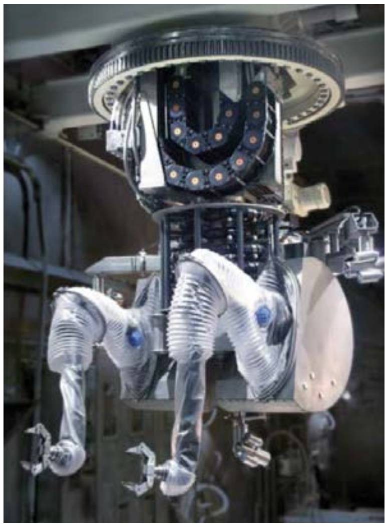
A work cell containing robot arms and conveyors is used to sort mixed waste.

Human workers process waste through glovebox portals.

The donning and doffing of a pressurized PPE suit requires extra personnel and medical health scans prior to and after work in the cells.

Modernization of the teleoperated robot systems is highly recommended. The efficiency of tasks such as the opening of waste barrels and sorting mixed waste could be vastly improved with a more intuitive master controller approach that is typical of modern nuclear and undersea operations (rather than individual joint controls operated from a non-intuitive, mirrored joint space). With technology upgrades, it is estimated that reductions in total task time could be in the range of 3-10x. Several industrial robot manufacturers currently offer electrical robot manipulator packages with the necessary payload and reach specifications. If they can survive the radiation field, electric manipulators of sufficient strength and speed could increase efficiency, reduce downtime due to hydraulic failures and maintenance, and minimize the need for personnel exposure to hazardous work conditions for repairs. The use of modern electric manipulators would not only provide drastically improved reliability, but would also facilitate the automation of many subtasks, thereby increasing throughput.

While the teleoperators of the Brokk manipulators are highly trained and experienced, the existing operations are crude and inefficient as compared to other remote manipulations routinely performed with mechanical master/slave manipulators and newer servo-manipulators. For instance, the Spallation Neutron Source at a modern DOE facility at Oak Ridge National laboratory employs a teleoperated dual-arm servomanipulator in its hot cell work areas. The manipulation system enables dexterous remote handling and features scaleable force reflection, joint indexing, tool weight cancellation, and other advanced control features to minimize operator fatigue and give the teleoperated arms capabilities beyond those of standard mechanical master-slave manipulators.



Left: A teleoperated dual-arm servomanipulator is used for dexterous remote handling operations in hot cell work areas at the Spallation Neutron Source at a modern DOE facility at Oak Ridge National laboratory. Right: A remote operator controls the dual-arm servomanipulator from a control room equipped with a multi-camera viewing system.

3.3. Summary of Hanford Visit

The Hanford Nuclear Reservation hosted an international team of robotics experts from August 11-12, 2015. The objective of the visit was to have a small subset of the larger team understand current practices related to the use of robotics for the continued decommissioning of the site and report back to the larger workshop at Savannah River. The hosted team included 9 individuals from the United States and Japan. Participants were selected from academic, industry, or other governmental departments that had expertise in either relevant areas of robotics or had experience in other high-consequence domains (space, military, infectious disease, etc.)

Dr. Roy Gephart kicked off the mini-workshop with an overview of the history of the Hanford Site from its establishment in 1943 as part of the Manhattan Project until today where the mostly decommissioned nuclear production complex serves multiple purposes. It holds approximately 66% of the nuclear waste (by volume) in the United States, facilities to process this waste, a commercial nuclear power plant, a nuclear research facility (PNNL), and one of the two observatories completed in 2002 to detect gravitational waves. At the height of the cold war, a total of nine reactors and five processing facilities were built. They produced 67 metric tons of plutonium from 1945 to 1987 which was about 70% of the plutonium for the US weapons program. The by-product high-level liquid waste (HLLW) from reprocessing, with a volume of 200,000 cubic meters, was stored in a total of 177 underground storage tanks (USTs). The original tanks were single-shell and the later ones were safer double-shell designs. There are a total of 149 single shell tanks and 28 double shell tanks holding a total of 56 million gallons[1] of radioactive and chemical wastes. Dr. Gephart noted that multiple reprocessing canyons for the various wastes were designed and built in parallel. The processes were designed for complete remote operation, maintenance, and change out of major process components, made possible by the development of the Hanford Remote Pipe Disconnect.

The waste streams are extremely complex and varied. Some liquid wastes were treated and precipitated into salt cake. Today it is estimated that the total UST inventory is made up of 23M gallons of salt cake, 21M gallons of supernate, and 12M gallons of sludge. Multiple tank farm areas are interconnected to other facilities through underground piping systems. Internal radiation levels can be as high as 2,000 rad/hr. The design basis for hardware being introduced into a tank is 1,000 rad/hr.

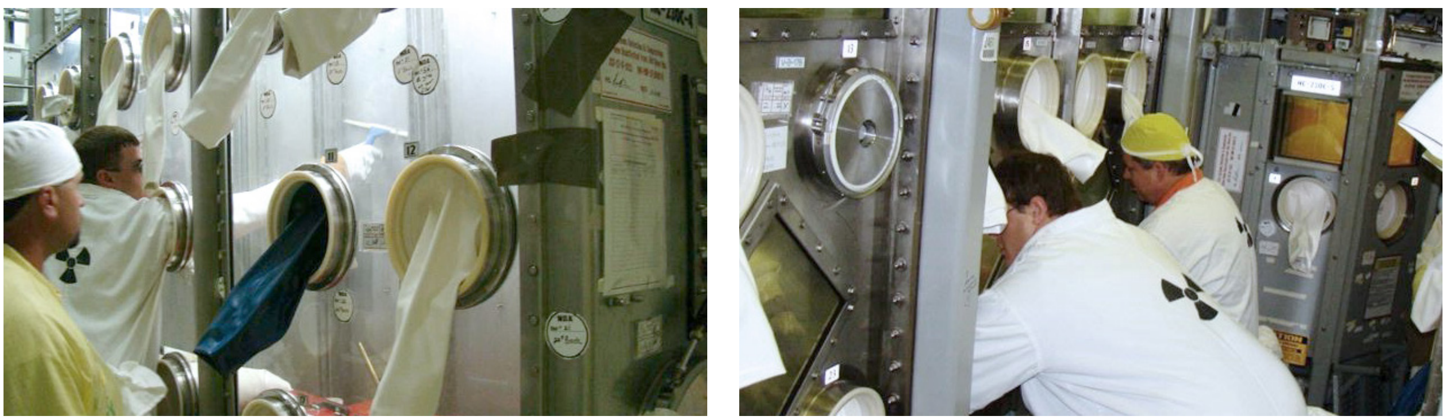
[1] One way to visualize or estimate 1 million gallons of waste is to picture a pool that is about 50 feet deep as well as 50 feet long and wide. It is worth also noting that the amount of liquid processed will be closer to 250 million gallons once the water required for transport and processing is included.

3.3.1. GLOVE BOX OPERATIONS

Glovebox D&D is a challenging problem throughout the DOE complex. The removal of two 12-foot high gloveboxes from the Hanford Plutonium Finishing Plant (PFP) in February, 2016 was reported as some of the most hazardous operations at Hanford. The size of the boxes, the level of contamination, and the type of contamination combine to make this a particularly dangerous project. The gloveboxes were too big to be removed from the plant in one piece, so they had to be cut up and sealed for movement and disposal.

Sealing of one of the large 12′ gloveboxes at the Hanford Plutonium Finishing Plant (PFP) in February, 2016.

While these two gloveboxes posed unusual hazards, they are just two of the 238 gloveboxes in the PFP and an even smaller portion of all the gloveboxes at Hanford. The number of gloveboxes to be removed is daunting. Some are still actively used. In many cases, gloveboxes were abandoned during plant shutdowns with hazardous materials left inside because of the risks of cleaning them to workers. In some cases, this has led to degradation of the glass and materials of the boxes. Automation can address both the repetitive, hazardous tasks in active gloveboxes and the non-repetitive task of removing contamination from dormant gloveboxes prior to their removal and disposal.



Glovebox operations at the Hanford site.

3.3.2. UNDERGROUND STORAGE TANK FARMS

Plutonium production yielded millions of gallons of liquid waste which was pumped into storage tanks. The site has numerous underground tanks of varying age (as much as 75 years old), size, construction type, and current condition. The Hanford Site includes 149 single-shell tanks and 28 double-shell tanks. All Hanford tanks are carbon steel, as opposed to the largely stainless-steel storage tanks of INL. These tanks have piping that runs in/out, riser pipes that provide access from the above ground, and vary from single wall carbon steel to more complex double walled tanks with concrete liners. The contents vary from sludge, to salt cake, to a liquid mixture called "supernate." As some tanks have begun to fail (i.e. leak), material has been processed or moved to newer tanks. Some of the newer tanks are linked, but older ones are either not linked or linked by piping that is too old to use. The goal is to clean out all the tanks and pipe the waste to the new Waste Treatment Plant[2] for processing once it is operational.

There are many challenges to decommissioning and decontaminating waste storage tanks:

- Characterize the waste;
- Access the waste;
- Dislodge and/or mobilize the waste as necessary based on its current form(s);
- Convey the waste from the tank;

[2] https://www.hanfordvitplant.com/about-project

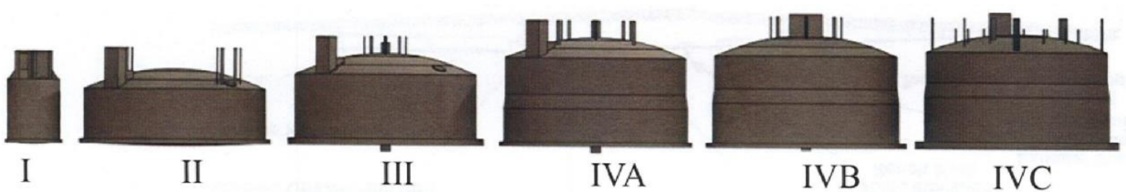
- Transport the waste;
- Inspect and ensure the viability of tanks that contain waste; and
- Decommission the tanks and grout-in-place once as much waste as possible has been removed.

Emptying a tank is a problem because the tanks are below ground, access is limited to small pipes (3-12 inch), the tanks and waste are large (1 million gallons), acidic, thermally hot, radioactive, humid, and filled with a mixture of sludge, cake and liquid. They may contain explosive vapors. Another problem is the inspection of the interstitial volume in between the inner and outer walls of double walled tanks.

Existing methods to transfer material from a tank use spray hoses to push material to a central pump and dissolve it. Pusher robots are lowered into the tanks and then used to push material with a bulldozer blade. Some have articulating pan/tilt units with spray nozzles on their ends, or articulating arms that have spray and vacuum tools on their end-effectors. All these tools must enter the tanks from above, through 3-12" diameter risers (some newer tanks have larger risers) or with the excavation of larger access tunnels.

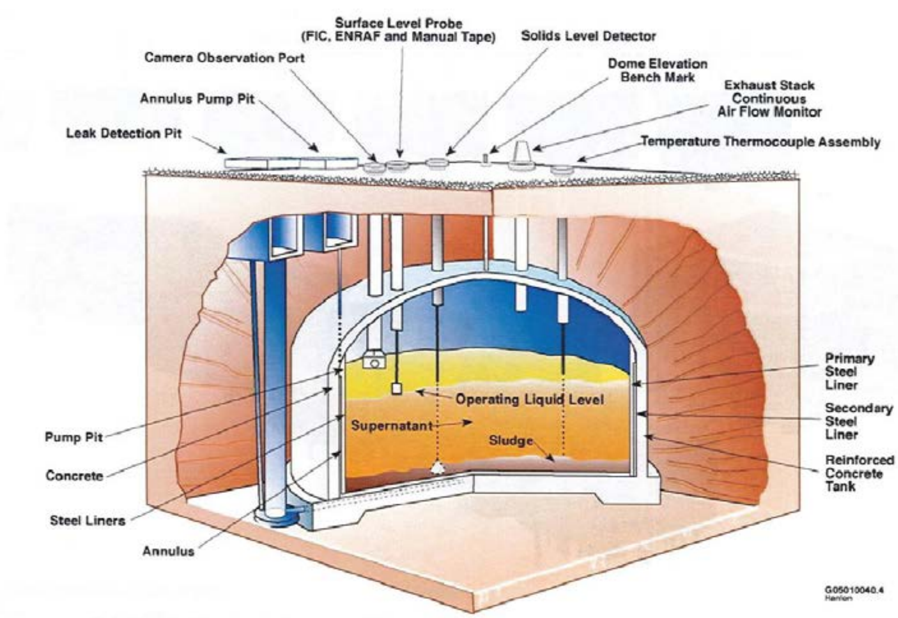
Hanford waste storage tanks during and after construction including one example of the waste stored inside a tank.

The single-shell tanks come in a variety of sizes and are illustrated below.



The six variations of single-shell tanks at Hanford.

A cut-away of a typical double-shell tank is illustrated below.

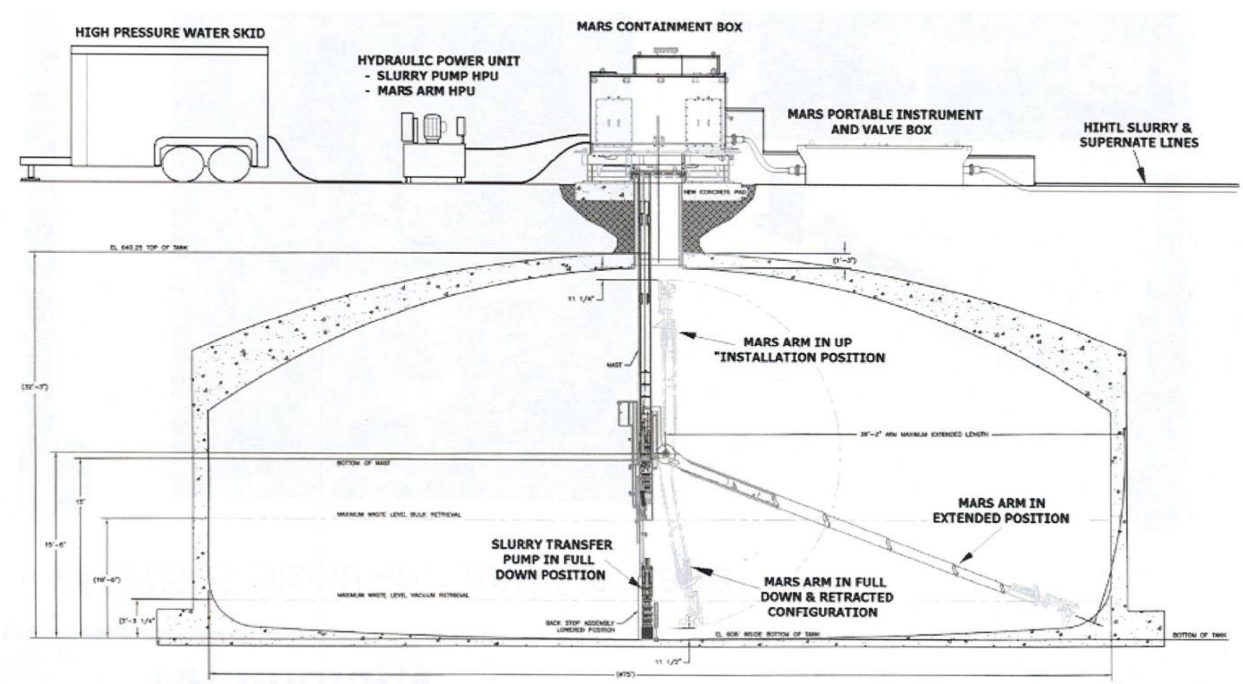


Cut-away of a typical double-shell tank.

Robotic tools are needed that can enter through the 12 pipes, breakup material and push it to the center of the tank floor. Robots are also needed to inspect wall integrity, take samples, map/measure contents, and monitor conditions. Thus, some robotics systems have been used and/or evaluated for cleaning and inspecting waste tanks. During inspection or waste removal tasks, the tanks environment must be continually monitored to ensure safety including temperature, humidity, gas content, dose, and – ideally – isotopic identification. Such monitoring is necessary even if human operators are completing the work.

The Mobile Arm Retrieval System (MARS) is a commercial robotic device for cleaning of the tanks. It inserts through a 55″ riser and can reach 35 feet horizontally and 40 feet down into a tank. It can be fitted with a sluicer or vacuum. The system is controlled with a standard game controller. For many remote systems (such as remote hot cell manipulators), kinesthetic correspondence has the potential to help reduce training times and decrease the cognitive burden on the operator, but – as the QWERTY keyboard demonstrates – the human operator is capable of learning to effectively use counterintuitive user interfaces.

MARS in the double-shell tank mock-up facility.



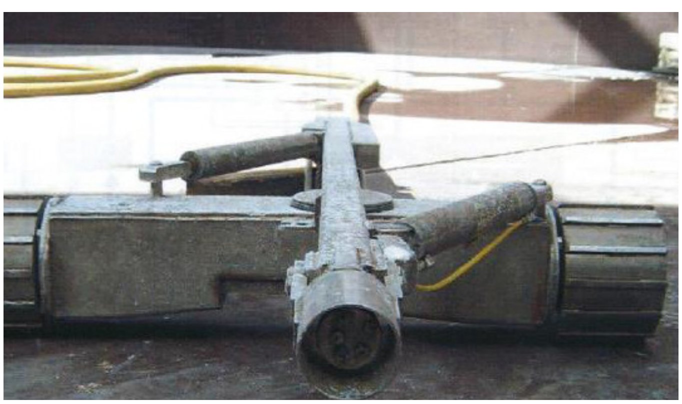
The FoldTrack, developed by Non-Entry Systems Limited, was used inside tank C-110 for 230 hours.

The MARS was used in tank A-105. It was provided by a local equipment supplier that positions a multi-jet high pressure sluicing head for salt cake mobilization. The fluidized materials are then pumped out of the tank. A vacuum end-effector was used for the removal of "tails". A 24-inch riser was used for access and approximately 300 hours of jet time over several months was required for each tank. The MARS-S system was abandoned in place after project completion. The MARS cannot be used in some tanks that have internal equipment. For example, the Savannah River tanks are more likely to have internal cooling pipes and other obstacles inside the storage tanks. The Waste Retrieval System is a sluicer that can be used in tighter situations.

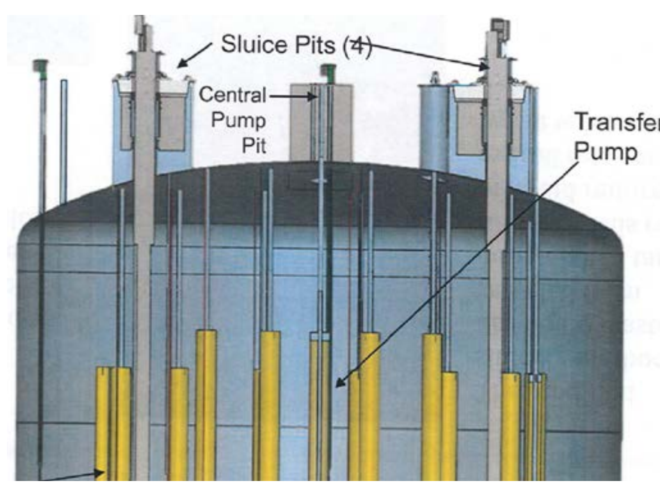
The objective of the FoldTrack vehicle from NESL (used in tank C-110) was to push sand-like residual waste towards the center of the tank's floor. The system could be introduced through a 12" riser, but there were issues with the tracks coming off the system and the need to leave room for placing the centrifugal pump. Despite some of the issues with these approaches, DOE expressed a strong interest in improving and building on the successes of existing solutions like MARS instead of considering proposals for new, but untested MARS-like systems.

The FoldTrack robotic vehicle for cleaning inside of tanks with limited access risers.

Another in-tank vehicle, made by TMR, was used to clean up the last 4% of the heel inside a tank. (The other 96% was cleaned by the MARS or other means.)



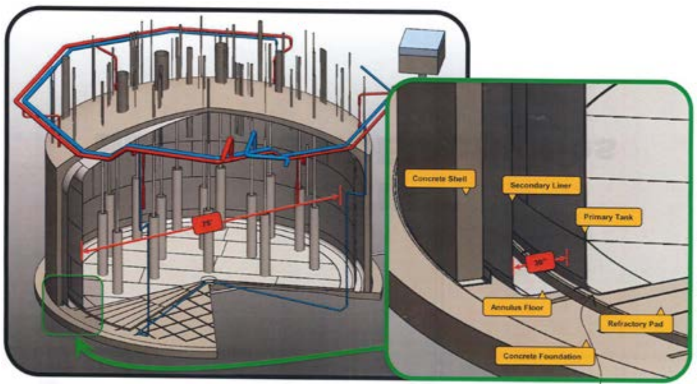
In-tank device made by TMR.



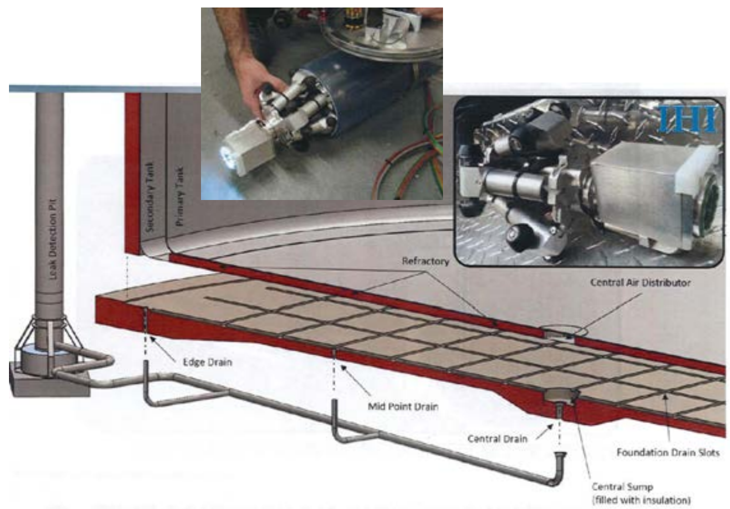
Example of a tank with additional internal obstacles such as piping for cooling, etc.

Inspection tasks on the outside of the tank have also been addressed with robotics. The air shaft below a tank or the area between the two hulls in a double hulled tank can be remotely inspected to detect leaks, undesired material build-up or areas where the tank walls are deteriorating. The cooling slots are typically 1″ x 3″ and would require sufficiently small and maneuverable (possibly sacrificial?) robotic devices. Such areas can be extremely confined and vary greatly from one tank to the next.

Magnetic wall climbers with NDE capabilities are used to inspect welding seems on the DSTs with good results. Building on these successes, additional inspection tasks should be automated and include many upper tank operations to avoid operator exposure to tank vapors. Illustrative examples are shown in the following figures.

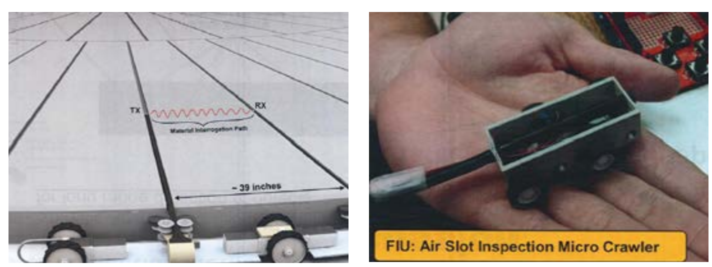


The areas between the hulls, channels in the refractory pads, and ancillary piping should all be remotely inspected and/or decontaminated.



Pipes – including tank drainage systems can be accessed by snake robots.

Compact systems deployed for inspection and decommissioning



Examples of miniaturized systems under development for inspecting air slots and other extremely small spaces.

Given the combined number of tanks at Hanford and Savanah River that must be addressed, a long-term investment in robotic systems that can be redeployed makes sense if their use can be viewed across a multi-year, multi-tank basis to properly amortize the development and operational costs.

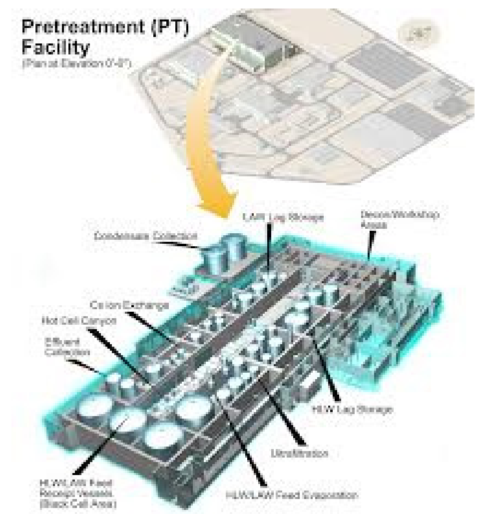
3.3.3. HANFORD WASTE TREATMENT PLANT

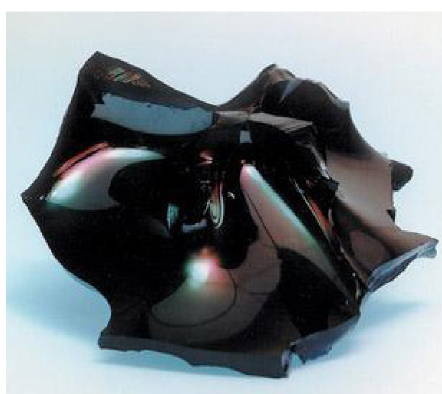
When completed, the Waste Treatment Plant (WTP) will process the liquid wastes stored in the multiple tank farms. Liquid waste will be pumped from the Hanford tanks to the new facility over distances of up to seven miles. The material is pumped through a pre-treatment facility then routed to either high- or low-level facilities. Both outputs are vitrified into glass, then poured into stainless steel canisters for final transport and storage. These facilities are huge, concrete structures filled with pumps, piping, storage and mixing tanks, heaters, canister-handling gantries, rail cars and massive vault doors. The operational concept involves few human workers once treatment begins.

Black cells are regions of the facility where no people (or ideally their surrogate robotic systems) will ever go once treatment begins. A concern involves the use of jet pulse mixers to continuously stir the waste and prevent sediment fallout. There will be limited sensing in place to monitor this process and detect issues before they become a problem. The facilities will include HEPA filters, but access to the inner side of the filter channel requires people in suits for monitoring and then replacement if a spray/spill occurs. When inevitably necessary, working in the black cells will be difficult because there are few openings. The cells have no power and limited sensing. If a spray leak occurs, the entire cell could be contaminated before a radiation sensor in the sump detects a problem. If this happens, HEPA filters will also be contaminated, and they will need to be inspected and replaced.

Even though they are designed for zero maintenance, we must assume that such maintenance will be necessary as their task is estimated to take 50-75 years to complete. As a comparison, the Mars Rover's mission was completed in just 10 years in – arguably – a less hazardous environment.

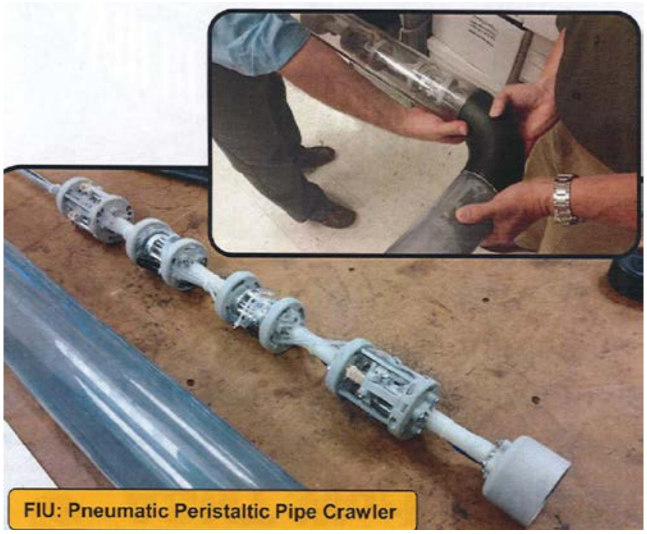
The Waste Treatment Plant (circa 2015) under construction at the Hanford Site.





Examples of waste after the vitrification process is completed by the WTP.

Before construction is completed, it is recommended that the design be changed to accommodate robots if they are ever needed to enter the black cells for sensing, monitoring and future repairs. It may also be beneficial for robots to enter areas built for people if contamination is detected in order to reduce exposure to human operators.



One example of many pipe crawling robots under developed at various academic institutions.

3.3.4. PIPE INSPECTION

In addition to tank piping, pipe and duct inspection is a major issue that was highlighted in many facilities at Hanford and throughout the DOE complex. Given number and range of pipes and ducts at the site (from the tiny air pathways under the DSTs, to the multitude small pipes that run through the WTP's black cells, to large distribution pipes that move waste across the entire site) inspection and – inevitably – repair will be necessary. Inspection of the water lines on-site is also necessary. Security is also an issue in the cross-site transfer lines – which can be up to 7 miles long – since they carry highly contaminated waste.

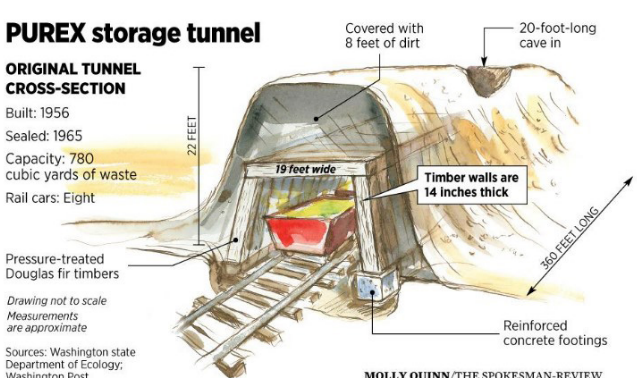
Some lessons and solutions can be collected from industries with similar issues (i.e. Oil & Gas transmission, sewage system inspection, etc.), but Hanford's challenges are unique given the variety of pipes, lack of standardization, and unique hazards (i.e. radiation, etc.).

3.3.5. PUREX TUNNELS FOR STORAGE OF ODD-FORM WASTE

The plutonium/uranium extraction (PUREX) process was a chemical process to remove the cladding from spent fuels. The PUREX facility is one of the major D&D sites at Hanford because of the high levels of radiation that remain. Yet, a curious feature of the PUREX facility is the creation of two "PUREX tunnels" for the underground storage of large contaminated equipment, adjacent to the canyon buildings. These tunnels were primarily used for the storage of "odd-form" pieces of equipment, which include the ambulance used to transport the "atomic man" to a local quarantine facility after a 1976 chemical explosion exposed him to the largest dose of radiation from americium ever recorded.[3]

Aerial picture of the PUREX tunnels.

Inspection and cleanup of the underground tunnels presents many unique challenges above and beyond the challenges of the underground tanks and the remaining decommissioned facilities and are a clear opportunity for robotics and remote technology. In fact, the urgency of these challenges was made apparent by the recent collapse of a section of the smaller PUREX tunnel in 2017.



A diagram of a cross-section of the smaller PUREX tunnel (left), showing its construction. An overhead picture (right)

[3] http://www.oregonlive.com/today/index.ssf/2014/07/feds_to_clean_site_of_1976_ato.html

Grouting operation in November, 2017 to stabilize the smaller PUREX tunnel after a section collapsed.

3.3.6 MAJOR PROCESSING FACILITIES AND CANYON AREAS

Other Hanford challenges presented included the handling of nuclear materials in telemanipulation cells, and the processing of ^{137}Cs and ^{90}Sr waste. The major processing facilities (B-Canyon, T-Canyon, U-Canyon, Redox, and PUREX) all need near-term monitoring prior to their eventual decommissioning, demolition, or grouting-in-place. Some of these facilities have no HVAC and are losing the ability for manual entry for inspection and characterization. Mobile robotics will be necessary to complete many of the required D&D tasks.

One area of interest is the sump in Building 324 under B-Cell[4] where a spill occurred in 1986. This sump has a high build-up of 137Cs and 90Sr with a dose rate of up to 8,900 rad/hr. Contamination may be up to 11m below the building foundation. Some sort of digging robot was suggested as a possibility. There is a significant need to characterize the spill.

3.4. Summary of Savannah River Site Visit

The Savannah River National Laboratory hosted an international team of robotics experts December 7-10, 2015. The visit was jointly sponsored by DOE-EM, the National Science Foundation and Purdue University. The objective of the visit was to understand current practices related to the use of robotics and automation for handling “High Consequence” or Special Nuclear Materials (SNM) to develop an accurate picture of the current state-of-the-art. The visiting team is interested in surveying and identifying opportunities to develop and deploy new (or existing) technologies which would improve the safety of its workforce, reduce the cost of decommissioning and decontamination (D&D) activities, and ensure that DOE meets its obligations to close and remediate the remaining legacy sites related to the past research and production of SNM.

The visiting team included 26 individuals from four countries. Participants were selected from academic, industry, or other governmental departments that had expertise in either relevant areas of robotics or material handling in other hazardous domains (space, military, etc.).

3.4.1. GLOVE BOX OPERATIONS

A lot of testing is done on waste materials at different points in the treatment process. A sample is taken from within the environment (using a crane), put into a lead box, transported to a nearby facility, and into a glove box where human workers perform measurements on the sample (using chemical processes). Workers either put their hands into this environment through plastic gloves, or use a master-slave manipulator to do the experiments. Both approaches are tedious; the glove boxes are dangerous due to the risk of puncturing a glove. One of the glove boxes at SRS has substantial airborne plutonium leftover from a grinding operation, which is difficult to clean. SRS has built a mock-up of the glove box and are trying to determine how they can safely start decontamination of this facility based on the hazards (workers need to wear suits in addition to the gloves).

[4] http://www.pnnl.gov/main/publications/external/technical_reports/pnnl-21214.pdf

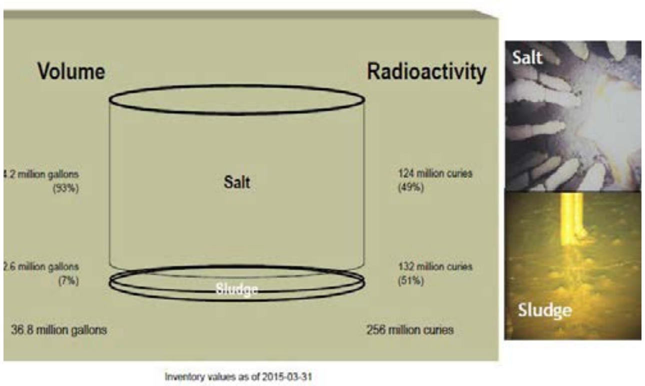
3.4.2. WIPP CAMERA

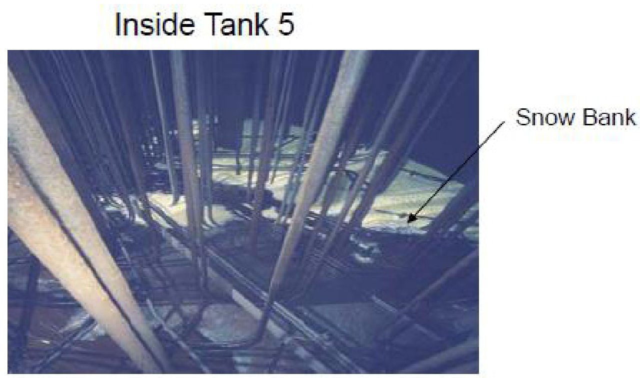
When the radioactive incident occurred at the WIPP in February of 2014, it was initially uncertain what had happened. There was little information other than the Continuous Air Monitors tripped alarms detecting radioactivity. Nobody was in the mine at the time, nor was anyone allowed to enter, so the staff was it the dark for several weeks. Eventually, as evidence was pieced together, it became necessary to develop a remote camera system to try to inspect the extent of the incident.

It was suspected that a drum in panel 7 had ruptured, but the drum was inaccessible, near the interior of the cache of materials. An extended-boom camera system was developed by SRNL to inspect the drum and verify that the problem.

3.4.3. UNDERGROUND STORAGE TANK FARMS

The underground storage tanks at Savannah River have both important differences and similarities with the tank farms at Hanford. In both cases, the amount of radioactive material is enormous. The Savannah River tank forms contain about 256 million curies of radiation, while the Hanford farms contain about 195 million curies. The Savannah River tank material has been evaporated to remove much of the water, leaving the 43 single- and double-wall tanks with a volume of about 37 million gallons, with the largest tanks holding up to 1.3 million gallons. A key practical difference is that most of the Savannah River tanks are laced with internal cooling coils, making internal cleaning much more difficult. A centralized manipulator, like the MARS system is not practical in most of the tanks.





Disposal is done at Savannah River by separating out the sludge (high-radiation) from the dissolved salts, then distilling the salts several times to remove the highest-radiation components. These two streams of high-radiation materials are sent to a "vitrification" process where they are mixed with sand, melted and turned into glass, and poured into steel vessels for indefinite storage (initially planned for Yucca Mountain). The lower-radiation stream is mixed with concrete (grout) to a consistency of latex paint and poured into a large concrete vat for on-site storage above ground. Once a tank (or a whole canyon) is clean "enough", it is typically filled with concrete (grouted in place) and decommissioned on site. Clean "enough" is defined as removing all "transferrable" contamination, leaving only the "fixed" (e.g., can't migrate).

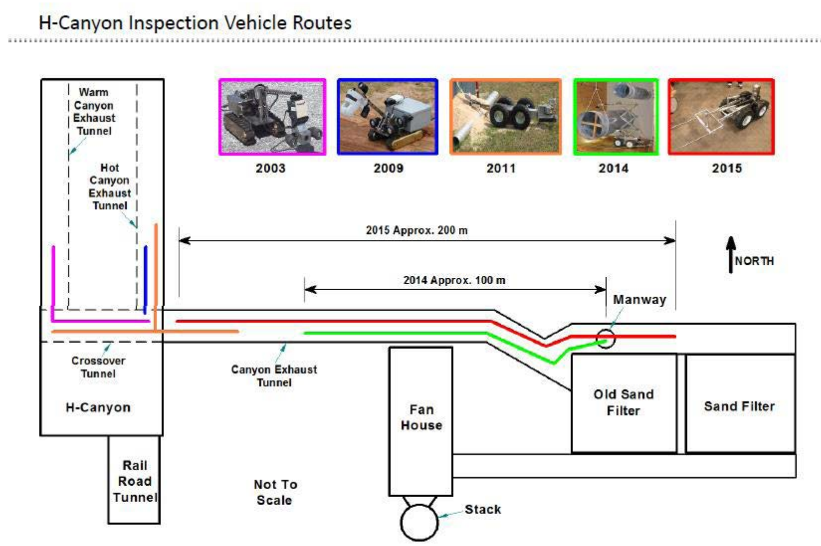
Some custom manipulators were developed for tank inspections. The robot below was used in tank 18F to sample sludge not directly under the riser entry point.

3.4.4. CANYON OPERATIONS

Canyon cranes present an interesting history of automation and remote operation. SRS initially had a worker in the crane pod that used a periscope system to remotely handle high gamma, and high neutron dose materials. Now these are teleoperated. Wireless cranes and cameras are controlled by workers in remote areas.

A unique problem within the canyons at Savannah River is the H-Canyon Exhaust Air Tunnel. The H-Canyon is the only hardened nuclear chemical separations plant still in operation in the United States. The exhaust air tunnel carries acid-laden, radioactive air to a bank of sand filters at a velocity of up to 30 miles per hour. Because of the caustic composition of the gases, the tunnel has eroded on the inside over the many decades of operation and needs periodic inspections. The tunnel represents a particularly challenging environment for both man or machine due to the acidic gases, large amounts of erosion and debris, and puddles, but over the past twelve years, six inspections have been attempted with five different robotic vehicles. In fact, these inspections have been successful with their limited objectives, although most robots have been abandoned in the tunnel. While each vehicle has cost less than $75,000 (the sacrificial part), the total costs of development have been much higher. From the images of two of the vehicles in the figure below, it is apparent that much is changing from iteration to iteration and it is not clear a strong body of generalizable expertise is building up across trials.

Two of five different robots developed for the H-Canyon Exhaust Tunnel at Savannah River. (reprinted from Reid 2015)



3.4.5. PIPE INSPECTIONS

As at the other sites, there is a large need for pipe inspections. A unique application at SRNL was the development of the "Large Diameter Pipe Crawler" to redirect a 36-inch diameter air flow pipe in the F-Canyon. The pipe crawler employed a custom-designed tether system to navigate roughly 300 feet to the point at which it was used to successfully remove a section of pipe inside the canyon. The plasma arc cutting torch was teleoperated via onboard cameras. The tether system required heavily-protected workers to manage tethers.

3.4.6. ADDITIONAL OBSERVATIONS

The existing manual intervention points represent opportunities for robotics. Manual operation in the tanks and canyons is done using a large overhead gantry. Pinch-type end-effectors are generally used. For example, in the vitrification facility, the canisters are put in place, reoriented, and taken out using a master-slave manipulator. Another remote manipulator is used to clean up the pour spout when it gets clogged. Due to radiation, most electronics are remote (outside of the environment), with pulleys inside.

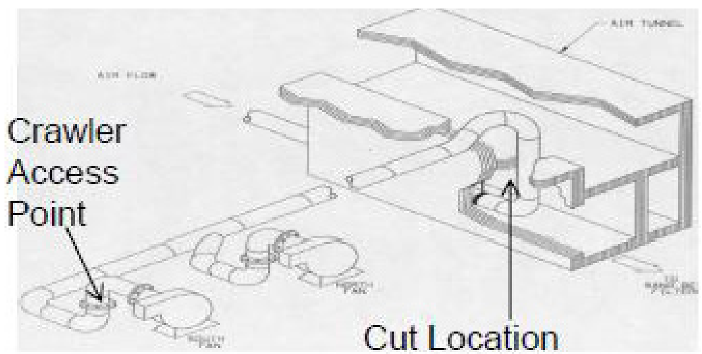
There is an interest in inspecting the tanks (and other facilities such as air handling) for structural stability (e.g., finding cracks) and radiation levels. Most of these structures were built in the 1950's-70's. Sewer inspection robots have been used extensively, all teleoperated, sent in with a tether and video for inspection (sometimes 2 robots, one to watch the other). Often the robots are left inside the environment afterwards (due to difficulty of decontamination), creating more obstacles. It may take 5-7 weeks to inspect a tank. If samples are needed, they are taken by the robot, put in a basket, pulled out with the crane (then the basket is dropped down again). The inside of the tank may be full of piping making access for robots difficult.

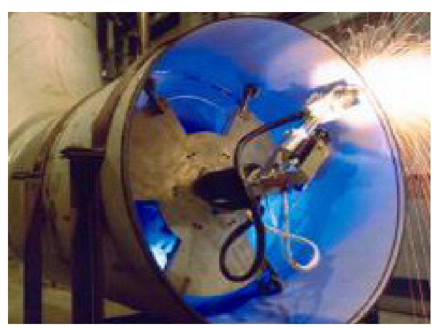
Aerial robots could be interesting for inspection, but the airflow inside a canyon or ventilation duct could be up to 30mph. Also, a rotary-wing platform could disrupt the contaminated material within in the environment, increasing the measurement and characterization challenge.

Aging workforce is another issue. Workers are very well-trained (they've been working on these problems for 20+ years) but not always ready for change. The replacement workforce may be more open and accustomed to working with robots and automation.

Safety is paramount. There are at least four primary risks: (1) common industrial hazards, (2) chemical hazards, (3) radiological hazards, and (4) criticality (nuclear explosion, to be avoided at all costs). During the recent economic stimulus, the complex received additional funding and hired many new workers, but there were some accidents. There are risks to doing this type of work, and risks of not doing it (some level of clean-up must be done).

Several of the issues that have already been identified in previous sections about INL and Hanford also apply at SRS but are not included in this section to avoid redundancy.





A recurring set of questions arose around the criteria used to justify and fund projects at SRS. What are the key decision factors that ultimately drive solutions? For example, the cost of worker radiation exposure is clearly a factor. What does a man-rem cost at SRS? The value of providing jobs is clearly valued at SRS. What are the tradeoffs between human labor and capital equipment? What is the relation between TRL and fundability for new technology insertion?

Another item of note is that full-scale mockups appear to have been a critical factor in successful safe operations from Day 1 but transition to varying grades of virtual/augmented reality remains low (e.g. for F canyon D&D). The VR implementation appears to not have kept pace with the increased levels of immersivity feasible (including haptic/visual and other multimodal interactions).

NON-DOE SITES AND ROBOTIC CAPABILITIES

The direct observations by the committee at the four sites discussed in previous sections (Hanford, INL, WIPP, and SRNL) can and should be augmented by independent observations by the committee of other efforts and/or solutions in place across the DOE complex and in other nations with related needs. Based on discussions within the committee, several additional efforts are documented here including:

- Automation at the Sellafield, UK
- Automation efforts resulting from the Fukushima incident in Japan
- Automation efforts in South Korea
- Robotics efforts in non-government organizations in Texas

4.1. Summary of Sellafield Visit, UK

A United States delegation of government representatives took a week-long tour of various facilities on and around the Sellafield nuclear waste processing site in the United Kingdom. The tour was organized on the U.S. side by Dr. Rod Rimando of the Department of Energy Environmental Management group (DOE/EM), and included Dr. Monica Regalbuto, presidential appointee for the position of Assistant Secretary for Environmental Management, DOE, Dr. Richard Voyles, Assistant Director for Robotics and Cyber-Physical Systems, White House Office of Science and Technology Policy, Dr. Albert Kruger, Bill Hamel, and Brad Eccelston, all of DOE/EM. Sellafield is the only site in the United Kingdom for handling non-military high-level nuclear waste.

The team met with individuals from three distinct entities: Sellafield LLC, National Nuclear Laboratory (NNL), and the Nuclear Decommissioning Authority (NDA). Sellafield LLC is responsible for the operation of the plants, NNL performs nuclear research and development, and NDA provides oversight and strategic direction.

4.1.1. ROBOTICS AT SELLAFIELD

The UK appears to have a substantial lead over the United States in development and application of robotic technologies for the problem of nuclear waste remediation. Nuclear processing sites all over the world use “manipulators” to allow humans to work remotely during nuclear processing operations. These manipulators are basically unpowered master/slave mechanical grippers that couple human motions at the “master,” through the wall of a hot cell, to the “slave” inside the hot zone. These manipulators may provide active or passive gravity compensation, but possess no intelligence and offer no autonomous capability.

The difficulties of these manipulators are manifold. Fatigue and repetitive strain injuries are common, due to the loads and friction of the mechanical system. The hot cells, which may have walls of concrete up to 2m thick, require costly windows to be installed with leaded glass from 1.2 – 2 m thick, as well. These windows are costly to produce and must be installed, sealed, and inspected.

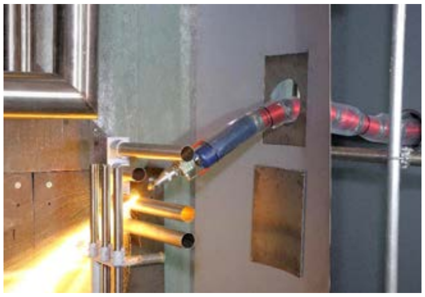
In contrast, the NNL has explored several robotic technologies for operations, inspection, and maintenance that are in use or in development at sites such as Sellafield. Base-mounted robot arms are being developed for opening containers and sorting waste. ROVs (remotely operated vehicles) have been used in spent fuel pools to inspect and sort waste for processing. Manually operated “sensor snakes” are used to measure the wall thickness of pipes and inspect welds. UAVs have even been tested to map the distribution of material inside rooms with overlays of information such as material temperature.

4.1.2. ROBOTIC SORTING

The cell pictured below at NNL uses large Kuka robots to re-process waste composed of a variety of largely unknown materials. While primarily teleoperated at this time to use various end effectors to open cans, pour and sort contents, and crush things, NNL envisions semi-autonomous and autonomous capabilities to improve the slow pace of human-driven operations through thick glass windows. They provide numerous video cameras around the work cell, eliminating the need for expensive and restrictive lead windows for operator viewing. They also tie the robot to a real-time CAD model of the work cell to provide a form of virtualized reality that enhances situational awareness.

Example fixed-base robot arm similar to those under development at Sellafield, left (image courtesy Kuka), CAD model from Sellafield, right.

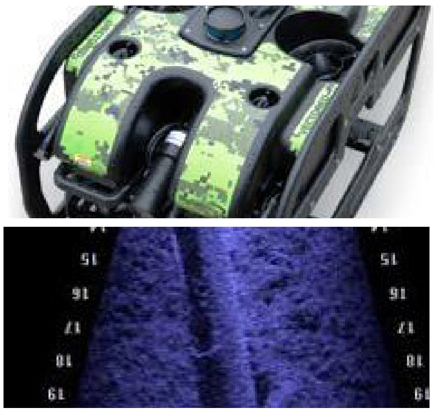
Workers at NNL set up a lab test with a mock pick-and-place operation.



The LaserSnake cutting a pipe in a mock cell.

4.1.3. LASERSNAKE

Another application of robotics the Sellafield team is pursuing is the “LaserSnake.” This is a highly articulated continuum manipulator (elephant-trunk-like) with a laser head for cutting. As shown in the picture, the continuum manipulator can reach into difficult and cluttered spaces, avoiding multiple complex obstacles in its path, and use its high-power solid state laser to cut metal and other potentially contaminated waste into manageable pieces.



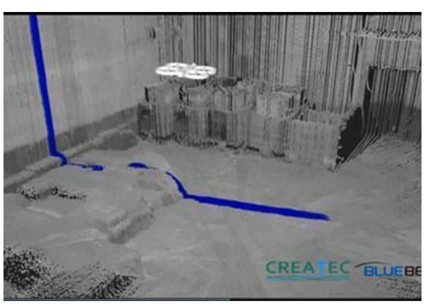
Example ROV and high-resolution SONAR images of an underwater pipe.

4.1.4. UNMANNED UNDERWATER VEHICLES

UK researchers are advanced with the use of ROVs in spent fuel pools relative to US counterparts. Operators at Sellafield use pairs of ROVs with manipulators to sort waste using both vision and sonar feedback. The ROV pairs permit better situational awareness while the matching of high-resolution, 3-D sonar data to CAD models of the environment and known objects in the pools. This provides photo-realistic visualizations of the scene, even in the presence of sediment plumes stirred up by the ROV thrusters.

4.1.5. PIPE INSPECTION

Pipe inspection inside active evaporators is achieved with long, unpowered snakes carrying arrays of displacement sensors. The snake is first pushed down the inside of the pipe and then pulled back out while the inductive sensors (typically eight arranged radially around the “spine” of the snake) provide high-precision measurements of pipe diameter. Each array of sensors, while only roughly centered in the pipe, provides an accurate measure of cross-section to an accuracy of about 60 microns. While some “shine” affects the sensor snake, it is on the “clean” side of the pipe and not prone to contamination.



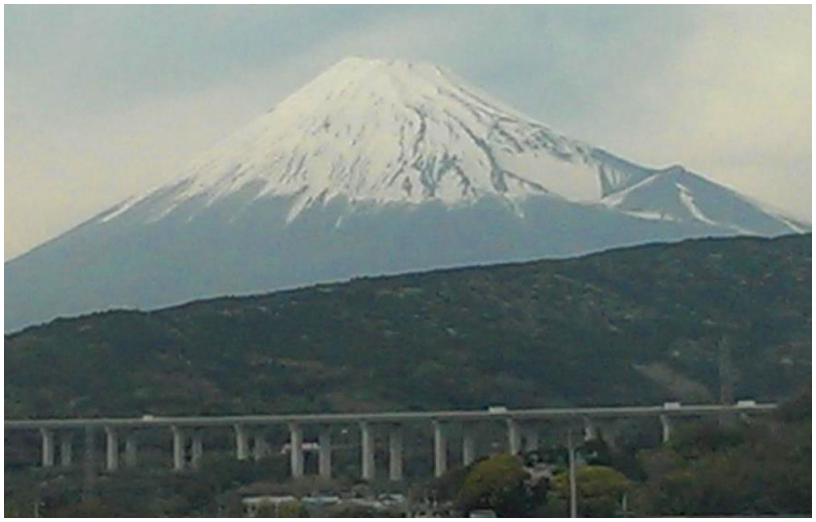
The point cloud resulting from a UAV scan of a room in the lab.

4.1.6. UAV-BASED SLAM

NNL researchers have used UAVs equipped with LIDAR to map complex areas with overlays of temperature imagery which can help them localize “hot spots” and areas of concern. The 3-D models of the piles can also provide initial plans for sorting and unpacking the waste. An example point cloud is shown in the adjacent picture.

4.2. Summary of the "DOE Satoshi Tour", Japan

A United States delegation of DOE personnel, national labs administrators and researchers, Electric Power Research Institute (EPRI), and university researchers took a week-long tour of various Japanese facilities engaged in robotics research and development related to the clean-up of Fukushima Daiichi. The tour was organized on the U.S. side by Dr. Rod Rimando of DOE-EM, and included Dr. Richard Voyles, Professor and Associate Dean for Research, Purdue University, Dr. Robin Murphy, Professor, Texas A&M University, Dr. Bill Hamel, Professor, University of Tennessee, Dr. Steven Tibrea, Savannah River National Lab (SRNL), Dr. Tom Nance, SRNL, Dr. Phil Heermann, Sandia National Lab (SNL), Mr. Jon Salton, SNL, Dr. John Jansen, Electric Power Research Institute (EPRI), Dr. Rob Ambrose, NASA, and Dr. Josh Mehling, NASA. The tour was organized on the Japanese side by Dr. Satoshi Tadokoro, Professor, Tohoku University and President of the International Rescue Systems Institute.

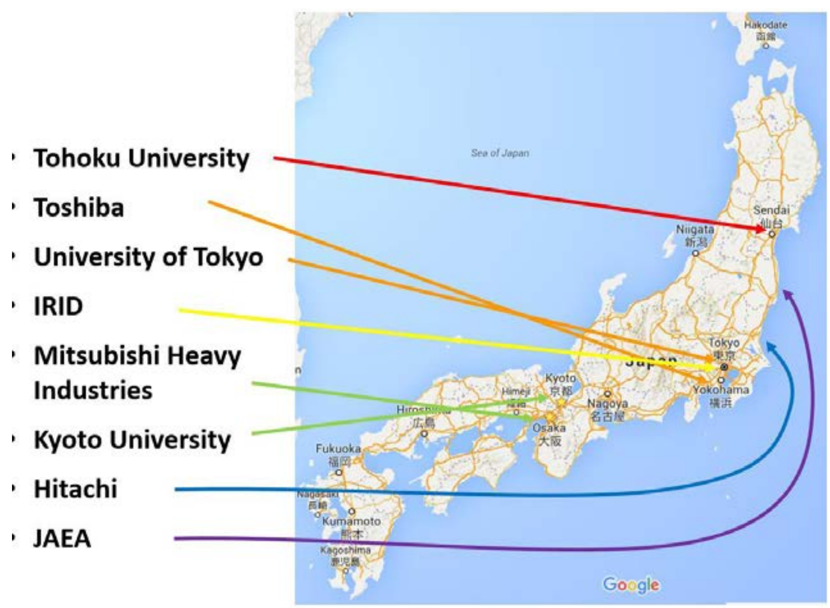


The team met with individuals from three universities, three companies and two quasi-government entities: Tohoku University, University of Tokyo, and Kyoto University; Toshiba, Mitsubishi Heavy Industries, and Hitachi; Japan Atomic Energy Agency (JAEA), including the Naraha test facility, and International Research Institute for nuclear Decommissioning (IRID).

4.2.1. TOHOKU UNIVERSITY

Tohoku University, in Sendai, was directly impacted by the earthquake and tsunami. Several buildings were damaged at the university and in the surrounding city of Sendai and loss of life in the local community occurred. Tohoku also has significant investment in emergency response robotics, which includes response to nuclear disasters. They have played a key role in the investigation and clean-up of Fukushima Daiichi, including being the driving force behind the insertion of the Quince research robot into early investigations of the inside of the reactor buildings (along with the iRobot PackBots).

Researchers at Tohoku University have been actively involved in robotics for hazardous environments for many years. Prof. Satoshi Tadokoro organized the visit of our delegation as he was involved in the roadmapping effort of which this report is a product and was also directly involved it the robotic response to Fukushima Daiichi. In addition, Prof. Tadokoro was one of the founders of the IEEE TC on Search and Rescue Robots and is the current President of the IEEE Robotics and Automation Society.



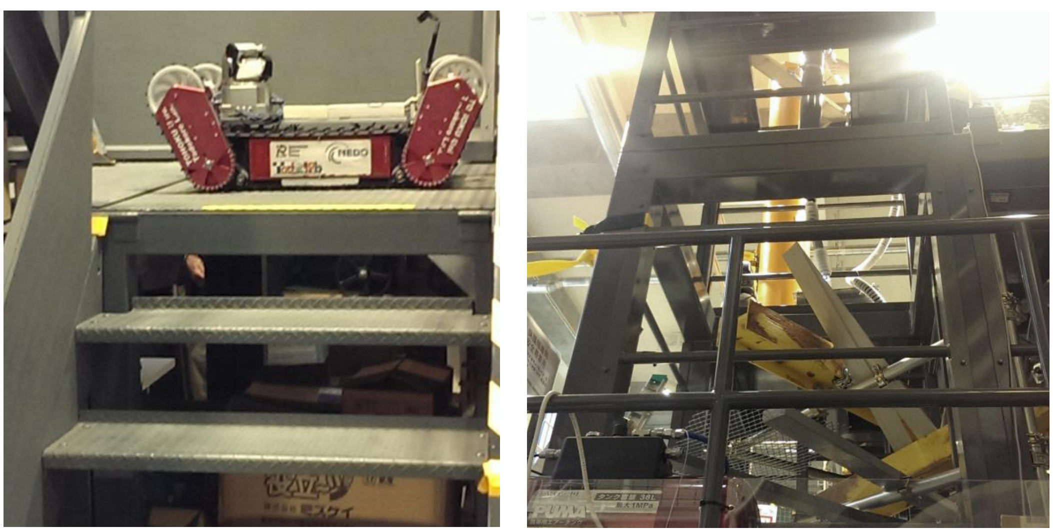
Map of Japan with visited sites chronologically color-coded in ROY-G-BIV order.

The team met with several professors and other researchers in an impressive test facility purpose-built for emergency response robotics. Some of the faculty involved in the tour included Profs Tadokoro, Tadakuma, Ohno, and Okada. The high bay contained a customizable tower for mock-ups of pipes, walls, and various forms of debris along with steps for climbing and descent. The steps included landings and variable tread materials.

Quince robot on a rubble pile (left) and in-use at Fukushima Daiichi (right).

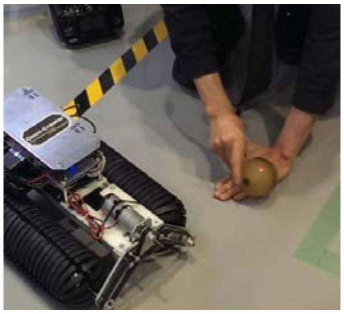
The high bay is a spacious area with Vicon cameras for ground-truth positioning that allows for numerous types of ground robots as well as flying space for UAV inspection robots. Demos included the Quince robot mapping its environment and climbing stairs and the Omni-Crawler, with its unique cylindrical tread mechanism. The ball-enclosed quadrotor UAV for inspection was demonstrated with its ability to come in contact with structures for stable viewing and up-close inspection. The Active Scope Camera, which is a serpentine-like device with a steerable, active tether that delivers a camera to remote inspection sites, was demonstrated inspecting the tower through pipes and debris. The tether has vibratory motion and directional scilia to propel itself while a twisting motion allows for highly agile locomotion through complex terrain. Finally, research with canines in search and rescue is enabled with dogs carrying camera/sensor packs into difficult environments.

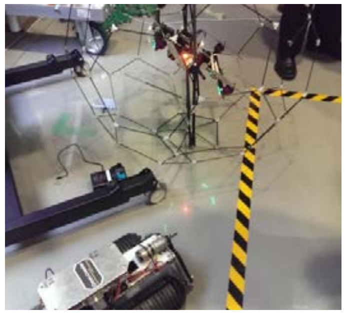
Quince was tethered with an onboard reel with 400m of tether. They needed the entire length to reach the second floor of the reactor building. The robot was exposed to up to 75 mSv/hr (7.5 rem/hr).



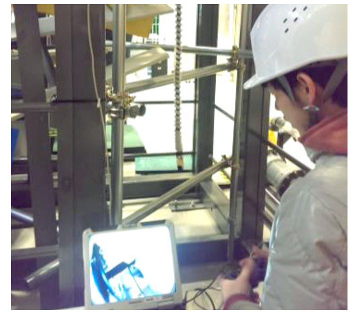
Mock-up tower at Tohoku University rescue robotics facility with Quince robot (left).

Overall, there was much activity around emergency response robotics with numerous innovative devices and approaches for inspection and remote navigation through complex environments. The labs the team visited had a clear emphasis on disaster sites and de-engineered inspection and situational awareness, which is directly relevant to the disaster climate caused by the Fukushima incident. This work is highly relevant to DOE for preparation and response to emergency scenarios and has applicability to decommissioning activities as well. The team saw nothing relevant to the routine processing and handling of waste.





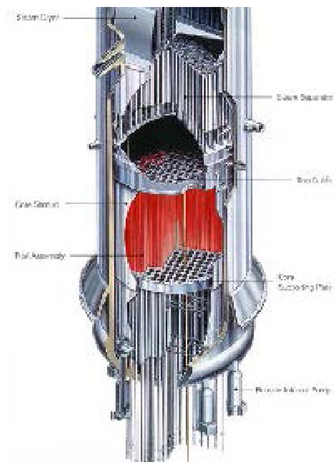
The Tohoku Omni-Crawler (left) and the UAV contact-inspection ball with Omni-Crawler (right).



Tohoku's Active Scope Camera (ASC) on a pile of rocks in the lab (left) and the operator console with PlayStation controller (right).

4.2.2. TOSHIBA

Toshiba has long been involved in the construction and maintenance of nuclear reactors and have been involved in robots for the remote handling of materials. A strength of Toshiba in Yokohama is the design and construction of reactor pressure vessels and turbines. They spent considerable time explaining to us their 6D CAD system for project management and immersive 3D projection room.



Toshiba has strong expertise in the nuclear industry for producing reactor vessels (left) and power turbines (right).

Toshiba has been engaged in the development of robots for the Fukushima clean-up and we were shown a few robots in a lab environment. They have developed a quadruped robot that can climb stairs and carry a wheeled tethered robot for inspection, but we didn't see it in action. It is designed to handle radiation at a rate of 100 mSv/hr (10 rem/hr) and be ready by 2020 for actual clean-up operations. They also have developed a small, scorpion-like, shape-shifting robot for crawling through pipes to access the primary containment vessel (PCV), but it is not clear if it has been deployed. A large amphibious robot for retrieving spent fuel rods was developed and tested in Fukushima. It was described to us as a manual operation, but published reports suggest autonomy. We were not shown this work, however, nor provided significant details, but they expect it to be operational by 2017.

They noted that there is a collaboration ongoing with United States entities on the water treatment system for tritium and technicium. Fukushima Daiichi has about 1000 tanks of about 1000 m3 (264,000 gal) each.

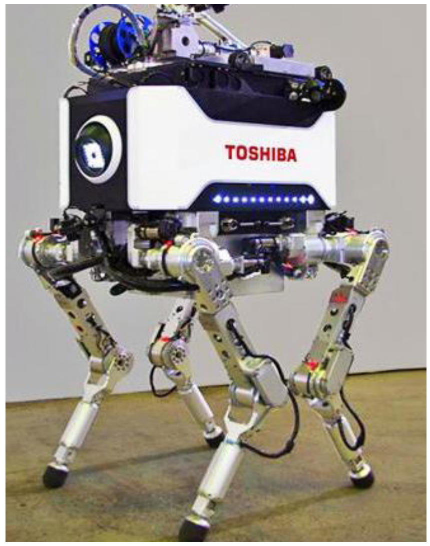
Toshiba used a custom robot with laser scanners to scan units 2 and 3, then used the scans to simulate the removal of a large structure that fell into the pool during the explosion. Unit 2 has internal radiation levels of about 20 mSv/hr (2 rem/hr). Toshiba built some pipe crawling robots, which rely on fairly simple actuation. They don't have any onboard sensing, but can deploy an inflatable bladder to seal off flow.

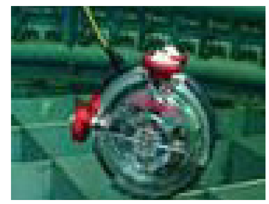
Rod Rimando, DOE, at Toshiba with a copy of the shape-changing "scorpion" robot that plans to enter the containment vessel (left). Posed image of the robot on a grate (right).

4.2.3. UNIVERSITY OF TOKYO

The University of Tokyo has a rich tradition of research in engineering and related fields, including robots for emergency response and search and rescue. The University of Tokyo also works with the Quince robot and the team saw computer vision work for greater situational awareness by providing synthesized third-person views of the robot and its immediate surroundings. (This was a common theme across several of the robotics labs that were visited.) In addition, the team saw acoustic analysis of materials by tapping. (This has an analogy to the WIPP, where they tap the ceiling to determine where to bolt.)

Researchers reported the Fukushima PCV could contain as much as 100 metric tons of melted mass at the bottom (64 tons of fuel melted together with other structures). TEPCO apparently built and 3D printed their own tracked robots with smartphones.





Toshiba quadruped robot that can climb stairs and carries a remote, tethered robot for inspection. An underwater inspection robot, far right, inspects inside the reactor vessel.

4.2.4. IRID

IRID is a government-mandated and government-funded consortium of stakeholders in the Fukushima Daiichi accident response that was formed in 2013. The members include TEPCO, JAEA, AIST, Toshiba, Hitachi, Mitsubishi, ATOX, and eleven additional power companies. Projects are funded 65% by the government and 35% by the member companies. It is not clear what level of funding the Japanese government provides, nor the method by which projects are proposed and selected. Projects seem to vary considerably in quality. According to published IRID reports, projects range from 300M yen ($2.8M) to 4B yen ($37M). Listed government subsidies are either 50% or 100% on a per-project basis. It is not clear how it is determined what level of subsidy is applied to each project.

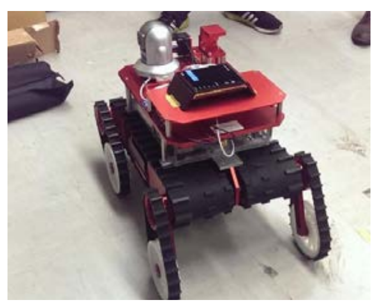
Through muon tomography, they had confirmed there is no heavy metal in the core area of unit 1. The fuel in the cores of the units prior to the tsunami included:

Unit 1: 69 tons

Unit 2: 94 tons

Unit 3: 94 tons

Unit 4: 0 tons

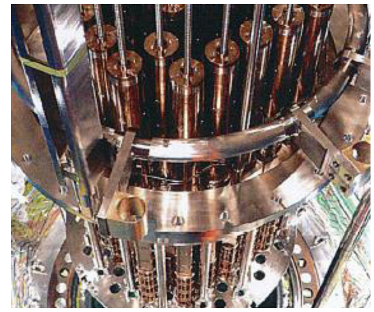


The Quince robot, left, is also being used at the University of Tokyo for research on autonomy and computer vision. Acoustic analysis of materials is represented on right.

4.2.5. MITSUBISHI HEAVY INDUSTRIES

Mitsubishi Heavy Industries is also a major builder of nuclear reactors and reactor components. The Kobe site also builds and services the new submarines built for the Japanese navy.





The US team (left), a reactor vessel produced at the Kobe site (center), and reactor internals (right).

Mitsubishi MEISTER two-armed robot with heavy duty versions of the PA-10 commercial manipulator (left). The MHI power suit allows heavy loads to be borne by the exoskeleton (right).

4.2.6. KYOTO UNIVERSITY

Kyoto University is another university with a rich history in emergency response and search and rescue robotics. Some of the faculty involved in the tour included Profs Matsuno, Nakanishi, Kamegawa, and Tanaka.

The US team with a Yamaha Rmax autonomous helicopter at Kyoto University.

Pipe inspection snake robots.

4.2.7. HITACHI

The shape-changing robot that was part of the demonstration was designed to fit through a 100 mm diameter, 7 m long pipe. The robot was designed to withstand 1000 Gy cumulative dose. It operated for three days inside the vessel until the camera died at about 10 Sv/hr. The robot took radiation measurements and pictures and the human operator used a map of the vessel to manually localize the robot. IRID sponsored the development and did the investigation. Hitachi also built a swimming robot to investigate the suppression chamber for leaks. To detect leakage, they used two ROVs; one to release a liquid target and the other to watch for drift with 2-D SONAR.

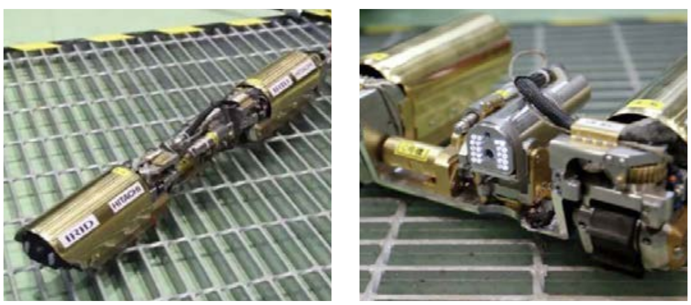


Figure 4.20: An example of the shape-shifting, tread-driven robot that was deployed into the PCV in April of 2015.

Figure 4.21: Actual image of the first deployed robot inside the PCV from the perspective of the second deployed robot. The first robot died after about three hours.

4.2.8. JAEA/NARAHA TEST FACILITY

The Naraha Test Facility is very impressive, with a 60 m x 80 m x 40 m high bay facility to house such things as a full-scale mock-up of a portion of the Torrus Room from Fukushima. Naraha also has an MOU with Disaster City (Texas A&M University) to share test methods and exchange exercises.

In the following figure, simple teleoperated robot of their own design is climbing a stairwell. A copy of the NIST step field is also available (middle). A large tank for underwater robots is available, as well (right).

The Naraha Test Facility has a customizable stair system to model stairs of different sizes and formats (left).

4.2.9. LESSONS FROM JAPAN TOUR

There are several lessons to draw from the Japanese experience:

- Workforce issues are important - TEPCO refused to use trained iRobot or Qinetiq operators. Instead, trained their own operators for one month
- Toshiba had some 3D laser scans of Fukushima before the tsunami which proved useful. Pro-active scans would be a good idea for all sites
- Communications have frequently dropped, some causing failure
- Operators have poor spatial awareness.
- Cameras gradually failed from radiation, but, in general, electronics did surprisingly well
- Lots of failures due to misoperation - training and HRI are key to operation
- Modularity is valuable due to familiarity, but usability is key to successful application
- Many universities use the Quince platform; commonality breeds leverage
- Active acoustic tapping can classify materials, like WIPP ceiling tapping to assess bolt quality
- Successful use of a consortium for oversight requires strong leadership
- Interoperability and standardization are important

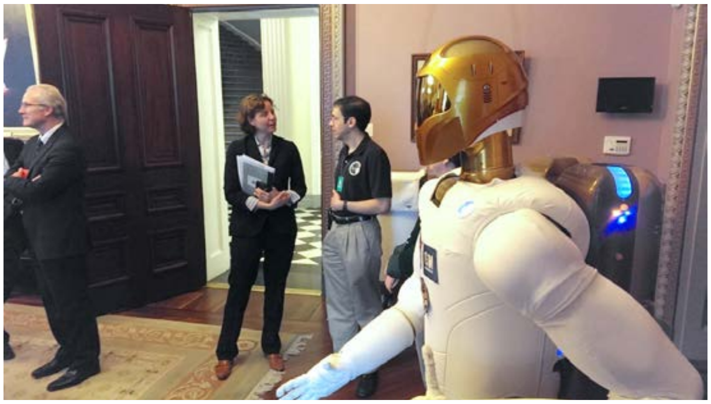
4.3. Report of Sites Visited During the "Texas Two-Step"

Yet another, but overlapping, delegation of government DOE personnel, national labs administrators and researchers, and university researchers took a week-long tour of various American facilities in Texas that are engaged in robotics research and development that have relevance to emergency response and clean-up operations. Texas was chosen as the first of several planned states to tour, due to the rich selection of government facilities, universities and non-profits that are engaged in nuclear clean-up R&D. Again, Dr. Rod Rimando organized the visits, which included Richard Voyles, Purdue, Robin Murphy, Texas A&M, Bill Hamel, University of Tennessee, Wendell Chun, CU Denver, Mike McLoughlin, Johns Hopkins University Applied Physics Lab, Mitch Pryor, UT Austin, Phil Heermann, Sandia National Lab, Young Park, Argonne National Lab, and Paul Dixon, Los Alamos National Lab. Presentations were made by Rob Ambrose, NASA/JSC, Josh Mehling, NASA/JSC, Robin Murphy, Texas A&M/Disaster City, Mitch Pryor, UT Austin, Ashish Deshpande, UT Austin, Paul Hvass, Southwest Research Institute (SwRI), Jerry Towler, SwRI, Morgan Quigley, Open-Source Robotics Foundation (OSRF), Debra Sparkman, American Society of Mechanical Engineers (ASME), Patty Loo, ASME, and Patrick Beeson, TRAClabs.

The team met with individuals from one federal facility, two universities, one company and two non-profit entities: NASA Johnson Space Center; Texas A&M University and University of Texas at Austin; TRAClabs; Southwest Research Institute and Open Source Robotics Foundation.

4.3.1. NASA/JOHNSON SPACE CENTER

NASA/JSC performs a wide range of research and development in extra-planetary vehicles and human-assistive robotics, including RoboNaut. RoboNaut-2 was a GM-NASA collaboration for a humanoid robot for astronaut assistance on the International Space Station (ISS). Currently, a version of RoboNaut-2, with legs, resides on the ISS. Valkyrie is a new generation of humanoid, derived from RoboNaut-2, that NASA hopes will find use in industrial applications for the handling of high-consequence materials in radiological and biological applications.



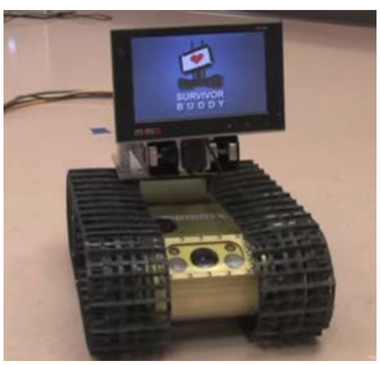
A copy of RoboNaut-2 currently resides on the ISS, with a pair of legs to move around in zero-G, left.Right, the RoboNaut torso is on display and can travel to remote sites, as in this file photo (courtesy Richard Voyles).

Valkyrie is the latest NASA/JSC humanoid that competed in the DARPA Robotics Challenge. Right, the RoboGlove, a "power glove" for human augmentation to reduce fatigue, is derived from Valkyrie. (right image courtesy NASA)

4.3.2. TEXAS A&M AND DISASTER CITY

Disaster City is a 52-acre emergency response "sandbox" operated by the Texas A&M Engineering Extension (TEEX). It is located adjacent to the Brayton Fire Training Field, also operated by TEEX, which hosts over 45,000 emergency responders every year. Disaster City is a unique facility with a wide variety of simulated disaster sites that covers nearly every type of structure, mode of transportation, and environmental hazard to host training exercises, equipment demonstrations, and test scenarios for commercial and research concepts.

Disaster City is a 52-acre complex adjacent to Texas A&M University. (right picture courtesy TEEX website)

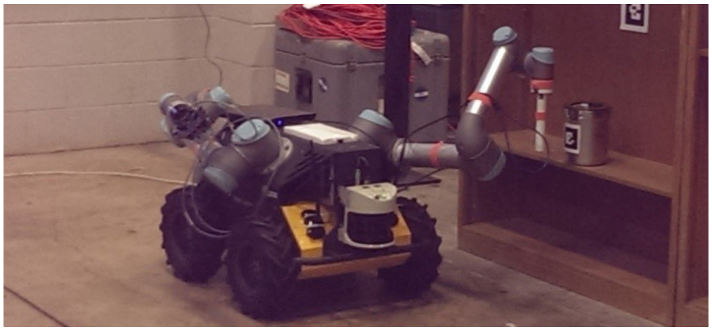


Dr. Robin Murphy's "Survivor Buddy." (courtesy Robin Murphy)

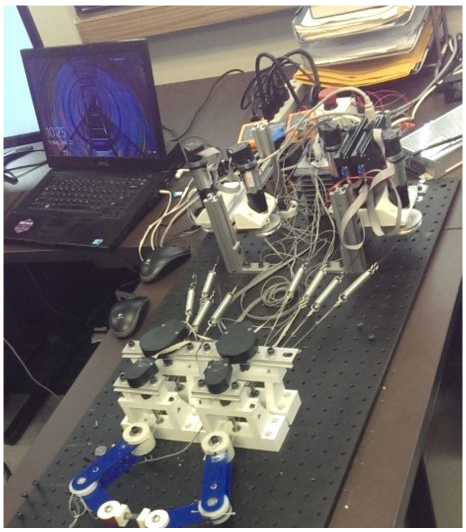
To bolster the activities at Disaster City, researchers at Texas A&M explore many aspects of emergency informatics. Robin Murphy explores human/robot interaction with "Survivor Buddy," a bi-directional emotive interface to reduce the stress of emergency survivors. Dylan Shell explores robotic information collection and sharing around spatial fields, representing such things as nuclear contamination.

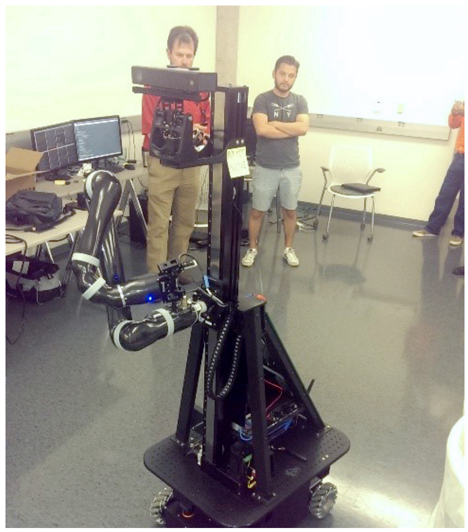
4.3.3. UNIVERSITY OF TEXAS AT AUSTIN

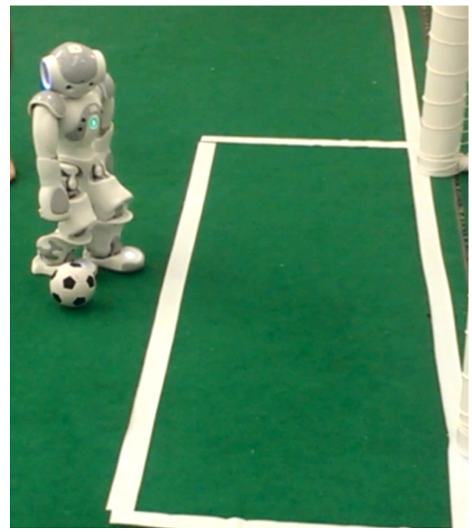
The University of Texas at Austin has particular strengths in both compute science and nuclear engineering. The nuclear engineering program is housed within the Mechanical Engineering Department and researchers study the remote sensing and characterization of nuclear samples and the facilities in which they reside.



A bi-manual mobile robot for inspecting radiological samples in a warehouse environment, left. Another warehouse inspecting robot "sniffs" the floor to look for possible spills and other forms of localized contamination, right. This robot tirelessly searches the entire floor and maps evidence of contamination for future comparisons.





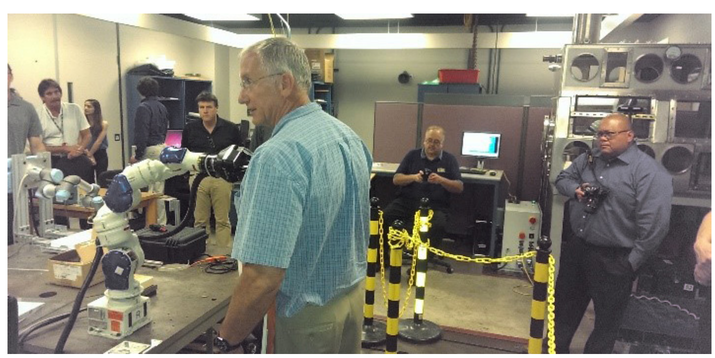


Ashish Deshpande's lab, left, examines human grasping and control. Andrea Tomaz's lab, right, explores human-centered robotics and natural interfaces.

A small humanoid robot in Peter Stone's lab has learned to play soccer on a robot team. They can kick, pass, and even use mis-direction to fool opponents.

4.3.4. SOUTHWEST RESEARCH INSTITUTE

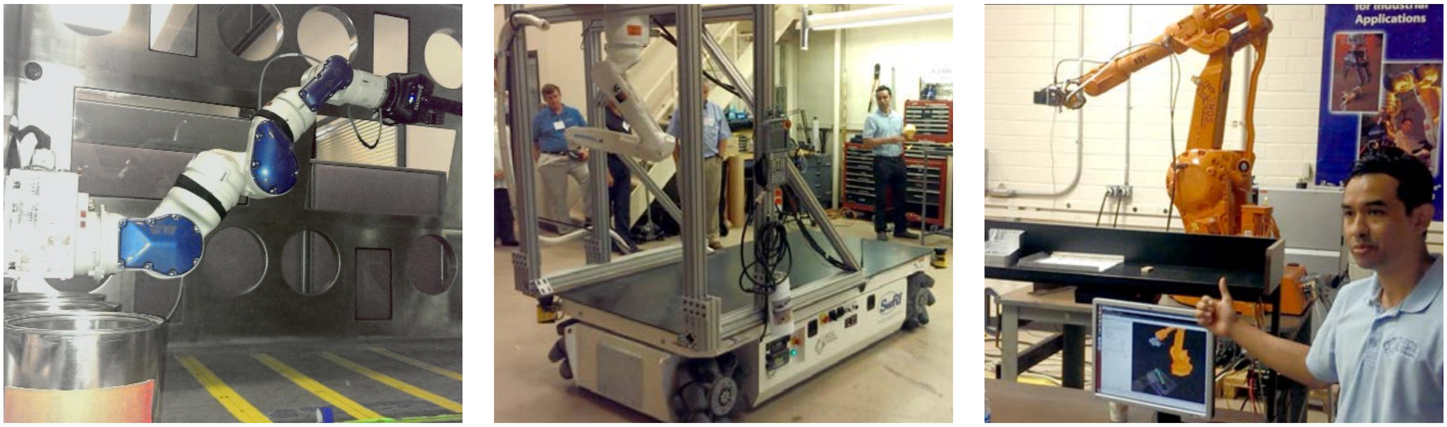
SwRI also represents a wide range of research interests, spanning many key topics of national significance. For example, SwRI leads the ROS-Industrial (ROS-i) initiative, which is an industrial consortium promoting the hardening of ROS packages and basic components to make them more suitable for incorporation into commercial products. Morgan Quigley, of OSRF, presented status on the ROS 2.0 and ROS-i software developments, including a description of the benefits of open-source development for for-profit entities. SwRI uses ROS for much of its robot-related development, including several DOE projects. The team was also given a primer on software quality assessment standards and their relationship to nuclear quality assessment.



Left, the SwRI autonomous vehicle took attendees on a fully autonomous drive on a closed test course on the SwRI grounds. Right, Philip Heerman, center, and Rod Rimando, right, look on as SwRI personnel demonstrate a glove box robot.

SwRI treated the team to rides in their self-driving car on a closed test track. This project is of direct relevance to DOE needs as fork lift automation is under consideration to improve worker safety and reduce accidents. Some of SwRI's self-driving car technology and expertise have been integrated into a self-driving fork lift that was demoed at the Portsmouth Site in August of 2016 as part of the Science of Safety program.

The team also saw several projects for the safe handling of high-consequence materials in or around glove boxes.



In a project similar to that at the Sellafield site, above, SwRI researchers are creating a virtual representation of the robotic workcell to test programs and operations.

4.3.5. LESSONS LEARNED FROM THE "TEXAS TWO-STEP"

After the tours, a "Robotics Retreat" was held in San Antonio to discuss the trip and to plan future actions leading toward a robotics roadmap for DOE/EM.

4.4. Summary of the ISOFIC Visit, South Korea

A small delegation of United States individuals took a week-long visit of a few sites in South Korea in connection to their nuclear waste handling activities. The tour was organized on the U.S. side by Dr. Young Soo Park, Argonne National Lab, and on the South Korean side by Dr. Jisup Yoon, and included Dr. Richard Voyles, Professor, Purdue University, Dr. Wendell Chun, Professor, University of Colorado at Denver, Prof. Leo Lagos, Professor, Florida International University, and Dr. Mitch Pryor, Research Scientist, University of Texas at Austin.

The team presented talks on their own research and development work on nuclear waste handling at the International Symposium on Future Instrumentation & Control for Nuclear Power Plants (ISOFIC), meeting numerous individuals from universities and government entities. They also visited a Korea Atomic Energy Research Institute (KAERI) facility and met with two representatives of the Korea Ministry of Science and ICT (Information and Communications Technology). The team also was given a tour a several cultural sites important to the Republic of Korea.

4.4.1 ISOFIC SYMPOSIUM

ISOFIC is an international symposium held every three years in South Korea. Started in 2002, the symposium brings together experts from around the world to report on challenges and solutions for instrumentation and control of nuclear power plants, their safety systems, and related facilities. The team exchanged information with the Korean hosts on robotics roadmapping efforts in both countries. The Korean roadmap was presented by Dr. Kyung-Hoon Kim, Program Director of the Korean Evaluation Institute of Industrial Technology, a part of the Ministry of Trade, Industry and Energy (MOTIE). The Korean roadmap is in its second 5-year period with an investment at around $60M per year. (The roadmap is available on the web in Korean only with no English translation -- http://www.korearobot.or.kr.) Korea sees the need to take a leadership role in robotics, starting with manufacturing and expanding towards the service industry.

Members of the US delegation join the ISOFIC conference in Gyeongju, South Korea.

For Korea, robotics is considered a Next Growth Engine and one of 12 Industrial technologies for industrial restructuring . For example, Hyundai uses a combination of their own robots and Robotstar robots (cheap and modular to assemble individual joints one at a time). Korea is expanding into the service sector with robotic vacuums and medical robots. There is AI shock in Korea, and the country has embraced the coming 4th Industrial Revolution. For the next generation of robotics, they are working on collaborative robots, dual arm robots, and plan for 20,000 Smart Factories.

Dr. Jisup Yoon presented the status of the Nuclear Robotics Laboratory at KAERI. They are chartered with the maintenance and inspection of nuclear power plants. A major focus in their lab are on emergency response systems (K-R2D2, ATV with multi-rotor copter, high extension mobile robot), D&D robots, Calandria robot, and a Raman LIDAR for hydrogen detection.

4.4.2 KAERI FACILITY

Left, the US delegation joins the Korean KAERI delegation in Daejeon, South Korea. Right, presentations by the US and Korean delegations focused on nuclear materials handling and policy.

The team was able to see first-hand the many robots presented at the ISOFIC conference. For example, the K-R2D2 robot of Dr. Sun Young Noh was presented that is being developed for emergency applications. The team also observed Dr. Jongwon Park's collaborative robotic ATV with a large multi-rotor drone carried on its tail for a two robot team by a teleoperator. The teleoperator would drive the ATV to a site, then switch to flying the drone. He is also preparing for an underwater robot challenge with a UUV in Australia later this year. The KAERI robot group is led by Dr. Kyungman Jeong, supported by Dr. Young Soo Choi and Dr. In Soo Koo. They showed two generations of a large hydraulic manipulator, a mobile robot that has an extendable mast that can rise over twenty feet, and various ground robots with articulated tracks. Of note is a full-scale mockup of a facility for an emergency response challenge, similar to the DARPA Robotics Challenge. A robot must climb a ladder or stairs two stories to a top floor where the robot must close a large valve. They also showed a medical imaging mechatronic device/robot used in the past, and a clever mechanism to exchange cylindrical fuel rods. In addition, there was a second warehouse of older robots, including an old PUMA manipulator and KUBO humanoid robot.

4.4.3 MINISTRY OF SCIENCE AND ICT

The last day included a meeting between the visitors and Mr. Woochul Kim from the Ministry of Science and ICT. He schedules US-Korea relations, and discussed opportunities for collaboration. Mr. Kim has open line opportunities for D&D activities including robotics, and would like to add another new line item for both countries to collaborate on. He has some candidate Korean entities that they would fund from their side that matches US investments.

4.5. Future Opportunities for DOE

The US DOE used to be a leader in robotic nuclear waste handling in the 1980's and 90's, when a greater premium was placed on technology development. In the early 2000's, EM emphasis shifted to site closure, based largely on the "low-hanging fruit" opportunities created by extensive technology development. Now that these remediations enabled by prior technology efforts has been harvested, it is time to refocus on the next generation of technologies that will enable the next leaps forward. It appears, from comparisons to other international sites, DOE is now behind the curve, so this is an important area of R&D for both efficient and safe processing of nuclear waste and for the control of the massive costs of nuclear processing.

DOE could experience substantial benefits in economics and efficiency from a comprehensive program of research and development in robotics for nuclear waste processing and remediation. In turn, investment in such a program will return quality of life benefits for many US citizens employed in the nuclear waste processing and remediation industries and the environmental health of the nation will also be enhanced. This program should consist of a mix of the following:

- Use-inspired extramural research engaged with the academic community through the National Robotics Initiative
- A university/industry center of excellence (COE) focused on robots and sensors for nuclear waste management
- Development of open testbeds for the evaluation of new technologies by industry, academia, and the national laboratories
- A workforce development program, that stresses the STEM Continuum "from HS to MS," and includes curricular development, student recruitment and placement, and targeted media
- National labs
- SBIR topics
- The formulation of a set of grand challenges for the re-processing industry

This could start in FY16 with modest investment of $5-10M in the NRI, plus some initial foundations for the broader program, such as the CoE and grand challenges. In FY17, a $40-50M program could:

- Continue investment in NRI projects
- Compete and award the center of excellence
- Initiate the workforce development program
- Launch some SBIR topics

Subsequent years could build programs at the national labs and initiate testbeds at the COE and at national laboratories.

4.5.1. NATIONAL ROBOTICS INITIATIVE

To participate in the NRI in FY16, existing money would have to be carved out, the MOU draft must be finalized and signed, and text must be written for the solicitation. FY17 money could be hashed out in the budget process. Some potential solicitation text:

In the evermore interconnected world, our nation has to address high consequence but low probability events across multiple disciplines. What might be needed in one high consequence situation could be applied to another. The potential synergistic application of robotics has the potential to provide greater safety in handling biological, extra-planetary, radionuclear, and environment materials in ways never imagined before and allow for sharing tools and benchmarks. Generalizations of worker studies could lead to greater understanding of the science of safety.

4.5.2. WORKFORCE DEVELOPMENT

Existing sites employ a large number of STEM workers at all levels and a comprehensive program should be initiated to feed the pipeline for the generations of workers that are needed for this critical industry. A key aspect of this work is raising the profile of the opportunities and benefits of working in hazardous waste cleanup through a media campaign. Coupled with this must be an effort to improve the image of the value and working conditions of this industry.

Curricular development at the AS, BS and MS degree levels could be helpful in raising the profile of the industry. The recruitment of potential students, including scholarships for candidates sponsored both by government and industry, would feed several national priorities.

4.5.3. CENTER OF EXCELLENCE

Establishing a national center of excellence on Robotics Handling of High Consequence Materials at a leading university or collaboration of universities could serve as a focal point for curriculum development in nuclear materials handling; as a catalyst for technology transfer between universities, national laboratories, and private companies; as an innovation incubator; and as a hub for research and results dissemination.

KEY FINDINGS AND OBSERVATIONS

Based on the observations from the four primary U.S. site visits (Hanford, INL, WIPP, and SRNL), a summary of the committee member's experience related to other DOE activities, and the collective previous experiences working with the DOE Complex and recent participation in other related workshops and meetings, the committee makes the following recommendations:

- There are DOE-EM activities that – in the short term (1-4 years) – can be completed using robotic technology available today and that will have quantifiable and positive impact on the DOE-EM mission as it relates to safety, cost, and reduced mission time.
- These short-term activities can be used to not only demonstrate and deploy robotic technological solutions, but also used to develop the next generation of DOE lab and site engineers in the medium term (3-6 years) that ensure that the DOE complex has the internal capabilities utilize and further develop automation and robotic technologies.
- Given the 50+ year extended timeline for DOE-EM, this workforce is then well-positioned to look at the DOE-EM mission needs with the clean slate to develop and deploy solutions in the long-term (6-20 years) that utilize the rapidly advancing capabilities seen in robotics today.

These recommendations provide impact in the short-term and – with the continuous dedication of DOE – provide momentum that ensures robotic and automation technologies can and will positively impact the many sites and challenges remaining across the complex for decades to come.

5.1. Specific Recommendations

The 1945 publication of Science the Endless Frontier, at the behest of the Roosevelt administration, was a watershed moment for research and development in the United States. World War II represented the first investment in private research and development as a national resource by the federal government and the first recognition of R&D as an infrastructural priority. The resulting public/private partnerships produced incredible advances in the war effort, including radar and atomic technology, and Science the Endless Frontier paved the way for continued investment in that infrastructure.

Nearly 75 years later, that tradition of investment in R&D has grown stronger and much more significant and has infused civilian and military agencies. NSF, NIH, DARPA, DOE and many others invest considerable resources into public/private partnerships in both direct R&D and also the infrastructure that begets R&D. The laser, Google search, battery advancements, and stealth aircraft have all been born of federal investment in private research and have all had enormous benefit to the American economy. Many examples of robotic technology have been amplified by federal investment for the greater good.

One such example is the Robotics Operating System (ROS). ROS is properly described as "software infrastructure" that has enabled many researchers and even corporate developers to "stand on the shoulders of giants" by sharing code, applications and data sets and has substantially reduced the need to "reinvent the wheel." While ROS was popular among developers and researchers, leading to significant advances, it floundered in the commercial world as corporate interests preferred proprietary systems. But a forward-thinking consortium of government agencies, consisting of NSF, NASA, DARPA and the Army, saw the value in the common infrastructure that ROS provided and the economic multiplication of their research investments as fewer researchers were reinventing the wheel.

The recognition that investment in research and research infrastructure is good for federal agencies, for financial stewardship, and for the American economy is an important cornerstone of what the participants in this survey activity view as key to their recommendations. The DOE has a long and successful history of funding R&D and DOE-EM, in particular, has reaped the benefits of strategic investment in future technologies that have reduced the cost of operations and improved the safety of workers engaged in the EM mission. The R&D investments made in the 1980s and 90s laid the foundation for the exceptional cleanup efforts that DOE-EM has achieved over the past 15 years. But, the operational budget priorities that have resulted in these stunning cleanup efforts have become out of step with the developmental budget priorities needed to achieve the cleanup efforts of the next 20 – 50 years. The top recommendation of this report is the return of budgetary support for R&D and R&D infrastructure at levels commensurate with the 1990s: roughly 5.5% of the total DOE-EM budget.

5.1.1 RESTORE TECHNOLOGY DEVELOPMENT INVESTMENTS TO PRE-2000 LEVELS

DOE made a conscious effort over the past 15 years to accelerate the pace of cleaning up and shutting down a large number of aging, highly contaminated facilities. This effort has been highly successful, both in objective measures of progress and in subjective measures of community citizenship. However, the remaining difficulties are complex and long-term (multiple generations of engineers and technologists) and demand technological solutions that do not currently exist. Current EM stakeholders must devise a long-term plan to realize these solutions.

5.1.2 STUDY THE IMPLICATIONS OF WORKFORCE DEVELOPMENT AND TRAINING ON THE INTRODUCTION OF ROBOTIC SYSTEMS

Robots can have a profound impact on the workforce, both physical, mentally and emotionally. The pride of employment at a government lab or site, the fear of losing a job, the drudgery of menial jobs that only “feed” a robot, and the lack of proper training for new technologies are all important concerns for robotic adoption. It was clear from many site visits that workforce implications at DOE installations are critical to decisions on robotics and other technologies, but are rarely made explicit. These aspects should be examined and explored in greater detail.

For example, most robotic systems require some training for them to be operated safely and effectively. This training should not be neglected or underemphasized. As robotic tools become more prevalent at EM sites, site managers should consider providing general robotic safety courses, in addition to system-specific training. Dual-use applications, such as inspection robots that can double as emergency response tools, can increase the efficiency of training. In addition to training the workforce, site managers should actively solicit feedback from the workforce to ensure that the systems are meeting their needs and that potential improvements can be identified and fed back to TDO and developers. Proper training and preparation will help avoid the misuse of technology which can cause skepticism among the workforce and reduce openness to new capabilities.

5.1.6 ENGAGE THE R&D ECOSYSTEM

It is necessary that technology providers gain an in-depth understanding of the EM site needs and challenges and carefully consider the implications of that knowledge in order to make implementable proposals. Most academic and corporate researchers have little appreciation for the environments and complexities faced at DOE sites, as the relationships needed to grow this appreciation are difficult to nurture. Yet it is in DOE’s interest to expand the pool of performers that can adequately respond to DOE site needs, both short term and long term. DOE should do more to purposely engage the R&D community as this can not only result in more successful implementations, but can also significantly reduce long-term operational costs through more efficient competition.

Likewise, it is important that the DOE complex stay in intimate contact with innovators outside its reach. It was apparent, in certain contexts, that DOE capabilities have fallen behind those of others within the national sphere or the international community. It is vitally important that a vigorous and engaging climate maintain familiarity with and the ability to harvest these developments that are happening outside the normal DOE purview.

5.1.7 PLAN FOR TECHNOLOGIES OF THE NEXT SEVERAL DECADES

Technology is advancing at such a profound rate that it is difficult to foresee opportunities on the time scales that DOE-EM regularly faces. Looking back over what has transpired in the past 40 or 50 years presents only a glimpse of the magnitude of changes expected in the next 40 or 50 years. “Planning for the un-plannable” should be a mantra at DOE. An example is “black cells” with no access for future robotic systems. Building in access ports for systems we can’t yet conceive seems like low-cost insurance for a difficult-to-foresee future.

Contributors

A large number of individuals from universities, companies and government agencies contributed their time, their insights, and their expertise to produce this report. Numerous visits to domestic and international sites involved expert observations and comments, discussions amongst visitors and site personnel, as well as demonstrations and physical artifacts that were invaluable to the effort. The editors listed below could not have completed this report without their valuable observations and notes.

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