Operator Evaluation of Mobile Robotic Systems for Inventory, Inspection, and Contamination Survey Tasks in D&D Environments-17314

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ABSTRACT

The Nuclear & Applied Robotics Group (NRG) has developed two mobile systems with simple, intuitive Human-Machine Interfaces (HMIs). Thus, the systems can be operated by operators who are not robotics experts to perform inventory, inspection and routine contamination surveys in areas where Special Nuclear Material (SNM) is stored and handled. This effort presents feedback collected from EM operators using the two systems at the Portsmouth Gaseous Diffusion Plant in Piketon, OH who used the robotic solutions to perform tasks on site and with minimal training. This approach has the potential to address issues related to ALARA, ergonomics, and reliably completing dull, repetitive tasks while maintaining domain-specific experts in the control loop. The two systems were shipped to - and demonstrated in - a DOE designated area and demonstrated completing contamination testing using a combination of real and surrogate sensors. This paper reviews the initial hardware development, demonstration requirements, and the modifications/improvements made to deploy the systems for this effort. It then summarizes the feedback garnered from EM operators who used the systems at the DOE facility.

INTRODUCTION

Under sponsorship of Los Alamos National Labs, University of Texas at Austin formed the Nuclear & Applied Robotics Group (NRG) in 2008 [1] whose goal is to reduce dosage or the chance of unplanned dosage uptake in workers handling Special Nuclear Material (SNM), particularly in the area of Pu Sustainment. The NRG developed two mobile systems (see Fig. 1) to perform inventory, inspection and routine contamination surveys in areas where SNM is stored and handled. One system is based on the Adept Pioneer LX with a customized suite of sensors. The second is a Clearpath Husky platform with dual-arm UR5 Universal Robotics manipulators for detailed inspection and contact tasks.

This effort summarizes feedback from EM operators at the Portsmouth Gaseous Diffusion Plant in Piketon, OH, which is undergoing final inspections prior to decommissioning. This effort provides an opportunity for the LANL developed technologies to be broadly utilized by DOE and dramatically increase their potential application space and user groups, including for the challenging applications in EM such as D&D. The systems were shipped to - and demonstrated in - a DOE designated area in September, 2016. They completed contamination, inventory and inspection tasks using a combination of real or surrogate sensors selected by DOE officials. Demonstrations are completed under the supervision of DOE designated operators who were nominally trained (and supervised) by NRG personnel.

Fig. 1. Two robotic systems developed by UT Austin for LANL: (left) the “VaultBot” dual-arm mobile manipulator and (right) the Pioneer LX Platform.

The considered real and surrogate sources were defined as follows:

Source	**Near Field**	**Far Field**	**Gaseous**
Real	Alpha source	Gamma source	Fluorine
Surrogate	Magnetic Field	Thermal or vision	CO_2

In the final determination, the demonstrations were completed with DOE supplied alpha sources, vision (for far field), and CO_2. The systems can operated at a variety of control fidelities as desired. For example, the operator can

- Operate remotely with a high level of operator involvement using a standard controller,
- command the system remotely to traverse automatically generated points on a virtual fixture associated with an item of interest,
- via high level commands to traverse a robot generated map, or
- in an autonomous inspection mode using predefined locations selected in a map previously generated by the robotic system, or
- using configuration agnostic and fully autonomous routines for contamination testing.

This paper reviews the requirements and system development for LANL applications, the modifications/improvements made to deploy the system for EM applications, and the feedback garnered from EM operators who used the systems. A key secondary goal of the systems develop at UT Austin is to have Multi-User/Multi-Use (ME^2) capability spanning EM & DOE Complex needs. Therefore the conclusions of this paper reviews the potential uses beyond those demonstrated as a part of this effort.

BACKGROUND

Robots have been used extensively in nuclear environments for remote handling [2], SNM manufacturing [3], Decommissioning and Decontamination (D&D) [4][5], remote inspection [9], emergency response [6][7], etc. The use of mobile robots with shared autonomy at national laboratories to reduce the operator's burden can be traced back to a semi-autonomous surveying system developed by Bruemmer et al. [8] at Idaho National Labs. This system allowed the user to navigate a mobile platform via a point & click Graphical User Interface (GUI) instead of commanding the system at a lower level (forward, back, or rotate). Preliminary use demonstrated great promise. For example, one survey took three days compared to three months without the system and the operators recorded a personal dosage reduction of 7 mRem from 82 mRem. System developers concluded several areas needed additional investigation including operator trust, job satisfaction, and training. The NRG began researching these topics using similar Levels of Autonomy (LoA) for remote radiation surveying with an inexpensive mobile system [10]. With slight adjustments for mobile manipulation, these levels are:

- Joint: direct, low-level, and continuous.
- Safe: adds self-collision avoidance.
- Shared: sends goal to the robot with autonomous path planning.
- Collaborative: increases the intuitiveness of the control interface.
- Autonomous: user input is only required to start.

The experimental results found a nominal increase in the system's ease-of-use rating for increased autonomy. But the small testing pool, task ease, and simulated environment reduce the significance of these results. One of the goals of this work is to decrease operator burden through the use of semi-autonomous behaviors. A recently published work also builds on Bruemmer's effort. Chiou et. al. [11] evaluated various LoAs for navigation of a maze-like environment. Overall, the number of collisions were highest with teleoperation. Completion times were higher with autonomous navigation, but obviously with a greatly reduced burden on the operator.

On June 24, 2011, the first mission of a customized Quince mobile platform was conducted at the Fukushima Daiichi nuclear power plant [7]. After six weeks of training, TEPCO operators attempted to complete six missions. The robot was unable to return from the last mission. System developers documented the lacking critical elements during the project:

- Field knowledge for researchers
- Precise communication between researchers and users
- Education of users

Again, the lessons learned were not technical, but programmatic. The first lesson was magnified by the nature of the tragedy and the severe time constraints imposed on the team. The second insight was that advanced hardware and autonomous capabilities, initially rejected by the Quince users, might have increased mission efficiency. Given the limited training, there was an understandable desire to simplify the user interface by minimizing "middleware." To "get a feel" for robot operation, the user must be able to tele-operate motors/joints individually but this approach is untenable in the long-term. Operators will make mistakes which could be avoided with LOAs controlling low-level robot functions when applicable. Such mistakes may cause delays, failures, or damage to the robot. But the operator’s ability to interrupt autonomous operations must be available in case risky or unproductive behaviors are observed. User control and autonomous algorithms must be complimentary.

A significant factor in complementary nature is Human-Machine Interface (HMI). In [12], the authors review the performance of eight of the 15 DARPA Robotics Challenge Trial teams. The authors broke the competition down based on team success, critical incidents, team utterances, subtasks, interface displays, operators/input devices/screens, and control methods. The overall result of this analysis reinforced the currently held guidelines that “more sensor fusion, fewer operators, and more automation lead to better performance.” [12] The highest scoring team displayed everything on one monitor.

This is just a small sample of the literature related to robotics and remote handling in hazardous environments, but from this representative sample, we make some interesting observations. These observations help to conclude that visits to DOE sites – such as the one documented here – are necessary to build DOE’s trust in the use of robotic systems to augment human efforts, reduce dosage, increase efficiency, and increase safety.

HARDWARE PLATFORMS

The two robotic systems used for these demonstrations were shown in Fig. 1. This section briefly summarizes their hardware configurations and capabilities. A final section summarize the key elements of the hands-free user interface utilized as a part of this effort.

VaultBot: A dual-arm mobile manipulator

The VaultBot robotic system was designed and assembled to evaluate the feasibility of inspecting and retrieving SNM material from a long-term storage area at LANL. A detailed design analysis can be found in [10] and [13]. A detailed hardware description and performance evaluation can be found in [14].

The VaultBot was co-developed with Clearpath Robotics. Industrial manipulators were selected over co-robotic compliant options to maintain accuracy, and robustness. The 6DOF Universal Robotics UR5 industrial manipulators were selected for the cost, low power consumption, torque monitoring, and existing dual-arm capabilities. The UR5 has a payload of 5 kg and working radius of 850 mm. The Clearpath Husky platform was selected because it met the payload and power requirements of two UR5s as well as Clearpath's ability to perform system integration. The Husky required several modifications to support the arms including higher torque drive motors, stronger drive belts, ventilation fans, and a steel bulkhead on which the UR5s are mounted. These modifications considerably shortened the battery life from three hours to one hour and limited the maximum speed of the system to 0.5 m s^{-1} from 1.0 m s^{-1}. The Husky platform has the capability to support an additional or denser battery pack. The VaultBot platform has additional hardware including a UM6 IMU, a SICK LMS511 2D LIDAR, an Intel RealSense R200 RGBD camera, a Robotiq two-finger gripper, and a laptop running Ubuntu 14.04. A wireless router allows the operator to command and monitor activity remotely.

The VaultBot hardware and sensors are integrated though Robot Operating System (ROS). ROS is an open-source software used for motion planning, trajectory execution, navigation, and sensor integration. The software is modular in nature and emphasizes a high level of abstraction. The greatest benefit of ROS is its collaborative and open source nature. It has approximately 80 supported robots and over 2000 software packages. [15] Another major advantage of the Husky and UR5 combination is the existence of ROS drivers from Clearpath (Husky) and ROS-Industrial consortium (ROS-I) (UR5) respectively. ROS-I is an open-source project which seeks to expand the capabilities of ROS to industrial robotic systems for advanced manufacturing.

The ROS package for manipulator motion planning, MoveIt! [17], was developed to be easy for novice users to get started with but allows detailed customization for experienced users and has been used on over 65 robots. RViz [18] is ROS's 3D robot visualizer used to display multiple information types including robot configuration, scene obstacles, sensor, and navigation information in a single window.

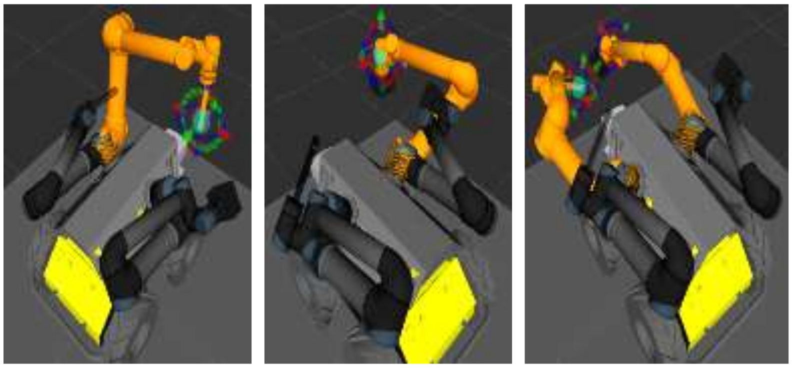

Fig. 2. Left, Right, and dual UR5 control through interactive markers, MoveIt!, and RViz with goal poses shown in orange

Scene obstacles loaded as collision meshes create Forbidden Region Virtual Fixtures (FRVF) for motion planning. Manipulators can be controlled through 6DOF interactive markers [19] in RViz as shown in Fig. 2. This means master control is commanded through a virtual representation of the manipulator instead of more traditional interfaces such as a joystick, slave manipulator, or other common manual controllers. Thus, there are is a complex system of software nodes and hardware interactions (Fig. 3). The RViz window can be customized by adding or removing panels or writing custom plugins.

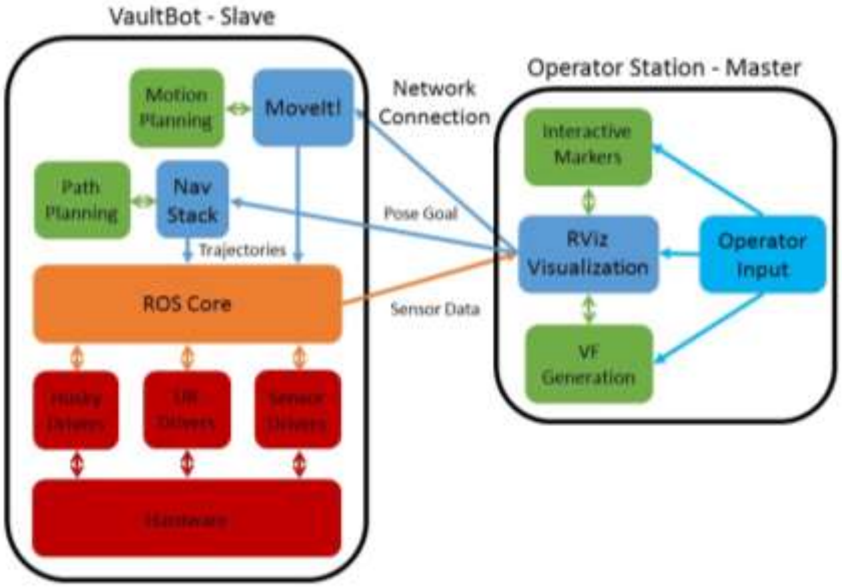

Fig. 3. Software node and hardware system interactions.

Hands-free Human-Robot Interface

Another method aims to minimize task execution time by automating repeatable (possibly tedious) subtasks and creating an intuitive human-centered interface [20]. An interface can be considered intuitive if task completion requires no or minimal additional training over normal completion of the task. To achieve this goal, users are able to relay intent through hand gestures and natural language. For instance, the operator can gesture to a pose in the RViz environment or utter the appropriate phrase to command base and/or manipulator. The interface consists of three human input devices. A Leap Motion Controller™ (LMC) for detecting operator’s hand movement, Griffin PowerMate USB turn knob for dynamically adjusting scaling factor between human and robot motions, and a microphone for receiving verbal instructions.

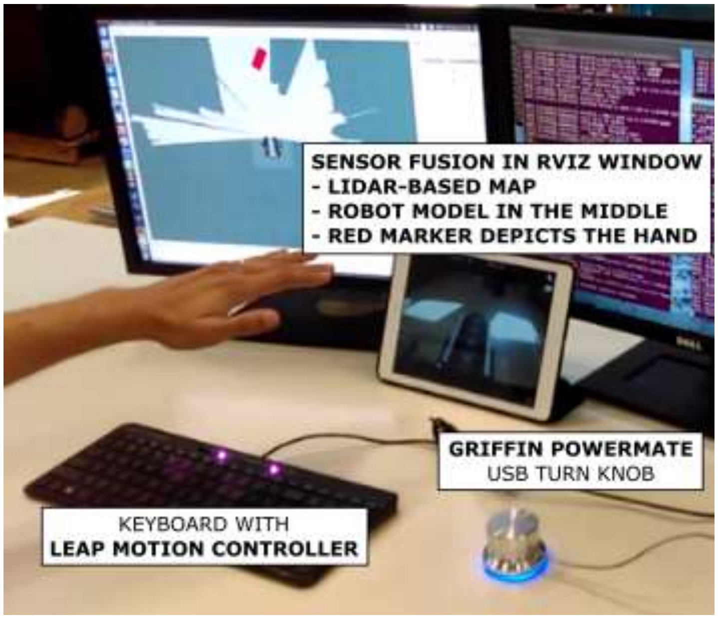

Fig. 4. The gesture- and speech-based telerobot interface contains Leap Motion Controller, Griffin PowerMate USB turn knob, microphone (not shown in the figure), and RViz visualization.

The LMC is a cost-effective (less than $100) commercially available device for robust detection of human hands and common gestures. The key advantages of LMC are low-latency, robust, marker-free hand tracking and very good precision. The Griffin PowerMate USB turn knob serves as a minimalistic control for adjusting the scaling factor between the amplitude of operator hand movement and resultant robot motion. In the past, we have established that scaling reduces the burden of precision on the operator by enabling fast and robust execution of high-precision tasks, such as threading a needle with an industrial robot manipulator [20]. For mobile robots, adjustable scaling allows also setting large-scale robot movement targets (e.g., in the range of dozens of meters) while the operator's hand moves span an ergonomically comfortable range. A headset with a microphone and earpiece enables two-way natural language communication between the human operator and the telerobotic interface.

Operator visualization is provided in a single RViz window where robot's model representation is fused with a LIDAR-based 2D map, a 3D point cloud depicting immediate surroundings, and visual cues for movement quantification as well as depth-perception. Different control perspectives and motion constraints serve to allow more straightforward control over the robot whereas automatically adjusting the point of view in RViz reduces context switching. All linear and rotational input gestures are interpreted in the human coordinate frame so that the operator is not required to handle coordinate transforms in their head.

Currently the telerobotic system allows setting 2DOF navigation goals and 6DOF EEF poses. Through spoken interaction, the operator can add or remove constraints, switch between control perspectives, request planning or execution of movement, and trigger preprogrammed autonomous subtasks.

Adept Pioneer: A Radiation/contamination sensing & inspection robot

The Adept pioneer contamination and inspection system is shown in Fig. 1. It consists of an Adept Pioneer LX mobile platform, two Ludlum alpha sensors, and a Zippermast which allow the camera, gas, gamma, and other sensors to rise as high as 3 meters above the floor.

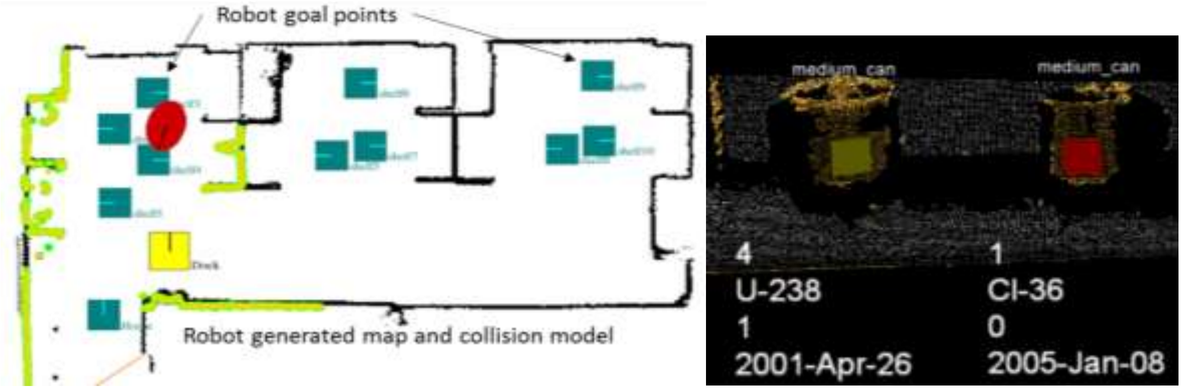

Fig. 5. A diagram of our mock vault (left) showing three rooms with a number of cabinets. Locations can be designated for inventory (a sample result on the right) or the room can be "swept" for routine contamination testing.

Inventory is completed by integrating results from a subset of selected sensors including AR tags, object recognition & pose estimation, and radiation signature. Thus inventory results not only verify the presence of the object, but also if it has moved or exhibits higher than normal radiation emissions. Inventory results can be compared to both an existing database as well as to previous inventory results.

The system is capable of testing a room for alpha contamination, which can also be done during an inventory task. The speed of the system can be precisely controlled to prevent rapid frisking and the sensor - with an adjustable floor clearance – is protected by "whisker" sensors to prevent damage from larger debris. When contamination is detected, the desired autonomous behaviors of the system can be modified. It is currently programmed to stop and audibly beep The alpha sensor has been integrated into ROS so inspection could be completed using other robots compatible with ROS. The mobile system has sufficient power for 13 hours of autonomous operation and can autonomously return to its charging base if power runs low or some other fault is experienced. In addition, the system has a full 360° of collision detection/avoidance capability to prevent collisions with both unmodelled objects and personnel in a shared workspace. To inspect higher shelves, we have integrated a ZipperMast retractable tower (from Geo Systems Inc.) on top of the existing system which is capable of reach up to 8 feet from its 8" fully retracted height.

PORTSMOUTH DEMONSTRATIONS

Three demonstrations were developed and completed at the Portsmouth Gaseous Diffusion Plant in Piketon, OH. These were:

Remote Hands-Free Pipe Inspection - An operator (shown in Fig. 6, left) uses the hands free controller described above to command the VaultBot across a room, and then command one of the manipulator arms to inspect a ventilation duct. The task was complete when the operator is able to read a small note hidden inside the duct using a camera attached to the gripper.

Autonomous Inspection – For this task, the operators (shown in Fig. 6, right) initiated and supervised a simple inventory and inspection task of canisters stored on shelves inside the Piketon facility. The canister type, label, and location were all verified against a previous inventory record created by NRG researchers. In this demonstration, both the alpha and gas sensors were active and randomly triggered by either alpha sources randomly placed on the floor or UT researchers simulating a gas leak by opening a CO_2 cartridge in the vicinity of the sensor.

Autonomous Routine Contamination Testing – For this task, a 3 m by 3 m floor area was comprehensively inspected for alpha contamination. Alpha sources were supplied and randomly placed by facility radiation technicians. The system was operated by the same operators used in the previous demonstration and the gas sensors could also be randomly triggered. All sensor detection events in both demonstrations triggered a loud siren and required the operator to approve that the task continue via a simple GUI.

DEMONSTRATION RESULTS AND OPERATOR FEEDBACK

All three demonstrations were successful. John was the operator for the VaultBot, and after one hour of training, he was able to successfully inspect the mock ventilation pipe and read the message hidden inside. Theresa was operator responsible initiating and supervising the contamination testing and inspecting demonstrations that were completed without issue. Kim was the Radiation Control Technician (RCT) responsible for sample sources used for the contamination testing, and responding when the robot detected the "contamination." Kim only required 10 minutes of training prior to the live demonstration. UT researchers collected feedback from the operators both during and after the demonstrations.

Fig. 6. VaultBot operator John (left) and Pioneer Operators (right) Theresa (right in picture) and Kim (left in picture).

John trained on the hands free system in order to direct the dual-arm's manipulator to inspect the ventilation shaft. He spent about 45 minutes of training the system with majority of that time (about 30 minutes) used to learn the voice commands. Overall, John was enthusiastic about using the system, and provided positive feedback. Given the task, he thought of the system's potential in terms of emergency response applications instead of routine inspection.

The time needed to learn the voice commands was unexpected, but should have been anticipated. While the commands were intuitive, they did not as easily imprint in the memory of a new operator as that of the developer who selected the language. In this iteration, the commands are inflexible. The operator was able to learn them in a reasonable amount of time, but retention could be an issue. This could be addressed by either building some flexibility into each command statement (i.e. "Robot, please go," "Robot, please move," "Robot, go now," etc.), but there could be some risk that building out the viable commands creates ambiguity if not done carefully. Another option is to provide a list of viable commands on a screen, possibly even a predictive list based probabilistically on the robot's current state. It is worth noting the selected speech recognition software [21][22] was very robust with respect to the varying accents of the users and developers who used the system.

A minor but significant (and addressable) flaw was the lack of support for operators who choose to use their left hand. While it is not common for computer operators switch the mouse to the left side of the keyboard. The ability to do so is essential for some operators and most operating systems provide the option to switch. It was our luck that John prefers his left hand describing it as "more steady." There is nothing in the interface to would prevent us from adding this functionality.

John questioned the need for the spatial interface when commanding the mobile base. Since the task was to move the system across a flat floor, the mouse could be used just as easily. For the spatial motion commands for the manipulator, its use was more clear although still not necessary when the commanded moves were restricted to a plane. In some cases, using the mouse can be both clear and unambiguous. When so, if is feasible to provide it as an option to the user. There is plenty of precedence for operators to have more than one interface option to complete a task (i.e. mouse, touchpad, keyboard shortcuts, etc.).

Even though the contamination sweeping demonstration required the operator only to click a single button on the GUI using the mouse, the operator, Theresa, expressed anxiety about the task. This was attribute to 1) a general lack of comfort with computers in general, and 2) concern over what to do if something went wrong. She had observed UT researchers set up, test, and debug the system, so she had recently observed the underlying software complexity. Thus, these issues may be addressed by restricting operator training to interactions to include fully developed systems. A second option is to move the interface from the computer onto a simpler (and more restrictive) interface such as a teach pendant.

Overall, her feedback was extremely positive. Her enthusiasm focused on applications that address operator ergonomic issues more than ALARA issues. Many conversations turned into discussions of potential applications or Theresa interviewing us about demonstrations we may have already done. Here primary concerns related to “nooks and crannies” and other real world issues and how the robot could test in all the same locations a human operator would. It was noted that in a large building such as those at Portsmouth, the Pioneer system would eliminate much of testing done by operators including the most dull and ergonomically challenging aspects of routine testing. She specifically mentioned the repetitious task of sweeping with a perpetually bent back.

The RCT, Kim, also completed the demonstration as well as interacted with the robot when the sample “contamination” was detected. He was significantly more comfortable with the computer, and had similar enthusiasm for the potential to address ergonomic issues. It is worth noting the samples used at Portsmouth were significantly stronger than those used in similar demonstrations at UT Austin. It was clear that the seasoned operators were much more comfortable and knowledgeable of the dosage and danger or radiation sources than UT’s student and faculty researchers.

CONCLUSIONS

This paper outlines the hardware systems and demonstrations prepared for use by the operators at the Portsmouth Gaseous Diffusion Plant in Portsmouth, OH in September, 2016. These hardware platforms had been previously developed for applications in nuclear environments at Los Alamos National Labs. Thus it was possible to quickly adapt, modify, and extend the demonstrations for use in Portsmouth on the aggressive (<3 month) timeline. Feedback from both management and the system operators was positive and all of the suggestions for improvement above are technically feasible with minimal development and in a reasonable time frame.

One key finding was the operator’s stronger interest to use the robotic systems to address issues related to ergonomic and drudgery more than dosage (ALARA) issues. All operators were able to learn to use the systems in very short timeframes, but future efforts should be undertaken to develop multimodal interfaces (i.e. where the operator can command the robot in multiple ways), and then evaluate longer term system usage to better understand the observed anxiety issues as well as user preferences given multi-modal interfaces.

Overall, the demonstrations appeared to generate enthusiasm for using robotics in conjunction with existing workers. This enthusiasm was observed in the workers, plant management, project funders, and technical observers. The critical next step is to determine how to build on that enthusiasm.

The event demonstrated EM's belief in robotic enhancement of worker health, safety, and performance as robotics research organizations from all over the country were invited. Rodrigo Rimando, director of EM's Office of Technology Development, noted at the event:

> *“Structuring the demos to have the workers and operators conduct the demos provided us a unique opportunity to gain their perspectives on the utility of the technologies and to offer their insights on ways to make their work safer and easier to do.”*

This event helped to address the key lessons learned from [7] by developing lines of communication between researchers and operators to encourage the utility of future robotic research to nuclear domains.

REFERENCES

[1] Pryor, M., Landsberger, S., “Development of a graduate curriculum for automation in the nuclear domain” *Proceedings of the 2009 ASEE Annual Conference and Exposition,* Austin, TX, June, 2009.

[2] Goertz, R., “Mechanical master-slave manipulator,” *Nucleonics*, 1954.

[3] Turner, C., Harden, T., “Robotics for nuclear material handling at LANL: capabilities and needs,” *ASMe IDETC/CIE Conference*, San Diego, 2009.

[4] Reynolds, D., et. al., “Modified impedance control for robotic saw cutting simulation and implementation in three degrees of freedom, *Fifth topical meeting on robotics and remote systems*, Knoxville, TN, 1993.

[5] “Next stage for robotic decontamination,” *World Nuclear News*, June 13, 2014.

[6] Sandia National Laboratories, “Mighty mouse robot frees stuck radiation source.” "share.sandia.gov/news/resources/releases/2005/manuf-tech-robotics/mm-robot.html" Accessed: 2015-09-30.

[7] Nagatani, K., et. al., “Emergency response to the nuclear accident at the Fukushima Daiichi nuclear power plants using mobile rescue robots,” *Field Robotics*, 30:44-63, 2013.

[8] Bruemmer, D., “Intelligent robots for use in hazardous DOE environments,” *Performance metrics for Intelligent Systems (PERMIS),* Gaithersburg, MD, 2002.

[9] Byrd, J., and Pettus, R., “A robotic inspector for low-level radioactive waste,” *Proceedings of the ASCE conference on robotics for challenging environments,* Albuquerque, NM, 1996.

[10] Sharp, A., and Pryor, M., “Operator control modes for implementing autonomous search behaviors,” *ANS Student Conference*, College Station, TX, 2015.

[11] Chiou, M., et. al., “Towards the principled study of variable autonomy in mobile robots,” *Proceedings of the 2015 IEEE International Conference on Systems, Man, and Cybernetics*, Hong Kong, 2015.

[12] Yanco H. et. al., “Analysis of human-robot interaction at the DARPA robotics challenge trials,” *Journal of Field Robotics*, 32(3):420-444, 2015.

[13] Sharp, A., Kruusamae, K., Ebersole, B., and Pryor, M., “Semi-autonomous dual-arm mobile manipulator system with intuitive supervisory interfaces,” *Proceedings of the 2017 IEEE ARSO Conference*, Austin, TX, 2017. (submitted)

[14] Ebersole, B., and Pryor, M., “Intelligent navigation of a skid steer dual-arm manipulator with dynamic center of gravity,” *ANS Decommissioning and Remote Systems Topical*, Pittsburgh, PA, August, 2016.

[15] M. Quigley, B. Gerkey, and W. D. Smart. Programming Robots with ROS A Practical Introduction to the Robot Operating System. O'Reilly, 2015.

[16] S. Edwards and C. Lewis. ROS-Industrial-Applying the Robot Operating System (ROS) to Industrial Applications. In IEEE Int. Conference on Robotics and Automation, ECHORD Workshop, 2012.

[17] Sucan, I, and Chitta, S., "MoveIt!," [Online]. Available: "moveit.ros.org/”.

[18] D. Hershberger, D. Gossow, J. Faust. "RViz". [Online]. Available:” wiki.ros.org/rviz".

[19] D. Gossow, A. Leeper, D. Hershberger, and M. Ciocarlie, “Interactive Markers: 3-D User Interfaces for ROS Applications [ROS Topics],” IEEE Robot. Autom. Mag., vol. 18, no. 4, pp. 14–15, Dec. 2011.

[20] Kruusamäe, K., and Pryor, M., “High-Precision Telerobot with Human-Centered Variable Perspective and Scalable Gestural Interface,” *9th IEEE International Conference on Human System Interactions (HSI)*, pp. 190–196, Portsmouth, UK, 2016.

[21] Web site: https://wiki.ros.org/pocketsphinx, last accessed: November 18, 2016.

[22] Web site: “https://cmusphinx.sourceforge.net,” last accessed: November 18, 2016.

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