Advanced Teleoperation and Shared Autonomy for Nuclearized Robotic Systems – 17333

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ABSTRACT

Remotely-initiated operations have existed for more than 50 years in the nuclear weapons complex, as the environments are far too extreme for humans. We introduce the scope of the nuclear waste cleanup effort and describe some existing applications of robotics technology at specific sites. We offer summaries of both the technology that is currently used, as well as a discussion of the types of problems that the technology is applied to. We contrast this with the current state of practice in other areas where robots are deployed in the real world, such as with military infantry units. We then go on to summarize and discuss the current state of the art in advanced teleoperation research and in shared autonomy, where humans collaborate with closed-loop automation to complete tasks. Our discussion focuses on areas with particular relevance to nuclear waste management, such as remote inspection and manipulation.

Armed with this background, we then identify specific technology gaps that must be closed in order to successfully bring advanced teleoperation and shared autonomy technologies to bear on problems in nuclear waste management, such as (1) environmental remediation; (2) sampling, characterization, and disposition of tanks with hazardous and highly radioactive waste and (3) decontamination and decommissioning of facilities with gloveboxes and hot cells.

We propose a roadmap for how to transition the current state of the art approaches in advanced robotics and shared autonomy to practice in the nuclear industry and how to close the technology gaps previously identified. This roadmap covers not only the technical advances that need to be made, but also considers the social and societal aspects. Drawing parallels with the adoption of similar technologies in the military and other areas, we offer concrete suggestions for how to deploy these new technologies effectively into the nuclear industry from a human-centered perspective.

INTRODUCTION

As the 1982 Nuclear Waste Policy Act is no closer to being implemented than it was when it was originally passed, the United States currently has no long-term strategy for managing high level waste. The Nuclear Waste Council of the Bipartisan Policy Center (BPC) states in a 2016 report that "prospects for successfully constructing and opening a geologic disposal repository in the United States appear no better than they were decades ago." [1] To address this concern, President Obama constituted the Blue Ribbon Commission on Americas Nuclear Future in 2010, which generated several recommendations to redefine and strengthen the federal approach toward waste management [18].

While no formal legislation has passed as result of the commissions findings, the U.S. Department of Energy (DOE) is proactively taking steps to execute several recommendations in its 2013 Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste (HLW). Additionally, the House of Representatives Nuclear Cleanup Caucus, is bringing together government and industry to raise awareness of technological needs in order to achieve their mission of a safe and efficient cleanup of DOE 'legacy sites' [11]. Caucus chairman Rep. Chuck Fleischmann (R-Tenn.) has stated that it's a federal obligation to clean up these legacy sites all over the country.

In addition to 72,000 tons of used nuclear fuel from commercial nuclear power operation, DOE is also responsible for a substantial amount of waste historically generated from processing of material in the U.S. nuclear weapons complex. The DOE Office of Environmental Management (DOE-EM) has successfully completed cleanup of 91 of the 107 sites that generated nuclear waste, but acknowledges a significant effort remains, and estimates the mission will continue out until 2065 at the cost of another $235 billion.

One key challenge of the cleanup effort is the approximately 88 million gallons of radioactive waste that is currently being stored in underground tanks, and and the additional 4000 cubic meters of solidified waste resultant from the liquid currently in storage bins [1]. A majority of this material is still being stored on location at the Hanford (Washington State) and Savannah River (South Carolina) Sites, with smaller quantities also existing at the Idaho National Laboratory (Idaho) and West Valley Demonstration Project Sites (New York).

Hanford is home to a majority of the HLW (57% of the total present in the weapons complex), and it is primarily contained in 177 underground storage tanks that are beyond their design lifetime and known to be leaking. The total volume is of Hanford tank waste is estimated at 53 million gallons. The Savannah River Site (SRS) generated another 36 million gallons of HLW that is stored in 53 underground carbon-steel tanks. All of the HLW generated at Idaho National Lab (30,000 gallons) has been removed from tanks and converted to a granular solid. Further treatment is planned in preparation for for final disposition.

The waste forms within the underground tanks are a mixture of highly radioactive sludge and lower level supernate and saltcake. The HLW mixture is not well characterized but is known to contain both radionuclides and chemicals such as bismuth, cadmium, chromium, iron and nickel at very high concentrations levels. As a result of the 2005 National Defense Authorization Act, much of this HLW volume can be reclassified as waste incidental to reprocessing (WIR), and treated as transuranic or low-level waste if criteria are met and key radionuclides are removed. The DOE, in conjunction with monitoring by the Nuclear Regulatory Commission (NRC), is working on waste determination for final disposal as WIR. Ultimately, this massive undertaking of waste characterization, extraction of highly radioactive sludge, and treatment of the residue is hazardous, time consuming, and expensive. The treatment and immobilization of this waste is estimated to take several decades and cost over $50 billion [29].

Savannah River Remediation (SRR) serves as the DOEs liquid waste contractor and and develops and utilizes advanced processes to remove actinides and extract radioisotopes that are then transferred to the Defense Waste Processing Facility to be blended and melted into a glass. The Defense Waste Processing Facility recently celebrated its 20th year of operation as the nations only vitrification plant, and has contributed to the closure of eight tanks on the Savannah River Site, equating to the removal of approximately 58.6 million curies from the liquid waste [2]. SRRs Interim Salt Disposition Process is also essential to managing the remaining 90% of the waste that is composed of salt. A permanent salt waste processing facility is scheduled to begin operation in December, 2018.

ROBOTICS APPLICATIONS IN WASTE MANAGEMENT

While robots are potentially applicable at any nuclear facility, it is clear that they will be essential to the safe and effective cleanup effort that remains as a part of the DOE-EM mission [21]. Robotic applications could reduce occupational exposure of workers as well as reduce traditional occupational risks associated with working around sharps and heavies in a high dose rate environment. Manipulators currently in use at nuclear facilities are often limited in dexterity, involve restricted viewing of the operating area, and require repetitive motions that can lead to injuries [21]. An additional benefit of implementing robotics is the reduction in low level radioactive waste created in the use of personal protective equipment. SRS estimated a reduction of 82 cubic meters of plastics suits and a savings of $1,000,000 in radiological laundry in a 12-month period [11]. While the nuclear industry is traditionally slow at adopting new technologies, often the cost associated with performing routine tasks in personal protective equipment compared to costs of investing in robotics is not fully considered [27].

As a specific illustration, robotics have been deployed for several waste characterization and remediation related projects at the Savannah River Site. In 2011, Savannah River National Lab reported their first robotic deployment into a High Level Waste Tank, Tank 18, which required additional sampling to characterize some anomalous material [28]. The Research and Development Engineering (R&DE) group inserted a crawler with two on-board samplers, two drive tracks and attached cameras into the tank riser and guided it to the tank floor where it sampled two targeted sludge waste piles. R&DE also developed a pipe crawler with an attached plasma arc cutting torch and used it to remove a section of the ventilation duct in the SRS F Canyon separation facility. R&DE also designed a custom remote vehicle for cleaning the Defense Waste Pilot Facility melt cell floor using Inuktun tracks to move, a single actuator to raise the arm, an electric gripper to grab tools, and cameras for navigation.

Working with HLW in hot cells and gloveboxes is another major opportunity for the deployment of robotic devices. The performance of operators working in existing hotcells and gloveboxes is degraded as a result of reduced visibility, lack of flexibility and dexterity, and repetitive motion, over-stress and over-work injuries [21]. Robotic arms composed of specially engineered materials are potentially attractive as alternatives to traditional master/slave manipulators as they may afford greater range and types of motion, reduce the physical burden on operators, and better withstand the extreme environmental conditions (radiation, combustion, corrosion). A recent request for bids from robotics supplies for the procurement of 23 plutonium glovebox robots is a relevant case study in the challenges involved with embracing advanced technologies in the nuclear field [14]. Twenty potential suppliers were contacted, five bids were received, and ultimately only one bid was acceptable given the stringency of the NQA-1 audit requirements. In addition, the decontamination, decommissioning and/or routine cleanup and maintenance of these facilities could be made safer and more effective with autonomous or teleoperated sampling, characterization and collection robots. Challenges to the use of robots in these applications include cost, availability, reliability, and modularity of the hardware. Because these devices are often safety significant and collect and transmit (sometimes wirelessly) classified and sensitive information, pre-qualification, testing and quality assurance auditing of the hardware and software is also necessary [14].

This past year, SRNL personnel have developed a substantial list of potential robotic applications that includes: a) repair of damaged concrete and removal of degraded concrete material in canyon cells, b) inspection and/or repair of piping and other canyon structures, c) movement, stacking and assay of waste and storage drums, d) response to chemical and/or radiological emergencies, e) semi-autonomous inspection and scanning of building components and structures, f) underwater building inspections and removal of cask lid bolts and g) fuel inspections [33]. This list is not unique to SRS; throughout the weapons complex as contractors deal with HLW, robots have the potential to have significant impacts on the safety, efficiency and cost of these projects.

A statement made by DOE Assistant Secretary for Environmental Management Monica Regalbuto at the recent September 14th meeting of the House Nuclear Cleanup Caucus expresses a common perspective on robotics for nuclear waste cleanup: "We have a lot of instrumentation, cameras and drones and we wonder why we havent used this in our industry. Its time to modernize the way we do business." [11]

APPLICATIONS OF ADVANCED TELEOPERATION AND SHARED AUTONOMY

Robots are increasingly being used to extend the range of humans in hazardous environments. Rather than relying on the robots to be autonomous and self-sufficient, a growing trend is to use shared autonomy systems. These are systems where one or more robots and one or more human operators collaborate on a shared task, dividing responsibility for the parts of the task that each party is best at. This typically means that the humans take on the high-level perception and decision making, while the robots do the low-level control, repetition, and sensor-driven closed-loop movement and manipulation. The main advantage of this approach is that it has allowed us to deploy practically useful robots in real world scenarios, without having to wait for them to become fully autonomous.

Robots have seen extensive use in military operations [31], starting out as remote tools for bomb disposal specialists. These systems allow the human experts to perform their work at a safe distance, dramatically reducing their risk. These systems are typically fully remote-controlled, with very little on-board intelligence. The operator drives them out to the target, using joysticks, buttons, and a video feed. Simple arms and grippers, also equipped with cameras, can then be used to investigate and, if necessary, explosively disable the suspect device. More recently, unoccupied aerial vehicles (UAVs) have been increasingly used for both reconnaissance, defensive, and offensive operations. Again, these are largely remote controlled systems, albeit with an increasing amount of on-board autonomy, that let humans project their actions from a safe location. As the amount of autonomy increases in these systems, the human becomes more of an operator than a pilot, and issues higher and higher level commands. Rather than directly flying the UAV, the human can give it a set of waypoints and leave the rest to the autopilot. However, as with the ground-based systems, this is still very much a shared autonomy system, with the human and the robot sharing a common task.

Perhaps the most well-known shared autonomy robot system is the daVinci surgical robot [12], a system that allows a human surgeon to perform a range of minimally-invasive surgeries more easily that is possible by hand. The surgeon sits at a console, looking into a stereoscopic display while the robot, often across the room, performs the physical actions of the surgery. While it does protect the surgeon from danger, as military robots often do, it does afford them better ergonomics as they perform surgery, and allows them to make more precise movements, scaling down physical movements of the controllers to extremely small movements of the robot manipulators. There is starting to be some evidence to suggest that these shared autonomy surgical procedures lead to better patient outcomes and fewer complications, although they are often longer than human-only surgeries [20, 34].

While these two areas are the most well-known applications of shared autonomy teleoperation, there are numerous other examples currently being developed. The early work of Michelman and Allen [17] looked at shared autonomy grasping of objects. This use case is still under investigation today. For example, Pitzer et al. [19] looked at manipulation from a mobile robot base, Leeper et al. [16] considered the more complicated case of grasping in clutter, and [22] use a shared autonomy approach to help a robot operate common household electronics devices. In an outdoor setting, Sa and Corke [23] used a shared autonomy approach to inspect hard-to-reach infrastructure with small flying robots. Recently, and more pertinent to this paper, robots were used at the Fukushima Daiichi plant after the accident in 2011, although there are reports that they are starting to fail [4].

IN-WATER ROVS FOR NUCLEAR WASTE MANAGEMENT

A key application of autonomous vehicles in nuclear waste management is in-water evaluation of the health of canisters containing extreme radiation sources, such as those stored at the Hanford Site Waste Encapsulation and Storage Facility (WESF), the Savannah River Site, and other similar facilities. Such technology also has dual use for general monitoring and mapping in water tanks throughout nuclear facilities.

The current method for detecting and locating a leaking canister relies on detecting unintended contamination in the pool water. After contamination is detected, each canister is individually subjected to the inner canister movement test (also known as the clunk test) to see if the inner canister is able to move freely within the outer canister [25]. If the inner canister can move freely, the assumption is that the inner canister not significantly bulged and there is not a significant amount of water in the annulus between the inner and outer canister walls [32]. Such operations are currently performed with either a diver (in low radiation tanks) or a manually controlled remotely operated vehicle (ROV). There is potential in this area for autonomous or semi-autonomous vehicles capable of (1) removing cognitive load from operators, (2) performing in environments where operator would have difficulty, and (3) reducing the training required for operators to perform these task.

Time efficiency is essential for operational efficiency and to reduce total dose to both the system and to human users operating the system. Past work uses autonomous and semi-autonomous behaviors to maximize inspection data quality while minimizing total inspection time, and minimizing risk to the inspected environment and the system itself. The design of the time-efficient real-time inspection component has been divided into two subtasks: (1) human-robot interfaces and (2) inspection planning.

Coordinating autonomous vehicles in inspection planning scenarios dates back to classical active perception problems, where the path and sensor views must be planned to maximize information gained while minimizing time and/or energy [3]. As such, ROV systems have been used to perform inspection planning in uncertain environments using a trajectory optimization framework [9]. Such a framework seeks to optimize some data quality metric (e.g., the accuracy of a mapped environment) subject to a budget constraint (e.g., time, fuel, or radiation exposure). Optimizing this reward metric requires solving the the following maximization problem:

$$P = max_{P \in \varphi}\ I(P)\ \ s.t.\ c(P) \leq B, \qquad \text{(Eq. 1)}$$

where φ is the space of achievable configurations for the ROV, B is a budget, and I(P) is a function representing the data quality gathered along the trajectory P. We note that the space φ can be defined broadly and may contain such optimization parameters as (1) vehicle location, (2) sensing configuration (e.g., direction a sensor is facing), and (3) sensing parameters (e.g., internal configuration parameters like the aperture of a lens). To date, such frameworks have focused primarily on ship hull inspection [10] and offshore inspection [15], with less focus on nuclear tank operations.

One of the key aspects of nuclear tank operation is that the environment provides a number of constraints (e.g., radiation exposure in no-fly zones), which need to be dealt with explicitly in the optimization. In addition to inspection planning optimization, ROV systems also utilize a human-robot interface for integration with the human operator. These interfaces allow the human to provide both high-level and low-level goals for the system, while the system can potentially determine efficient, safe, and effective actions to complete these objectives.

There is a recent thrust in environmental monitoring towards the development of Decision Support Systems that allow the human operator to seamlessly track the progress of autonomous vehicles and to issue commands on the fly [5]. Such systems are capable of monitoring the progress of autonomous vehicles operating in unstructured environments by providing data to operators in real time. Another main challenge in developing time-efficient mission planning is to carry out the high-level goals of the operator safely, quickly, and successfully. To achieve this goal, the vehicle must plan an inspection path based on the instructions from the operator. Inspection planning optimizes a data quality objective using a combination of sampling-based planning [9] and gradient- based trajectory optimization [7, 24]. The main idea is to sample the trajectory space of the vehicle and incrementally refine these trajectories over time. An alternative approach is sampling the configuration of the vehicle [13], but this can have scalability concerns in high-dimensional spaces. After a sufficiently large number of trajectories have been examined, the system can extract an efficient trajectory that satisfies the mission goals. While the algorithm is refining trajectories, solutions that are not promising (e.g., have low data quality and high cost) can be pruned to reduce the computational complexity.

There is a growing body of work on utilizing a human operator as part of a human-robot team. Much of the recent work has focused on the use of natural language processing to guide the actions of mobile robots [26]. This prior work has developed sophisticated machine learning architectures that allow autonomous systems to infer intent from verbal commands for complex tasks. Similar techniques have also been applied to underwater domains using hand signals [8].

Prior work has examined techniques using sampling-based planning for inspecting the hull of a submerged ship using an underwater vehicle equipped with a scanning sonar [9]. The goal was to plan the path of the AUV to generate an accurate 3D reconstruction of the submerged portion of the ship’s hull. This modeled uncertainty on the mesh reconstruction using an extension to Gaussian Process regression [30] and Gaussian Process implicit surfaces [6]. The use of this metric casts the AUV path planning problem as a reduction in the expected variance of the Gaussian Process uncertainty model. Such techniques have cross-cutting potential for mapping and inspection in nuclear waste management applications.

OPPORTUNITIES FOR ROBOTICS IN WASTE MANAGEMENT

Based on the work we have presented here, we have identified several key areas with potential for robotic systems in nuclear waste management:

1. In-water nuclear tank inspection and non-destructive evaluation: Remotely operated vehicles have great potential to provide data regarding nuclear material in large water tanks. Existing ROV technology, which has typically been applied in ocean applications, are mature enough to provide the mapping and NDE data necessary to evaluate and service water tanks for nuclear material disposal and storage.

2. Telepresence in hot cells and glove boxes: Existing manipulators in hot cells often utilize a master-slave architecture where the human's movements are translated to the hot cell through a mechanical mechanism. Existing technology in the medical robotic domain (e.g., the daVinci robot) utilize more sophisticated techniques to provide shared autonomy. These systems can augment the user's capabilities through advanced haptics and force feedback. Transitioning such technology to hot cell and glove box operations has the potential to improve dexterity, reduce fatigue, and reduce training requirements for operators.

3. UAV characterization of nuclear sites: Unmanned aerial vehicles with radiation sensors have the potential to autonomously characterize sites and provide information about radiation levels, or identify an unknown source of contamination, without endangering humans or requiring expensive aircraft operations. Existing UAV technology allows for waypoint following and other autonomous functions that would reduce or remove operator involvement. Current FAA restrictions have recently lifted somewhat with the small UAS Rule (Part 107) and the implementation of 333 exemption. However, non-line-of-sight operations and non-daylight operations are still restricted. As these restrictions continue to be revised, UAV technology is currently available for site characterization, security, and monitoring of nuclear sites.

4. Clean up of contaminated facilities: Another key potential area for robotic technology in nuclear waste management applications deals with clean up of contaminated sites. Rad-hardened robotic technology could autonomously enter contaminated sites and remove nuclear waste through vacuuming, scrubbing, or otherwise manipulating the site. Such technology would reduce risk to humans and also allow for clean up in areas that are currently inaccessible due to safety concerns.

CONCLUSION

We have provided a preliminary roadmap for utilizing robotics systems for nuclear cleanup, waste management, and general remote operations relating to nuclearized systems. It is clear that there is significant potential for human-centered robotic systems to improve efficiency and safety, expand the range of tasks possible, and reduce cost in nuclear waste management applications. In particular, we have identified nuclear tank inspection, remote telepresence in hot cells and glove boxes, UAV site characterization, and nuclear materials clean up as key areas that could benefit from robotic technology. Adoption of this technology is critical for meeting the needs of nuclear waste management going forward in the next decade.

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