Generating Survey Plans for Autonomous Robots using Source and Instrumentation Data

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Abstract: This paper reviews components for generating survey plans for a robotic system at UT Austin used autonomously survey safety travel corridors, laboratory spaces, and other areas that require routine radiation surveys. Survey results can be archived and compared to previous surveys in order to detect either changes in the field or new hot spots that exceed a given threshold. The system already utilizes dynamic obstacle avoidance and a robust supervisory controller accounting for closed doors, temporary obstacles, and battery limitations, etc. In order to automate survey planning, the software must automatically select sensors, survey resolution, survey locations, and counting time necessary in order to generate meaningful survey data in a reasonable amount of time. In our approach, the survey points span a rectangular grid pattern with spacing either set by the operator, designated by survey requirements, or optimized with respect to confidence levels and/or survey time. The system considers counting statistics in its data collection function that tracks the count uncertainty and guarantees confidence limits given by a Poisson distribution specified by the task. Previous iterations of the system have been deployed in U.S. Department of Energy environments, and newly developed automated planning algorithms are tested at U.T. Austin to evaluate effectiveness and feasibility.

Keywords: Robotics, Remote Surveys, Radiation, Nuclear

1 Introduction

Most nuclear facilities are required to perform routine, periodic surveys of the radiation levels in general work spaces. This requires well-trained, costly Radiation Control Technicians (RCT) for long periods and – in some settings – results in a significant radiation dose to the workers. Mobile robots are a potential solution for mitigating the expense and safety risk of this activity while also increasing the data quality[1][2]. Radiation counts can be collected using a grid or – more generally – a set of static locations across a specified survey region. Unlike a human worker, the system computes the statistical uncertainty and confidence limits of the data in real-time, and therefore can collect data until the required certainty is achieved.

A practical system must navigate the non-static environment of a real work space. This involves both high-dynamic obstacles (such as people walking), static obstacles (walls), and low-dynamic obstacles (the occasionally moved trash bin). The system must be able to traverse the same spaces as a human surveyor. The survey results must be repeatable and verifiable. While they do not need to be fast, they need sufficient speed and battery life such that surveys can be performed at the desired intervals. Also, deployment methods must be scalable given the typically large spaces where these systems are required. They must be operated and maintained by current on-site operators and not require the continual presence of robot experts on the premises. Finally, the system must generate and archive all necessary survey reports to meet the survey task and regulatory requirements.

The Nuclear and Applied Robotics Group (NRG) at the University of Texas at Austin has developed capabilities for autonomous surveying of beta/gamma radiation fields to address each of these issues. A survey system (see Figure 1) has been developed and demonstrated for survey, inventory, and contamination monitoring in facilities where Special Nuclear Materials (SNM) are stored. Operators can meet their annual dosage limits of 5 rem (0.05 Sv) after spending 10-20 hours in the facility. Thus a robot would be in accordance with "As Low As Reasonably Achievable" ALARA principles.

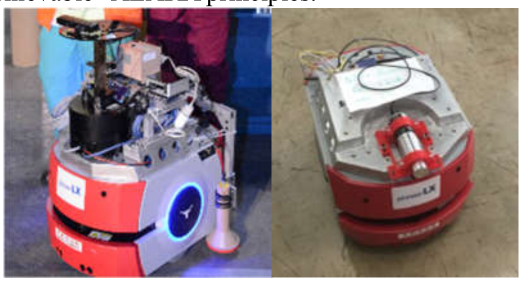

Fig 1. Radiation Survey System[1]. Configured to sweep floors for alpha contamination (left) or for beta/gamma detection as presented in this paper (right).

The system utilizes various sensors including alpha radiation, gas, barcode readers, RGB-D cameras, thermal sensors, and gamma/beta sensor(s) to perform a given inspection or survey task. The mobile base is a commercially available Adept Pioneer LX mobile system with an estimated 13-hour battery life. The NRG has utilized existing software for obstacle avoidance and Simultaneous Localization and Mapping (SLAM) and has developed its own supervisory controller[2] to ensure the system can complete the mission in event of complications such as temporarily restricted access issues, low battery, sensor failure, contamination detection, etc. How to best address low-dynamic obstacles or when to re-plan offline survey plans due to low frequency temporal changes in the environment are currently being addressed by the NRG in a parallel effort[2].

The goal of this effort is to present the components of the survey system that allow the proposed solution to 1) scale to large facilities, 2) be deployed by non-robotic experts, and 3) provide and archive the data necessary for reporting. To meet these goals, a Graphical User Interface (GUI) has been developed to be used by non-robotic experts and is integrated with the rest of the survey system components. An improved sensor for gamma/beta source detection is utilized. The Lanthanum Bromide ($LaBr_3$) scintillator allows the system to portably generate reliable counts and provides potential for localization and isotopic analysis.

After a quick review of previous efforts in this area, the survey task requirements are specified, the user interface is presented, the sensors capabilities are experimentally validated and analyzed, and the hardware system is reviewed in detail. Two demonstrations were developed. First, a small illustrative survey is completed to verify component integration. It allowed for user feedback to be collected and addressed in a reasonable amount of time. It was then extended to a larger grid to evaluate the system's scalability to survey new, larger spaces. It assumed radiation levels that were simulated but commensurate with levels anticipated in the field. A second demonstration was completed at scale and involved multiple sources and rooms. Lessons learned and topics for future work are discussed in the concluding section.

2 Previous Efforts

Robotics systems have been used by the U.S. Department of Energy (DOE) to perform remote inspection and surveys for decades. Most deployments have been in response to emergencies and are not intended for routine use. Bookends to these efforts include deployments at the Three Mile Island (TMI)[4] and Fukushima nuclear reactor facilities**Error! Reference source not found.**.

At TMI, a robot known as Rover successfully performed tasks such as core sample drilling, visual inspection, and radiation measurement. The system was rugged but simple; for example, rather than receiving radiation readings electronically, operators had to point the cameras at a dial display on the instrument.

Over 30 robots have been deployed to perform variety of tasks at Fukushima[5] to perform a variety of survey tasks. After recent deployments, Nagatani**Error! Reference source not found.** identified three key impediments to deploying their system: 1) lack of domain expertise on the team developing the robotic system, 2) lack of communication and training between the final system users (TEPCO) and system developers, and 3) lack of training available for operators in a simulated environment. While systems developed for routine survey have critical differences from those used for emergency response, these lessons should also be considered for this effort. With respect to the first lesson, the NRG requires its students to complete a significant portion of the nuclear curricula and thus have the necessary domain knowledge. To help address the second issue, the system is designed to be simple enough for non-experts to use which simplifies the communication component. Finally, the surveys are designed in a simulation environment and can be tested in the same simulation environment where they are defined.

Early efforts in routine inspection were reviewed by Ward et. al.[7] and included inspection of contaminated junction boxes, outdoor pump diversion pits, and weld inspections inside reactor vessels. In the final case, the dose rate was approximately 1,000 R/h. In total the reviewed systems largely eliminated worker dose when completing such routine tasks, but the systems were tele-operated and designed for a specific task and environment, and often used expert operators.

Idaho National Laboratory (INL) performed a real-world test of a mobile radiation survey robot.[8] Operators again used a teleoperated system to survey a heavily contaminated decommissioned pump facility. The resulting human radiation exposure was reduced by over 90% compared to baseline operations. More labor was required to deploy the robot than the baseline operation, but many more data points were collected. The system also featured a variable autonomy system that allowed the operators to use a point and click interface to direct the robot to a new location instead of manually driving it using a joystick. The planned path was shown to the operator via their Graphical User Interface.

INL installed a gamma and isotopic identification instrument from the Russian Research and Development Institute of Construction Technology (NIKIMT), which allowed isotopic identification by gamma spectroscopy. A demonstration was performed in a decommissioned waste treatment plant at INEEL, and the robotic system performed the task with better data quality, less time, and lower worker dose than when the task was performed by human technicians[9].

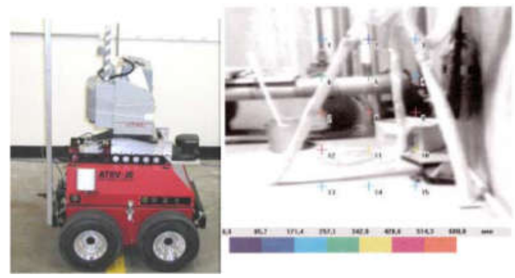

Fig 2. INL Mobile Radiation Surveying Platform and Data Display [9]

The main difficulty encountered was in wireless communication, as the thick reinforced concrete walls of the facility blocked the wireless signal in some areas. Tethered communication was necessary to operate in those cases. The platform was also not capable of navigating the stairways, so operators had to carry it between floors. Operators also entered the facility to install wall cameras in the rooms that the robot would be working in. Despite this, total human exposure was greatly reduced since it was not necessary for them to approach the contaminated equipment to be surveyed. Therefore, this deployment demonstrates the improved worker safety and data collection that robotic systems can provide in radiation surveying tasks. The software was developed from scratch and utilized a custom Linux machine and was specific to the hardware used for the demonstration. The software was never publically released.

A series of robots were deployed to the H-Canyon facility at Savannah River Site[10] to inspect/survey the condition of an air-exhaust tunnel used to maintain negative pressure in the facility. While visual inspection has been the primary goal, radiation measurements are collected and additional detail is desired in the future. These robots are operated remotely under the supervision of multiple robotics experts. They survey plans are informal and directed by individuals who notice items of interest in real-time.

Some routine radiation survey studies have been completed in academia, but the available results are insufficient for field deployment. LANL has sponsored prior work in robotic radiation surveying. Cortez *et al*[18] performed tests of a small mobile robot for finding floor contamination. The tests focused on low-rate counting in which Poisson statistics are significant to search for discrete sources of radiation. The test area is broken up into square tiles, and the robot performs a sequential search of the tiles. Interestingly, the robot is never stationary while taking measurements and the robot lowers its drive speed when the count rate for a given tile exceeds a specified detection threshold. The moderated drive speed allows it to achieve lower uncertainty on suspect areas. Cortez compares the time efficiency of sequential survey against an algorithm which bases the survey pattern on uncertainty gradients of the readings[19]. The information maximizing approach of is expanded to multi-platform systems[20].

Vaughn *et al*[22] built a human-driven radiation survey vehicle equipped with a $LaBr_3$ detector. The hardware resolution was sufficient to distinguish between natural and depleted uranium in a field soil survey. McDougal[23] found up to three sources of unknown intensity in an unobstructed environment using a Markov Chain Monte Carlo (MCMC) approach.

From this review of the academic, government, and commercial efforts, most technical capabilities have been developed and/or demonstrated at some point, but many of the demonstrated technologies were proprietary, were task/environment specific, or are no longer accessible. They must be redeveloped. This harsh lesson motivates the use of the Robot Operating System (ROS)[21] as the foundational software for this effort. In-house development of these technologies will be necessary to accomplish the goals of this work. Some established technologies also have room for improvement to make them more user-friendly or to implement additional features. Significantly, the review did not find any previous work on the alpha radiation surveying. Most prior efforts in radiation measurement have been driven by reactor accident response, and so are focused on beta, gamma, and neutron radiation data collected in an *ad hoc* manner. Routine, planned surveys using an autonomous system have received little direct attention. What attention it has received has been too simplistic to be effectively deployed.

3 Survey Task Requirements

The objective is to collect a radiation counts at a sequence of waypoints spaced regularly along the survey region and report/archive the results. The survey plan for realistic facilities can be generated by the RCT without the aid of a robotics expert. The mobile platform then navigates to each waypoint and is stationary while the data are collected.

Areas covered by static or dynamic obstructions will be excluded from the survey space (see Figure 3). The system can recognize when a survey point is obstructed and will move on to the next. After completing the survey plan, the system will return to the obstructed survey points to determine if the obstruction is no longer present. If a survey point is still not reachable, the system will mark it as such in the final report. Visual documentation of the obstruction would be included in the final report.

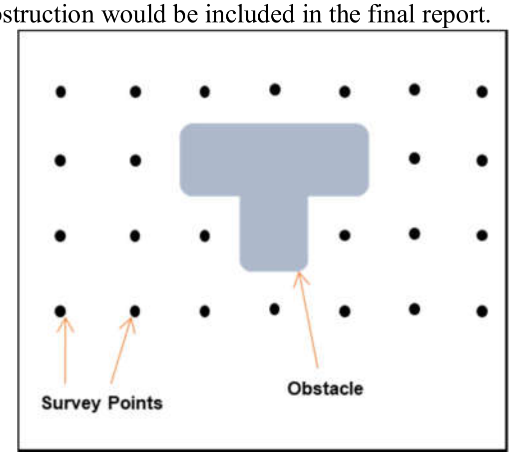

Fig 3. Radiation Survey Task

The number and spacing of the survey points will be determined by the RCT. Survey plans can be reviewed, modified, saved, and recalled.

4 User Interface: Planner/Operation

Operator awareness is mainly provided by RViz, a ROS package used for visualization. RViz presents a virtual environment to the user, rendering 2D maps, physical objects such as robots, vision data from the robot, and overlays of other sensor data. Developers can expand RViz' functionality by writing plugin classes. One such plugin is a point-and-click tool for defining survey patterns. The user can construct the survey region using a map tool or by selecting a previously saved one. A survey region can be built from a combination of individual survey points and rectangular areas. The map tool can set the number of points in the survey and the spacing between them, and specify the statistical certainty demanded for the data.

Fig 4. Pop-up in survey generation system used by operator to define grid size and resolution.

The survey construction tool is shown in Figure 4. The operation is simple; first the user places the origin of a rectangular grid of points by click-dragging an arrow. The size and resolution of this grid is given by the user, and the grid can be reduced to one just point. Multiple such grids or points can be combined in a survey plan. Points can be adjusted by click-dragging, and individual points can be deleted from a grid. With this method, the operator can efficiently build a survey plan with arbitrary geometry. As stated in Section 3, obstructed areas of the survey plan will be automatically excluded by the system during operation.

During and after the survey, radiation readings are displayed in the virtual environment as 3D dots. The dots are color coded to the intensity of the reading, and the user and view details such as timestamp and intensity by clicking on the dot (Figure 6 or Figure 8).

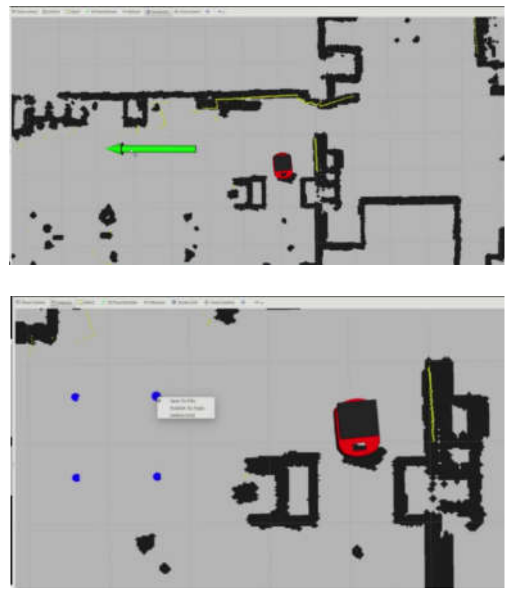

Fig 5. Survey Grid Tool. The user places the grid origin with an arrow (top). After adjustments, send the survey plan to the robot or save to file (bottom). Once the grid is place, it can easily be selected and then translated or rotated in the mapped space before the user saves the proposed survey.

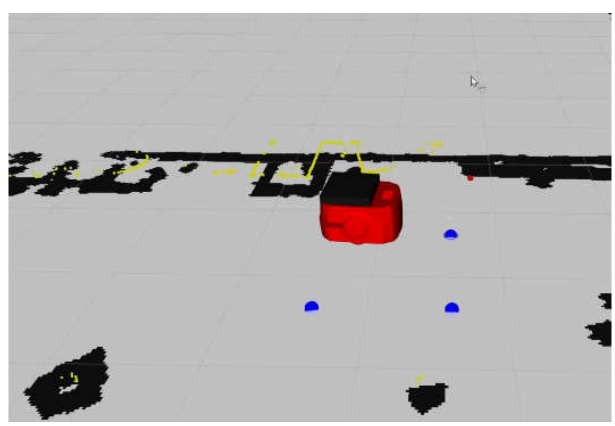

Fig 6. The RViz-based GUI allows the user to rotate the real-time updates from the system to any desired 3D perspective. Note also that the real-time obstacle data (yellow) is layered on the original map (black)

5 Statistical Considerations

The number of decays that a radioactive sample will undergo in a given time is a random variable, since, each atom in the sample has a 50% chance of decay per half-life. Since the decay events are independent of each other, the process conforms to the Poisson distribution:

$$P(x;\lambda)=\frac{\lambda^{x}e^{-\lambda}}{x!} \qquad (5.1)$$

where x is the number of decays. Since the standard deviation of the count is $\sigma=\sqrt{x}$, the relative uncertainty is $\sqrt{x}/x=1/\sqrt{x}$. Therefore, the relative uncertainty improves with increasing x. Since in a radiation survey the total count is (on average) proportional to the count time, it is necessary to collect each set of data until the specified data certainty is achieved.

The survey system continuously updates the lower and upper 95% confidence bounds as counts are collected. For each survey point, it will continue counting until the certainty given by the task specification is achieved. This real-time computational capability is one of the major advantages over human workers.

However, the necessary counting time grows disproportionately longer for tighter certainty requirements. It is necessary to consider this effect since survey time is not unlimited. Particularly in survey regions where the total count rate is low, tight certainty requirements may not be practical. The system addresses this problem in two ways. The user can set an optional limit on the count time per waypoint. The system will move on to the next waypoint when that time has elapsed, regardless of the achieved certainty. Additionally, if the region has been surveyed before then the previous data can be used to produce an estimate of the survey time for a given certainty. This allows the operator to manually tune the requirement.

6 Mobile Platform

The platform used for this task is based on an Adept Pioneer LX mobile robot as show in Figure 1. Built-in features include navigation sensors and software along with remote access and ready payload attachment. The 60-kg payload is sufficient for most radiation detection hardware. The autonomous platform for this work was developed from the base by adding hardware and software components to the original. A third-party elevation system called the ZipperMast enables payloads up to 5kg be raised to commanded heights up to 8 feet above the ground, which allows radiation data to be captured at various (and repeatable heights). Thus this system is capable of completing 3D, spatial surveys. This capability is not possible using human operators due to time, repeatability, and ergonomic considerations.

Fig 7. ZipperMast[24] has been integrated into the mobile survey system at UT (as seen in Figure 1) and allows for sensors to easily deployed at a desired or multiple heights.

The Pioneer base is provided with a charging station along with a manufacturer API for docking and undocking. The autonomous behavior developed by NRG includes charging when the battery runs low during the survey.

Software was developed using the open source Robot Operating System (ROS) framework. The modular, node based code architecture of ROS enables the hardware integration on the survey platform. A detailed description of the supervisory controller can be found in [1] and [2].

7 Demonstration & Evaluation

The system capabilities were developed and first evaluated using a simple 2x2 grid with 1 meter spacing. The small grid allows for complete survey procedures to be quickly completed in a timely fashion for debugging and user feedback. For feedback, developers relied on more experienced students who had interacted with radiation technicians at LANL. The map and survey are seen in Figures 4 and 5. Some key observations were made from this effort.

A noisy map may be intimidating to non-expert users. It may be necessary in the longer-term to integrate clean static maps that are autonomously aligned with the data collected by the robot. This should be technically feasible given the well-modeled spaces that are typically surveyed. This problem was also mitigated when testing happened in larger spaces and/or sparse spaces likely related to ratio of the signal noise and size of the area to be survey as can be seen in Figure 9.

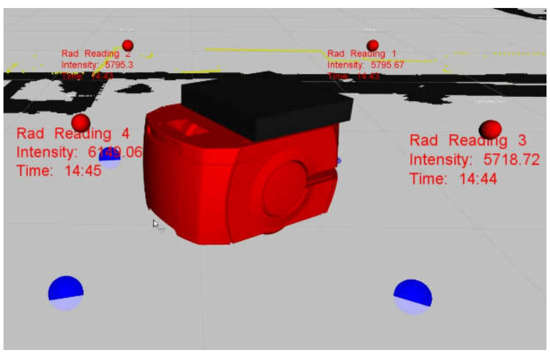

Fig 8. Displayed radiation data just visualize prior to archiving step.

While the key elements for generating a survey plan can be made generally clear to the non-robotic end-user, there are still many generation parameters that are specific to robotics (path planning, obstacle models, etc.) that cannot be exposed to the operator, but are still too often necessary for the 'operator' to 'tweak.'

Once developed, the system was demonstrated using real radiation sources in a laboratory environment. A survey plan of 50 points with spacing between 0.75m and 1.5m was created covering an area of approximately 45 square meters. The area contained general laboratory obstacles including tables, chairs, and large equipment. The radiation sources were Cs-137 of 10 µCi (370 kBq). The system was instructed to achieve count data of 5% uncertainty (95% confidence).

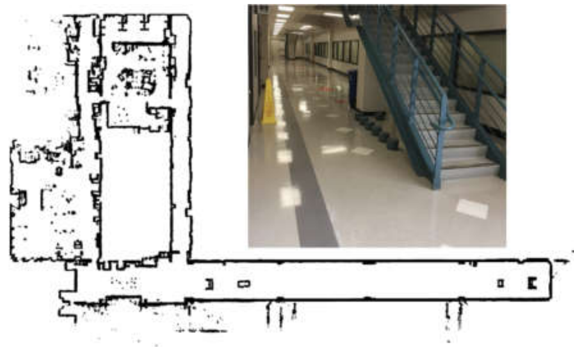

Fig 9. Lab and hallway space at UT mapped by survey system.

Of the 50 points of the survey plan, the system was able to reach 35, the remainder being obstructed by the environment. The reachability count was similar to what a human operator would have achieved. The survey was completed in 40 minutes. Most of this time was spent navigating between points. Data collection was typically less than 10 seconds per point. We estimate that a technician performing an equivalent survey in a DOE storage vault for SNM would receive about 10-20% of their annual allowable dose. Furthermore, the autonomous system can more accurately record location and count data. The map produced by the robot is shown in Figure 10.

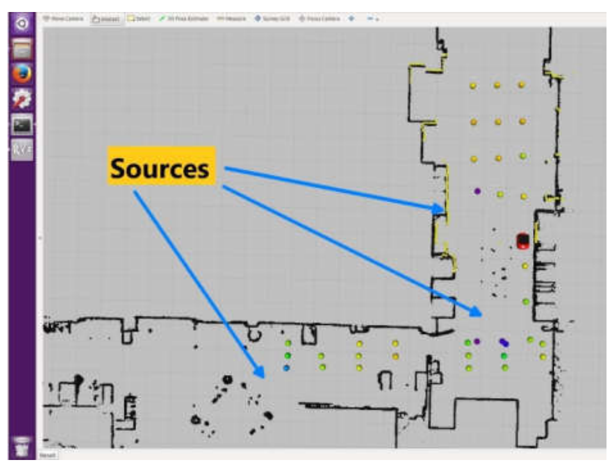

Figure 10. Map produced by the robot. Dots are color coded by radiation intensity. Violet is the strongest readings with higher wavelength colors for lower readings.

8 Conclusions & Future Work

Future work will involve testing with the $LaBr_3$ detector in operational nuclear facilities at UT Austin. Additional cold space survey demonstrations will be performed using regulatory allowable Cs-137 gamma sources. The survey environments will be varied to challenge the navigation capabilities of the platform. $LaBr_3$ detectors also allow for directional and isotopic identification capabilities. The GUI needs to be extended to allow for radiation readings at varied elevations using the ZipperMast system so that surveys can be extended into 3D space.

Now that a GUI has been developed, our ability to effectively communicate our user requirements is bolstered and has allowed us to better explain our user-interface requirements to experts in developing user interfaces that have no expertise in either the nuclear or robotic domains. This has allowed us to begin development on a second generation user interface grounded in the comprehensive theory and established design principles related to user interface designs and human computer interactions. In particular, this work revealed challenges with building intuitive radiation-maps. Further work will consider other color-coding techniques, such as logarithmic scaling and/or comparable vs. unit of the intensity. It will also investigate the proper use of 3D vs 2D representations.

Additionally, the NRG is actively pursuing improved coverage path planning algorithms, which will be integrated when completed. The algorithms have address issues related to localization verification, robust coverage analysis, addressing low-dynamic obstacle (i.e. a trash bin that occasionally changes locations), and autonomous path generation and/or optimization.

References

[1] Anderson, B., Pitsch, M., Wanna, S., Park, D., Landsberger, S., and Pryor, M., "Autonomous inventory in nuclear environment using a remote platform," ANS Decommissioning and Remote Systems Topical, Pittsburgh, PA, August, 2016.

[2] Anderson, B., Sharp, A., and Pryor, M., "Low-cost mobile platform and sensor suite for remote radiation surveying," *Proceedings of the ANS Embedded Topical on Decommissioning and Remote Systems*, Reno, NV, June, 2014

[3] Pitsch, M., and Pryor, M., "Temporally static environment coverage with offline planning techniques," *IEEE Workshop on Advanced Robotics and its Social Impacts*, Austin, TX, 2017.

[4] Lovering, Daniel. "Radioactive Robot: The Machines That Cleaned Up Three Mile Island." 27 March 2009. 15 November 2015. <http://www.scientificamerican.com/article/three-mile-island-robots/>.

[5] Hajime workshop presentation

[6] K. Nagatani *et al.*, "Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots," *J. Field Robotics*, vol. 30, no. 1, pp. 44–63, Jan. 2013.

[7] Clyde R. Ward, W. Ivan Lewis, Robert F. Fogle, Paul S. Hebert, Phillip J. French, and Frank M. Heckendorn. "Robotics Applications at the Savannah River Site." *50th Anniversary Symposium of the SRS*. 2000.

[8] Bruemmer, D. J., et al. "Intelligent Robots for Use in Hazardous DOE Environments." *Performance Metrics for Intelligent Systems (PERMIS)*. Gaithersburg, MD: NIST, August 2002.

[9] M. O. Anderson, C. C. Conner, V. E. Daniel, M. D. McKay, N. A. Yancey. *Demonstration of the Robotic Gamma Locating and Isotopic Identification Device*. Idaho Falls, ID: INEEL, 2002.

[10] Minichan, Richard L., Robert F. Fogle and Athneal D. Marzolf. "H-Canyon Air Exhaust Tunnel Inspection Vehicle Development." *ANS EPRRSD - 13th Robotics & remote Systems for Hazardous Environments, 11th Emergency Preparedness & Response*. Knoxville, 2011.

[11] Sahi, Manoj. "Sensabot Is the First Inspection Robot Approved for Use by Oil and Gas Companies." 16 October 2016. 14 1 2017. <https://www.tractica.com/robotics/sensabot-is-the-first-inspection-robot-approved-for-use-by-oil-and-gas-companies/>.

[12] LP, Iris Power. "Robotic Inspection Vehicle (RIV)." November 2013. 16 January 2017.

[13] Solutions, Areva - NDE. "Multi-Functional Underwater Inspection System." July 2013. 3 April 2017.

[14] Thierry Pasquir, Philippe Degrave, and William Delpouve. "The JASPER System, an Innovating, Competitive Tool for Rod Cluster Control Assembly (RCCA) In-Service Inspection ." *European Conference on Non-Destructive*

Testing. Berlin, 2006.
[15] Areva NDE-Solutions. "Steam Generator Inspection and Repair." July 2013. 3 April 2017.
[16] Szondy, David. *GE atomic swimmer robot keeps tabs on nuclear reactors*. 3 August 2015. New Atlas. 4 April 2017.
[17] Duke Energy. *Nuclear embraces robotic technology*. 1 April 2014. Duke Energy. 4 April 2017.
[18] Cortez et al, "Experimental Implementation of Robotic Sequential Nuclear Search." *IEEE Mediterranean Conference on Control and Automation* (2007): 1-6.
[19] Cortez et al, "Smart Radiation Sensor Management; Nuclear Search and Mapping using Mobile Robots." *IEEE Robotics & Automation Magazine* (2008): Vol 15, Issue 3, pp. 85-93.
[20] Cortez, R.A., H.G Tanner and R Lumia. "Distributed Robotic Radiation Mapping." *Springer Tracts in Advanced Robotics* 54 (2008): 147-156.
[21] W. Smart, M. Quigley, and B. Gerky, *Programming Robots with ROS*. O'Reily Media, 2015.
[22] Charles M. Vaughn, Ronald J. Unz, Donna M. Rogers, Jay P. McCown, Charles Jones, Charles A. Waggoner. "A Sodium Iodide and Lanthanum Bromide Detector Equipped Gamma Survey System for Enhancing Discrimination between Contamination and Naturally Occurring Radiological Material." *Waste Management Conference*. Phoenix, AZ, 2011.
[23] McDougall, Robin. *Robotic Radiation Mapping Using Modelling and Probabilistic Analysis of Sparse Data*. Oshawa: University of Ontario Institute of Technology, 2015.
[24] https://zippermast.com/