Contract No:

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Disclaimer:

Gamma-Ray Raster Imaging with Robotic Data Collection

Currently, in order to create gamma-ray images, some form of collimation is required. The foremost imaging techniques either require physical collimation (such as the heavy shielding required for a pinhole imager) or restrictive algorithms (such as event reconstruction for a Compton imager). In addition, physically collimated approaches (pinhole or coded aperture) result in a limited field of view.

This project has developed an alternative imaging capability for characterizing and imaging radioactive materials in situ. This approach uses a robotic-mounted gamma-ray detector which can move around an area of interest, sampling the space at an extremely high frequency. By rastering across the gamma-ray field, an image can be created with no physical collimation and a high efficiency. A regression model was developed to map out material distribution as the robot moves through the environment. An informative path planning algorithm was also developed to maximize the information collected throughout the movement path.

The system has been tested using small lab sources, as shown in the figure at right.

The use of a robotic mount allows data collection for long periods of time unattended, and it will also eliminate uncertainties in positioning typically introduced by personnel. This approach will be particularly relevant for gloveboxes, shielded cells, or process piping which may have complex, non-uniform distributions of material.

Intellectual Property Review

This report has been reviewed by SRNL Legal Counsel for intellectual property considerations and is approved to be publically published in its current form.

SRNL Legal Signature

Signature	**Date**

LDRD-2018-00082
LDRD Report

Gamma-Ray Raster Imaging with Robotic Data Collection

FY18 Annual Report

SRNL-STI-2018-00554

Project Team:
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Thrust Area:
Environmental Stewardship

Project Start Date: October 1, 2017
Project End Date: September 30, 2019

This project has developed an alternative imaging capability for measruing radioactive materials in situ. This approach uses a robotic-mounted gamma-ray detector which can move around an area of interest, sampling the space at a high frequency. By rastering across the area, an image can be created with no collimation and a high efficiency. A regression model was developed to map out material distribution as the robot moves through the environment. An informative path planning algorithm was also developed to maximize the information collected throughout the movement path. The use of a robotic mount allows data collection for long periods of time unattended, and it will also eliminate uncertainties in positioning typically introduced by personnel. This approach will be particularly relevant for gloveboxes, shielded cells, or process piping which may have complex, non-uniform distributions of material.

FY2018 Objectives

- Assemble data acquisition: This task involves purchasing components, mounting detector and other hardware onto the robotic system, and integrating the detector data acquisition system with control of the robotic platform.
- Test data acquisition: Next, develop and test the system's ability to move and acquire assays in a repeatable manner.
- Calibrate and demonstrate: Known radioactive sources will be measured in order to calibrate the system and develop algorithms for localization and quantification.
- Evaluate performance: Finally, evaluate the system's performance in a number of test configurations, including a real-world scenario if available.

Introduction

Gamma-ray assays and images are a key tool for holdup characterization in a facility. Images can be used to create radiation maps, which can be used for establishing procedures, assist decontamination and aid radiological control. This project uses a small gamma-ray detector on a robotic platform to sample an area at high frequency in order to create an imaging. This approach is:

- Lightweight: requiring little to no lead shielding
- Autonomous: requiring minimal operator time and input
- Precise: relying on camera, LIDAR, and software to map out the space

In addition, this work integrates state-of-the-art robotics developments to improve the acquisition of gamma-ray data. Informative Path Planning (IPP) is used to design a path for a robotic sensor platform to gather the most information about the radiation distribution while operating under the set of constraints given by the dynamics of the robot and other requirements such as minimizing the overall mission time.

The key challenge for IPP is the tight coupling in multiple layers of decisions:

- Selects the locations where a robot should take samples
- Produces paths for the robot to use when travelling from one location to the next
- Generates a radiation map using a Gaussian process regression (GPR) framework

Given a robot equipped with a basic gamma detector and LIDAR sensor, how can we efficiently explore an unknown environment in such a way that we can satisfy the robot's constraints while simultaneously maximizing the accuracy of the map and minimizing the total runtime?

There are existing approaches which use directional sensors [2] to gain further information about where a radiation source might be. In this work, an omnidirectional gamma sensor is utilized, meaning that the origination of the radiation when measuring at a location is not known. This greatly lowers the cost of the equipment needed but increases the complexity of localization. The use of Gaussian process regression (GPR) and an associated utility function has been proposed by several authors [3, 4]; however, the added difficulties of navigation in an unknown environment and the rapid drop-off of the radiation signal provide additional challenges.

Approach

A gamma-ray detection system, in this case a cadmium zinc telluride (CZT) semiconductor detector from Kromek, is mounted to a remote-controlled platform). The CZT provides excellent energy resolution in an extremely small package, keeping the payload light. The detector is controlled by an Intel Joule single-board computer, which in turn talks wirelessly to a laptop. Experiments were also carried out on a Turtlebot Waffle, which comes equipped with a laser detection system (LDS) and a light detection and ranging (LIDAR) system (shown in Figure 1). Gamma-ray spectra are saved along LIDAR scans and positioning information.

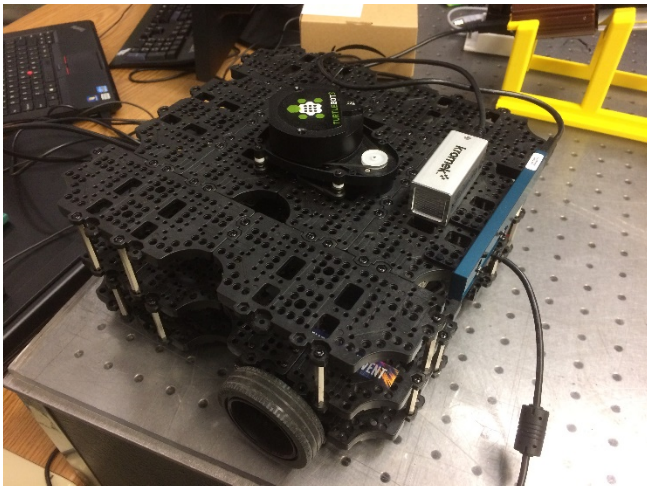

Figure 1: The Turtlebot Waffle robot, with important components and sensors

Regression algorithms were analyzed using various weighting schemes which leverage exploitation (gathering more information on known locations) versus exploration (gathering information on unknown locations). Quantitative evaluations often favored exploitation-heavy weighting schemes, whereas qualitative comparisons would favor exploration-biased schemes. Given a set of possible sampling locations, the next sampling location can be iteratively selected by maximizing the appropriate utility function.

Results/Discussion

A number of weighting schemes were tested and scored against the root mean square error (RMSE) both locally (for the region immediately surrounding a point source) and globally. With an exploration weight of 1.5, a good balance is found as the environment is explored, leading to low overall uncertainty and a later focus on exploring the local maxima. Interestingly, the weighting scheme of evenly balanced exploitation, exploration, and distance travelled gives the most rapid minimization of RMSE.

Experiments were then conducted with the robotic system. Data was gathered by the robot following a random trajectory (shown in in Figure 2), which was then used as a ground-truth to both reconstruct the radiation distribution and provide a simulated environment for a virtual robot. The reconstructed distribution (shown in Figure 3) closely aligned with the truth, where the peak of the reconstruction aligned with the actual position of the point source.

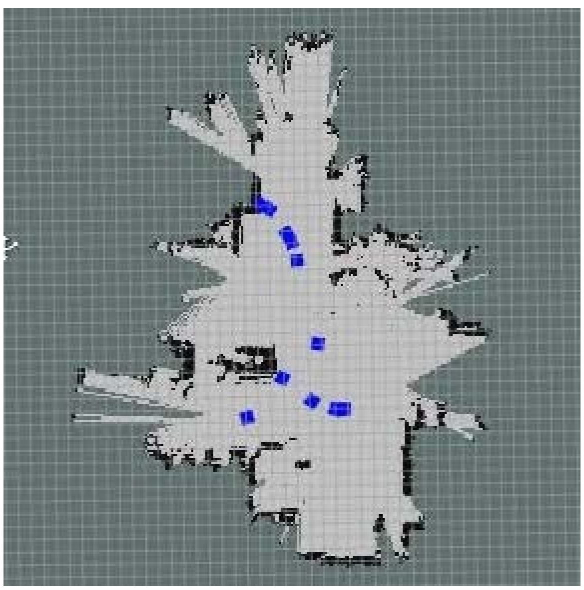

Figure 2: LIDAR scan of the room (black points) and spectrum acquisition locations (blue points).

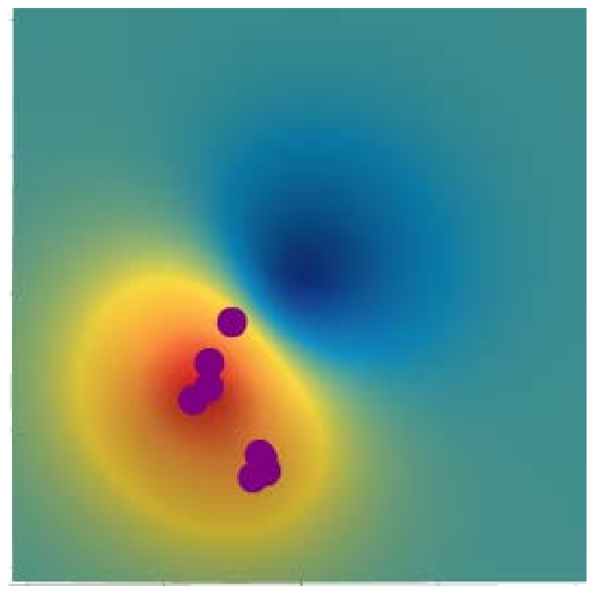

Figure 3: Reconstructed radiation distribution after seven spectra. Purple points correspond to locations where samples were taken. Red areas indicate higher expected radiation, and blue indicates a lower expectation.

Results for the path planning algorithm were tested in software models, using the ground-truth data collected by the system. The robot was able to localize the point sources with few samples, while further samples were used to provide further detail to the overall map. In the future, the robot's LIDAR could be used to perform simultaneous localization and mapping (SLAM) in conjunction with the radiation mapping, and to finalize integrating online IPP with the robot platform.

FY2018 Accomplishments

- Assembled TurtleBot, including camera, LIDAR, and CZT detector
- Developed software interface for operating robot in conjunction with CZT detector
- Demonstrated ability to take CZT data in conjunction with contextual data
- Developed and tested GPR algorithms for reconstructing gamma ray source distributions
- Developed IPP algorithms for optimizing robot travel path

Future Directions

- Implement SLAM in real time while robotic platform is travelling, to combine with reconstructed gamma-ray image.
- Integrate IPP algorithms onto the platform, including real-time communication with the robotic operating system (ROS)
- Take data in facilities, in order to test algorithms on complex, real-world distributions.

FY 2018 Publications/Presentations

Presentations:

S. Zanlongo, Y. Tan, T. Aucott, "Informative Path Planning for Mapping Radiation," ANS Winter 2018 Meeting, Scheduled November 2018.

Partnerships: Florida International University

Publications:

L. Ocampo Giraldo, A. E. Bolotnikov, G. S. Camarda, S. Cheng, G. De Geronimo, A. McGilloway, J. Fried, D. Hodges, A. Hossain, K. Ünlü, M. Petryk, V. Vidal, E. Vernon, G. Yang, and R. B. James, "Arrays of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors: Results from a 4x4 array prototype", IEEE Trans. on Nucl. Science 64, No. 10, 2698-2705 (2017). Digital Object Identifier: 10.1109/TNS.2017.2743160. Published November 2017.

Partnerships: Brookhaven National Lab, University of Texas, North Carolina State University

Alexander Moiseeva, Alexey Bolotnikov, Gian Luigi DeGeronimo, Elizabeth Hays, Ralph James, David Thompson, and Emerson Vernon, "High-energy 3D calorimeter for use in gamma-ray imaging based on position-sensitive virtual Frisch-grid CdZnTe detectors", Journal of Instrumentation, accepted December 2017.

Partnerships: NASA GSFC, University of Maryland, Brookhaven National Lab

L. Ocampo Giraldo, A.E. Bolotnikov, G.S. Camarda, G. De Geronimo, J. Fried, R. Gul, D. Hodges, A. Hossain, K. Ünlü, E. Vernon, G. Yang, R.B. James, "Study of sub-pixel position resolution with time-correlated transient signals in 3D pixelated CdZnTe detectors with varying pixel sizes", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 884, 11 March 2018, Pages 136-139, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2017.12.024.

Partnerships: Pennsylvania State University, Brookhaven National Lab, University of Texas

A. E. Bolotnikov, G. S. Camarda, G. De Geronimo, J. Fried, D. Hodges, A. Hossain, K. Kim, G. Mahler, L. Ocampo Giraldo, E. Vernon, G. Yang, R. B. James, "A 4x4 array module of position-sensitive virtual Frisch-grid CdZnTe detectors for gamma-ray imaging spectrometers", Nuclear Instruments and Methods in Physics Research A, accepted, August 2018.

Partnerships: Brookhaven National Lab, University of Texas, Korea University, North Carolina State University

L. Ocampo Giraldo, A. E. Bolotnikov, G. S. Camarda, G. De Geronimo, J. Fried, D. Hodges, A. Hossain, K. Ünlü, E. Vernon, and R. B. James, "Using A Linear Array of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors for Uranium Enrichment Measurements", Nuclear Instruments and Methods in Physics Research A, submitted April 2018.

Partnerships: Pennsylvania State University, Brookhaven National Lab, University of Texas

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[2] M. Lee, M. Hanczor, J. Chu, Z. He, N. Michael, R. Whittaker, "3-D Volumetric Gamma-ray Imaging and Source Localization with a Mobile Robot," Waste Management Symposia 2018.

[3] R. Marchant and F. Ramos, "Bayesian Optimisation for informative continuous path planning," Proc. - IEEE Int. Conf. Robot. Autom., pp. 6136–6143, 2014.

[4] G. Hitz, A. Gotovos, F. Pomerleau, M. É. Garneau, C. Pradalier, A. Krause, and R. Y. Siegwart, "Fully autonomous focused exploration for robotic environmental monitoring," Proc. - IEEE Int. Conf. Robot. Autom., pp. 2658–2664, 2014.

Acronyms

CZT	Cadmium Zinc Telluride
IPP	Informative Path Planning
GPR	Gaussian Process Regression
LDS	Laser Detection System
LIDAR	LIght Detection And Ranging
RMSE	Root Mean Square Error
SLAM	Simultaneous Localization And Mapping

Intellectual Property

None to report

Total Number of Post-Doctoral Researchers

This project employed one post-doctoral intern (Sebastian Zanlongo) and one graduate student intern (Aimee Gonzalez) through the MSIPP program.