Contract No:

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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.

The detector was calibrated in three dimensions as a function of energy, distance, and angle. A Bayesian particle filter was implemented to localize and quantify a radioactive source in a search arena. An informative path planning algorithm was also developed to guide the robot's search path to obtain more accurate information on the source.

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 publicly published in its current form.

SRNL Legal Signature

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Signature **Date**

LDRD-2018-00082
LDRD Report

Gamma-Ray Raster Imaging with Robotic Data Collection

FY19 Annual Report

SRNL-STI-2019-00614

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 imaging and quantifying 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.

An open-source robotic platform was programed to search an open area, collecting gamma-ray spectra every second. Informative path planning was used to direct the robot to areas of higher dose. Finally, a Bayesian particle filter was used to locate the source with minimal counting statistics.

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.

FY2019 Objectives

- Implement simultaneous localization and mapping (SLAM) in real time while robotic platform is travelling
- Calibrate detector response in 3D
- Develop Bayesian particle filter analysis
- Integrate informative path planning algorithms onto the platform, including real-time communication with the robotic operating system (ROS)
- Evaluate the system’s performance in a number of test configurations.

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.

Ideally, such a system would couple multiple layers of decisions:

- Select the locations where a robot should take samples
- Produce paths for the robot to use when travelling from one location to the next
- Generates a radiation map using some reconstruction algorithm

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 [1, 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]. This project also explored the use of a Bayesian particle filter [5, 6] to localize and quantify the source. Informative path planning algorithms were developed [7] to direct the sampling locations closer to areas of higher dose.

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.

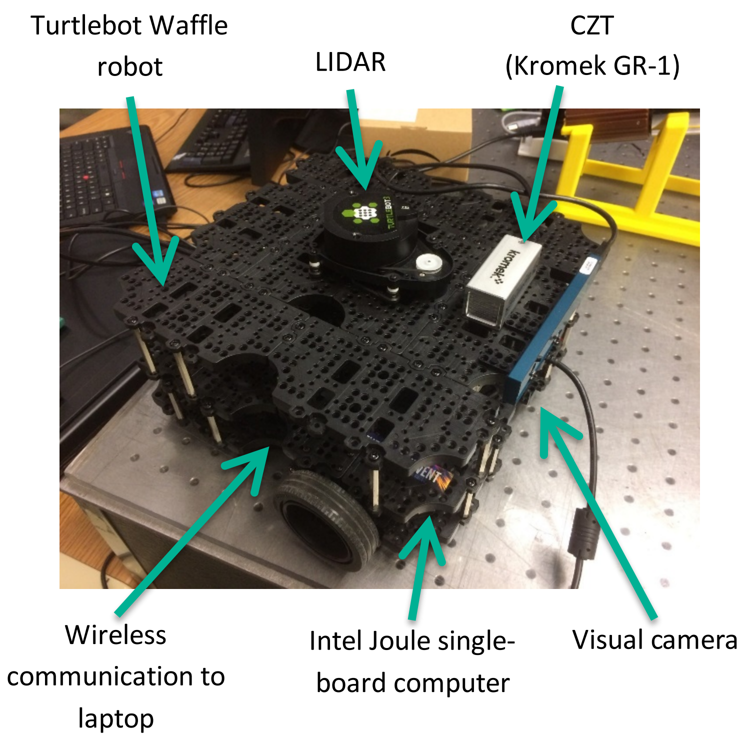

Figure 1: The Turtlebot Waffle robot, with important components and sensors

The detector was calibrated in three dimensions as a function of energy, distance, and angle using a Ho-166m calibration source. This calibration was used as the input to a Bayesian particle filter. A particle filter is a form of maximum likelihood estimation (MLE) which utilizes a large, finite number of hypotheses to approximate an unknown source distribution.

Results/Discussion

The robot was tested with a Cs-137 10 µCi source, placed in a large paint can-sized container for improved response from the robot's LIDAR to help prevent collision. The can was placed at a location of (1.58 m, -1.1 m) relative to the starting point of the robot, which is treated as the origin (0 m, 0 m). The robot's navigation consisted of near-random waypoints to traverse, in which locations which had experienced higher detector count responses were more favored than location which received fewer counts. A few main points about the test should be noted:

- The robot covered only half of the total quartered-off area in which it could survey
- The robot, for most of the test, never moved behind the source (i.e. it was always to one side of the source during the test; a full 360-degree coverage was not obtained, only 180 degrees)
- The source was located at the center of the test area

The collection of all data stored from the robot's various sensors and other programs was stored in a .bag file, commonly used to record robot sensor data in ROS. These ROS .bag files were converted into .csv files for easy manipulation. Position, orientation, and radiation count data were pulled from the .csv files and processed as such: position data on the millisecond level was averaged to generate an average position per second, angle of orientation was converted from standard quaternion to angle (in degrees), and radiation counts were arranged into a set of spectra with 4096 channels.

The algorithm ran for a total of 140 times on a data set of the Cs-137 10 µCi source test, each time with a different distribution of particles and positions selected randomly within the test area. The predicted x and y-coordinates and predicted activity, A, of each test was recorded. Because of the low efficiency of the CZT detector, the entire gamma-ray spectrum (not just the unscattered photopeak) was used for the analysis. As a result, although activity is predicted, it is dominated by down-scatter in the environment and did not accurately determine the source activity. The distribution of particles with position and activity (in color) is shown in Figure 2.

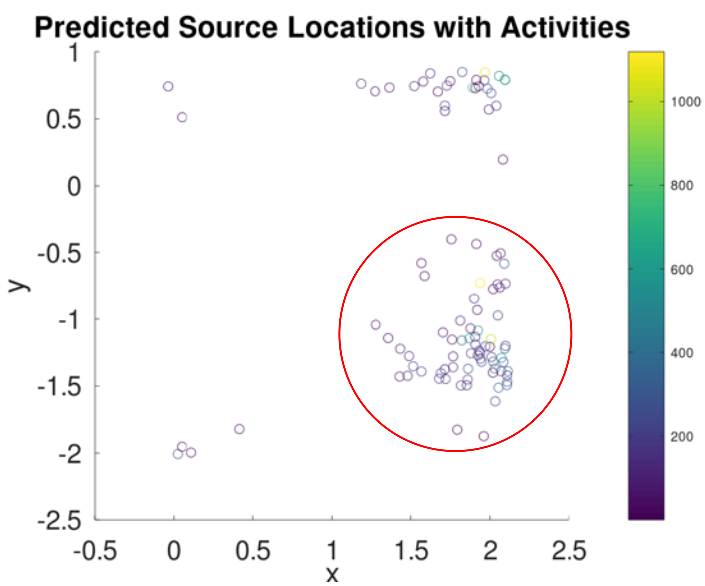

Figure 2: Distribution of most likely predicted source locations from 140 runs of particle filter algorithm.

The mean (µ ± 1σ) of the x and y-coordinates are: 1.76 ± 0.437 meters and -0.809 ± 0.851 meters.

Focusing on the highlighted cluster localized around (2 m, -1 m), the mean x and y positions, respectively, are: 1.86 ± 0.210 meters and -1.19 ± 0.296 meters

FY2019 Accomplishments

- Robotic platform was successfully programmed to integrate the CZT data acquisition into the robotic operating system.
- Bayesian particle filter was successfully used to localize sources in an environment. This algorithm succeeded with minimal counting statistics only a partial coverage of the search area.
- Informative path planning algorithm was successfully implemented, allowing for feedback between the CZT count rate and the robot's search path.

Future Directions

- Design system for use in real facilities: Some obstacles included the use of wireless communications, as well as limited battery life. These logistical concerns would need to be addressed prior to deployment, especially given the advantage of long survey times.
- Increased count times could compensate for the low efficiency of the CZT detector. Alternatively, a larger detector or multiple small detectors could be added to increase the efficiency. This would allow the system to accurately quantify activities by measuring a calibrated photopeak.

FY 2019 Publications/Presentations

Presentations:

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

Partnerships: Florida International University

B. Quiter, R. Pavlovsky, J. Cates, T. Aucott, IEEE Nuclear Science Symposium, Scheduled November 2018.

Partnerships: Lawrence Berkeley National Laboratory

Internal Publications:

SRNL-L4540-2019-00002, "Gamma Ray Raster Imaging," September 2019.

SRNL-L4120-2019-00028, "Bayesian Particle Filter for Robotic Gamma-Ray System," August 2019.

External Publications:

W. Wells, T. Aucott, "Gamma Ray Raster Imaging," Nuclear News, December 2019.

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[2] M. Lee, M. Hanczor, J. Chu, Z. He, N. Michael, and 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.

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[6] J. Towler, B. Krawiec, and K. Kochersberger, "Terrain and Radiation Mapping in Post-Disaster Environments Using an Autonomous Helicopter," Remote Sensing, vol. 4, p. 1995-2015.

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Acronyms

CZT	Cadmium Zinc Telluride
GPR	Gaussian Process Regression
IPP	Informative Path Planning
LDS	Laser Detection System
LIDAR	LIght Detection And Ranging
MLE	Maximum Likelihood Estimation
RMSE	Root Mean Square Error
ROS	Robotic Operating System
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, who performed work on site

Total Number of Student Researchers

This project employed two student interns, Aimee Gonzales and Mustafa Siddiqi, who performed work on site