Autonomous 3D and Radiation Mapping in Tunnel Environments Using Aerial Robots - 18156

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ABSTRACT

In this paper we present the algorithms and systems developed to enable autonomous 3D and radiation mapping, as well as radiological source localization in tunnel environments using aerial robots. The developed technologies aim to address the need of autonomous robotic inspection of nuclear sites such as facilities in the process of being decommissioned. As a motivational example, the PUREX tunnels at the Hanford Site are considered and the robot is designed to be able to conduct multi-modal 3D/radiation characterization of the tunnel environment without any prior knowledge or map provided beforehand. In order to enable the necessary GPS-denied simultaneous localization and mapping in dark, visually-degraded tunnel environments, a multi-modal mapping unit was developed which fuses the data from stereo vision cameras synchronized with flashing LEDs, inertial sensors, and three time-of-flight 3D depth sensors. The robot's pose and surrounding map are estimated at 20Hz through a depth-enhanced visual-inertial localization and mapping framework. Provided this ability to estimate the robot's pose and develop a dense map in real-time, a receding horizon sampling-based autonomous exploration path planning algorithm was utilized and equips the robot with the ability to explore its environment given no prior map.

The aforementioned key robotic functionalities are further extended through the integration of miniaturized fully solid-state scintillation detectors, utilizing advanced scintillators and Silicon Photomultipliers. The derived sensor data is employed for radiation mapping, which when fused with the 3D maps and the spectroscopic source localization methods, allow the aerial robotic platform to localize the radiation source and identify the specific source isotope. The source location is estimated through a geometric algorithm which can localize a source given only three measurements and short dwell times.

The developed systems were tested using two small aerial robot platforms of the F450 and F550 frame classes with weights of 2.6kg and 2.9kg respectively. All localization and planning as well as high-level control algorithms are executed onboard. The scintillation detector is integrated on the robot and its data is collected through a dedicated microcontroller. A set of field experiments were conducted inside the dark and GPS-denied environment of a 4.25m wide, 7.5m tall, and 137m long railroad tunnel. A Cs-137 source was placed within the tunnel, the associated 3D/radiation maps were derived, and the source location was estimated. Through these efforts, the goal is to develop the robotic technology that would enable the autonomous systematic inspection or emergency response in nuclear waste decommissioning facilities.

INTRODUCTION

Autonomous robots are ideal tools for exploring and characterizing environments which require personnel to perform dirty, dangerous, and dull tasks [1-6]. They are especially valuable in environments which are potentially hazardous to human health. Autonomous aerial robots in particular, equipped with GPS-denied localization and radiation detection capabilities correspond to excellent tools for remote access, monitoring and inspection. Aerial robotic characterization enables low-cost, low-risk, and highlyrepeatable missions which suit the inspection, monitoring, and exploration tasks consistent with activities such as nuclear facility decommissioning, nuclear disasters, as well as the tracking of illicit radioactive sources. Examples of such environments include the nuclear waste storage system left behind by the Manhattan Project and active nuclear power stations with on-site spent fuel depositories.

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Such environments require aerial robotic platforms which are not only robust and safe to operate, but are also capable of autonomously exploring their environments regardless of visual conditions and without prior information. In security scenarios, locating an illicit or "lost" source using an aerial robot would minimize the exposure of workers, as the robot could provide a search team with a highly accurate estimate of the source's position as well as intensity. In decommissioning scenarios, such as the PUREX tunnels, an aerial robot would reduce risk to workers not only from a radiation exposure perspective, but also from the inherent risks associated with working in aging facilities which may be prone to collapse and structural failure. Finally, in disaster response scenarios, such a robotic system could perform the initial radiation field mapping as well as guiding emergency responders and evacuees around the highly contaminated areas. For all of these scenarios, algorithms and procedures which allow inspection and monitoring must be designed to operate within the constraints of a robotic system operating in the real world. These constraints include highly contaminated environments, and visually degraded conditions.



Figure 1 - On the left is a photograph taken during an autonomous radiation source localization experiment. The derived radiation map is shown alongside the Radiation Counting and Spectroscopy System. On the top right, a photograph of the tunnel used in the experimental studies is shown. Finally, on the bottom right is a photograph of the robot taken during an exploration mission in dark, visuallydegraded conditions.

This paper details both the system and the methods required to explore and characterize unknown environments which contain a radioactive source from an aerial robotic platform. Throughout its mission, the robot produces a 3D occupancy map of the environment [7], collects radiation data as it navigates and localizes the source of the radiation in the environment. Exploiting the obtained occupancy map, the source localization algorithm constrains its solution space to the occupied areas of the environment. Most importantly, the source localization algorithm was designed to provide reliable and accurate results even when provided with only few measurements taken subject to the endurance limitations of the aerial platform. The system is able to navigate in challenging, visually degraded environments using a visualinertial-depth localization system named the Multi-Modal Mapping Unit (M3U), and is able to collect radiation data using a purpose-built scintillator spectroscopy system named the Radiation Counting and Spectroscopy System (RCSS). In the rest of this paper, the design of the M3U and the RCSS are detailed, alongside the source localization and isotope identification algorithms developed to enable 3D mapping and radiation source localization from an aerial robot. In addition, a number of experiments conducted to evaluate the performance of the M3U, the RCSS, and the associated algorithms are presented. An actual Cs-137 radiation source was utilized and deployed inside a tunnel for the purposes of our experiments. Figure 1 presents such an experiment.

DESCRIPTION

System Overview

To accomplish radiation detection and source localization, 3D mapping and autonomous navigation, an aerial robotic platform was developed. The robot maps and navigates using a multi-modal mapping unit (M3U), consisting of a stereo camera pair coupled with a high-performance inertial measurement unit (IMU), synchronized flashing LEDs to illuminate the environment, and Time-of-Flight (ToF) depth sensors for dense environmental reconstruction. A Radiation Counting and Spectroscopy System (RCSS) was developed to enable radiation detection and source localization on-board the aerial robot. The RCSS was required to be lightweight and power-efficient, while capable of producing spectroscopy information as well as counting statistics. The main processing of the image, depth, IMU, and radiation data takes place on the robot's Main Processing Unit (MPU). In this case, the MPU is an Intel NUC5i7RYH running Linux with the support of the Robot Operating System (ROS), while a Pixhawk autopilot is used for the low-level attitude control. Visual-inertial odometry is performed using the open-source package ROVIO [8], while the open sourced linear model predictive controller in [9] is utilized for position control.



Figure 2 - Diagram showing the components of the Multi-Modal Mapping Unit (M3U). The M3U consists of a pair of stereo cameras hardware synchronized with an Inertial Measurement Unit, Ultra-bright LEDs, and one to three Time-Of-Flight depth sensors.

The Multi-Modal-Mapping Unit

The M3U is a hardware synchronized visual-inertial-depth system capable of mapping and localization in dark environments. Figure 2 shows the M3U and diagrams the associated components. At the heart of the M3U is a 32-bit ARM microcontroller which produces the synchronization signals to the cameras, LEDs and the IMU, and also transmits the IMU data to the MPU. Images are recorded in monochrome from a pair of Global Shutter FLIR Chameleon 3 USB cameras which employ CCD (charge-coupled device) technology in lieu of the more common CMOS (complementary metal-oxide semiconductor) sensors due to their improved performance in dark and high dynamic range environments [10]. The cameras are separated by a baseline of 0.08m, triggered at 20Hz, and have a shutter time of 2 msec. The IMU is triggered at 200Hz and in a way such that every camera frame corresponds to an IMU frame taken in the middle of the camera's shutter. The stereo camera system is supplemented by a variable number of ToF Picoflexx depth sensors which provide a dense representation of the environment. Depending on the requirements of the mission, the M3U can utilize between one and three ToF sensors. Integration of three such depth sensors leads to very wide field of view which makes the system optimized for tunnel exploration.

In a tunnel, the environment is long but narrow, and therefore a system with wide field of view will reduce the amount of yaw motion required for mapping which greatly improves the exploration rate and range of the robot. Finally, the M3U is enclosed within a structure made of both 3D-printed nylon and carbon fiber, which assures structural rigidity while minimizing any additional weight.

Radiation Counting & Spectroscopy System

The Radiation Counting and Spectroscopy System consists of a scintillator interfaced with custom designed electronics for counting and spectroscopy data. The detector chosen is a Thallium-doped, Cesium-Iodide Scintillation Crystal, a Silicon Photomultiplier (SiPm) and a preamplifier in a small cylindrical package from Scionix. The scintillator itself weighs only 18g, and measures 66mm long and 16mm wide. This scintillator offers spectroscopy-grade energy resolution, is lightweight, and consumes less than 0.4W. A custom microcontroller circuit was designed to interface with the scintillator and provide both count-rate and spectroscopy information to the robot's MPU. Figure 3 depicts an architectural diagram of the RCSS.



Figure 3 - The high level architecture of the Radiation Count and Spectroscopy System (RCSS). A voltage pulse is output from the detector to the count and spectroscopy circuitry. A comparator array allows the microcontroller to log the height and frequency of the pulse.

The circuit consists of a series of 32 comparators which compare the scintillator's output signal against a series of reference voltages generated by two Digital-to-Analog Converters (DAC) on a 32-bit ARM microcontroller. This microcontroller counts the outputs from the comparators providing both the timing of pulses, as well as amplitude information for spectroscopy to the MPU. The use of the two DACs on the RCSS's microcontroller allows the system to vary the position and resolution of the reference voltages to tune the spectroscopy data for a specific energy range. In total, the RCSS, including the scintillator and all associated circuitry weighs only 41 grams. Figure 4 is a photograph showing the CsI scintillator and the counting and spectroscopy circuit.



Figure 4 - This figure shows the Radiation Count and Spectroscopy System (RCSS). The cylinder is a CsI Scintillator and Silicon Photomultiplier from Scionix, and the circuit is a custom designed system which interprets the pulses from the scintillator. The entire system weighs 41 grams.

The RCSS was calibrated with respect to its dosimetric response. A dosimetric calibration is necessary for inferring true dose rate statistics from the count rate output by the scintillator. Dosimetric calibration consists of placing the scintillator in a calibration chamber at various distances from a source of known intensity. As expected, this calibration revealed that the RCSS has a dose rate response which complies with the inverse square law, and therefore dose rate information can be extracted by fitting a linear equation to the count rate measured by the detector. Due to the unknown nature of the environment and therefore the unknown orientation of the source with respect to the detector, a pose-dependent calibration was also performed. This calibration procedure consists of orienting the detector at various angles with respect to the source. Figure 5 demonstrates that the scintillator used in the RCSS has a generally uniform response apart from a small cone directly behind the detector where the response is about 50% as sensitive, likely due to attenuation caused by the SiPm and preamplifier behind the crystal in the detector.



Figure 5 - Dosimetric and pose-dependent calibration results. The top plot shows the dosimetric response relationship between counts per second and the dose rate in terms of mR/hr. The bottom plot depicts the results of the pose-dependent calibration and the attenuation when the source is placed at 180 degrees with respect to the detector.

Source Localization Method

Radiation source localization on-board small aerial robots faces multiple challenges including the uncertainty in radiation field intensity measurements, and the limited flight endurance of such platforms. As scintillators count the number of discrete events, or interactions, that occur over a period of time, their measurements follow a Poisson distribution [11], and since a Poisson distribution dictates that the variance of the distribution grows with the mean of the distribution, the variance of their measurements increases with the strength of the radiation field. Therefore, in the presence of a stronger field, longer sampling times are required to accurately determine the intensity of the field. Second, a significant limitation of small aerial platforms is their limited endurance. Source localization methods on-board a small aerial platform, such as a quadrotor Micro Aerial Vehicle (MAV), cannot afford to employ strategies used in grid-based or rover-based radiation source localization methods as these typically consider a large amount of long dwell points.

The method used in this work accounts for the measurement uncertainty inherent in radiation measurements, and the limited endurance of aerial robotic platforms. The main challenge of radiation source localization in general, is that given a single measurement, the source can either be of weak activity nearby the sensor, or of stronger intensity further away. This method uses measurements obtained at "dwell points"; static positions where the robot is stationary (hovering) for a for a brief period ("dwell time"). The dwell time is set dynamically based on an initial and iteratively improved estimate of the field's intensity. Dwell points in higher intensity fields must have longer dwell times to allow the Poisson statistics of the individual samples to converge around the true mean of the distribution. Dwell points in background or in lower intensity fields should estimate the field strength quickly to reduce the burden on the robot's endurance. Figure 6 demonstrates the process of the algorithm.



Figure 6 – Illustration of the source localization algorithm in a step-by-step manner. Dwell points are the larger light green spheres, where the smaller green spheres show the position of the radiation detector. The translucent red spheres are the concentric spheres spawned at each dwell point. The blue circles show the circle of intersection between two matching intensity spheres. The yellow lines in Figure 6.g demonstrate how every point on a circle of intersection is evaluated against every other measurement. The small red sphere in Figure 6.h represents the source position estimate with the highest probability. The yellow arrow and cube in Figure 6.i represent the source location estimate using the occupancy map generated from the stereo camera and ToF depth perception systems.

In Figure 6.a, the robot arrives at a dwell point and starts collecting radiation measurements. After the dwell point's collection time has completed, the algorithm creates a series of concentric spheres around the dwell point which are visible in Figure 6.b. Each of the spheres is annotated with the appropriate source intensity given the radius of the sphere and the measurements collected at the dwell point. In Figure 6.c, the robot has arrived at a second dwell point. The algorithm again draws another set of spheres with respect to the second dwell point. The algorithm then finds the circles of intersection between spheres from different dwell points which match in intensity, these circles are visible in Figure 6.d. Subsequently the algorithm then discretizes these intersection circles into points which are visible in Figure 6.e. In Figure 6.f, the robot has arrived at a third dwell point, the algorithm compares the readings obtained at the third dwell point with all intersection points found between the spheres of the first and second dwell points. The algorithm evaluates how well each intersection point satisfies the inverse square law given the readings obtained at the third dwell point. This process is visualized in Figure 6.g.

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The algorithm thereby finds the probability of obtaining the measurement at the third dwell point if a source of the expected intensity was found at the intersection point. The intersection points with the highest probabilities are then found and their centroid is used as the source location estimate, as visualized in Figure 6.h using a red sphere. Finally, in Figure 6.i, the algorithm finds the closest occupied voxel to the source position estimate using the occupancy map from the mapping solution, and uses this new position as its radiation source position estimate.

This source localization method addresses two important challenges of aerial robotic radiation source localization. First, with respect to radiation measurement uncertainty, the method utilizes an adaptive dwell time process to dynamically adjust measurement periods dependent on an initial estimate of the field at the measurement point. Second, the method was found to efficiently deal with the limited endurance of the robot by requiring as few as three measurements to obtain a reliable estimate of the source's position, and by adaptively tuning the dwell times to measure stronger fields for longer periods of time.

Source Identification Method

To suit scenarios in which the identity of the source isotope is unknown, a source identification method was developed. Using the spectroscopy information obtained from the RCSS, identification of the particular source isotope is performed using a least-square-error fit. The standard energy calibration procedure for scintillators and multi-channel-analyzers consists of exposing the scintillator to sources of known energies, finding the channels which corresponds to the peak energies of the sources, and extrapolating the corresponding energies for each channel. As these experiments only seek to identify the source isotope, the exact energy calibration is unnecessary. Instead, the energy calibration in this work involves exposing the detector to the isotopes of interest.



Figure 7 - Characteristic spectroscopy plots for Cs-137, Co-60, and Ra-226, as well as experimental spectra from the active exploration experiment. The source identification algorithm correctly identifies the source in the experiment as Cs-137.

Spectral information for each isotope is collected for a period of three minutes. The spectroscopic data is then normalized to provide a characteristic, idealized spectra for each type of source. These spectra collected during calibration therefore represent the ideal spectra for that isotope.

If the robot had an infinite amount of time to dwell and measure a source's spectra it would approach these ideal spectra assuming the field is not attenuated, the background field doesn't have strong energy characteristics, and the sensor is noise free. The first three plots in Figure 7 show the ideal energy spectra for Cs-137, Co-60, and Ra-226 before normalization. During flight, as the robot collects the spectroscopic data from the scintillator, it first performs normalization and then an analysis that relies on least-squares-error minimization principles is run on the data collected against the characteristic spectra collected for each source type. This data, collected during the active exploration experiment, is shown in the bottom right of Figure 7. The analysis consists of calculating the average squared error across all channels between the experimental data and the idealized spectra for each isotope. The comparison result which has the smallest average error is determined to be the isotope which is causing the observed measurements, and the source position estimate from the localization algorithm is further annotated with the isotope identity of the source.

EXPERIMENTAL RESULTS

A series of experiments were conducted to validate the performance of the M3U and the RCSS alongside the associated algorithms for mapping and source localization, as well as based on the integration of autonomous exploration path planning functionalities. All experiments were conducted inside the Yellow Jacket Tunnel, a train tunnel located in Virginia City, Nevada. The tunnel is approximately 4.25m wide, 7.5m tall, and 137m long. The tunnel features a standard rail track in the center of the tunnel, and exposed rock walls with wooden beams and steel ribbing representing a realistic and challenging environment both for navigation and mapping, as well as for radiation source localization.

Degraded Visual Environment Exploration

The first experiment presented is an autonomous mission within the Yellow Jacket Tunnel. It consists of the robot flying in complete darkness exploring the tunnel autonomously using the receding horizon next-best-view exploration path planner [12]. The specific algorithm spans a tree of possible robot trajectories and identifies a finite-depth branch that maximizes the expected exploration gain. The first step of this path is conducted, while the whole process is then iteratively repeated as the robot explores and maps the environment. Figure 8 demonstrates that accurate localization and dense mapping was achieved. It is noted that the receding horizon exploration planner is open-sourced as a ROS package.



Figure 8 - The dense 3D mapping obtained from the M3U exploration mission. Even in darkness, the robot can localize itself and develop a dense reconstruction of the environment.

Radiation Source Localization & Isotope Identification

Two radiation source localization and isotope identification experiments were conducted to evaluate the performance of the RCSS. The experiments consist of a Cs-137 source placed within the Yellow Jacket Tunnel, about 10m from the entrance. The Cs-137 source is a non-destructive testing device used in industrial radiography which measures approximately 618.1uR/hr at a distance of 0.65m. The first experiment consists of the robot autonomously following a predetermined grid-pattern above the source. The robot obtains a source location and isotope estimate at the third measurement with a localization error of 0.28m. At the end of the experiment the system has a final estimate of similar localization error against the ground truth position of the radiation source. The results of this experiment are depicted in Figure 9.



Figure 9 - The radiation source localization algorithm performing over a predetermined trajectory consisting of eight dwell points. Reliable radiation source localization (distance error of less than 0.3m) is achieved already at the third measurement (dwell point) of the robot.

The second experiment consists of an autonomous flight using the receding horizon next-best-view planner as in the first presented experiment. In this experiment, the robot explores and maps the environment autonomously and simultaneously conducts radiation detection and source localization. In particular, the planned exploration viewpoints are also used as dwell positions leading to reliable source location and isotope identity estimation at the third measurement point. The robot completes the experiment with a final radiation source localization error of 0.38m. The result of this experiment is depicted in Figure 10.

A video of the above experiment can be found here: https://youtu.be/GoVHEM4Ju14



Figure 10 – The results of an autonomous exploration experiment. Three dwell points (represented by the translucent green spheres) allowed the robot to localize the Cs-137 source within 0.28m. The red sphere denotes the source localization algorithms initial estimate. The yellow arrow and the yellow cube show the nearest occupied voxel to the source location estimate.

CONCLUSIONS

In this paper, a system for exploration, mapping and characterization of nuclear facilities was presented. The localization and mapping system which was designed to enable the robot to navigate in dark visually degraded environments was described and experiments which tested functionality of the multimodal mapping unit were outlined. The radiation counting and spectroscopy system which gives the robot the ability to measure radiation fields was presented and algorithms which allow the system to localize radiation sources were detailed. Most importantly, the system and algorithms designed function robustly within the endurance limitations of small aerial robots ideal to be used in GPS-denied, possibly visually-degraded indoor environments such as the PUREX tunnels and other facilities. Finally, a series of experiments which demonstrate the robotic system as a whole were presented and validate the system as a tool for mapping and characterization of nuclear facilities. Future work will emphasize on system reliability, capacity to handle large, distributed radiation fields, as well as extensive field evaluation and demonstration.

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