Unmanned Aircraft Applications in Radiological Surveys

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***Abstract*—Unmanned vehicles, equipped with radiation detection sensors, can serve as a valuable aid to personnel responding to radiological incidents. The use of tele-operated ground vehicles avoids human exposure to hazardous environments, which in addition to radioactive contamination, might present other risks to personnel. Autonomous unmanned vehicles using algorithms for radioisotope classification, source localization, and efficient exploration allow these vehicles to conduct surveys with reduced human supervision allowing teams to address larger areas in less time. This work presents systems for autonomous radiation search with results presented in several proof-of-concept demonstrations**.

Keywords*—*Aerial gamma-ray survey, Emergency response, unmanned aircraft, Non-linear dimension reduction

I. INTRODUCTION

The use of unmanned aircraft to assist in radiological surveys, both pre- and post-detonation, remains an emerging technology coincident with the evolution of unmanned aircraft and payloads for sensing and sampling. Some of the past novel work includes development of a tethered nuclear materials sampling payload, a spatially variant deconvolution method for source localization, and collaborative Unmanned Aerial Vehicle (UAV) Unmanned Ground Vehicle (UGV) sensing and localization to safely map source distributions. As threats continue to emerge and the acceptance of unmanned aircraft grows, an expanded portfolio of uses including event clearing, intelligent search, post-detonation analysis, and tiered search strategies is being proven.

This paper reports on work at Virginia Tech in pre and post-detonation data collects with UAVs ranging from 10 kg hexacopters to 90 kg single-rotor helicopters. We have shown the integration of UGVs into a measurement system designed to reduce risk to first responders while generating accurate analytics of chemistry and location when mapping radiological distributions. Results are presented for several experiments that define use cases of interest to first responders.

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II. MOTIVATION

The use of unmanned systems, both UAVs and UGVs, to assist in the search of nuclear materials has been an outgrowth of applications in disaster response, with significant investment after 9/11. Despite the advantages of autonomous unmanned systems, the transition to full autonomy has been slower than with other Unamnned Aerial System (UAS) applications, such as 3D mapping. This is due in part to a conservative response community that has shown reluctance in the past to embrace the full benefits of autonomy in support of human-machine teaming. More recently, acceptance of perception and autonomy in nuclear materials identification and localization has accelerated, and their useful applications are growing.

Scalable and complementary unmanned systems are a focus of research to integrate small autonomous systems into existing search methods that include large manned aircraft as well as backpack-carried detectors. Some of the mission protocols include initial assessment of a post-detonation environment, localization of sources, 3D data collection, and the expanded use of sensing in the non-visible EM bands.

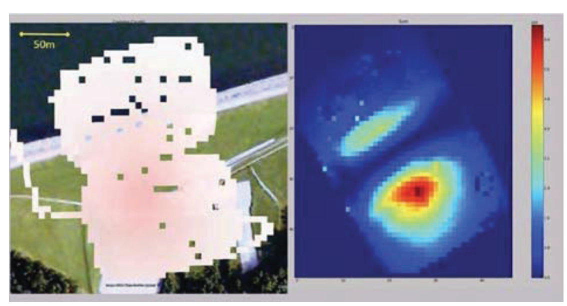

Fig. 1. Deconvolution method of source localization. The presence of a weaker source is hidden in the raw count data shown on the left, but is revealed when deconvolution is applied, shown on the right.

III. RADIOLOGICAL ISOTOPE MEASUREMENT AND MODELING

After collection of aerial radiological measurements and terrain imagery, there is a challenge in finding the ground-level radioactive distribution which has numerous solution strategies. Kochersberger, et. al [1], showed that a spatially variant point spread function could be employed in deconvolution to map the location of point sources using raw gamma count data. Fig. 1 shows the result of localizing two closely spaced sources from a 60 m overhead scan using a Yamaha RMAX autonomous helicopter. The stronger source obscures the location of the weaker source in the summed gamma counts shown on the left.

The use of summed gamma counts is a first-order method of localization. Incorporating spectral and visual data has the potential to identify sources with an intensity nearly equal to the background radiation level. Computational harmonic analysis has been applied to support dimension reduction, multiscale representation, and multi-modal data fusion resulting in robust spectral anomaly detection. Sources that would normally be buried in background radiation signatures are extracted with these methods.

Laplacian Eigenmaps (LE) and Schroedinger Eigenmaps (SE) have already been successfully used to perform, respectively, unsupervised and supervised clustering of radiological data [2]. An example of this is seen in Fig. 2, where the application of the Eigenmap nonlinear dimension reduction reveals relatively subtle spectral signatures without the need for a human spectroscopist. Class 5 in the figure is determined to be significant despite the fact that the gross count levels were the same as background; small peaks in the low energy region are discerned from the unsupervised method indicating the unexpected presence of Cs-137.

Moreover, preliminary results have shown that the Fourier Scattering Transform (FST), a hybrid Fourier and neural network transform that was developed in Czaja and Li [3,4] is effective at locating relatively weak sources. Fig. 3 shows a plot of predicted radiological anomaly source location using FST.

IV. MULTI-AGENT SEARCH METHODOLOGY

Operating a multi-agent search mission has benefits in complex environments where air and ground systems provide complementary data for analysis. Aerial search can be employed

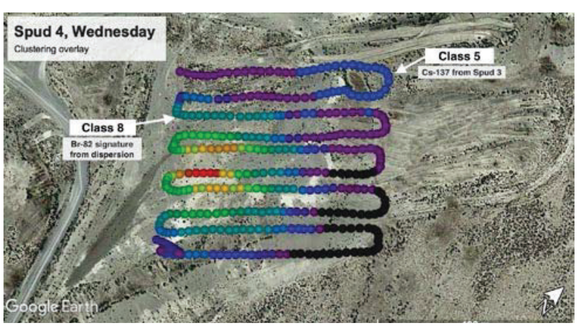

Fig. 2. An aerial scan conducted by Virginia Tech with a 2" x 2" NaI scintillation-type detector over a dispersion site of Br-82 using conventional explosive.

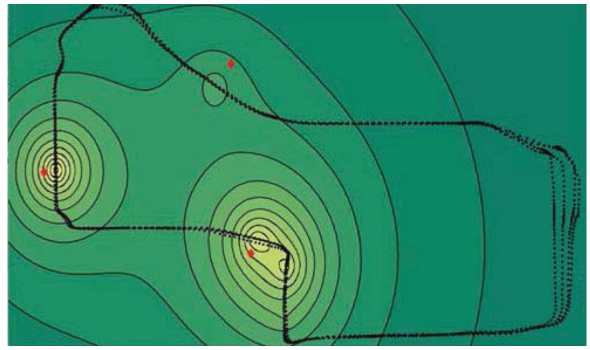

Fig. 3. Spectral data showing source prediction using FST. The black points are sample points and the red diamonds are true source locations. Half of the data was used as a training set for the FST coefficients while the other half was used for test.

in hard-to-traverse areas, and terrain classification is simplified using nadir aerial imagery. Ground robotic systems can be directed to areas of interest based on classified traversability from the aerial imagery, and they have the capability of long dwell data collection not possible using UAVs. Combined, this data allows the robotic system to answer the question: *what does the classified environment and the radiation map tell us about the next place to search?* Furthermore, generalizing a search mission to include human agents offers additional flexibility to the autonomous system while improving overall search efficiency.

Our approach to a multi-agent search and localization strategy is subdivided into three main tasks: Data collection, initial radioactive source location/distribution estimation, and final estimation. The following sections will describe different data collection hardware, and approaches for source estimation.

A. Data Collection

Methods of aerial data collection range from use of the Yamaha RMAX autonomous helicopter carrying a 3” x 9” NaI scintillation-type detector, to a custom-designed hexacopter that carries a 2” x 8” crystal or 2” x 2” crystal plus a Cadmium Zinc

Fig. 4. RMAX with NaI detector and stereovision system in-flight.

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Fig. 5. VT-designed hexacopter with CZT and NaI detectors installed (16.8 kg gross weight).

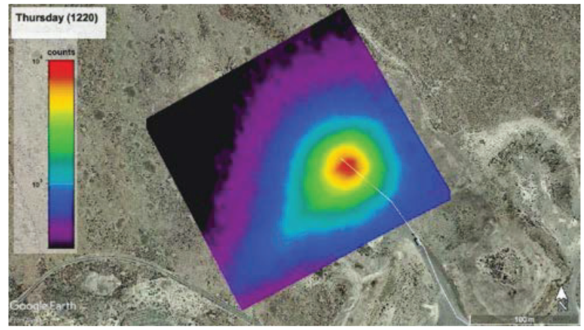

Fig. 6. Radiation contour generated from the INL flights, July 2018.

Telluride (CZT) imager. The RMAX, shown in Fig. 4, has been equipped with a stereovision system useful in classifying terrain traversability and performing 3D reconstructions. As a 90 kg system capable of lifting 20 kgs of payload, the RMAX has also been used to carry a custom-designed, tether-deployed ground sampling robot which remains tethered throughout its mission for retrieval.

A VT-designed hexacopter shown in Fig. 5 has been developed as a low-cost aerial platform with a 6 kg payload capacity. It's high payload capacity combined with a Swiftnav Piksi Multi Real Time Kinematic (RTK) Global Position System (GPS) allow it to accurately hold position while carrying the gamma-ray imager.

A smaller hexacopter adapted from a comercialy available airframe has also been utilized, shown in Fig. 10. An Nvida TX-2 computer and Swift Piksi Multi RTK GPS provide computational power and positional accuracy necessary for adaptive sampling and route planning for ground systems. These systems has the flown experiments summarized in Table 1.

An example of the utility of drone measurements is provided in Fig. 6 where the spatial resolution is much greater than what a manned aircraft can accomplish since their speed and altitudes do not favor data resolution. Drones fill a significant need for higher resolution data in a tiered discovery, where initial findings from manned aircraft point to areas of interest that demand further investigation by drones. More accurate source classification and safe perimeter definition follow from the higher quality data products.

Table I. 2018 Experiments

Date	Location	Experiment
1/18	SRNL	Aerial scan, identification of sources, classification, and secondary ground robotic and aerial long-dwell data collect
4/18	INL	Aerial scan over dispersion site of Br-82. Data is dense enough to create accurate plume maps. Dimension reduction is used to find weak isotopes
7/18	INL	Another aerial survey campaign over dispersal site of Br-82.
10/18	NNSS	Scan at crater to identify interesting isotopes. The system was designed for BVLOS flights inside the crater

Radiation measurements from an unmanned aircraft should be complemented by nadir imagery which provides context to the radiation data and is also used to inform ground robotic and manned searches. Using a custom stereovision system, we have developed a data processing architecture to compute disparity maps and find feature point matches to produce 3D mosaics for route planning *during* an overflight, accelerating the speed at which ground-based inspections can occur shown in Fig. 7. Christie [1] showed the benefits of reasoning about 3D and 2D information to obtain accurate classes on the ground which reduce mission failure with low-risk route plans in a detailed search.

B. Online Radioactive Source Location Estimation

A challenge in most data collection scenarios is to extract meaningful source information when background radiation levels can be at the same order of magnitude as the source. By leveraging an analytical model between the counts observed in a detector volume and the activity of sources of radiation, environments may be efficiently explored to reduce misclassification risk and hypothesis uncertainty.

This analytical model was derived for a spherical detector volume with mono-energetic point and validated in Geant4 [5], a particle transport simulator. If the relative position of a

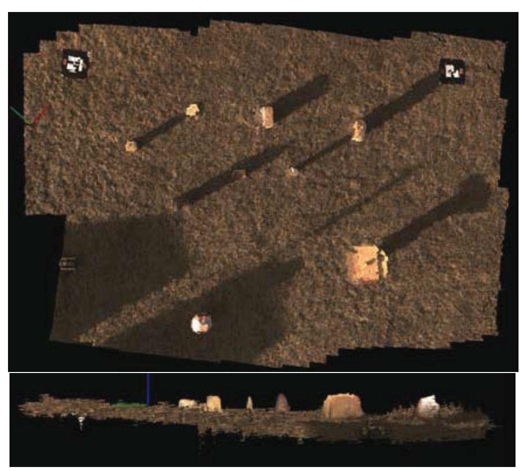

Fig. 7. A progressive 3D mosaic created during image capture to accelerate ground-based route planning for inspection in time-critical situations.

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measurement and a source is known, then there is a linear relationship between the unknown activity of the source and the counts recorded in the measurement. A set of hypotheses on the position of sources within the environment can be constructed. Then the strength as well as an uncertainty of each source in each hypothesis may be estimated through Maximum Likelihood Estimation. The likelihood of each hypothesis itself may be computed to identify the most likely hypothesis out of the set.

With this model, it is possible to estimate the expected reduction in uncertainty that would occur in each hypothesis if the robot were to make additional observations. For each candidate in a set of trajectories, this improvement may be characterized by metrics such as mutual information and the reduction in misclassification risk, allowing the system to select the most informative trajectory. Misclassification risk is the risk that given a user defined threshold on source activity, a source which is currently estimated to have a strength above that threshold is actually weaker than that threshold and vice versa. This risk may be estimated on a per source basis by examining the estimated strength and uncertainty in strength of each source in each hypothesis. Mutual Information, given by the difference in entropy of the distribution, measures the reduction in uncertainty in the estimate of the strength. Maximizing Mutual Information maximizes the reduction in uncertainty. By optimizing over these rewards, the system is able to select the most informative trajectory through the environment.

This method enables observations from multiple independent robots with separate radiation detectors to be combined to form single estimate of the position and strength of a source in the environment. The planning method described above allows the paths of these robots to be coordinated to efficiently explore the environment by reasoning over their joint effects on the distributions.

Fig. 8 shows an example of a trajectory navigated by the UGV when aerially collected radiation measurements were used to initialize the model for a good initial guess on the location of the point source.

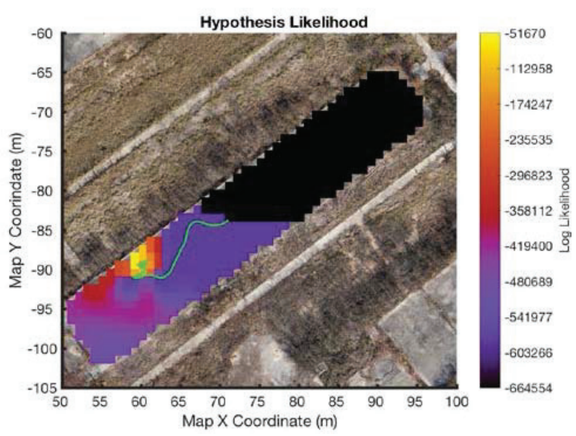

Fig. 8. Trajectory taken by UGV to localize point source of radiation. This trajectory was informed by aerially collected radiation measurements. Color indicates the log likelihood of hypotheses on the position of the point source. Warmer indicates more likely.

Fig. 9. In this example, aerial data is collected over two weak sources (pink), and a single source (red) is identified. Starting 100m away, a ground robot takes the minimum cost path to visit the source based on a power consumption heuristic and distance.

C. Terrain Based Source Inspection

We approach the problem of source estimation as a two-step process where the second step leverages data from the first round to improve the allocation of air and ground sampling resources. Reconstructing the 3D environment from nadir imagery and semantically classifying the visual 2D data allows ground vehicles to efficiently navigate the environemnt. Fig. 9 shows an experiment conducted at Kentland Farm, near Virginia Tech, where the first aerial scan provides a source location estimate. The UGV then navigates to the estimated source location to collect longer dwell data using the estimated terrain classes to minimize cost.

Operational tempo is maintained in the overall search mission by generating 3D terrain reconstructions while the initial survey flight is in progress. Aerial data will provide the bulk of the planning information, but ground vehicles will augment this with higher resolution data for obstacle detection and the capacity for on-line learning of terrain costs to reduce the dependence on comprehensive training data sets.

Using aerial data generated by the UAV, the LE spectral clustering provides an initial probability distribution map for the distribution of radioactive sources. The UGV then surveys the most likely locations following a trajectory computed by the path planning algorithm. This method adapts the work of Bhattacharya, Ghrist, and Kumar [6] that uses persistent homology to find trajectories in environments with uncertain traversability.

Once the UGV reaches a target location, it collects higher quality data for the supervised FST algorithm to classify. The FST computes oscillatory features of the spectral data and satisfies several desirable properties for classification: it is energy preserving, it is stable with respect to additive noise, and it contracts sufficiently small translations and diffeomorphisms.

After classification, the spectral information corresponding to the scouted location is incorporated into the global dataset and the probability distribution is recomputed using the supervised spectral clustering algorithm of SE. The path for the UGV is recomputed according to this new distribution. This process continues until all suspected locations are checked.

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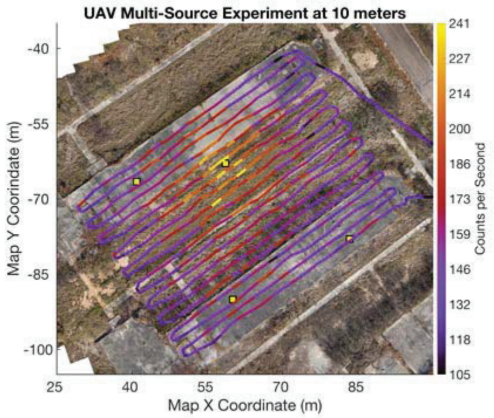

Figure 10. Initial exhaustive scan result. The yellow points indicate where sources have been placed. The colored track indicates the path of the UAV and the measured counts per second.

When an environment is large, complex, and includes locations inaccessible to ground vehicles, the combined deployment of both UAVs and UGVs allows the system to localize sources. Multi-agent task allocation ensures that the environment is efficiently and completely explored while considering the mobility constraints of the vehicles and the effectiveness of the sensors equipped to each vehicle.

A demonstration of a search and classification mission with variable terrain traversability was performed at a National Labs in January, 2018. In this experiment, three sources were located on concrete pads, considered traversable for the UGV, and one source was placed in a grassy area, considered not traversable for the UGV. An initial scan of the area provided source contours that would be used to inform a secondary search using either the UGV or UAV, depending on the terrain type. Fig. 10 shows the initial scan result.

LE dimension reduction was performed on the exhaustive search data to estimate locations for secondary exploration. Additionally, the aerial imagery was classified to determine where the UGV can explore, and a route plan was generated for both the UAV and UGV, shown in Fig. 11. The air and ground vehicles are tasked to dwell at each exploration point to obtain higher quality data.

V. CONCLUSION

This work has reviewed several uses of UAVs in response to radiological incidents. UAV's are able to fly at low altitudes enabling them to make effective radiation measurements despite their limited payload capacities. Methods such as LE and SE have been used to automatically detect anomalous sources in raw gamma-ray spectra. Aerial vehicles are also suitable to carry scene mapping sensors in the form of either Lidar or stereo vision systems. This combination of scene information and radiation measurements not only improves the accuracy of radiation models, but also enables terrain informed navigation for UGVs to investigate candidate source locations. Operational tempo may be improved by utilizing online algorithms for terrain reconstruction and source localization.

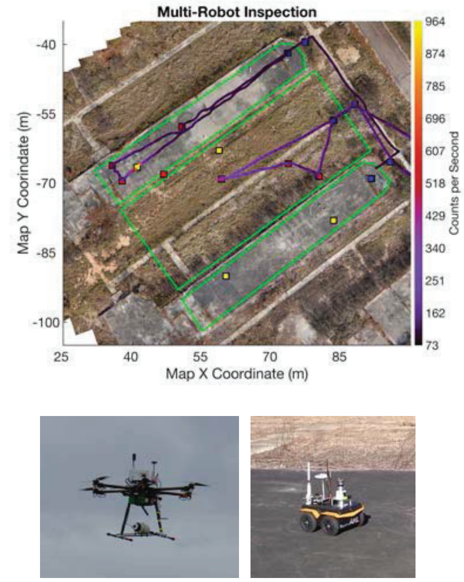

Figure 11. The top and bottom concrete pads and the center grass area are identified as traversable and non-traversable regions respectively for the ground robot (UGV). Yellow points are the actual radiation sources while the red points are the estimated location

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