CALL
HDTRA-1-11-16-BRCWMD-BAA Amendment 4 (December 2014)

TOPIC
Period E - Topic 1: Methodologies for Autonomous Radiological and Multi-mode Information Collection (Thrust Area 1)

TITLE
Collaborative Autonomous Decisions of Vehicle Teams for Radiological Search

EFFORT
Multidisciplinary - $350,000/yr
Three base years plus two options years

ABSTRACT
Effective search of radiological weapons-of-mass-destruction (RWMD) using autonomous teams of unmanned vehicles is important and immature. It is important because small unmanned vehicles can reach places that humans cannot physically or safely go and do so while sharing data far more efficiently than human teams [1,2]. This field is immature because the powerful predictor-corrector techniques developed for robotic search algorithms have not yet been applied to the RWMD search problem's unique mix of sensing and processing capabilities. Proposed here is a multi-year multi-disciplinary effort aimed at developing information gathering policies for scalable teams of autonomous vehicles operating collaboratively to search for RWMD in large and complex structures. A major theme of this work is the study of the real time decisions the vehicles will make (e.g., next sensing position and relative positions) based on the team's constantly updating estimate of the local radiological background and salient features of the local environment. We will employ both simulation and live experiments to both demonstrate and test the custom predictor-corrector algorithms.

MOTIVATION and SCOPE
Human search of complex and large structures (warehouses, buildings, containerships) for radiological weapons-of-mass-destruction (RWMD) is cumbersome, imprecise, and sometimes spatially limited. For example, human teams may have restricted physical access to an area without disassembly or rearrangement of the contents of the structure. Further, existing detectors can be heavy or awkward to carry, and present information that cannot be easily processed in real-time to support collaborative sensing. Many times, either or both these constraints thwart the search team from following the plan as intended, limiting the overall certainty of localizing or clearing a structure of a RWMD.

Unmanned vehicle teams carrying sensor packages and operating autonomously can overcome many of the challenges presented above. By fusing their data in real time from multiple positions, they can yield a higher net certainty for localizing a RWMD, potentially providing both higher spatial precision of detection events and greater evidence that a clear area is, in fact, clear. It is the object of this work to understand, simulate and test methods that will enable the marriage of radiological sensing intelligence with the physical and networking capabilities of teams of unmanned vehicles.

The theoretical motivation for our approach comes from the successful application of Bayes' Theorem to similar search problems in other robotic domains [3,4]. Bayes' Theorem allows us to estimate the probability of an event, such as the presence of RWMD in a location, from a sequence of measurements rather than trying to directly measure and analyze faint and noisy signals. While the power of this statistical predictor-corrector approach has been demonstrated in multiple applications, each one requires developing a fundamental understanding of the properties of the signal generation and detection to ensure it is applied correctly.

Therefore, the scientific challenges that will be addressed in this work are:

(1) how signal level and type influence the autonomous team's real time estimate of relevant information (proximity, background, foreground);

(2) how to quantify the information gain from permutations of sensor types (e.g., gamma-ray intensity, gamma-ray spectra, neutron arrival time, and other direct radiological sensor information) and vehicle location, to minimize unnecessary sensing redundancy;

(3) how to couple indirect radiological sensing (infrared, acoustic, hyperspectral) with the flexibility of autonomous vehicles to estimate the presence and locality of a RWMD.

In all cases, net certainty of RWMD source localization will be the primary feedback metric.

APPROACH and RESEARCH PLAN

Cooperative decision making between many vehicles with varying mobility and sensing capabilities, without human interference, to localize or clear a structure of a RWMD source has not been treated from the ground up. There are a number of groups and published works that have treated isolated parts of the problem, which we will use and build from, but not the generalized problem. From another perspective, no one has really thought about how one can or should use all of the information that can be made available from tens or hundreds of vehicles to attack the RWMD sense problem within a large and complex structure, how to minimize unnecessary sensing redundancy, and how to deal with inconsistent data from redundant or complementary sensors [5].

Paramount to the success of autonomous searches are the design of robust rulesets for many vehicles with sensors of low absolute efficiency, which are capable of changing their relative positions to maximize their information gain. In comparison, the use of a few vehicles (or humans) with sensors of higher absolute efficiency can be inhibited by mobility limitations due to their large size, weight constraints, and power requirements. To approach this problem the investigators will first demonstrate (by simulation) that the whole is greater than the sum-of-the-parts. To do this, the investigators will develop an information theoretic weighting system for each of the detector types depending on their relevancy and a map-based predictor-corrector system that will provide more information than is available from individual detectors alone.

During the initial phase, the team will also perform ground level research to determine the minimum and most effective combination of sensors capable of adequately monitoring sensor position, radiological detection, and non-radiological characterization of the environment. Possible sensors include acoustic sensors for positioning and obstruction detection, modified range sensors, solid-state gamma detection, solid-state neutron detection, Raman, FTIR, and imaging cameras to name a few. This will include sensor testing, data fusion algorithm development, and experimental validation of results.

The next phase of the project will involve researching how to perform real-time autonomous parameter input into radiological simulation software such as the SoftWare for Optimization of Radiation Detectors (SWORD). Detailed simulation of radiation transport in complex environments is an important part of this effort. For this purpose, the SWORD package developed at the Naval Research Laboratory (NRL) will be used. SWORD allows multiple Monte Carlo and discrete ordinates transport codes to be applied to complex simulation models, including moving objects. Since development is via a CAD-like interface, the time required to create the large number of simulation objects required for this program is reduced. Real-time, autonomous updating of the input parameters to the SWORD package will improve background radiation estimation and improve search accuracy in areas of low source activity, high background and/or shielded WMD sources.

EXPECTED OUTCOMES and IMPACT to C-WMD SCIENCE

As a direct result, the science of C-WMD searches will benefit from the ground level research in autonomous decision making and advances in sensor fusion. This work aims to improve on this concept with the fusion of multiple sensors with high degrees of orthogonality including: position/mapping, radiological signal intensity, and characterization of the local environment.

Success of the work proposed here will carry-over to not only, chemical and biological detection, but also alternative sensing communities that are aided by the use of unmanned vehicles operating autonomously including the developing field of emergency response search and rescue. The fields of data fusion and computer science will also benefit from the research into multiple dataset fusion and mobile neural network development.

BUDGETARY ESTIMATE

Proposed is a multi-disciplinary multi-organization program for $350,000/yr for three base years and two option years; the base total would be $1,050,000 and the option total would be $750,000. UMKC will serve as prime, and NRL Code 7651 and NRL Code 5514 as subawardees. Vehicle and sensor procurement, and integration supplies thereof, will represent a minor portion of the budget. The bulk of the effort will be salaries for three graduate students, three undergraduate students, and the NRL scientists for the simulation work and phenomenology development.

TEAM and MANAGEMENT PLAN

The team is composed of three investigators: the PI, X from the University of Missouri – Kansas City (UMKC) Dept. of X, Co-PI Y and Co-PI Z. The technical workload and reporting will be split evenly between the PI and two Co-PIs. The administrative responsibilities for report submissions and budget oversight will be the sole responsibility of the investigator from the prime institution. Three graduate students from UMKC will be individually supervised, one by each of the investigators, and all investigators and students will participate in monthly status meetings. There will be three undergraduate students, one assigned to aid each graduate student. The overall team will hold biannual meetings in Washington DC, one of which will coincide with the annual review. In terms of technical contributions, X will oversee RWMD specific algorithm development, Y will oversee simulation of the algorithms, and Z will oversee testing, including algorithm implementation; in all technical work, each investigator will overlap, provide suggestions/recommendations, and, analyze comparisons (a 60% overlap in our Venn diagram of technical responsibilities).

CHALLENGES and RISK

While the sum of the individual detectors being greater than their whole equivalent has merit, spurious or false counts from the individual detectors could potentially increase the background, decrease the net certainty (despite their delocalization ability) and disprove the posited position. As an exaggerated example, 1000 miniaturized photomultiplier tubes coupled to detectors with $1/1000^{th}$ the absolute efficiency of a single detector with single photomultiplier tube would likely yield a false count rate well in excess of the single large detector. While this is a potential risk, a detector specific metric may be emplaced, additional constraint through energy analysis may be applied, or, the number of detectors may be reduced to reduce the background until at or below the single detector certainty. We really won't know what impact a higher background has until the delocalization merit of the individual detector with lower individual absolute efficiency is studied.

Representing vehicle and detector capabilities (openings sizes that can be entered, battery life, payload, detector positioning and angle, on-board processing, effective communication distance, communication rate, obstacle traverse) in the phenomenological projections and simulation work, to ensure realism, will be a challenge. To address this problem, all vehicle capabilities will be listed and given values – when the vehicle approaches an obstacle or has to use its capability in the simulation, with a value close to its capability value, the action (e.g., traversing stairway) will be given a simplified Monte Carlo-like roll of the dice to determine whether it achieves the intended goal providing some realism.

REFERENCES

1. K. Ryu, *Autonomous Robotic Strategies for Urban Search and Rescue*, Dissertation, Virginia Polytechnic Institute, Blacksburg, VA.,(2012)
2. E. Olson et. al., "Exploration and Mapping with Autonomous Robot Teams", *Commun. ACM* **56** (2013).
3. T. Furukawa, F. Bourgault, B. Lavis, H. F. Durrant-Whyte, "Recursive Bayesian Search-and-tracking Using Coordinated UAV's for Lost Targets", *IEEE Inter. Confer. Robotics Auto.* 2006, Orlando, Fl., (2006).
4. T. Furukawa, L. Chi Mak, H. Durrant-Whyte, "Autonomous Bayesian Search and Tracking, and its Experimental Validation", *Advanced Robotics* **26** (2012) 461-485.
5. A. Howard, L.E. Parker and G.S. Sukhatme, "Experiments with a Large Heterogenous Mobile Robot Team: Exploration, Mapping, Deployment and Detection", *Intl. J. Robotics Res.* **25** (2006) 431-447.